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NARIÊ RINKE DIAS DE SOUZA

CLIMATE AND LAND USE IMPACTS OF INTEGRATION OF BIOENERGY AND LIVESTOCK VALUE CHAINS IN BRAZIL

IMPACTOS CLIMÁTICOS E DE USO DA TERRA DA INTEGRAÇÃO DAS CADEIAS DE PRODUÇÃO DE BIOENERGIA E PECUÁRIA NO BRASIL

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Tese apresentada à Faculdade de Engenharia de Alimentos da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutora em Ciências.

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"Cada (tic-tac) es un segundo de la vida que pasa, huye, y no se repite. Y hay en ella tanta intensidad, tanto interés, que el problema es sólo saberla vivir. Que cada uno lo resuelva como pueda."

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RESUMO

Há uma necessidade urgente de agendas nacionais destinadas à mitigação das emissões de gases de efeito estufa (GEE) para desacelerar o aquecimento global. Enquanto isso, projeções futuras indicam uma expansão na demanda de alimentos e energia, aumentando a pressão no uso da terra. Práticas aprimoradas de manejo da terra são fundamentais para intensificar a produção agrícola sob diferentes cenários de mitigação das mudanças climáticas. Ao empregar subprodutos de biocombustíveis como ração animal para liberar terras para produzir biomassa, os sistemas integrados bioenergia-pecuária (BLI) podem ser vantajosos para ambas as partes e para mitigação de GEE, simultaneamente atendendo às demandas de alimentos e energia do Brasil. Entretanto, sua viabilidade técnico-econômica e implicações ambientais ainda são incertas, e dependem da disponibilidade de biomassa, logística e impactos nos ecossistemas, todos altamente dependentes da localização e fatores regionais. Esta tese avalia 1) oportunidades, desafios e localizações potenciais para expandir o BLI no Brasil; 2) implicações técnico-econômicas e ambientais numa perspectiva de uso da terra; 3) impactos econômicos e emissões de GEE georreferenciados da expansão do BLI em localizações potenciais e a contribuição para futuras demandas energéticas e metas de mitigação de GEE. As biomassas consideradas para a produção de bioenergia são cana-de-açúcar, milho e soja em biorefinarias produzindo ração para engorda de gado de corte. A avaliação técnico-econômica e a Avaliação do Ciclo de Vida foram modeladas utilizando inventários gerados pela Biorefinaria Virtual, desenvolvida no LNBR/CNPEM. A avaliação georreferenciada dos BLI considera produtividade de biomassa e recolhimento de palha espacialmente explícitos; áreas disponíveis para expansão são restritas a pastagens dentro do Zoneamento Agroecológico da Cana de Açúcar (ZAE), excluindo biomas e *hotspots* de biodiversidade. Comparados aos sistemas convencionais, os BLI apresentaram impactos tecno-econômicos positivos e menores emissões de GEE, reduzindo o tempo de retorno do investimento por quase metade, e resultando na razão valor presente líquido para investimento 5 vezes maior. Produzir mais biocombustíveis usando menos terra possibilitou cortar pela metade as emissões de GEE do BLI em comparação ao convencional. Áreas potenciais de expansão estão concentradas em seis estados da região Centro-Sul do Brasil (SP, PR, MT, MS, GO e MG). Até 89 bilhões de litros de etanol poderiam ser produzidos e 139 milhões de toneladas de CO_2eq poderiam ser mitigadas em 16 milhões de hectares. A expansão dos BLI no Brasil poderia atender à demanda projetada de biocombustíveis do RenovaBio em 2030. Todas as opções BLI poderiam atender pelo menos 50% das demandas de etanol dos *Shared Socioeconomic Pathways* para 2030 e 2050. As emissões evitadas poderiam representar até 15% dos GEE a serem mitigados até 2030, conforme compromisso assumido no Acordo de Paris. Este estudo pode fornecer importantes informações para políticas estratégicas tanto para o setor de biocombustíveis quanto da pecuária. A avaliação da sustentabilidade dos BLI pode ajudar a atender às demandas futuras globais de energia e metas de mitigação de GEE, ao mesmo tempo em que reduz a pressão do uso da terra para produção de alimentos e energia, sem comprometer os *hotspots* de biodiversidade e os biomas protegidos.

Palavras-Chave: biocombustíveis, análise técnico-econômica, avaliação do ciclo de vida

ABSTRACT

The world urges for national agendas aiming at mitigation of greenhouse gas (GHG) emissions to decelerate global warming. Meanwhile, projections indicate an expansion in food and energy demands, increasing pressure on land use. Improved land management practices are fundamental to intensify land-based outputs under different climate change mitigation scenarios. By employing biofuels by-products as animal feed to free up land for further crop production, bioenergy-livestock integrated systems (BLI) can be a win-win strategy for climate change mitigation while meeting food and energy demands in Brazil. However, their techno-economic feasibility and environmental implications are still unclear, and they depend on the availability of biomass, logistics and impacts on ecosystems, all of which are highly dependent on location and regional factors. This thesis assesses 1) opportunities, challenges, and potential locations to expand BLI in Brazil; 2) techno-economic and environmental implications from a land management perspective; 3) georeferenced economic impacts and GHG emissions of BLI expansion in potential locations and the contribution to future energy demands and GHG mitigation targets. Considered feedstocks for bioenergy production are sugarcane, corn, and soybean used in biorefineries to produce feed, finishing the cycle of beef cattle production. Techno-economic assessment and Life Cycle Assessment were modelled using inventories generated by the Virtual Biorefinery platform, developed at LNBR/CNPEM. Spatially explicit assessment of the integrated value chains considered site-specific crop yields, residue recovery rates and availability of land for expansion that can expand only on pasture areas inside Sugarcane Agroecological Zoning (SAEZ), excluding biomes and biodiversity hotspots. When compared to conventional systems, BLI systems present positive techno-economic impacts and lower GHG emissions, while reducing payback time by almost half, and yields a 5-fold increase in the ratio of net present value to investment. Producing more biofuels using less area with the BLI systems, cuts GHG emissions per hectare in half compared to conventional approaches. Potential expansion areas are concentrated in six states of Center-South region of Brazil (SP, PR, MT, MS, GO e MG). In a spatially explicit perspective, up to 89 billion liters of ethanol could be produced and 139 million tons of CO2eq could be mitigated (when compared to fossil fuels) in 16 million hectares. The expansion of BLI systems in Brazil could meet projected biofuels demands from RenovaBio in 2030. All BLI options could meet at least 50% of Shared Socioeconomic Pathways ethanol demands for 2030 and 2050. Avoided emissions represent up to 15% of GHG to be mitigated by 2030 as stipulated by the Paris Agreement. This study provides important insights for strategic and integrated polices for both biofuels and livestock sectors. A comprehensive sustainability assessment of BLI systems facilitates meeting future global demand of energy and targets climate change mitigation, while land use pressure for food and energy purposes is reduced, and biodiversity hotspots and biomes are protected.

Keywords: biofuels, techno-economic analysis, life cycle assessment

LIST OF ACRONYMS AND ABBREVIATIONS

1G	First generation ethanol
2G	Second Generation Ethanol
ADG	Average Daily Gain
ANP	Agência Nacional do Petróleo, Gás Natural e Biocombustíveis/National Agency of Petroleum, Natural Gas, and Biofuels
AZM	Agroecological Zone Methodology
BECCS	Bioenergy With Carbon Capture and Storage
BLI	Bioenergy-Livestock Integrated Systems
C	carbon
CAPEX	capital expenditures
CAT	Crop Assessment Tool
CBIO	Carbon credit from RenovaBio program
CCEE	Câmara De Comercialização De Energia Elétrica/Electric Energy Trading Chamber
CEPEA	Centro de Estudos Avançados em Economia Aplicada/Center for Advanced Studies on Applied Economics
CH_4	Methane
CHP	Combined Heat and Power
CLFI	Crop-Livestock-Forest integration
CLI	Crop-Livestock integration
CNPEM	Brazilian Center for Research in Energy and Materials
CO_2	Carbon Dioxide
CONAB	Companhia Nacional de Abastecimento/ National Supply Company
COP 21	21th Conference of Parties
Cu	Cooper
DDG	Dried Distillers Grains
DDGS	Dried Distillers Grains with Solubles
DG	Distillers Grains
DGS	Distillers Grains with Solubles
EIA	Energy Information Administration
EJ	Exa joule
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária/ Brazilian Agricultural Research Corporation
EPE	Empresa de Pesquisa Energética/ Energy Research Company
eq	equivalent
EtOH	ethanol
FAO	Food and Agriculture Organization of the United Nations
g	grams
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
GWh	Giga Watt hour
ha	hectare
IAM	Integrated Assessment Model
IBGE	Instituto Brasileiro de Geografia e Estatística/Brazilian Institute of Geography and Statistics
IFES	Integrated Food-Energy Systems

IPCC	Intergovernmental Panel On Climate Change
IRR	Internal Rate of Return
ISO	International Organization for Standardization
kg	kilogram
kWh	kilo watt
l	Liter
LCA	Life Cycle Assessment
LCM	Lignocellulosic material
LNBR	Brazilian Biorenewables National Laboratory
LUC	Land Use Change
LW	Live Weight
M	million
m^2a	Squared meter per year
MAPA	Ministério da Agricultura, Pecuária e Abastecimento/ Ministry of Agriculture, Livestock and Supply
Mha	Million Hectares
MJ	Mega Joule
MMA	Ministério do Meio Ambiente/Ministry of the Environment
MME	Ministério de Minas e Energia/Ministry of Mines and Energy
Mt	Million tonnes
M USD	Million dollar
N	Nitrogen
NASEM	National Academies of Sciences, Engineering, and Medicine
NDC	Nationally Determined Contributions
NOx	Nitrogen oxides
NPV	Net Present Value
OPEX	Operational expenditures
P	Phosphate
PJ	Peta joule
PM2.5	Particular Matter
RFA	Renewable Fuel Association
SAEZ	Sugarcane Agroecological Zoning
SDG	Sustainable Development Goals
SIRENE	Sistema de Registro Nacional de Emissões/National Emissions Registry System
SO_2	Sulphur dioxide
SOC	Soil Organic Carbon
t	Tonne
TEA	Techno-Economic Assessment
UNEP/SETAC	United Nations Environmental Programme/Society of Environmental Toxicology and Chemistry
USA	United States of America
USD	United States Dollar
USGC	United States Grain Council
VB	Virtual Biorefinery
w/	With
w/o	Without

Summary

Chapter 1

General Introduction

1.1. The global climate crisis in a context of growing world population

Global average temperature rose 1.5 °C since the end of 19th century due to higher concentrations of CO_2 and other greenhouse gases (GHG) in the atmosphere (IPCC, 2019). Among the many effects of global warming are changes in precipitation, changes in the agriculture production (e.g., variations on start and end dates of crop growth), crop yield reduction, stressed availability of freshwater, endangered biodiversity, and extreme weather events (IPCC, 2019). Our lifestyle has drastically contributed to increase the atmospheric CO_2 concentration, mostly driven by a fossil-based economy. Currently, not only the transportation systems, but the entire economy runs on fossil-based resources. Around 100 million barrels of petroleum are used daily worldwide, mostly as transportation fuels (EIA, 2021a; 2021b). At the same time, deforestation, land use changes and agriculture sector (e.g., fertilizers use, livestock production) also contributed to a massive release of anthropogenic GHG emissions to the atmosphere (Frank et al., 2017).

In 2015, representatives from all over the world committed to take actions to mitigate GHG emissions aiming at limiting global warming from 1.5º up to 2°C, compared to pre-industrial levels, during the 21st Climate Conference – COP 21 in Paris. Each country established domestic goals to achieve the greater cause, usually including land-based mitigation options and initiatives for decarbonization of the transport sector (Roelfsema et al., 2020). In this context, decarbonization programs for the transport sector are being implemented worldwide to incentive the replacement of fossil fuels with low-carbon fuel options, usually bio-based alternatives (Souza et al., 2021a), since biofuels are usually pin-pointed as key option to mitigate GHG emissions in comparison to fossil sources (Daioglou et al., 2019; Jaiswal et al., 2017; Frank et al., 2021). However, the implementation of decarbonization measures worldwide seems not to be happening as fast as it would be necessary (Roelfsema et al., 2020; Rogelj et al., 2016).

At the same time, global population is constantly growing, consequently, an increase in food and energy demands (Alexandratos and Bruinsma, 2012; Riahi et al., 2017; Bauer et al., 2017, Popp et al., 2017).

1.2. Future socioeconomic narratives

To facilitate the understanding of climate change mitigation and adaptation coupled with world population growth, a generation of scenarios, the so called Shared Socioeconomic

Pathways (SSPs), were established by the climate research community (Bauer et al., 2017; Riahi et al., 2017). These future global scenarios constitute a comprehensive representation of future developments in several sectors of society. They are resultant of consistent application of several integrated assessment models (IAMs) taking into consideration global temperature targets described in the IPCC reports (Myhre et al., 2013). These global scenarios consider narrative storylines of challenges to adaptation and mitigation of climate change (Figure 1) that combines social, economic and environmental trends (e.g., future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources) (O'Neil et al., 2017, 2014).

SSP 1: Sustainability—Taking the green road considers low challenges to adaptation and mitigation due, mostly, to high levels of education, income growth, low population growth, reduction in inequality, strong institutions prioritizing sustainable development and a society aware of social, cultural, and economic costs of environmental degradation. This scenario presents modern energy, technological development, low patterns of energy consumption and social acceptability for renewable energy and bioenergy, which leads to a reduction in fossil fuel consumption (Bauer et al., 2017; O'Neil et al., 2017, 2014; Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017).

SSP 2: Middle of the road is not only an extrapolation of current trends but includes historical patterns such as emerging economies growing quickly and then slowing down after reaching higher levels of income, but also uneven growth patterns among countries. Overall, this uneven development reflects an intermediate scenario compared to SSP1 (low challenges to mitigation and adaptation) and SSP 3 (high challenges for both mitigation and adaptation). There is a medium population growth, medium energy intensity, a gradual reduction of fossil fuel consumption and energy use, and a moderate modernization of the final energy mix (Bauer et al., 2017; Fricko et al., 2017; O'Neil et al., 2017, 2014; Popp et al., 2017; Riahi et al., 2017).

In ***SSP 3: Regional rivalry—A rocky road***, countries are concerned with local development, which negatively affects the global development and generates inequality. The slow growth in income and technological improvements, paired with ineffective institutions (i.e., low environmental concern) and low investments in education leads to high population growth (mostly in developing countries) as well as high challenges to both mitigation and adaptation. It presents high resource intensity and fossil fuel dependence and environmental degradation, due to low priority for environmental concerns. In the energy sector, the traditional bioenergy remains important; there is low technological development and high fossil fuel dependence (Bauer et al., 2017; Fujimori et al., 2017; O'Neil et al., 2017, 2014; Popp et al., 2017; Riahi et al., 2017).

SSP 4: Inequality—A road divided presents a mixed world; there is a huge gap between elites and poor countries. High-income countries walk to sustainability, leaving poor countries behind. This scenario faces low challenge to mitigation due to high technology improvements, and high challenges to adapt due to the existence of inequality, low education, and low income in some regions. There are investments in both carbon-intensive fuels, and in renewable energy and bioenergy; in low-income countries the use of traditional bioenergy remains important, while fossil fuels use is restricted in high income countries. Only high- and medium-income economies are concerned with environment and land use regulation, while deforestation still happens in low-income nations; in agriculture, high income countries present high technological advances, as opposed to poor ones; food is traded internationally, but the market is reduced in low-income ones (Bauer et al., 2017; Calvin et al., 2017; O'Neil et al., 2017, 2014; Popp et al., 2017; Riahi et al., 2017).

In ***SSP 5: Fossil-fueled development—Taking the highway*** there is a global view of a world strongly committed with economic and social development, without concerns for environmental and climate issues. However, the investment in human capital (health, education) is high, generating high income growth, slower population growth and low challenge to adaptation. Investment in renewable energy is low and there is a huge exploitation of fossil resources, leading to an energy-intensive lifestyle and high challenges to climate change mitigation. Although agricultural productivity increases rapidly, land use regulation is incomplete, and deforestation continues; international trade is strong, and diets remain with high animal consumption and high waste production (Bauer et al., 2017; Kriegler et al., 2017; O'Neil et al., 2017, 2014; Popp et al., 2017; Riahi et al., 2017).

The investments in human capital (education, income growth, health) have great impact in the challenges to both mitigation and adaptation. High investments in human capital leads to slow population growth and in equality and, therefore, low challenges to adaptation (SSP 1 and SSP 5). Such investments can also imply in high technology development and entail low challenges to mitigation (SSP 1 and SSP4) (O'Neil et al., 2017, 2014). In addition to the qualitative narratives (storylines), the SSPs provide quantitative outcomes (population, economic growth, rates of technological change) that can be used as inputs to IAMs (O'Neil et al., 2017). The SSPs have been quantified using different IAMs to deliver quantitative projections of energy, land use, and emissions (Bauer et al., 2017; Riahi et al., 2017). These results of different IAMs for each SSPs project an increase in agricultural land for food, feed and bioenergy production, anticipating an additional pressure over land use and, consequently, environmental and socioeconomic impacts (Riahi et al., 2017; Bauer et al., 2017, Popp et al., 2017).

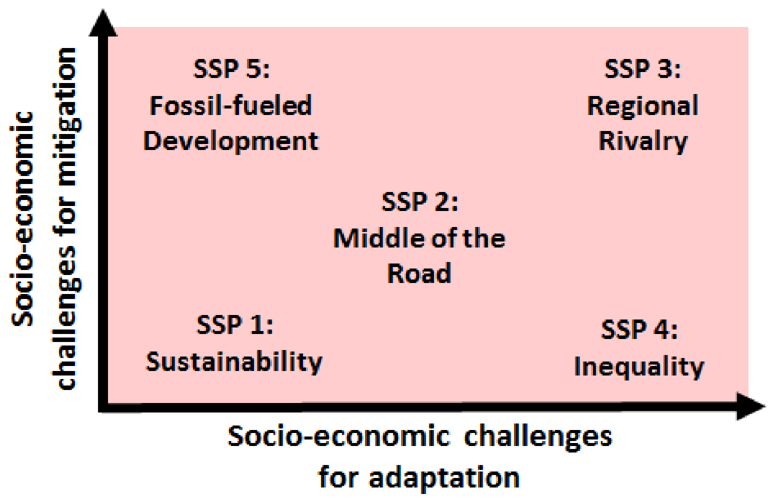

Figure 1: Combination of challenges to mitigation and adaptation of the five SSPs
Source: Adapted from O'Neil et al. (2017)

1.3. The role of bioenergy-livestock integrated systems as alternatives to climate change mitigation

Climate change mitigation options that are land-based are pointed as key alternatives to strategically decelerate global warming while ensuring food and energy for the growing population (Frank et al., 2019; 2021). To fulfill future food and energy demands in a sustainable way, deployment of production systems that can optimize land-based outputs under climate change mitigation scenarios are increasingly necessary. Improvements in land use management strategies, restoration of degraded pasturelands, and livestock intensification (e.g., increased cattle stocking rates) are frequently proposed measures to release land for bioenergy crop production without jeopardizing food and fiber supplies, as well as reducing potential negative land use change impacts often associated with bioenergy crop expansion (Berndes et al., 2016; Cardoso et al., 2016; Santos et al., 2020). Furthermore, livestock intensification can be a cost-effective way to reduce associated GHG emissions (Cardoso et al., 2016; Silva et al., 2017).

To improve agricultural efficiency and relieve land use pressure, land management within integrated value chains is often promoted (Reis et al., 2021, Bogdanski, 2012, Bogdanski et al., 2010). Among the options of integrated food-energy systems (IFES), the Food and Agriculture Organization of the United Nations (FAO) defines two main types: 1) diversification of land use, by producing food and energy on the same area (i.e., intercropping, agroforestry), and 2) maximization of synergies among food, livestock, and energy systems, by using agro-industrial residues as animal feed supplement and/or biofuel production, in a circular economy concept (Bogdanski et al, 2010).

Bioenergy-livestock integration can be assigned to the second type of IFES and represents a land-based mitigation option that can intensify land use to alleviate pressure on land resources in a sustainable way, while also mitigating GHG emissions (Souza et al., 2019; 2021b). This system is largely based on the nutritional value of bioenergy by-products as animal feed, which replaces or minimizes grazing and reduces the amount of land required to produce animal feed (Moreira et al., 2020; Popp et al., 2016).

Bioenergy-livestock integrated systems are especially interesting in Brazil considering the country is an important player in global food and bioenergy production and it is likely to remain as one of the largest food and biofuel producers in the next decades (Alexandratos and Bruinsma, 2012; MAPA, 2020). Brazil produces annually around 30 billion liters of ethanol and 5 billion liters of biodiesel (CONAB, 2020; ANP, 2021) and has about 214 million cattle heads (IBGE, 2021). A large deployment of biofuels is expected in the near future and RenovaBio, a national program that sets annual national decarbonization targets for the fuel sector, foresees the production of 48 billion liters of ethanol and 11 billion liters of biodiesel annually by 2030 (MME, 2021). Also, the country committed to reduce GHG emissions by 2030 and increase the share of bioenergy on energy matrix on its Nationally Determined Contributions (NDCs) (MMA, 2015). Pasture intensification in Brazil is a viable way to increase agriculture production without additional land use (Vale, 2014; Latawiec et al., 2014). For example, there are around 20 to 50 million hectares of pasture that are moderately and highly suitable for sugarcane expansion, mainly in the states of Goiás, Mato Grosso, Pará, Paraná, São Paulo, Mato Grosso do Sul and Minas Gerais (Alkimim et al., 2015; Hernandes et al., 2021; Lossau et al., 2015).

1.4. Sustainability assessment of bioenergy-livestock integrated systems

There is still potential to explore the use of biofuels co-products as animal feed and its potential to reduce pressure over the land resources (Popp et al., 2016), and to explore different biorefinery configuration to integrate bioenergy and livestock value chains. The sustainability implications of such systems must be better explored to ensure their advantages compared to conventional food and energy production systems. Furthermore, climate action is only one of the 17 Sustainable Development Goals that the United Nations set in 2015 to be implemented by 2030 (United Nations, 2019), and large-scale deployment of bioenergy could give rise to other sustainability concerns such as feedstock availability, food security, water use, emissions from land use changes, and biodiversity losses (Cherubin et al., 2021; Frank et al., 2021; Humpenöder et al., 2018). A quantitative assessment of techno-economic and environmental impacts of multiple alternatives of bioenergy-livestock integrated systems in Brazil is key to understand whether they are a feasible option to meet future energy demands compared to conventional systems.

Sustainability aspects of bioenergy production are dependent on biomass availability, logistics, and ecosystem impacts, all of which are highly dependent on the local environmental conditions (Hiloidhari et al., 2017; Humpenöder et al., 2018). Site-specific assessments are especially important to account for variable biomass productivity, land use changes and land conditions, and climatic variables (Field et al., 2020; Granco et al., 2019; Zullo et al., 2018).

1.5. Contribution to knowledge gaps of bioenergy-livestock integrated systems in Brazil

A deeper assessment of IFES such as bioenergy-livestock integrated systems is required to provide reliable information for policy making, considering they are relatively complex systems integrating multiple value chains, their successful implementation is likely to depend on region-specific characteristics (Bogdanski, 2012). Also, a detailed sustainability assessment of bioenergy-livestock integrated systems in Brazil may unravel important issues related to the sustainability of these systems before their large-scale production, including site-specific aspects. This assessment can benefit from life cycle thinking, applying the Life Cycle Assessment (LCA) methodology in combination with conventional techno-economic assessment and Geographic Information System (GIS) to account for possible impacts related to the sustainability issues of each stage of bioenergy-livestock integrated systems. In addition, the contribution of bioenergy-livestock integrated systems to future energy demands and GHG mitigation targets in Brazil is still unclear, since projection studies usually account for conventional food and energy production systems, missing the possible synergies and opportunities of integrated value chains. However, bioenergy-livestock integrated systems are still not broadly applied in Brazilian agricultural and industrial sectors. A comprehensive assessment of opportunities, challenges, synergies, possible adverse effects, and potential locations to implement them in the country may contribute for its large-scale deployment (Souza et al., 2021b).

This study aimed to help to understand potentials of this land-based alternative to meet future energy demands and GHG mitigation targets in more sustainable way, by exploring the integration of two important value chains (i.e., bioenergy and livestock). The structure of this thesis is represented in Figure 2.

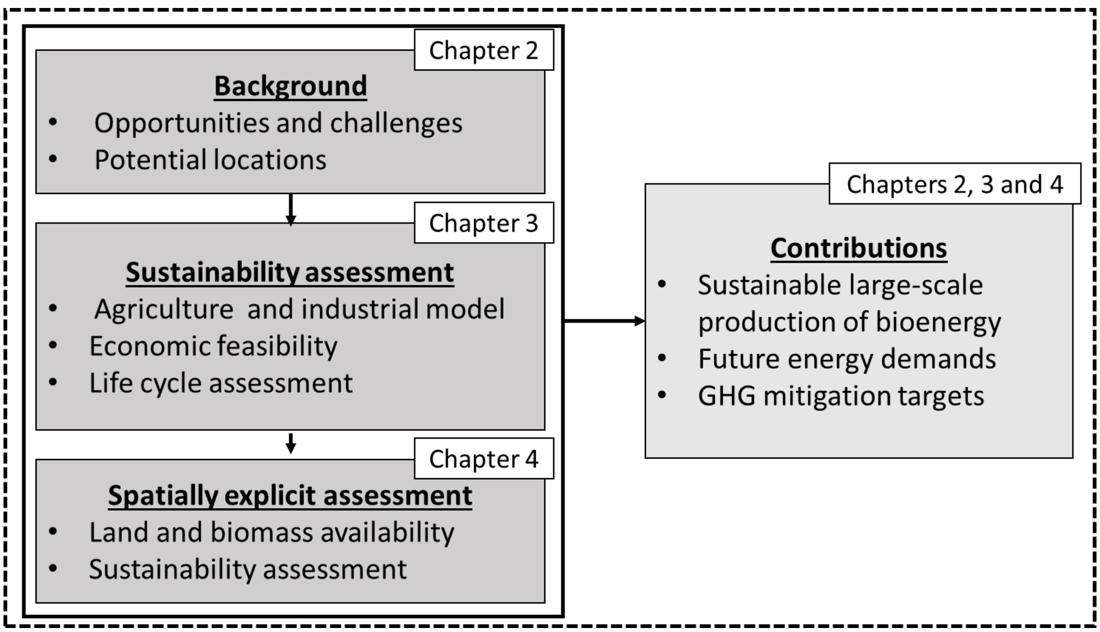

Figure 2: Overview of chapters organization to explore climate and land use aspects of bioenergy-livestock integrated systems in Brazil

1.6. Objectives

The main objective of this study is to explore the climate and land use aspects of bioenergy-livestock integrated systems in Brazil and how these systems can synergistically contribute to climate change mitigation in Brazil, while still contributing to attend projected energy demands. The specific objectives include:

- Explore opportunities and challenges of bioenergy-livestock integrated systems and identify potential locations for successful implementation in Brazil.
- Model and simulate bioenergy-livestock integrated systems to assess their techno-economic and environmental impacts, beyond GHG emissions.
- Obtain a spatially explicit assessment of bioenergy-livestock integrated supply-chains in the most important regions of Brazil, considering land and biomass availability and constrains to expansion, to assess their potential to mitigate GHG emissions while meeting future energy demands.

Chapter 2

Opportunities and challenges for bioenergy-livestock integrated systems in Brazil

This chapter was published by Nariê Rinke Dias de Souza[1,2], Tassia Lopes Junqueira[1,2], Otávio Cavalett[1,3]. Opportunities and challenges for bioenergy-livestock integrated systems in Brazil. Industrial Crops and Products, 173 (2021) 114091.
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ABSTRACT: Bioenergy is seen as a key option to meet future energy demands and mitigate climate impacts. However, large-scale deployment of bioenergy can cause an additional pressure over land resources and correspondent sustainability impacts. Enhanced land management practices are fundamental to intensify land-based outputs under different climate mitigation scenarios. Bioenergy-livestock integration (BLI) is a win-win strategy to climate mitigation while ensuring food and fibers demands from the society by using bioenergy by-products as animal feed to release land to additional industrial crops production. This study comparatively assesses BLI opportunities in Brazil to better understand the sustainability issues of the alternatives for integration of these value chains, highlighting the key techno-economic and environmental aspects. When compared to conventional systems, the BLI systems present positive techno-economic impacts and lower greenhouse gas emissions, reaching mitigations up to 32% and 22% for meat and ethanol production, respectively. The expansion of BLI systems in Brazil could meet projected biofuels future demands, using less than 20% of the expected area for this expansion. Potential expansion areas are concentrated in Center-South region of Brazil. BLI systems can be further advanced by including other synergies, such as codigestion of sugarcane vinasse and cattle manure, integration of flex ethanol plants with biodiesel plants, maximization of biofuels by-products as animal feed, and inclusion of novel promising alternative industrial crops such as macauba, sweet sorghum, energy cane and short rotation eucalyptus coppice. However, we identify many potential barriers including the operational complexity, specific know-how, and necessity of economic incentives. This study may provide important insights for strategic and integrated polices for both agricultural and livestock sections as the proper sustainability assessment of an early stage of the deployment of enhanced BLI systems may help to meet global future demands of energy while also contributing to climate change targets.

Keywords: land use intensification, sustainability, industrial crops, climate change, biofuels

2.1. Introduction

Bioenergy is projected as one of the key options to meet energy demands and at the same time mitigate greenhouse gas (GHG) emissions (Daioglou et al., 2019; Frank et al., 2021; Jaiswal et al., 2017). Although bioenergy is expected to decrease GHG emissions in comparison to fossil alternatives under certain conditions, its large-scale deployment may raise concerns related to feedstock availability, food security, water withdraw, emissions from land use changes, biodiversity losses and beyond other sustainability issues (Cherubin et al., 2021; Frank et al., 2021; Humpenöder et al., 2018). In addition, future scenarios, considering projected global socioeconomic pathways, indicate an increase in agricultural land for food, feed and bioenergy production (Bauer et al., 2017; Popp et al., 2017; Riahi et al., 2017), anticipating an additional pressure over land use and, consequently, environmental and socio-economic impacts (Frank et al., 2017; Humpenöder et al., 2018). Therefore, it is extremely important to guarantee global energy security while minimizing its sustainability impacts. This challenge can be accomplished by improved land use management strategies (Frank et al., 2021; Santos et al., 2020; Smith et al., 2013), since agricultural sector is expected to have a substantial transformation to attend future land use demands while also contributing to mitigate GHG emissions (Frank et al., 2017; Shukla et al., 2019). Improvements in land use management strategies, recovery of degraded pasturelands and livestock intensification (e.g., increase cattle stocking rates) are measures frequently proposed to release additional area to bioenergy crops production, without compromising food and fibers supply and decrease eventual land use change impacts often negatively associated to bioenergy crops expansion (Berndes et al., 2016; Cardoso et al., 2016; Santos et al., 2020).

The integrated bioenergy-livestock (BLI) system has potential to intensify energy production and alleviate the pressure over land use. However, it faces some barriers that make it still not broadly applied in Brazilian agricultural and industrial sectors. These BLI systems are intended to intensify and improve land use factors, therefore allowing additional bioenergy production for climate change mitigation with relatively lower sustainability impacts. In this context, the aim of this study is to comparatively assess opportunities within bioenergy-livestock integrated systems in Brazil to better understand their techno-economic feasibility and some environmental aspects. The study also discusses the main barriers for BLI systems implementation and identify the regions in the country with higher potential for specific BLI system deployment.

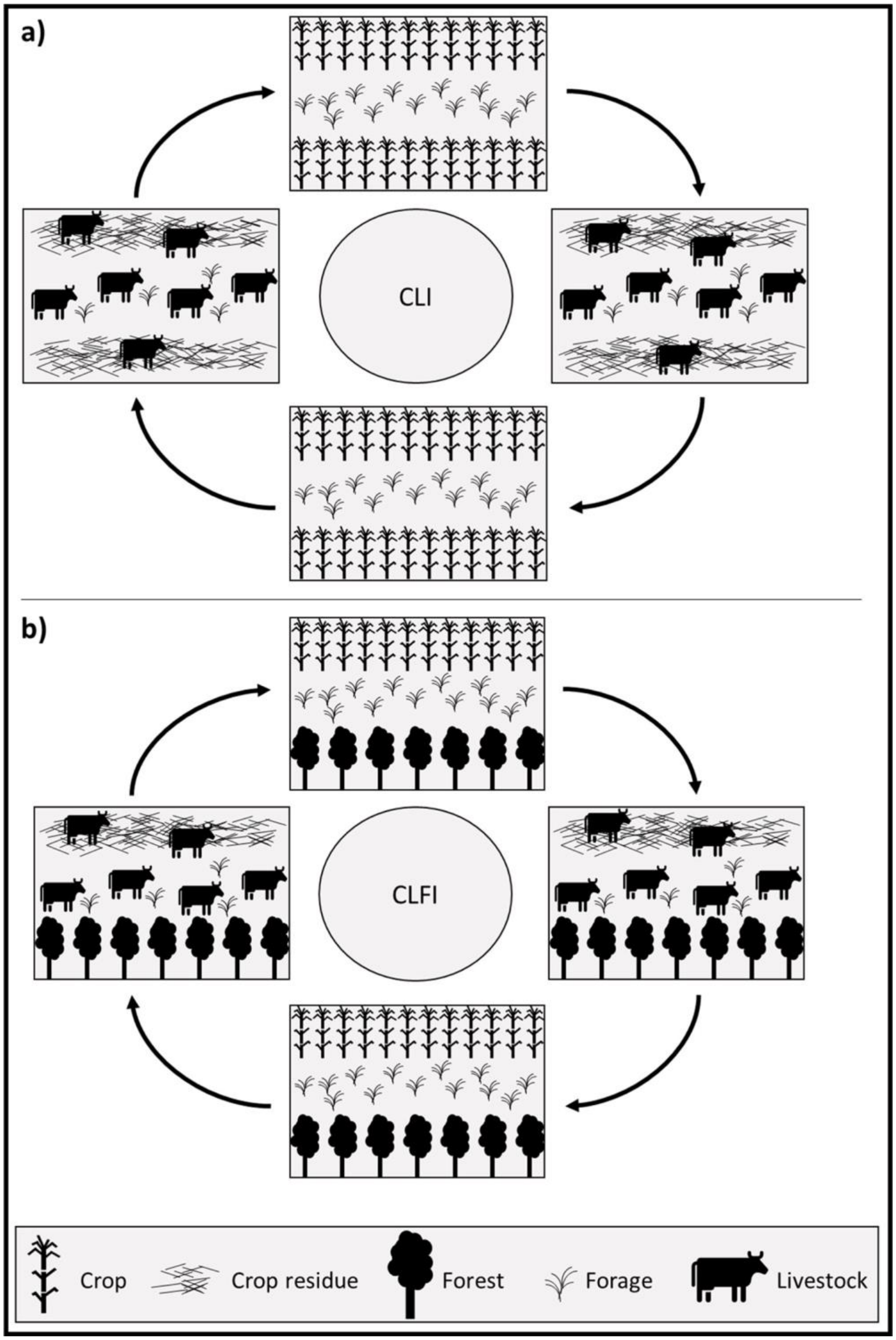

Figure 1: Representation of land use on crop-livestock integration (CLI) (panel a), and crop-livestock-forest integration (CLFI) (panel b).

2.2. Examples of integration of value chains aiming at land use intensification

Land management under integrated value chains is necessary to improve agricultural efficiency and alleviate pressure on land use (Reis et al., 2021). The integration of the bioenergy and livestock value chains can happen exclusively in a land use perspective, such as the crop-livestock integration (CLI), and crop-livestock-forest integration (CFLI) (Bonaudo et al., 2014; Bungenstab, 2012), or by also integrating the value-chains of bioenergy production with livestock to release land for biomass production, named here bioenergy-livestock integration (BLI). Bioenergy is considered as any energetic product from biomass, either in the form of electricity or liquid fuels. Most common livestock production considered in the integrated system is beef cattle, however it can also occur with poultry and swine production systems (Conroy et al., 2016).

2.2.1. Integration based on intercropping systems

CLI and CLFI systems may increase crop production without land expansion, with simultaneous, sequential, or rotational cultivation in the same area (Cordeiro et al., 2015; Esteves et al., 2018). CLI and CLFI are used as a strategy to integrate agriculture, livestock, and forest production in the same area, at the same time or in succession (Figure 1) (Bonaudo et al., 2014; Mbow et al., 2014). Therefore, the integration of value chains can be a win-win solution to energy production without compromising other food and fiber demands of the society, while also contributing to climate change mitigation and adaptation, and increasing land outputs (Sulc and Franzluebbers, 2014; Bungenstab, 2012; Cordeiro et al., 2015). Currently, the most common CLI/CLFI systems in Brazil are related to integration of grains production in the same area of pastureland, aiming at recovering it and improving cattle productivity (Cordeiro et al., 2015). CLI has also been identified as having socioeconomic and environmental benefits in Africa (Mbow et al., 2014), France (Bonaudo et al., 2014) and USA (Sulc and Franzluebbers, 2014).

2.2.2. Integration based on biofuel by-products as animal feed

The second type of integration is based on the use bioenergy by-products as animal feed to release land to industrial crops production, including additional biofuel crops. This type of integration has the potential to release the land that was used to produce the feed components that are replaced by bioenergy by-products. It is only possible due to by-products nutritional value as animal feed, that replaces or reduces grazing and decreases the land needed to produce corn and protein meal for animal feed (Fischer et al., 2010; Popp et al., 2016). The integration can happen by intensification of pasture with animal feed complement during part of the year, or by finishing beef cattle in feedlots (Figure 2). If the integration includes finishing cattle production in feedlots, then bio-fertilizer from manure is a possible interesting by-product from the system that can be applied on the fields (partially replacing synthetic fertilizers inputs) or sold to other agricultural production systems (Picoli, 2017).

A remarkable example of BLI is the corn ethanol and livestock integration that have been used for more than one decade in the USA (Conroy et al., 2016; Liska et al., 2009). The country is the largest ethanol producer in the world and responsible for a great part of global animal feed supply, around 40 million tons (RFA, 2021a, b). Other successful cases of BLI systems are also identified in Europe (Parajuli et al., 2018) and Brazil (Souza et al., 2019; Olivério et al., 2014; Moreira et al., 2020). Parajuli et al. (2018) evaluates the case where winter wheat, spring barley straw, forage grass, pigs and cattle are produced inside the integration boundaries, reducing overall GHG emissions, fossil fuel consumption, eutrophication potential and freshwater ecotoxicity compared to conventional systems. As described in Souza et al. (2019), sugarcane ethanol by-products are fed to beef cattle, and this integration makes possible to release pastureland to sugarcane production. These results showed that the system is techno-economic feasible and reduce GHG emissions compared to separated equivalent systems, although this configuration is implemented in very few cases in Brazil. Olivério et al. (2014) presented the benefits from the integration of soybean biodiesel and sugarcane ethanol plants in an existing facility, which included reduced operational costs, fossil fuel consumption and GHG emissions. In another example, corn ethanol plants operating the whole year and producing animal feed present socio-environmental benefits, as assessed by Moreira et al. (2020). In addition, the nutritional value of ethanol by-products can replace corn and soybean meal, which reduces overall GHG emissions of the integrated system.

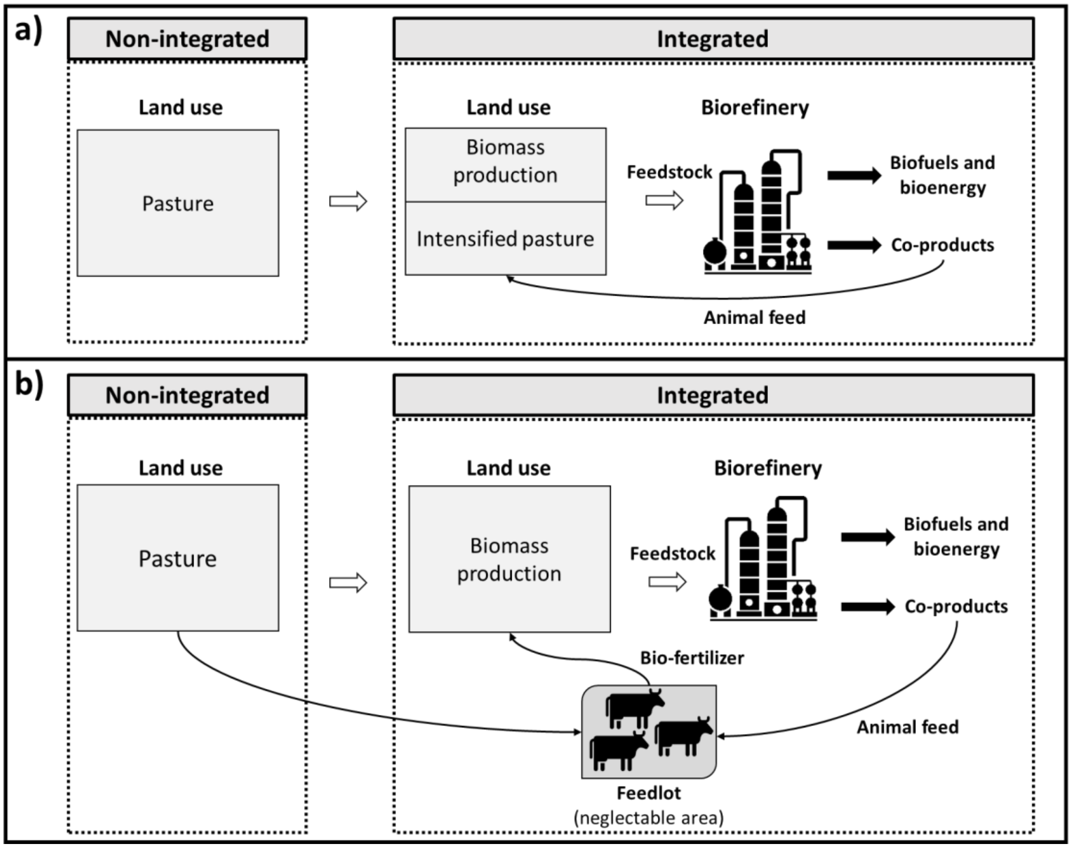

Figure 2: Representation of bioenergy-livestock integration (BLI), considering intensification of pasture (panel a), and livestock production on feedlots (panel b).

2.3. Methodology

We compared four main types of existing BLI systems that could be better explored in the Brazilian context (Table 1). We assess, based on a comprehensive literature review, the main aspect of BLI, including: a) opportunities to techno-economic and environmental feasibility, highlighting investments, costs, and GHG emissions, b) land use management options, c) and use of agro-industrial by-products and residues for feed and energy production. BLI systems consider biorefineries that produce not only bioenergy, but also animal feed products. In general, animal feed consists of by-products from the industrial stage of biofuels conversion systems. These are dependent on the industrial configuration and the feedstock for bioenergy production, that can be, for example, sugarcane, corn, and soybean. The selected BLI systems are a) BLI1: sugarcane-livestock integration, b) BLI2: sugarcane-corn-livestock integration, c) BLI3: sugarcane-soybean-livestock integration, and d) BLI4: corn ethanol-livestock integration. We performed a qualitative assessment in this work addressing the main opportunities and barriers for the deployment of these integrated systems in Brazil. Identified opportunities are those related to potential GHG mitigation, potential to release land to bioenergy production, diversified portfolio, and economic feasibility while barriers consider operational complexity, required additional investments, know-how requirement, and necessity of financial incentives.

Potential areas for BLI systems deployment in the country are identified following the schematic diagram presented in Fig. S1 in the Supplementary Material. First, we mapped production of sugarcane, second season corn, soybean and cattle herd on the different municipalities in center-south region Brazil using ArcGIS based on official data from IBGE (2021a, b, c). After that, we classified the BLI potential areas, considering whether the municipalities have livestock production and any cultivated crop among corn, soybean and sugarcane. Finally, we excluded the municipalities with production of these agricultural crops and cattle below the national average for each product (Table S1).

An additional BLI system is separately assessed in this work, aiming at exploring further sustainability opportunities from the use of by-products as animal feed, use of residues as feedstock for bioenergy, and from a land use intensification perspective. It corresponds to the sugarcane-corn-soybean-livestock integration (BLI5).

Nevertheless, part of Brazilian pastureland is located in challenging areas to produce traditional bioenergy crops such as sugarcane, corn and soybean. Challenging areas have factors that make difficult bioenergy production, such as soil quality, precipitation patterns, marginal and degraded pastureland. A possible solution is to explore the inclusion of alternative industrial crops in the integrated systems that have potential to be cultivated in such challenging areas. We selected four relatively new and promising feedstocks for biofuels production in Brazil: energy-cane, macauba, sorghum and short rotation eucalyptus coppice. Therefore, our study also highlights opportunities, challenges, and barriers regarding their potential to be used as feedstock to biofuel production and as animal feed, as well as their potential suitability to be produced in more challenging areas and as energy source to operate the industrial plants.

As a case study, we assessed how much land would be necessary to meet the future ethanol demand considering the implementation of BLI systems. RenovaBio, a national program that sets annual national decarbonization targets for the fuel sector, projected a demand of 48 billion liters of ethanol in Brazil in 2030 (MME, 2021), an addition of 18 billion liters from today's production of about 30 billion liters per year (CONAB, 2020). We calculated how much the necessary land would represent in relation to the 20 million hectares previously identified as available for sugarcane expansion on pasture areas, as presented in Hernandes et al. (2021), considering the exclusion of areas with high priority for biodiversity conservation from the 42 million hectares that are initially identified as suitable for sugarcane expansion inside the Sugarcane Agroecological Zoning (SAEZ) (Manzatto et al., 2009). BLI parameters considered in this assessment are presented in Table S2 from Supplementary Material.

Table 1: Bioenergy-livestock integrated systems.

	Description	Products	By-products as feed	References
BLI1	Sugarcane ethanol plants producing animal feed.	Electricity, sugar, ethanol, animal feed.	Hydrolyzed bagasse, *in natura* bagasse, molasses, yeasts, filter cake, vinasse.	Sparovek et al. (2009); Taube-Netto et al. (2012); Picoli (2017); Souza et al., 2019.
BLI2	Flex ethanol plants processing sugarcane and corn, producing animal feed.	Electricity, sugar, ethanol, animal feed, corn oil.	DDG[1] and DDGS[2].	Grippa (2012); Milanez et al. (2014); Iglesias and Sesmero (2015); Dias et al. (2016).
BLI3	Sugarcane ethanol plants integrated to soybean biodiesel plants.	Electricity, sugar, ethanol, animal feed, biodiesel, glycerol.	Soybean meal.	Souza and Seabra (2013, 2014); Olivério et al. (2014); Longatti et al. (2020).
BLI4	Full corn ethanol plants producing animal feed.	Electricity, ethanol, animal feed, corn oil.	DDG and DDGS.	Milanez et al. (2014); Moreira et al. (2020).

[1]Dried Distillers Grains, [2]Dried Distillers Grains with Solubles

2.4. Results and discussion

2.4.1. Techno-economic and environmental aspects of bioenergy-livestock integrated systems

Besides characteristics that are common to the four systems, such as diversification of portfolio, use of industrial by-products as animal feed, increase products outputs (energy and feed) per unit of area, a comparative analysis taking into consideration techno-economic and environmental sustainability aspects and adaptations needed to apply the BLI systems is presented in Table 2. Crops integrated to livestock production in each BLI are included in parentheses.

Table 2: Techno-economic and environmental aspects of BLI systems and adaptations needed to their application.

	Techno-economic and environmental aspects in integrated systems	**Adaptations needed in an existing sugarcane plant**
BLI1 (sugarcane)	Improved profits, low investments to produce animal feed, reduced GHG emissions compared to conventional systems, reduced use of mineral fertilizers replaced by manure as bio-fertilizer.	Investments to divert sugarcane by-products to animal feed production and to hydrolyze bagasse.
BLI2 (sugarcane-corn)	Improved profits, sugarcane bagasse use to supply energy to corn processing, low investments (shared infrastructure for corn and sugarcane ethanol production allowing whole year operation), reduced GHG emissions compared to gasoline (both sugarcane and corn ethanol classified as advanced biofuel).	Investments on corn grinding, liquefaction and separation, purchase of enzymes.
BLI3 (sugarcane-soybean)	Sugarcane bagasse use to supply energy to biodiesel plant, use of ethanol in oil extraction and in transesterification, intercropping of sugarcane and soybean, reduced biodiesel GHG emissions due to replacement of methanol, hexane, and diesel on the fields.	Investments on biodiesel plant.
BLI4 (corn)	Use of purchased sugarcane bagasse or eucalyptus chips as fuel, economically feasible, reduced GHG emissions compared to gasoline, classified as advanced biofuel, corn produced in rotation with soybean.	Not integrated to a sugarcane plant.

2.4.1.1. Integration of sugarcane ethanol plants with livestock production (BLI1)

BLI1 systems can be one of the alternatives to meet needed expansion of biofuel production while minimizing climate change impacts. From a land management perspective, extensive cattle grazing can be replaced by feedlots with animal feed composed of sugarcane by-products and supplemented with corn and soybean meal, produced outside of the integration boundaries (Sparovek et al., 2009; Souza et al., 2019; Taube-Netto et al., 2012). The released pasture area can be used to expand sugarcane production avoiding additional pressure for livestock displacement. For example, released area may range from 35% to 60% compared to original pastureland (Sparovek et al., 2009). A major advantage of this BLI system is that feed is produced mostly during dry season, when livestock needs nutritional supplementation (Sparovek et al., 2009; Souza et al., 2019). Bagasse in the main component of animal feed and most of can be processed using a simple batch hydrolysis process (commonly steam explosion of varied severity levels) to improve digestibility and nutritional value as cattle feed (Souza et al., 2019; Sparovek et al., 2009; Taube-Netto et al., 2012), but some feed compositions may include only in natura bagasse (Picoli, 2017). In the sugarcane sector, bagasse is normally used to generate steam and electricity in ethanol plants, and it is expected that its use as animal feed may lead to a correspondent decrease on electricity generation. However, the amount of bagasse diverted to cattle feed production normally represents only up to 10% of available bagasse (Taube-Netto, 2012; Souza et al., 2019; Sparovek et al., 2009). Sugarcane plants can be autonomous, as in Taube-Netto et al. (2012) and Picoli (2017), or annexed to a sugar mill, as in Souza et al. (2019) and Sparovek et al. (2009). In the latter references, part of the molasses, a by-product from sugar production, is also used to animal feed production. Molasses is often used for ethanol production, but again only a small fraction, up to 2%, of produced molasses was diverted to animal feed in Souza et al. (2019). In Sparovek et al. (2009), filter cake and vinasse were also included in the formulation of the feed for dairy cattle. Other sugarcane by-product that can compose animal feed is surplus yeast from cells recycle after fermentation (Souza et al., 2019). Sugarcane plants should go through minor adaptations to divert part of its by-products to produce animal feed. For instance, in Souza et al. (2019) investments for feed preparation represented only 0.3% of total investments in a sugarcane processing plant. The production of animal feed adds value to industrial by-products and residues and brings economic benefits due to diversification of products in the biorefinery portfolio and generation of additional revenues. Although integrated systems can improve livestock productivity, the intensification is normally more costly than extensive pastureland management. However, it is necessary to include the land opportunity cost of released pasture area to sugarcane production to 35mbientale the livestock economic feasibility (Sparovek et al., 2009; Souza et al., 2019). Differently from the management of livestock on pasture only, the cattle manure can be collected in the feedlots in the BLI systems and used as bio-fertilizer in sugarcane fields, which contributes to decrease GHG emissions due to replacement of mineral fertilizers, including urea, single super phosphate, and potassium chloride (Picoli, 2017). In addition to replacement of mineral fertilizers, reduced cattle production time and improved carcass yields per hectare are two other important points to decrease GHG emissions from livestock production systems (Souza et al., 2019; Taube-Netto et al., 2012; Sparovek et al., 2009; Picoli, 2017). In Figure S2 from Supplementary Material there is a simplified flowchart of an annexed sugarcane ethanol plant diverting part of by-products to animal feed production.

2.4.1.2. Integration of flex sugarcane-corn ethanol plants with livestock production (BLI2)

Sugarcane cannot be stored after harvested and ethanol plants using only this feedstock have the disadvantage of operating only during sugarcane season, around 200 days per year (Milanez et al., 2014). However, sugarcane plants in BLI2 systems can be adapted to produce corn ethanol during sugarcane offseason without excessive additional costs. These are so-called flex plants (Eckert et al., 2018; Milanez et al., 2014). One advantage of flex plants is the possibility of supply energy to the offseason plant operation with available sugarcane lignocellulosic material (LCM) (i.e., bagasse and straw) (Eckert et al., 2018; Manochio et al., 2017; Milanez et al., 2014). To take advantage of the existing sugarcane plant infrastructure (e.g., distillation, dehydration and combined heat and power generation), the limiting factors for the offseason operation are the availability of lignocellulosic material for energy supply and the daily volume of sugarcane ethanol production (Milanez et al., 2014; Dias et al., 2016). Besides ethanol, corn processing generates an animal feed with high nutritional value (Popp et al., 2016; USGC, 2012). Corn ethanol can be produced in wet or dry milling processes, where latter is the most common in modern plants both in Brazil and in the USA (Manochio et al., 2017). In the dry milling process, the whole corn grain is grounded, then it goes through the liquefaction step using enzymes to break down the starch molecules into glucose and proceeds to fermentation stage (Manochio et al., 2017; USGC, 2012). After fermentation, the wine is distilled to obtain ethanol, while animal feed is obtained from centrifugation of whole stillage generated in distillation process, called distillers grains (DG) (Klopfenstein et al., 2013; Manochio et al., 2017; USGC, 2012). The DG can be dried, generating Dried Distillers Grains (DDG), and can be mixed to the separated solids from evaporation of remaining thin stillage, generating Dried Distillers Grains with Solubles (DDGS) (Grippa, 2012). Moreover, it is possible to extract oil from the DG in a process called “back-end” oil extraction (Eckert et al., 2018; USGC, 2012). Additional investments are required to adapt a conventional sugarcane plant into a flex plant, such as adding equipment for corn milling, liquefaction of starch, and additional fermenter units due to the longer corn ethanol fermentation (Milanez et al., 2014; Dias et al., 2016). Despite the additional investment, the introduction of corn increases the yearly ethanol production, reduces operating costs, and improves the competitiveness of plants due to an increased products portfolio with additional animal feed production (Eckert et al., 2018; Milanez et al., 2014). Additional investments for corn represented 17% to 41% of the sugarcane plant investment in Milanez et al. (2014), 42% in Dias et al. (2016), and 34% in Iglesias and Sesmero

(2015). In the flex plants, corn is the largest cost component (Grippa, 2012) and ethanol generates the largest part of revenues, followed by its co-products and electricity (Milanez et al., 2014). As more corn ethanol is produced, better the profitability compared to conventional sugarcane plants (Milanez et al., 2014). For instance, Dias et al. (2016) indicated that longer corn season reduce general costs and improve the Net Present Value (NPV) and the Internal Rate of Return (IRR) of flex plants when compared to conventional systems. The ethanol produced in flex plants presents slightly higher GHG emissions compared to sugarcane ethanol, but it is still considered an advanced biofuel, reducing around 67% to 69% of GHG emissions compared to gasoline (Milanez et al., 2014; Dias et al., 2016). It happens mostly because GHG emissions derived from corn production are considerably higher than those from sugarcane. The illustration of a flex ethanol plant in the BLI2 system is presented in Figure S3 from Supplementary Material.

2.4.1.3. Integration of sugarcane ethanol and soybean biodiesel plants with livestock production (BLI3)

BLI-3 considers the integration of soybean biodiesel production with sugarcane ethanol plants, presenting opportunities to be explored due to the large production of soybean meal, which can be used as animal feed (Cremonez et al., 2015; Esteves et al., 2018; Popp et al., 2016). In this system, it is possible to produce soybeans in the sugarcane reforming areas, using bagasse to operate the biodiesel plant, ethanol in oil extraction replacing hexane and, in the transesterification, replacing methanol (Souza and Seabra, 2013; 2014; Olivério et al., 2014). This integration has many environmental and economic advantages compared to conventional (non-integrated) systems. It allows reducing overall GHG emissions, due to the replacement of some industrial chemical inputs used in large amounts (i.e., hexane and methanol) decreases costs and investments, as it is possible to share part of industrial infrastructure; reduces fossil fuel consumption by using biodiesel in agricultural operations; and has a diversified product portfolio including soybean-related products (Olivério et al., 2014; Souza and Seabra, 2013; 2014; Longatti et al., 2020). The products of this BLI system are sugarcane ethanol, soybean biodiesel, glycerin, and electricity. Soybean meal can be exchanged by oil in a system called Façon (Souza and Seabra, 2013; 2014), or used as animal feed. BLI3 is represented in Figure S4 (Supplementary Material), considering a sugarcane ethanol plant integrated to a soybean biodiesel plant.

2.4.1.4. Integration of corn ethanol plants with livestock production (BLI4)

Different from BLI2, in BLI4 system the ethanol plant operates the entire year using only corn as feedstock. Corn can be stored, but without the integration with sugarcane, it is necessary to have a complementary exogenous energy source for supplying the required thermal and electric energy for the plant. Unlike corn plants in the USA, which operates using coal or natural gas, in Brazil corn plants operating the whole year generally using purchased sugarcane bagasse or eucalyptus chips as fuel (Moreira et al., 2020). A key advantage of this system in Brazil is the possibility of using the so-called second season corn, produced in rotation with soybean (CONAB, 2021), which improves land occupation factor. In this system, the use of DDGS as animal feed, also intensifies land use and reduces associated GHG emissions, since it reduces the necessity of producing corn and soybean for feed purposes (Moreira et al., 2020). The products of this BLI are ethanol, DDGS and corn oil (Moreira et al., 2020). The ethanol emissions in this case are relatively similar to ethanol from sugarcane and flex ethanol plants, reducing GHG emissions in about 70% compared to gasoline. In Figure S5 (Supplementary Material), we present a flowchart of a corn ethanol plant producing animal feed.

2.4.1.5. Maximization of synergies on the bioenergy-livestock integrated systems (BLI5)

The possible synergies such as land use management and use of agro-industrial residues and by-products could be better explored in the BLI systems, since these aspects have great influence on bioenergy sustainability (Cherubin et al., 2021). Not only the biorefineries provide inputs to livestock production, but the other way around can also happen, creating a synergic cycle inside integration boundaries, maximizing the principles of the circular economy concept (Stahel, 2019). For instance, anaerobic digestion (biodigestion) of vinasse and possible codigestion with cattle manure could be applied in these integrated systems to increase bioenergy production, maximizing the utilization of these residual flows (Moraes et al., 2015; Meng et al., 2020). The integration of biodigestion in biorefineries are techno-economic feasible under certain conditions and help to reduce GHG emissions compared to conventional systems, mostly because of the increase in bioenergy output in the biorefinery process (Moraes et al., 2014; Khatiwada et al., 2016a). Similarly, in BLI4 systems in the USA, biogas can be produced from anaerobic digestion of livestock manure (Liska et al., 2009; Yue et al., 2013a, 2013b), increasing the bioenergy production inside the integration boundaries. Biodiesel production can increase with additional use of animal fat (tallow) as feedstock (Geraldes-Castanheira et al., 2014). Indeed, the use of tallow for biodiesel production is a common practice in Brazil, as it is the second largest feedstock used for biodiesel production in the country (ANP, 2021). In BLI2 and BLI3, sugarcane by-products, highlighting bagasse, could also be used as animal feed, since adaptations and costs necessary to divert sugarcane by-products are relatively small and costless (Sparovek et al., 2009; Souza et al., 2019). The pasture area released after integration could be used to expand not only sugarcane, but also second season corn in rotation with soybean, a very common practice in Brazil, which represents 73% of total corn produced in the country (CONAB, 2021). In this way, all the main feed ingredients would be produced inside the integration boundaries. Taking those points into consideration, we propose a fifth potential BLI, the BLI5 (Figure 3). In this system, flex ethanol plants can be integrated to soybean biodiesel plants, using sugarcane, corn and soybean by-products as animal feed. The released pastureland can be used to expand the three crops for bioenergy purposes, soybean can be produced in sugarcane reforming areas, or in rotation with corn, the most common practice currently in Brazil. Vinasse and cattle manure can be codigested in an annexed biodigestion facility and the produced biogas burnt in a combustion engine to generate electricity. Animal fat also can be used to produce biodiesel. The products of this system are electricity, sugar, ethanol, animal feed, corn oil, biodiesel and glycerol. The surplus LCM material, after meeting sugarcane plant energy requirements and cattle feed requirements, can be used to operate the soybean biodiesel plant and the corn processing during offseason. Instead of using hexane for oil extraction and methanol on transesterification, it is possible to divert part of ethanol produced for both purposes. Possible animal feed composition would contain hydrolyzed bagasse, in natura bagasse, molasses, yeasts, DDGS and soybean meal. The main positive aspects of this integration are increased biofuel production, improvements in the use of scarce land and resources, reduced fossil fuel consumption, reduced GHG emissions, use of agroindustry residues to energy production and as animal feed, diversified portfolio, and additional revenues. Under the right conditions, BLI5 systems may present great potential to maximize the synergies among bioenergy and livestock value chain in sustainable way. Such synergies can be maximized to find best supply-chain configuration options, as, for example, in Khatiwada et al. (2016b).

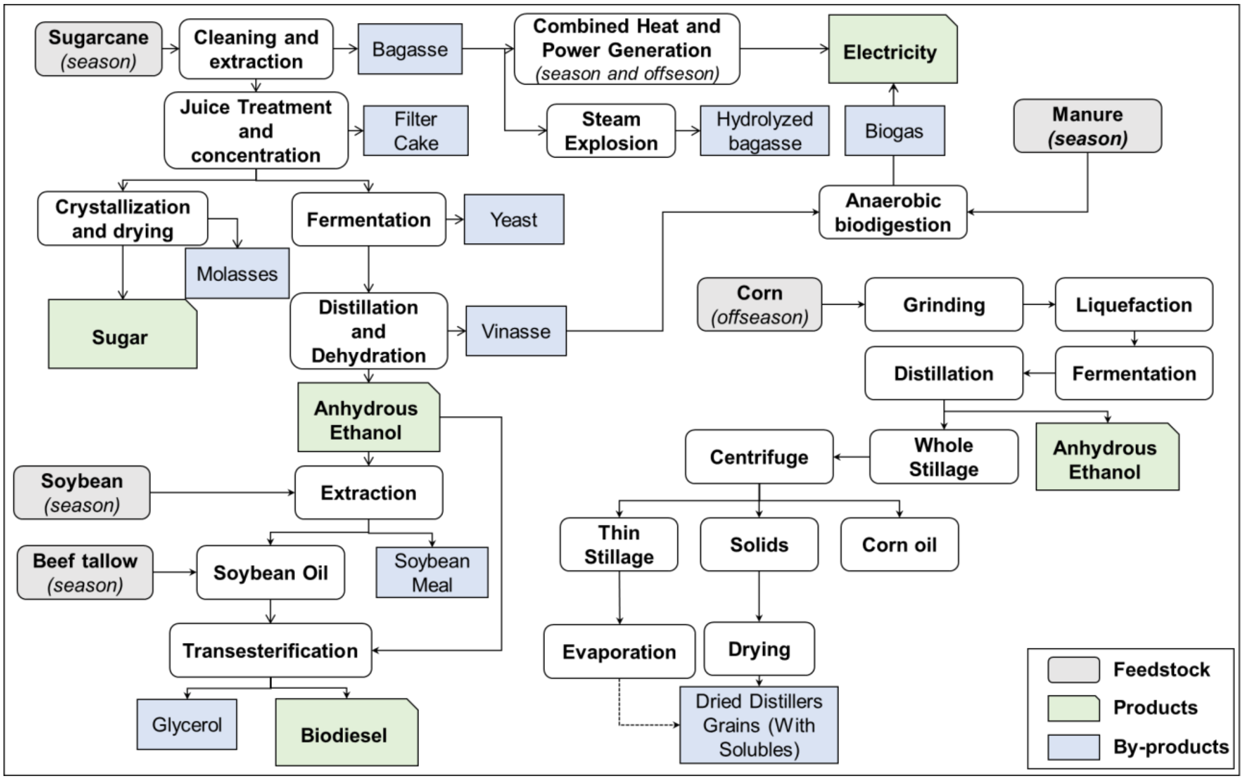

Figure 3: Flowchart of the proposed BLI5 system

2.4.2. Alternative industrial crops to be explored in the bioenergy-livestock integrated systems

Four novel bioenergy crops that have great potential to be included in the integration systems are presented in Table 3. These crops have been advocated to have the advantage of being adaptable to more challenging crop growing environments where the conventional feedstock (i.e., sugarcane, corn and soybean) cannot achieve feasible yields. In addition, most of these novel bioenergy crops have the potential to be used as feedstock for both bioenergy and animal feed production.

Table 3: Alternative industrial crops with potential to be included in the integrated systems

Alternative Biomasses	**Macauba**	**Energy cane**	**Sorghum**	**Eucalyptus**
Relative higher tolerance to low quality soils	Yes[1]	Yes[5]	No[8]	Yes[11,12]
Relative higher tolerance to drought conditions	Yes[1]	Yes[5]	No[8]	Yes[11,12]
Potential biofuels	Biodiesel[2]	1G and 2G ethanol[6] *	1G and 2G ethanol[9]	2G ethanol[13]
Potential by products as animal feed	Macauba meal[3]	Bagasse[7]	Bagasse, silage[10]	-
Potential additional energy sources	Husks and endocarp[4]	Bagasse[5,6]	Bagasse[9]	Chips and residues[14]

[1]Falasca et al. (2017); [2]Lopes et al. (2013); [3] Fernández-Coppel et al. (2018); [4]Evaristo et al. (2016); [5]Carvalho-Netto et al. (2014); [6]Junqueira et al. (2017); [7]Energy cane bagasse is very similar to sugarcane bagasse (Junqueira et al., 2016); [8]Ratnavathi et al. (2011);[9]Dias et al. (2016); [10]Wiseman et al. (2021); [11]EMBRAPA (2019); [12]Kenya Forest Service (2009); [13]Bressanin et al. (2020); [14]Moreira et al. (2020)
* 1G refers to first generation ethanol (from available sugars) and 2G refers to second generation ethanol from LCM derived sugars.

Palm oil biofuels is gaining attention mainly in Indonesia as, under right circumstances, presents good potential to substitute fossil fuels, with techno-economic feasibility and reduction of GHG emissions when compared to fossil fuels (Harahap et al., 2020). Macauba, a crop similar to palm but that can be cultivated in the tropical climate, has recently called attention as feedstock for biofuels production (e.g., biodiesel and biojet) in Brazil due to its promising high yields, high tolerance to extreme environment and adaptability to low quality soils (César et al., 2015; Falasca et al., 2017; Lopes et al., 2013; Klein et al., 2018). When compared to the other oil crops such as rapeseed, sunflower, castor seed, and soybean, macauba presents lower GHG emissions due to potentially higher agricultural yields (Fernández-Coppel et al., 2018; Klein et al., 2018). From the economic perspective, macauba biodiesel may present a favorable economic feasibility in Brazil, but this will highly depend on revenues from glycerol and macauba meal (Lopes et al., 2013). Macauba meal can be used as animal feed (Ali et al., 2017; Fernández-Coppel et al., 2018) and the lignocellulosic residues (i.e., empty brunches, husks and endocarp) present potential as energy source, such as pellets and 2G ethanol (Evaristo et al., 2016). Although Macauba presents great potential as feedstock production, it is not commercially produced in Brazil yet, but agronomic research is advancing in this regard.

Energy cane is a new cane variety developed with the objective of increasing 2G ethanol production (Thammasittirong et al., 2017; Shields and Boopathy, 2013). This variety presents considerably higher biomass yields, lower sugar content and reduced production costs compared to conventional sugarcane (Carvalho-Netto et al., 2014; Grassi and Pereira et al., 2019). Production costs of energy cane are similar to corn stover, switchgrass, miscanthus and short-rotation woody grass (Salassi et al., 2013). Energy cane is adaptable to conditions where sugarcane cannot thrive, which gives an advantage of using marginal lands to its production (Carvalho-Netto et al., 2014). This crop has great potential to complement or even replace sugarcane for 1G and 2G ethanol production and electricity generation (Carvalho-Netto et al., 2014; Junqueira et al., 2016; 2017). Bagasse from energy cane could also be used as animal feed component, considering it is relatively similar nutritional composition compared to sugarcane bagasse (Junqueira et al., 2016).

Sweet sorghum is suggested as a potential crop to reduce costs and increase revenues of ethanol production in Brazil due to the possibility of operating during sugarcane off-season (Rezende and Richardson, 2017; Dias et al., 2016). This crop can be grown on sugarcane renovation areas and the same equipment can be used for agricultural and industrial operations, after minor adjustments (Rezende and Richardson, 2017). Sorghum is a promising crop to biofuel production as it has been promoted that it can achieve high yields even in challenging environment, where sugarcane and corn would have low yields (Oikawa et al., 2015; Ratnavathi et al., 2011). The sorghum bagasse can also be burnt in boilers to generate steam and electricity or used for 2G ethanol production (Dias et al., 2016). Among the possibilities of sorghum by-products being used as animal feed are bagasse, sillage or distillers grains with soluble (Beretta et al., 2021; Wiseman et al., 2021). Just like sugarcane bagasse, a pretreatment is recommended to increase its nutritional content and digestibilitiy (Houx et al., 2013). However, uncertainties regarding actual achievable yields have been indicated as a barrier for a broader application of this crop in Brazil (Rezende and Richardson, 2017).

Despite of not having direct application as animal feed, eucalyptus presents great potential to be included in the integrated systems as energy source, and due to the possibility of being produced in the same area of crops in a CLFI system (Reis et al., 2021; Cordeiro et al., 2015). For instance, in Milanez et al. (2014) and Moreira et al. (2020), eucalyptus chips are the energy source to operate corn ethanol plants. In addition, it has potential to be used to produce other biofuels using different processes (e.g., 2G ethanol, biojet, green diesel and green gasoline) with potential techno-economic feasibility and reduced GHG emissions when compared to fossil equivalents (Bressanin et al., 2020). In special, the production of eucalyptus in short rotation coppice has the potential to achieve higher biomass yields for bioenergy and decrease costs due to reduced use of machineries and equipment on harvesting operations (Eufrade et al., 2016; Hauk et al., 2014).

2.4.3. Potential of bioenergy-livestock integrated systems to meet future biofuel demands

Brazil represents an important player in global food and bioenergy market, and it is likely to remain as one of the largest biofuel producers in the next decades (Alexandratos and Bruinsma, 2012; MAPA, 2020). Currently, Brazil produces around 30 billion liters of ethanol (about 90% from sugarcane and the remaining volume from corn) (CONAB, 2020), and 5 billion liters of biodiesel (about 74% of it from soybean) (ANP, 2021). In the near future, the new Brazilian Biofuel Program (RenovaBio) projects a demand of 48 billion liters of ethanol and 11 billion liters of biodiesel by 2030 (MME, 2021). However, there is no clear indication of where and how this expansion will happen. Historically, sugarcane has expanded over pastureland and will likely keep this trend (Cherubin et al., 2021). In this study, we made an exercise where BLI systems would be deployed in part of the 20 million hectares of pastureland inside SAEZ (Hernandes et al., 2021) aiming to meet the additional ethanol demand of 18 billion liters in 2030 (MME, 2021). To attend the additional ethanol demand in the country it would be necessary 2.6 million hectares dedicated to sugarcane production on BLI1 and 4.3 million hectares in BLI2 for sugarcane and corn production, since corn has a lower ethanol yield per hectare. In BLI3, the associated land use (sugarcane and soybean production areas) would be 2.5 million hectares (about only 12% of the 20 million hectares available for expansion without displacing livestock production), at the same time delivering 332 million liters of biodiesel (6% of estimated expansion in RenovaBio); and in the case of BLI4, 24% of the 20 million hectares would be necessary to meet the estimated ethanol demand with corn ethanol.

Other studies suggested that more suitable areas for sugarcane production could be released after pasture intensification, without land use displacement. For example, Alkimin et al. (2015), indicates that around 50 Mha of pasture could be released due to intensification of cattle production. Lossau et al. (2015) quantified that after intensification of pastureland productivity, a total of 37 Mha of land that excludes Amazon biome, protected and high biodiversity areas, could be used to expand bioenergy. The expansion of biofuel crops on pastureland can provide some beneficial ecosystem services such as soil carbon sequestration, soil carbon cycling, soil nutrient provision, water regulation and socioeconomic development (Khatiwada et al., 2016a; Oliveira et al., 2019). Currently in Brazil, most of cattle is produced extensively using management practices that can lead to soil quality degradation. (Reis et al., 2021). Estimates point out that about half of Brazilian pastureland can be considered degraded and/or has a low productivity, demanding remediation to soil quality losses (Bungenstab, 2012). Systems that can sustainably intensify pastureland use can eventually release area to crops and bioenergy production (Berndes et al., 2016, Santos et al., 2020). If properly deployed, cattle intensification can help to reduce associated GHG emissions, while improve economic feasibility of the systems (Cardoso et al., 2016; Silva et al., 2017).

2.4.4. Identification of potential areas to deploy bioenergy-livestock integrated systems in Brazil

Potential areas to deploy bioenergy-livestock integrated systems in Brazil are mainly concentrated in six states of Center-South region (i.e., São Paulo, Minas Gerais, Paraná, Mato Grosso, Mato Grosso do Sul, Goiás), due to their high suitability for corn (Figure 4a), soybean (Figure 4d) and sugarcane crops (Figure 4) close to a high concentration of cattle herd (Figure 4b). These six states are responsible for 94% of corn production as second season, 90% of sugarcane production, 67% of soybean production, and 54% of beef cattle production (IBGE, 2021a; 2021b; 2021c). In Figure 4e, it is possible to visualize that most of all municipalities in the six states already have some production of livestock and, at least, another one of the three biomasses (sugarcane, corn or soybean). Only few areas have only livestock production. In Mato Grosso, Goiás, Paraná and Mato Grosso do Sul states, there is a predominance of municipalities with all four products and livestock and soybean production, with just some municipalities with production of livestock and corn and/or sugarcane. In the east side of Minas Gerais state, most of municipalities have livestock and sugarcane production, while in west side all the products can be found. In São Paulo state all combinations are present, with a predominance of regions with livestock, sugarcane and soybean production, followed by all products. Livestock and corn can be found is just a few areas.

In order to provide additional guidance considering only major payers of agricultural and cattle production for BLI deployment, we excluded the production of a given product in municipalities with production volumes lower than the national average (Figure 4f). By doing this, in Mato Grosso, Mato Grosso do Sul and Goiás more areas of only livestock (light green) appear, which means that the other crops have a relatively low production volume in these areas. Mato Grosso still has a considerable area with both livestock and soybean production. Minas Gerais has a predominance of only livestock and a reduction of livestock and sugarcane and all products combination. In São Paulo, there is a predominance of livestock and sugarcane areas, and a reduction of all other combinations. Paraná state still has a considerable area with livestock and soybean production, but areas with all products are not present. This analysis provides an indicative that expanding crops production, considering BLI systems, in these areas could be feasible and that different combinations are possible, including the BLI-5 that would integrate livestock production and the cultivation of all three crops.

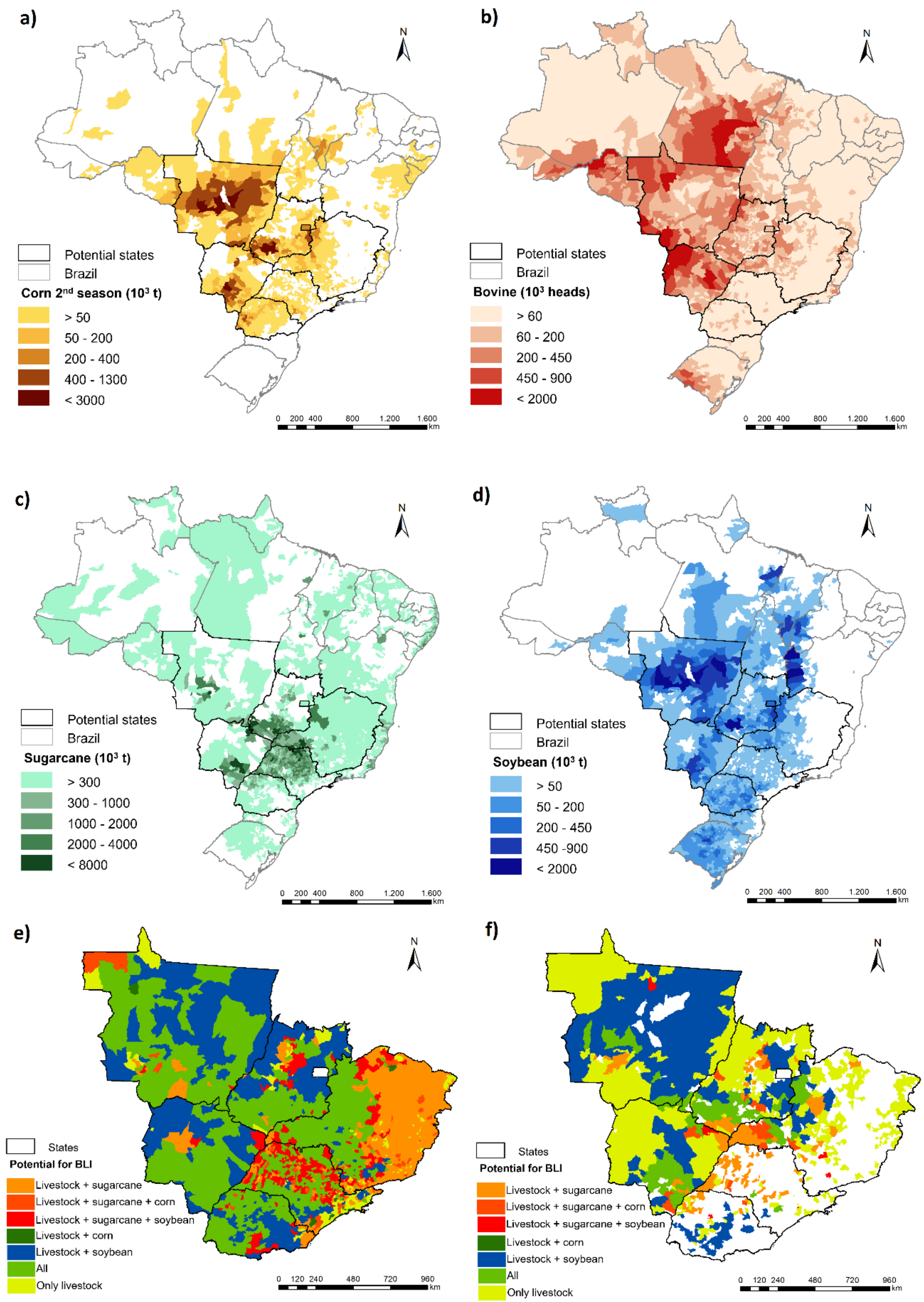

Figure 4: Strategic locations to expand the BLI systems in Brazil. (a) corn production as second season; (b) cattle herd; (c) production of sugarcane; and (d) production of soybean; I combined production of the different agricultural products and livestock in the different municipalities of center south of Brazil; (f) and major players only by considering only municipalities with production volumes higher than the national production average.

2.4.5. Challenges and opportunities of bioenergy-livestock integrated systems

Although the BLI systems are a great opportunity to expand bioenergy production in Brazil, while also mitigating GHG emissions, there are some challenges that must be overcome before its high-scale deployment. A qualitative assessment summarizing key opportunities and challenges of the BLI systems is presented in Table 4.

Table 4: Qualitative comparison of key indicators of the BLI systems.

Indicator	BLI1	BLI2	BLI3	BLI4	BLI5
Challenges					
Operational complexity	Low	Medium	Medium	Low	High
Additional investments	Low	Medium	Low	Medium	High
Know-how barriers	Medium	High	High	Medium	High
Necessity of incentives	High	High	High	Medium	High
Opportunities					
Potential to mitigate GHG	Medium	Low	Medium	Low	High
Potential to release land	High	Medium	High	Low	High
Diversified portfolio	Medium	High	High	Medium	High
Economic feasibility	Medium	High	High	Medium	High
Increase production value	High	*	*	High	*
Increase GDP	Low	*	*	High	*
Employment generation	High	*	*	High	*

*No available information

BLI5 system presents the highest challenges, but also the highest opportunities. The bioenergy-livestock integration presents higher operational and market complexity due to the additional value chains involved and the diversified portfolio of products. BLI1 and BLI4 present the lowest operational complexities due to less value chains integrated (i.e., only 2). Even though studies and real cases of integration in Brazil show it can be feasible to divert part of bagasse to animal feed production in 1G ethanol plants (Souza et al., 2019), the 2G ethanol could be a real competitor to the use of this feedstock (Junqueira et al., 2017; Khatiwada and Silveira, 2017; Picoli, 2017). However, the assessment of environmental and economic feasibility of bagasse for 2G ethanol and/or animal feed must be done for the specific cases, taking into considerations the specificities of the systems. Incremental investments in BLI2, BLI4 and BLI5 are higher than in BLI1 and BLI3, because the need of additional equipment for inclusion of corn, increasing from 17 to 41% in comparison to the investments of conventional sugarcane ethanol plant (Dias et al., 2016; Milanez et al., 2014). In BLI1, investments are 2% lower than in conventional ones (Souza et al., 2019); while they are about 22% lower BLI3 (Olivério et al., 2014). As DGS is a conventional coproduct of ethanol production from corn, no additional investment for animal feed would be required in BLI4. Know-how barriers are higher as more values chains are involved in the integrated systems. It is often advocated that the bioenergy and livestock sector should work closely in order to make a successful integration of these value chains (Picoli, 2017; Sparovek et al., 2009). In addition, the technological level of livestock production should increase with the integration, since it changes from an extensive management to an intensified one, with use of animal feed and the feedlot management system (Picoli, 2017). Currently only 14% of cattle is finished in feedlots and extensive management with grass-fed finishing is the most common way of production in Brazil (Abiec, 2020). Finally, there is the need of financial incentives and specific public policies designed to promote the deployment of integrated systems. In this way, the systems could be more rapidly and broadly applied in the country (Milanez et al., 2014; Sparovek et al., 2009, Souza and Seabra, 2014). A strong market for bioenergy by-products as animal feed and for carbon credits generated within the integration (e.g., inclusion of integrated pathways on RenovaBio) would be essential to strengthen the integrated systems in Brazil (Souza et al., 2019). Except for BLI4 system there is already being increasingly applied in the country, all the BLI systems will demand financial incentives to be further explored in Brazil.

BLI5 presents the larger potential to mitigate GHG emissions, because it has the higher level of integration resulting in relatively lower external inputs requirements and more outputs in comparison to separate systems. Sugarcane presents higher potential to mitigate GHG emissions and release land for other uses. As a result, BLI1 and BLI3 present better potentials in both cases when compared to BLI2 and BLI4. In Souza et al. (2019) the integration with livestock reduced GHG emission associated with ethanol production in 16% in BLI1. In BLI4, reduction compared to gasoline can reach 87% (Moreira et al (2020). In BLI3 (Souza and Seabra, 2014), emissions per unit of energy of ethanol were 3% lower than conventional systems. Not only the ethanol production had reduction in GHG emissions, in Picoli (2017) and Souza et al. (2019) emissions from meat production were 32% and 16% smaller than conventional production, respectively. Finally, due to larger diversified portfolio, BLI2, BLI3 and BLI5 present higher economic feasibility.

Although not always covered, social impacts from the integration of bioenergy and livestock value chain can be positive and can improve production value, employment generation and gross domestic product (GDP) (Arantes, 2018; Moreira et al., 2020),

Another opportunity that benefits the BLI systems in Brazil is the rapidly expansion of corn ethanol production in the country, that grew from 240 million liters in 2017 to 1.7 billion liters in 2020 and is expected to keep increasing (CONAB, 2020). Additionally, Brazil has great potential to produce eucalyptus, for instance, Cervi et al., (2020) estimated that currently around 26 Mt of eucalyptus residues are available per year for bioenergy purposes and in the future, it can reach 31 Mt per year. Although energy cane, sweet sorghum, and macauba are currently not largely produced, the two latter present potential to be produced in Center-South region (Cervi et al., 2019; May et al., 2013).

BLI systems are especially interesting to Brazil, as the country is pioneer in the large-scale bioenergy production (EPE, 2020), and it is intended to contribute to climate change mitigation and bioenergy deployment on its Nationally Determined Contributions (NDCs) (MMA, 2015). Qualitative assessments of key opportunities and challenges, as presented in this study, are intended as a first step for a better understanding of potentials from the BLI systems in the country. We highlight the importance of further studies assessing more specific and quantitative sustainability impacts considering case-by-case environmental, social and economic feasibility on these systems in comparison to alternatives. Case-specific assessments of the opportunities, challenges, and barriers to a broader implementation of BLI systems in the country can support decision makers and encourage the formulation of bioenergy public policies, based on the potentials to meet future energy demands and GHG mitigation targets, and to alleviate pressure on land use. In the case of BLI systems, there is a considerable limitation on social evaluation and a lack of studies covering other relevant sustainability impacts such as impacts on water use and on biodiversity.

2.5. Conclusions

We compared the sustainability opportunities and barriers of BLI systems in Brazil and explored synergies to improve its economic and environmental feasibility. They can happen by expanding industrial crops production in pasture areas without displacement of livestock, possible due to the use of bioenergy by-products as animal feed. The BLI systems can be techno-economically feasible and have potential to mitigate GHG emissions while meeting future demands of energy. Reduction on GHG emission compared with conventional system can reach up to 32% in the case of meat production and 22% for ethanol production. Depending on the integrated systems, total investments can vary from -22% to +45% compared to conventional systems, what did not compromise the feasibility of the system. The expansion of bioenergy-livestock integrated systems in Brazil could meet Renovabio's projected biofuels expansion in 2030, by using less than 20% of considered available area for that expansion. Potential areas to this expansion are concentrated mostly in Mato Grosso, Mato Grosso do Sul, Goiás, São Paulo, Minas Gerais and Paraná states. Potential barriers to a broader inclusion of this production system in the country are the operational complexity, required specific know-how, and necessity of financial incentives. There is still potential to explore BLI systems, such as the inclusion of codigestion of sugarcane vinasse and cattle manure, integration of flex plants with biodiesel plants, maximization of the use of biofuels by-products as animal feed, and inclusion of alternative industrial crops as macauba, sweet sorghum, energy cane and short rotation eucalyptus coppice, that can be grown in more difficult environments and are examples of strategies that are relevant not only for mitigation but also for adaptation to climate change. This study may support decision makers and encourage the formulation of enhanced public policies for the bioenergy sector based on the potentials to meet future energy demands and GHG mitigation targets, and to alleviate pressure on land use. Assessment of potential areas for implementation of BLI systems was presented, indicating that their implementation would be possible in the Center-South region of Brazil. We highlight the importance of spatially explicit assessments of sustainability impacts on future studies at the early stage of the implementation of BLI systems, also, the inclusion of other relevant indicators such as the ones related to social impacts, water use and biodiversity losses, and possibilities and opportunities of BLI in other countries and regions.

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Supplementary Material to: Opportunities and challenges for bioenergy-livestock integrated systems in Brazil

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Table S1: Average national production used to classify the study area as potential for BLI

Product	Value	Units per municipality
Livestock	38,803	heads
Soybean	15,160	tonnes
Corn	45,020	tonnes
Sugarcane	226,428	tonnes

Table S2: Potential ethanol production in BLI systems

BLI system	Ethanol yield (L/ha)	Reference
BLI1	6,816	Junqueira et al. (2017)
BLI2	4,183	Milanez et al. (2014)
BLI3	7,225	Souza e Seabra (2014)
BLI4	3,696	Milanez et al. (2014)

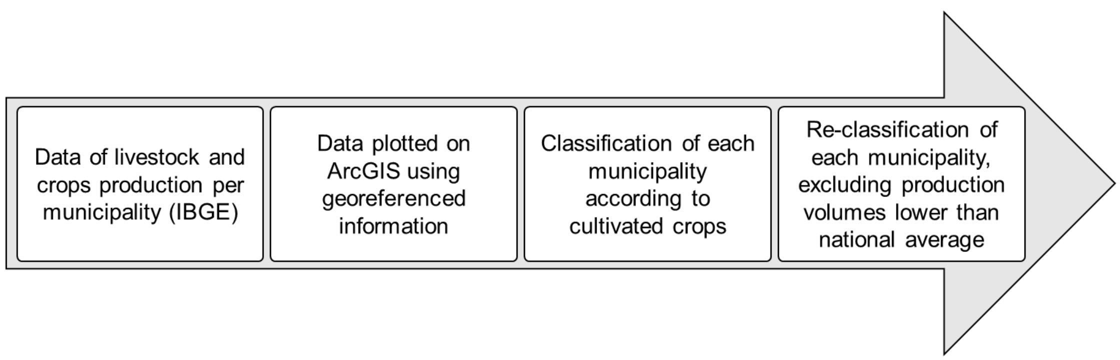

Figure S1: Diagram for the identification of potential areas to apply BLI in Brazil

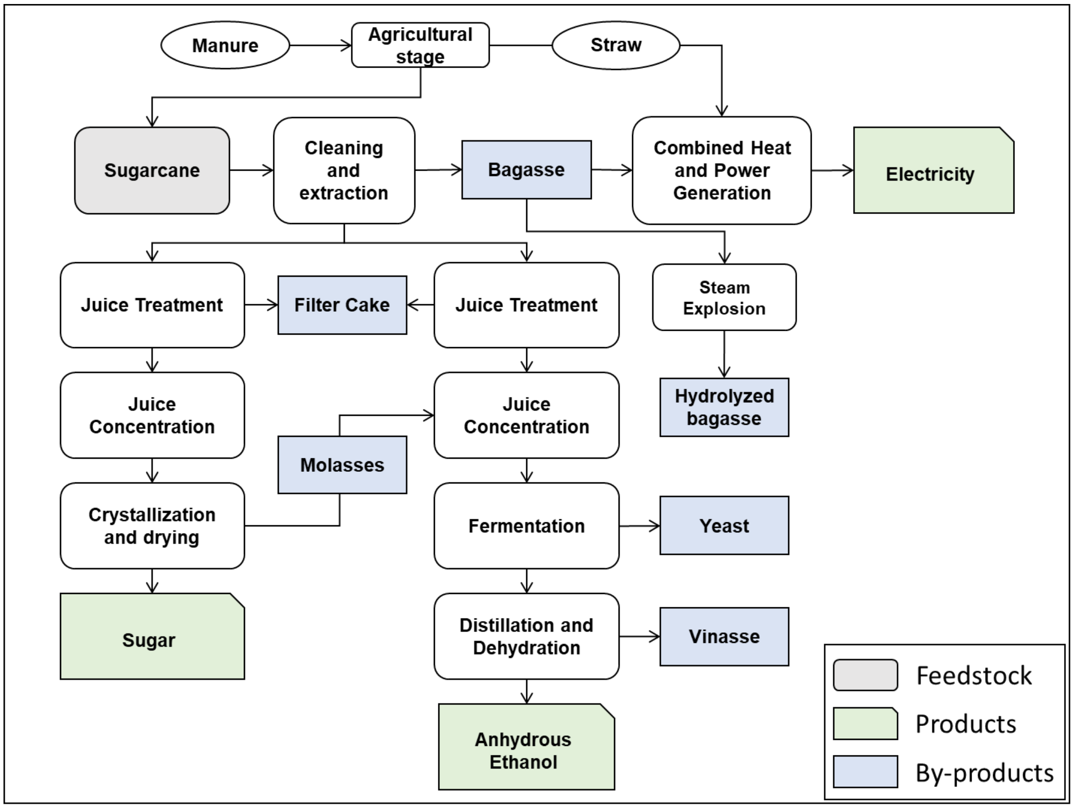

Figure S2: Simplified flowchart of sugarcane ethanol plant producing animal feed

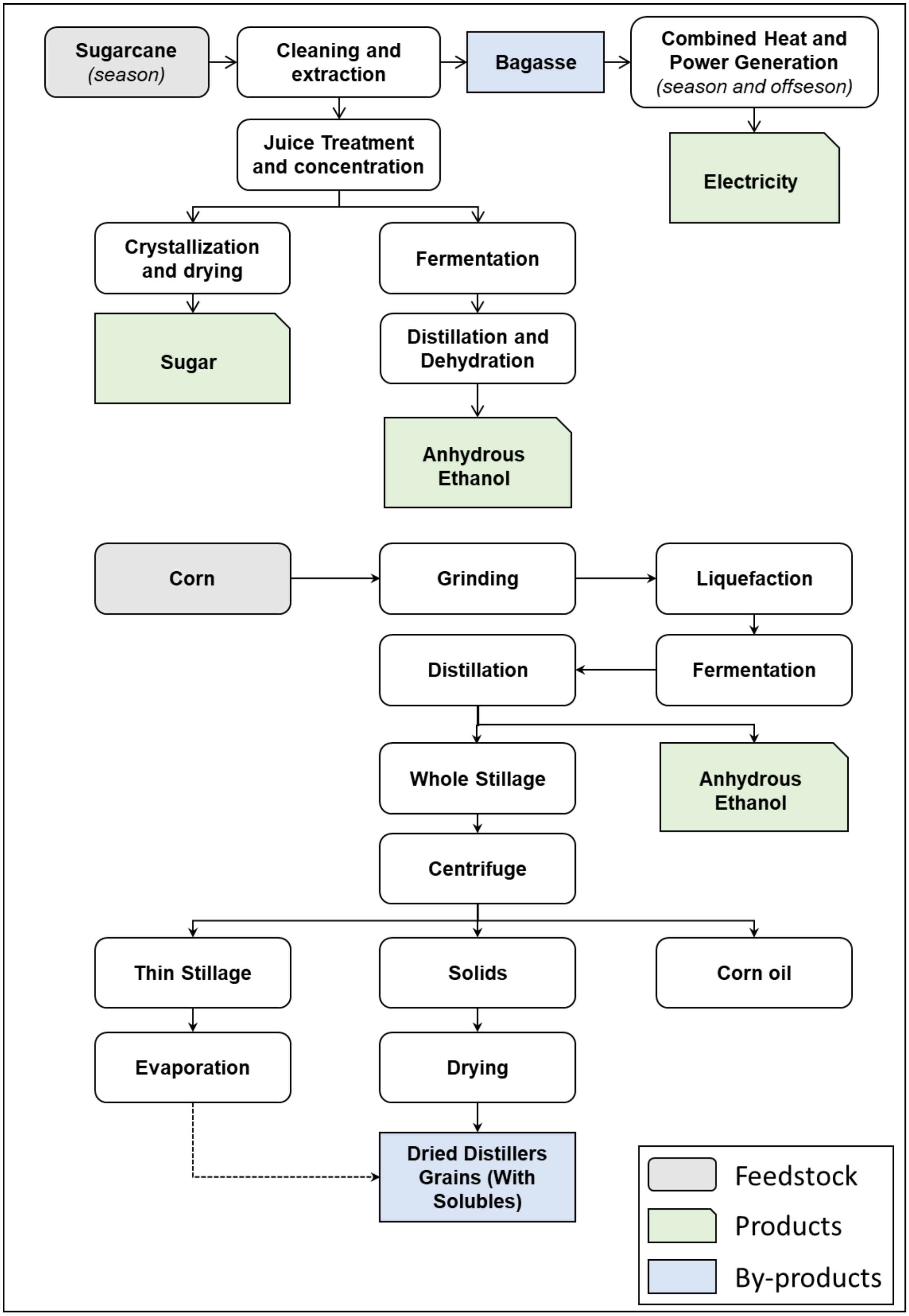

Figure S3: Simplified flowchart of flex ethanol plant producing animal feed

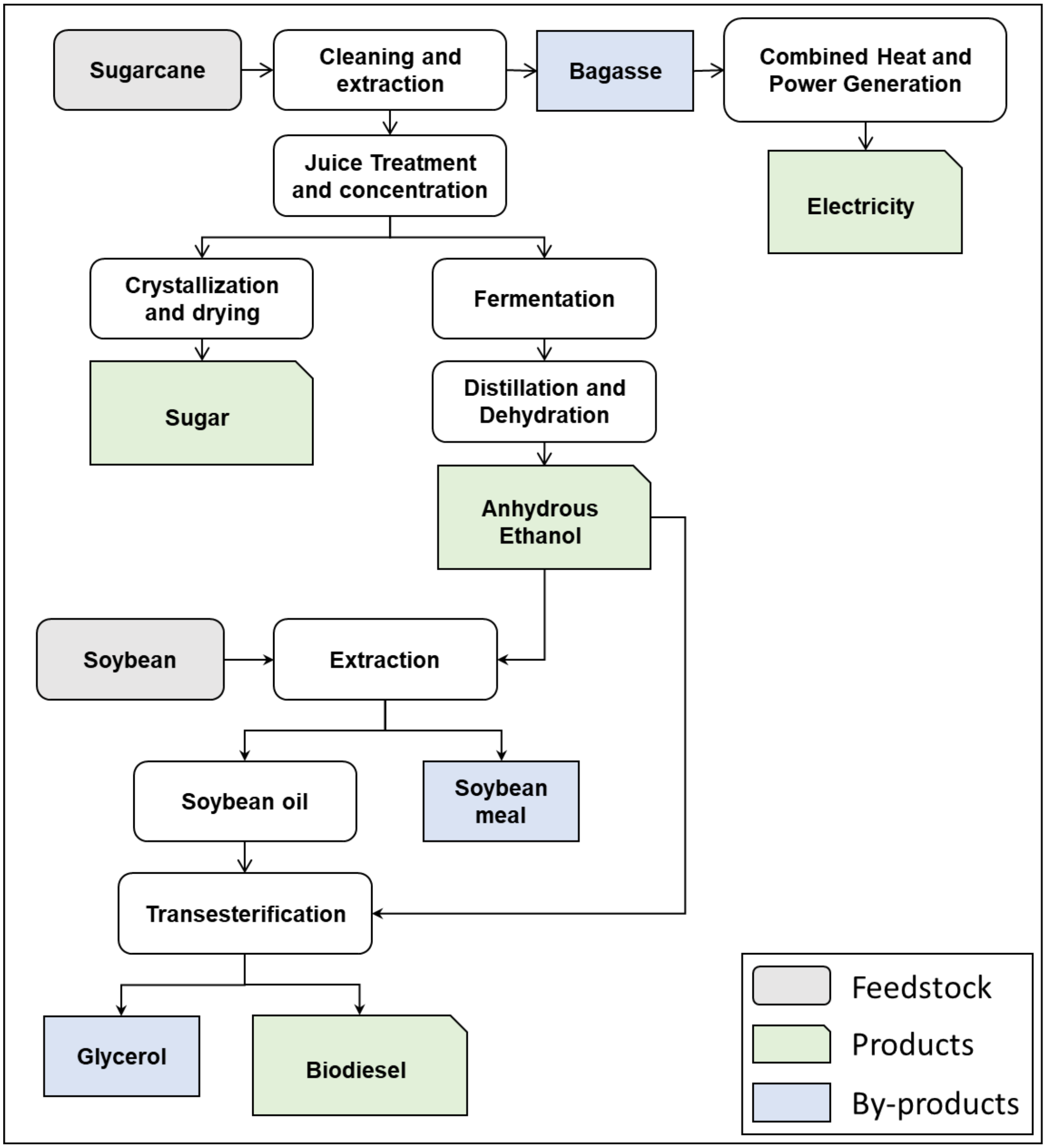

Figure S4: Simplified flowchart of sugarcane ethanol plant integrated to soybean biodiesel plant

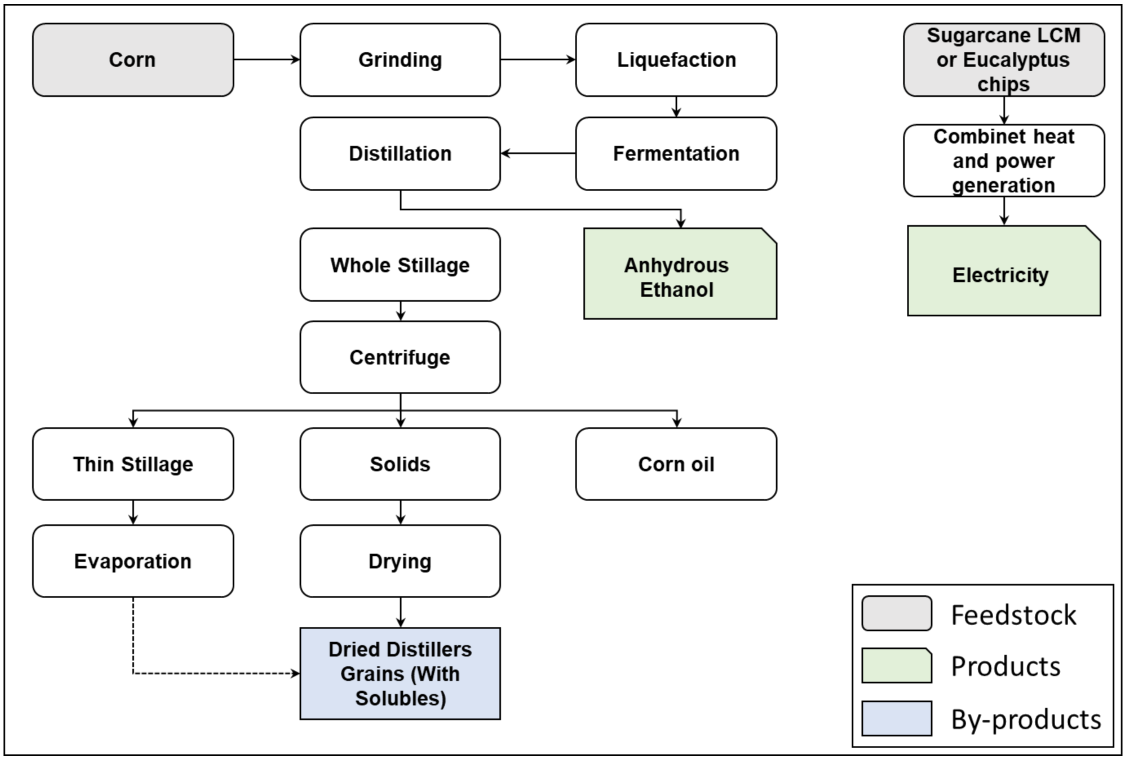

Figure S5: Simplified flowchart of full corn ethanol plant

Chapter 3

Techno-economic and environmental assessment of bioenergy and livestock integrated systems in Brazil

This chapter is a draft of a research paper for a scientific journal by Nariê Rinke Dias de Souza[1,2], Otávio Cavalett[1,3] and Tassia Lopes Junqueira[1,2].

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ABSTRACT: Bioenergy-livestock integrated systems (BLI) are a promising land-based mitigation option to meet future agricultural demands, while also alleviating pressure on land use and mitigating greenhouse gas (GHG) emission. However, their techno-economic feasibility and environmental implications are still unclear. This study performs a life cycle assessment and techno-economic assessment of BLI in Brazil from a land management perspective. It considers pasture intensification options and use of biofuels by-products as animal feed supplement to release pasture area for additional crops production. BLI presented higher techno-economic feasibility compared to conventional systems, reducing payback time by almost half, and resulting in a five-fold increased net present value to initial investment ratio. The potential to avoid GHG emissions per hectare (replacing fossil fuels) was about two times higher in BLI than conventional system, mostly due to the possibility of producing more outputs using less area. Sugarcane ethanol produced in BLI scenarios had better performances towards eight out of nine addressed Sustainable Development Goals (SDGs) compared to conventional systems, mainly because of manure application on sugarcane fields that led to lower urea demand. Crops production to feed cattle in feedlots can increase acidification and eutrophication of soil and water, negatively impacting the meat production scores on SDG 2: Zero Hunger, 6: Clean Water and Sanitation, and 14: Life Below Water, for example. Conversely, meat produced in feedlots resulted in lower impacts on air quality and increased GHG mitigation, mostly due to shorter cycle duration (120 days) and no agricultural operations on pasture (e.g., application of fertilizers and fuel consumption), with better scores in SDG 11: Sustainable Cities and Communities and 13: Climate Action. These results might help to design more assertive public policies regarding biofuel expansion in Brazil and contribute to achieve the ambitious targets stipulated by the country in the Paris Agreement and the SDGs.

Keywords: climate change mitigation, land use intensification, life cycle assessment, sustainable development goals, biofuels

3.1. Introduction

Brazil is among the land-rich countries with predicted expansion of agricultural commodities production, including food and energy crops (MAPA, 2020) to help to meet growing global demands associated with population growth (Bauer et al., 2017; Popp et al., 2017; Riahi et al., 2017). The country is an important player in global beef meat (IBGE, 2021a) and bioenergy production (RFA, 2021), and it is likely to remain as one of the largest biofuel producers considering the expected production in the next decades (MAPA, 2020; MME, 2021). At the same time, the world urges for national agendas aiming at mitigation of GHG emissions to deaccelerate climate change (Roelfsema et al., 2020; van Soest et al., 2021).

Worldwide, bioenergy-livestock integration has gained attention as a promising land-based mitigation option that takes advantage of possible synergies on using biofuel by-products as cattle feed, that can release pasture area to crops production (Buchspies and Kaltschmitt, 2016; Corré et al., 2016; Souza et al., 2021). Usually, cattle on pasture need feed supplementation during dry season and the finishing cycle can happen in feedlots with feed containing bioenergy by-products, grains and fibers (Souza et al., 2019).

Conventional biofuel pathways can generate by-products with high nutritional value. For corn ethanol, both dry-grind and wet-grind of corn grain generate by-products that are used as animal feed, such as distillers' grain with solubles (DGS) from dry-grind process and corn gluten meal, corn gluten feed meal, and corn germ oil from wet-grind process (Buchspies and Kaltschmitt, 2016). In the case of wheat ethanol, dry-grind of grains also produce DGS and wet-grind generates meal, gluten and condensed distillers solubles (Buchspies and Kaltschmitt, 2016; Mumm et al., 2014). Sugar beet ethanol generates beet pulp and stillage that have high nutritional value as animal feed (Buchspies and Kaltschmitt, 2016). Sugarcane molasses, bagasse and yeasts can be used as cattle feed highlighting beef and milk production (Egeskog et al., 2011; Souza et al., 2019). These studies accounted for opportunities associated with ethanol by-products reducing land use to produce grains and cereals for animal feed and mitigating GHG emissions. In the case of biodiesel, oil crops (e.g., soybean, palm oil, rapeseed) produce useful protein-rich by-products (mostly the cake, or meal) that can be used as animal feed and can improve biodiesel sustainability by improving land use and decreasing GHG emissions and energy use (Corré et al., 2016).

In Brazil, among potential options of bioenergy-livestock integrated systems (BLI) are some of the co- and by-products of sugarcane ethanol plants being used in animal feed formulations, such bagasse, yeasts and molasses (Souza et al., 2019). Likewise, corn ethanol plants producing DGS that have great nutritional content as animal feed (Moreira et al., 2020; Milanez et al., 2014), and integrated sugarcane-soybean plants, producing animal feed (i.e., soybean meal), are also attractive options (Souza and Seabra, 2013; 2014).

However, there is a need of more detailed quantitative assessments of techno-economic and environmental impacts, going beyond GHG emissions (Souza et al., 2021), as their implications to other environmental impacts are important to unravel their potentials and barriers for large scale implementation. It is also crucial to explore techno-economic effects of the key synergies, tradeoffs, and possible adverse effects of BLI systems when compared to conventional ones. For instance, integration of corn plants with sugarcane ethanol distilleries and/or biodiesel plants, application of cattle manure on the fields, and maximization of the use of biofuels by-products as animal feed.

This study assesses techno-economic feasibility of different strategies for integration of bioenergy and livestock value chains in Brazil, and benefits from a life cycle thinking to assess environmental impacts in relevant impact categories. Results from the life cycle assessment (LCA) and techno-economic assessment (TEA) are presented for different BLI scenarios compared to conventional production systems. We considered three biofuel crops representing the majority in the country. For instance, 90% of total 30 billion liters of ethanol produced in Brazil is derived from sugarcane, the remaining volume from corn (CONAB, 2020). Total sugarcane production account for around 10 million hectares of harvested area (IBGE, 2021b), about half of it for ethanol (CONAB, 2020). Total area of corn in Brazil is around 18 million hectares (IBGE, 2021c). Around 74% of the 5 billion liters of biodiesel produced in the country is from soybean oil (ANP, 2021) and total soybean area in the country is about 36 million hectares (IBGE, 2021c).

3.2. Methodology

3.2.1. Modelling and simulation of bioenergy-livestock integrated systems

The BLI scenarios were designed considering possible options of pasture intensification and use of biofuels by-products (e.g., sugarcane bagasse, molasses, yeast, corn ethanol, DGS, soybean meal) as animal feed supplement, considering a land management perspective. The integrated systems were designed based on the positive experiences in Brazil and in other countries (e.g., USA, see also Supplementary Material, Table S1). The integration is carried out by expanding biofuel crops on released pasture area. This release of pasture area is only possible due to the use of biofuel by-products as cattle feed, that are fed on feedlots. Simulations of BLI supply-chain were performed on the Virtual Biorefinery (VB) framework (Bonomi et al., 2016), developed by the Brazilian Biorenewables National Laboratory (LNBR), following the scheme shown in Figure 1. This framework allows simulating the whole supply-chain, from biomass production, logistics to deliver biomass to conversion facility, and industrial operations to convert biomass into products. The agricultural stage is modeled in the VB using CanaSoft® tool, an excel based series of spreadsheets considering all inputs and fuels used in each agricultural operation, such as soil preparation, planting, harvesting, application of fertilizers, agrochemicals, and industrial residues on the field. The industrial operations were calculated in spreadsheets considering mass and energy balances simulated on Aspen Plus® software, that is part of VB. The logistics include the transportation distances and consumption of fuels to deliver inputs for agricultural stage of production, biomass for biorefinery, and residues back to the fields. For this study, finishing stage of beef cattle value chain and feed production on biorefineries were inserted and modeled on the VB using data from both the literature and real cases of integrated systems. The biorefineries were designed to produce biofuels and animal feed. The inventories and mass and energy balances generated by VB framework were used to assess techno-economic feasibility of these systems and to the environmental assessment using LCA methodology.

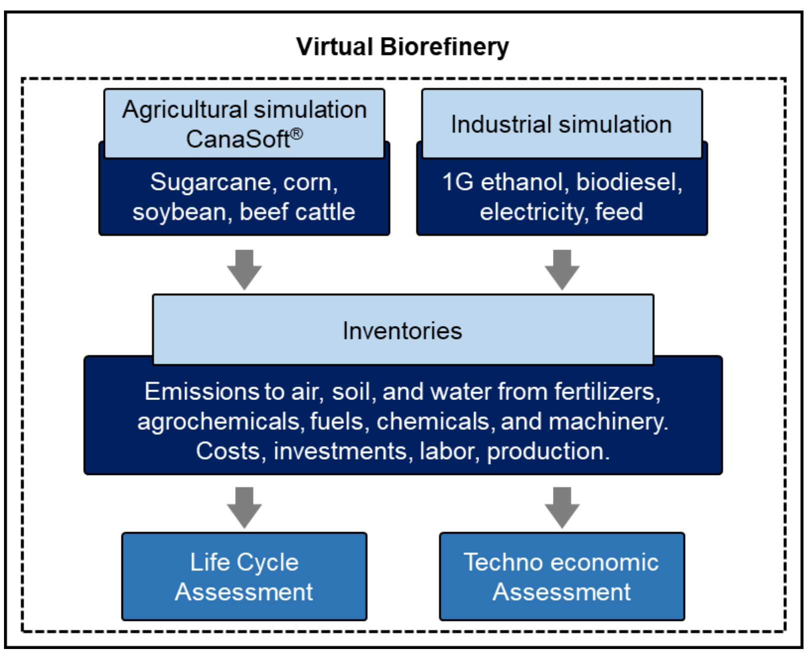

Figure 1: VB framework to assess BLI and conventional systems

We assessed 7 different scenarios (Table 1), considering different levels of integration with 3 main crops: sugarcane, corn and soybean. The first scenario (Base) is a base of comparison with beef cattle and sugarcane ethanol produced in conventional systems, without any integration. Scenarios 1, 2 and 3 are divided into two approaches (“a” and “b”), where “a” is the scenario without integration (i.e., cattle in grass-fed systems, no feedlots), and “b” with integration (i.e., cattle in feedlots with biorefineries producing feed). Integrated scenarios consider crop expansion (sugarcane area, plus corn in rotation with soybean area) on released pasture area. Feedlot area is considered neglectable, because it represents less than 1% of total area. Main parameters used to model the assessed scenarios are presented in Table 2. Additional information about industrial conversion systems is presented in Table S2 (Supplementary Material).

Table 1: Summary of the main characteristics of considered BLI scenarios

Scenarios	**Base**	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**
Cattle on pasture	x	x		x		x	
Cattle on feedlot			x		x		x
Sugarcane production	x	x	x	x	x	x	x
Corn and soybean production		x	x	x	x	x	x
Sugarcane 1G ethanol	x	x	x	x	x	x	x
Vinasse biodigestion	x	x	x	x	x	x	x
Electricity	x	x	x	x	x	x	x
Feed ingredients production			x		x		x
Soybean oil		x	x	x	x	x	x
Corn 1G ethanol				x	x	x	x
Biodiesel						x	x

Table 2: Main parameters considered for BLI modelling

Parameters	Value	Unit
Sugarcane plant		
Operation [1]	200	days
Electricity from biomethane [1,2]	3	kWh/t sugarcane
Steam yield [3]	2	kg steam/kg LCM, 50% moisture
Steam consumption [3]	350	kg/t sugarcane
Energy consumption [3]	30	kWh/t sugarcane
Energy consumption (straw) [4]	25	kWh/t straw
Ethanol yield [3]	85	l/t sugarcane
Bleed yeast yield [5]	11	kg/t sugarcane
Bagasse yield [3]	290	kg/t sugarcane
Soybean oil extraction		
Operation	200	days
Soybean oil yield [6]	190	kg/t soybean
Soybean meal yield [6]	800	kg/t soybean
Steam consumption [6]	271	kg/t soybean
Energy consumption [6]	35	kWh/t soybean
Soybean biodiesel plant		
Operation [7]	200	days
Biodiesel yield [7]	956	kg/t soybean oil
Glycerin yield [7]	117	kg/t soybean oil
Steam consumption [7]	300	kg/t soybean oil
Energy consumption [7]	15	kWh/t soybean oil
Corn ethanol plant		
Operation [8,9]	130	days
Ethanol yield [8,9]	403	L/t corn
DDGS yield [8,9]	171	kg/t corn
Steam consumption [8,9]	345	kg steam/t corn
Energy consumption [8,9]	106	kWh/t corn
Cattle on feedlot		
Duration [5]	120	days
Feed [5]	22	$kg/head.day^{-1}$
Meat yield [10]	55	%
Initial weight [5]	360	kg
Slaughter weight [5]	480	kg
Average daily weight gain [5]	1	$kg/head.day^{-1}$
Cattle on pasture		
Duration [5]	365	days
Meat yield [10]	55	%
Initial weight [5]	360	kg
Slaughter weight [5]	480	kg
Average daily weight gain [5]	0.3	$kg/head.day^{-1}$

[1]Junqueira et al. (2016); [2]Moraes et al. (2014); [3]Bonomi et al. (2016); [4]Sampaio et al. (2019); [5]Souza et al. (2019); [6]Bonomi et al. (2019); [7]Olivério et al. (2014); [8]Dias et al. (2016); [9]Milanez et al. (2014); [10]Matsuura and Picoli (2018)

Scenario 1b considers a sugarcane plant integrated to beef cattle production and sugarcane by-products (i.e., bagasse and yeast) used as part of animal feed. The necessary corn area in scenario 1b was calculated based on feed requirements. Soybean is produced in rotation with corn, and part of soybean meal produced in this area composes animal feed, while soybean oil and surplus meal are sold to the market. The equivalent crop area is considered in Scenario 1a, but the sugarcane plant does not produce any feed, therefore all soybean meal, soybean oil and corn grain are marketed.

In scenarios with corn ethanol production (2a and 2b), corn ethanol plants are annexed to sugarcane plants and operate during sugarcane offseason (130 days), in the so-called "flex" ethanol plants. Corn plants use heat and power provided by extended operation of sugarcane CHP run with sugarcane lignocellulosic material (LCM) (i.e., bagasse and straw) during sugarcane offseason. Sugarcane daily volume of ethanol production determines the corn plant size since corn plant uses sugarcane plant fermentation and distillation facilities. Corn processing capacity defines corn area. Corn ethanol is produced in dry-grind plants where the whole corn grain is ground. Ethanol is the main product, and the co-products DGS are dried, becoming DDGS, and area used as animal feed (USGC, 2012). In these two scenarios corn grain is replaced in the feed formulation by DDGS in a proportion of 1:1 (Hoffman and Baker 2011). As in Scenario 1b, surplus soybean meal and soybean oil are sold. Scenario 2a has the equivalent sugarcane, corn, and soybean areas, but without integration.

The difference between Scenarios 2 and 3 is that the latter uses all soybean oil to produce biodiesel integrated with sugarcane ethanol, which is partially used in the transesterification (Olivério et al., 2014; Souza and Seabra, 2014; 2013). Scenario 3a and 3b have an equivalent crop area, but only 3b has feed production.

In this assessment, assumptions include crop yields of 80, 5.5 and 3.4 tonnes per hectare for sugarcane (Dias et al., 2016), corn and soybean (CONAB, 2021), respectively. Except for the Base scenario, all scenarios have corn produced in rotation with soybean. In the agricultural phase of all integrated scenarios (1b, 2b, 3b), manure from cattle on feedlots is applied on sugarcane fields to replace part of the N fertilizer, according to the amount of manure produced in each scenario (Table S3), considering a 70% recovery of N content in manure. The agriculture inventory is presented in Table 3. In all scenarios, sugarcane processing capacity is 4 million tonnes per year, producing anhydrous ethanol and electricity. Electricity is produced from sugarcane bagasse, straw and biomethane obtained after purification of biogas produced from anaerobic digestion of sugarcane vinasse (Moraes et al., 2014; Junqueira et al., 2016). Around 120 kg of straw is produced per tonne of sugarcane (Menandro et al., 2017) and 50% of it is recovered from the fields using bales system (Carvalho et al., 2017). At the mill, sugarcane straw is washed and crushed, reaching a 50% moisture (equally to bagasse), subsequently it is sent to the CHP unit where it is mixed with bagasse (Mantelatto et al., 2020). All scenarios include a soybean plant to extract oil, obtaining soymeal as coproduct. Both sugarcane and soybean processing plants operate 200 days per year. Feed composition is based on Souza et al. (2019) and presented in Table S4 (Supplementary Material). To produce feed in the integrated scenarios, part of bagasse goes through a pretreatment process with steam explosion to increase its nutritional value as beef cattle feed (Souza et al., 2019). The total yeast from fermentation bleed is diverted to animal feed production. After meeting internal heat and power demands, sugarcane LCM can be diverted to feed, corn ethanol and biodiesel production. Sugarcane molasses, a by-product from sugar production, represent about 2% of feed composition and it is purchased from other sugarcane processing facilities.

Our assumptions for modelling the livestock system are simplified in face of the many specificities of the sector. For example, we considered a stabilized herd, with all animals at the same age and weight in the beginning and in the end of finishing cycle. For conventional systems we considered an extensive management with a stocking rate of one head per hectare. For integrated scenarios, we assumed that beef meat production would not be negatively affected by the crop's expansion, neither additional pasture area would be necessary, since for each hectare of released area for crop production, one cattle head should be fed with animal feed produced inside the integration boundaries.

The key integration aspects include: a) manure replacing part of mineral nitrogen fertilizer (i.e. urea); b) sugarcane plant providing power and heat for soybean and corn plants; c) soybean plant and anaerobic digestion plant operate during the 200 days of sugarcane season; d) corn plant operates during 130 days in sugarcane offseason; e) biomethane from anaerobic digestion of vinasse is burnt to generate electricity; f) yeast from sugarcane ethanol fermentation is used to supply part of animal feed; g) ethanol is used for biodiesel transesterification instead of methanol. Although methanol is the most applied alcohol for biodiesel production in Brazil (EPE, 2019), ethanol is used to maximize the integration in this study as in Olivério et al. (2014).

Table 3: Main agricultural inputs for sugarcane, soybean, corn and cattle in pasture and in feedlot

Inputs	Sugarcane	Soybean	Corn	Pasture	Feedlot*	Unit
Vinasse	40.2	-	-	-	-	m^3/ha
N fertilizer	101.3	6.3	75.3	-	-	kg/ha
P fertilizer	15.5	65.0	54.2	40.0	-	kg/ha
K fertilizer	108.6	82.8	51.6	-	-	kg/ha
Limestone	400.0	169.5	-	-	-	kg/ha
Gypsum	200.0	130.0	219.0	-	-	kg/ha
Pesticide	0.9	4.9	2.3	-	-	kg/ha
Diesel	141.0	34.6	70.5	47.7	19.8	kg/ha
Mineral Salt	-	-	-	18.3	-	kg/ha
Calf	-	-	-	360.0	360.0	kg/ha
Feed	-	-	-	-	2629	kg/ha

*Calculated in terms of hectares as a matter of comparison.

3.2.2. Life Cycle Assessment

Life cycle assessment is built on a life cycle thinking perspective to provide a standard method used for systematization, quantification and evaluation of the inputs, outputs, and potential environmental impacts throughout the life-cycle of a product, process or service, including emissions and use of resources from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (Hellweg and I Canals 2014).

The goal of this work is to assesses the environmental implication of BLI compared to conventional systems, under ISO methodology for LCA (ISO 14040 2006; ISO 14044 2006), considering selected environmental impact categories from Recipe 2016 method (Huijbregts et al., 2017). Our LCA considers a cradle-to-gate approach of seven scenarios described in Section 3.2.1, that produce biofuels and meat in conventional and integrated systems (BLI). The simplified system boundaries for both systems are shown in Figure 2. The functional units 1 MJ of biofuel (i.e., ethanol and biodiesel) and 1 kg of meat were selected as reference flows to compare results. We also addressed BLI impacts towards Sustainable Development Goals, following the methodology for LCA results interpretation under an SDG context proposed by Cavalett and Cherubini (2018) and Souza et al. (2022) (Table S5, from Supplementary Material).

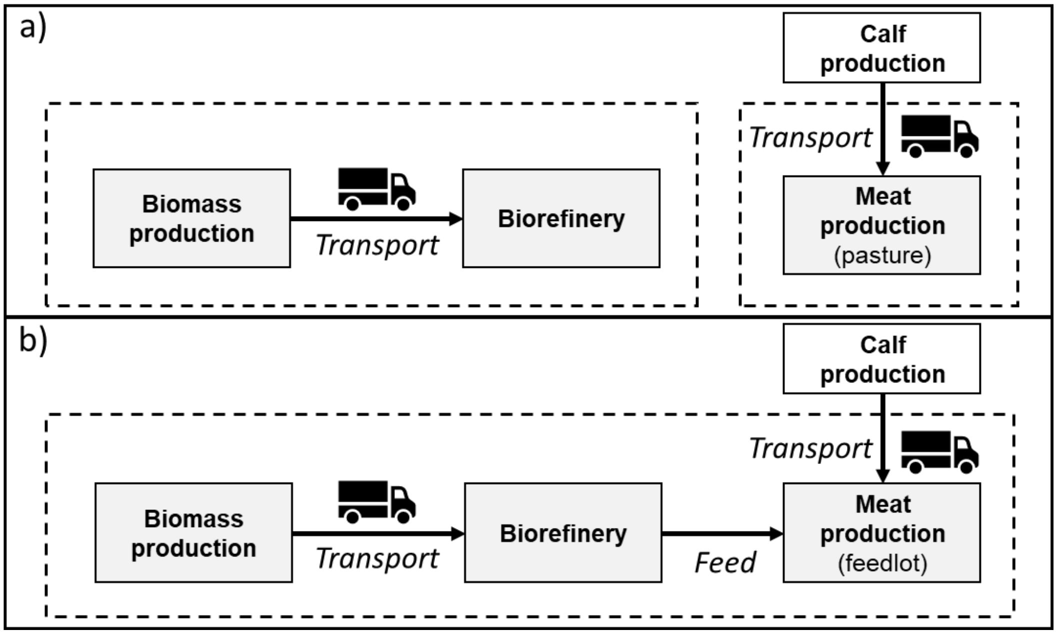

Figure 2: Simplified system boundaries for Conventional (a) and BLI systems (b)

In our approach, subdivision of the processes is applied whenever possible to avoid allocation. When subdivision was not possible, we used energy allocation (e.g., sugarcane electricity, ethanol; corn ethanol, oil and DDGS; soybean oil, soymeal, glycerin, and biodiesel) to be in line with the directives used in the RenovaBio program (Matsuura et al. 2018). Values for energy allocation are presented in Table S6 from Supplementary Material. Some intermediate flows (e.g., feed components and sugarcane electricity being used by corn and soybean plants) carry energy-allocated environmental impacts in their respective subsystems. An illustrative representation of the subdivided systems and intermediate flows from the biorefinery perspective is presented in Figure 3 for the most complex integrated scenario (i.e., scenario 3b).

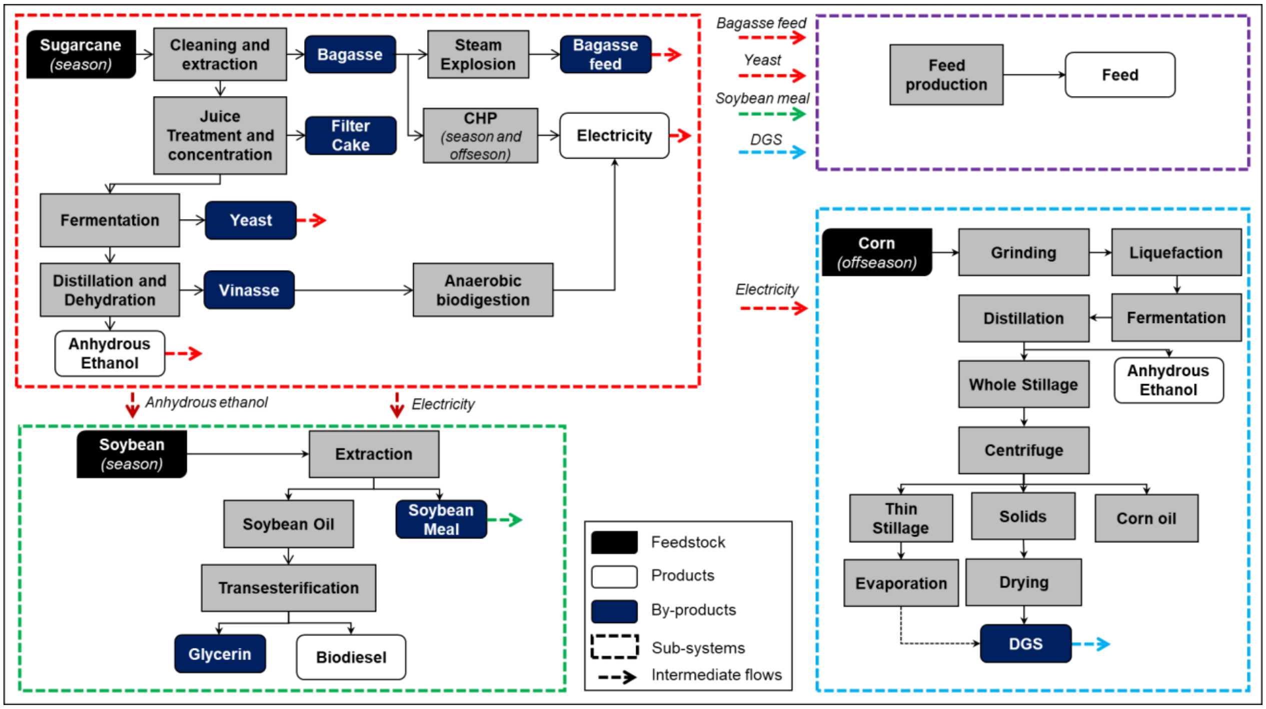

Figure 3: Subdivision of BLI in four sub-systems for the life cycle analysis a) sugarcane processing plant; b) feed production, c) corn processing plant, and d) soybean processing plant. Dashed arrows represent intermediate flows carrying impacts between different sub-systems.

Life cycle inventories considering use of inputs and emissions to air, soil and water derived from modelling using the VB framework. Biofuel inventories consider biomass production, transportation to the biorefinery and industrial conversion stages. Although only fattening stage of beef cattle production was considered in this study, the emissions from calves production and transportation were included. Inventories of finishing stage of beef cattle production systems include emissions from enteric fermentation and manure management and were calculated according to IPCC (2006) guidelines and Matsuura and Picoli (2018). A detailed description is presented in Section 1.1 and Table S7 from Supplementary Material. In the case of pasture management in scenarios without integration, we included dolomite emissions for lime and urea application (IPCC, 2006) in VB modelling. Although feed quality can have a significant impact on methane emissions from enteric fermentation (Smith et al., 2014), no specific values were considered due to scarcity of data. Default values from IPCC (2006) were applied.

No carbon emission or removals from land use change (LUC) emissions were considered, as the LUC from pasture to perennial or annual crops are site specific. However, these impacts are tested with a sensitivity analysis. Avoided GHG emissions were calculated comparing biofuels with their fossil equivalent. For ethanol, gasoline with carbon intensity of 87.4 gCO_2eq/MJ, and for biodiesel, diesel with carbon intensity of 86.5 gCO_2eq/MJ (MME, 2018).

3.2.3. Techno-economic assessment

The economic evaluation considers a greenfield project (i.e., starts from scratch, with no previous constructions, buildings, investments) using December 2019 as reference date. It considers a linear depreciation in 10 years period, 25 years of expected lifetime and a minimum rate of return of 12% per year (Watanabe et al., 2016). Main economic parameters are presented in Table 4 and additional information is provided in Table S8 (Supplementary Material). Economic inventories are calculated using the VB framework. We considered that biofuel and livestock enterprises are the same project, in a vertical approach.

The economic parameters selected for comparison are Internal Rate of Return (IRR), Net Present Value (NPV), payback time, and ratio of NPV to initial investment. These approaches rely on cash flow analysis, which depends on data collection of capital expenditures – CAPEX (investment in buildings, equipment, land, herd, working capital, etc.); on revenues (based on market prices of main outputs such as ethanol, sugar, electricity, beef cattle, and others); and on operating costs – OPEX (expenditures associated with feedstock, labor, maintenance, chemicals, utilities, feed, etc). Feed costs were estimated based on costs of ingredients produced internally in the BLI scenarios (corn grain, soybean meal, yeast, bagasse in natura and hydrolyzed, DDGS) and external market prices for mineral salt, molasses, yeast, and urea. For yeast and bagasse, we considered opportunity costs based on the sugarcane price calculated by CanaSoft®. Total agricultural and industrial costs of corn and soybean production were allocated to DDGS and soybean meal, respectively, accordingly to their production shares. Feed costs varied slightly in the three scenarios with integration due to different by-products costs.

Table 4: Assumptions for the economic evaluation

Item	Value	Unit
Expected plant lifetime [1]	25	Years
Minimum acceptable rate of return (per year) [1]	12	% per year
Depreciation [1]	10	Linear years
Anhydrous ethanol [2]	0.47	USD/L
Electricity [3]	51.37	USD/MWh
Soybean meal [4]	0.40	USD/kg
Soybean oil [4]	0.66	USD/kg
Biodiesel [4]	0.86	USD/kg
Glycerin [4]	0.54	USD/kg
DDGS [5, 6]	0.17	USD/kg
Corn oil [4]	0.67	USD/kg
Cattle, live weight [7]	2.40	USD/kg
US dollar exchange rate [8]	4.11	R$/USD dec-2019

[1]Watanabe et al. (2016); [2]CEPEA (2019); [3]CCEE (2019); [4]COMEXSTAT (n.d.); [5]Milanez et al. (2014); [6]Moreira et al. (2020); [7]Agrolink (n.d.); [8]Banco Central (2021)

3.2.4. Sensitivity analysis: maximization of BLI techno-economic and environmental performance

Four sensitivity analyses were performed to identify possibilities of maximizing overall techno-economic and environmental performance of BLI systems. 1) We considered that all diesel demand for agriculture operation and transportation of inputs and feedstocks would be replaced by biodiesel produced in scenario 3b. 2) Avoided GHG emissions from BLI systems could generate extra revenues in terms of carbon credits; each tonne of avoided GHG emissions is equivalent to 8.4 USD, according to CBIO price in RenovaBio program (B3, 2020; MME, n.d.). Another approach was also considered, taking into account possible avoided GHG emissions from cattle and electricity production. For cattle, the carbon intensity of meat in pasture was compared to meat in feedlot, calculated in this study; sugarcane electricity is compared with carbon intensity of natural gas electricity of 500 gCO_2eq/kWh (Ecoinvent, 2018). 3) Land use change emissions were calculated considering four approaches to understand their impact on total GHG emissions per hectare of land use for all BLI scenarios. Approach 1 considers the guidelines of Directive 2009/28/ECLUC (EC, 2010); Approach 2 considers LUC emissions calculated in Chagas et al. (2016) considering expansion of crops (i.e., sugarcane and corn/soybean) on degraded pastureland; Approach 3 considers LUC emissions calculated in Chagas et. (2016), but for severely degraded pastureland; Approach 4 considers LUC emissions only of sugarcane expansion on pasture calculated by Picoli (2017). Land use change emissions were calculated according to IPCC (2006) guidelines, applying the equations detailed in Section 2 and values from Table S9 of Supplementary Material. 4) Finally, we varied key integration aspects to understand their contribution to techno-economic and environmental results of BLI. The lower and upper bounds of these variations were placed from -50% to 50% in relation to the default values used in scenario 3b, the case with the highest integration. Table S10 from Supplementary Material has a detailed description of variations in sugarcane yields, recovery of N content from manure applied in sugarcane field, cattle stocking rate capacity, carcass yield, average daily gains in feedlot systems, total investments, and sugarcane bagasse for feed composition considered in this analysis.

3.3. Results and discussion

3.3.1. Production of biofuels and meat, and associated land use

In Table 5 the outputs of biofuels, electricity, feed, and meat in all the considered BLI and conventional scenarios are presented. Produced soybean meal was enough to meet the nutritional demand of cattle in feedlots in all integrated scenarios. In scenarios 2b and 3b it was necessary to purchase external yeast, since the amount provided by sugarcane plant was not enough to supply total feed demand. Produced DDGS in scenarios 2b and 3b was sufficient to feed all cattle in sugarcane and corn/soybean area.

Produced ethanol is the same in all scenarios, however, the considered output that can be sold is smaller in scenarios 3a and 3b, because around 4% of it is diverted to biodiesel production. After meeting the internal energy demands of sugarcane, corn and soybean plants, surplus electricity is sold to the grid in all scenarios. Surplus electricity presented in Table 5 account for electricity produced during sugarcane season and offseason. Comparing scenarios with and without integration (“a” and “b”, respectively), part of bagasse is used to produce feed when there is integration, and less LCM material is sent to the CHP. In scenario 1b, nearly 7% of total bagasse is used for feed production plus 1% of LCM is burnt in boilers to supply steam to the pretreatment step for feed purposes, it led to an 8% difference in surplus electricity compared to “a”. In scenario 2b and 3b, more cattle heads are finished in feedlots, thus 20% of sugarcane bagasse is diverted to feed production and 3% of total LCM is burnt in the CHP due to pretreatment of bagasse for feed. In all scenarios, part of LCM is diverted to soybean oil extraction plant to supply energy demand. In scenarios with corn ethanol production, part of LCM is stored to run the CHP during 130 days of sugarcane offseason (28% of total LCM in scenarios 2b and 3b, and 24% in scenarios 2a and 3a). All these LCM demands in scenario 2b compared to 1b reduced surplus electricity in about three quarters. Comparing scenario 2a with 1a, the reduction is only 35% since no feed is produced. The biodiesel plant demands electricity, which also reduces surplus electricity that can be sold to the grid, however, this reduction when comparing scenarios 3 to scenarios 2 was just 1% for both approaches "a" and "b". As mentioned before, scenarios 2b and 3b consider a larger area compared to scenario 1b (refer to Table 5), and all cattle heads from released pastureland must be fed with internal feed. In this way, scenarios 2b and 3b have a larger feed production. The same applies for soybean meal and oil, more is produced in scenarios 2b and 3b in comparison to scenario 1b. All by-products (i.e., meal, DDGS) are sold in approaches "a", while in "b", part, or all of them are used as animal feed. In scenario 1b, nearly one quarter of soybean meal composes animal feed, and this share grows to 94% in scenarios 2b and 3b, where more cattle heads are fed in feedlots. About 50% of all DDGS is diverted to animal feed in scenarios 2b and 3b. Soybean oil is used to produce biodiesel in scenarios 3a and 3b, and corn oil is always sold in all scenarios that include corn ethanol production. Meat production is larger in scenarios 2 and 3, due to higher area compared to scenario 1. Comparing the integration with conventional, the same amount of meat is produced whether in pasture or in feedlot system, however in the latter, less land is necessary. Finally, land use in base scenario and approaches "a" are higher as they are the sum of crop production plus equivalent pasture area.

Table 5: Main outputs and land use for the conventional and BLI scenarios

Scenarios	**Base**	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**Unit**
Outputs								
Sugarcane anhydrous ethanol	269	269	269	269	269	259	259	10^3t/year
Surplus electricity	694	694	640	511	363	508	360	GWh/year
Feed	-	-	147	-	403	-	403	10^3t/year
Surplus soybean meal	-	8	2	272	255	272	255	10^3t/year
Soybean Oil	-	2	2	65	65	-	-	10^3t/year
Biodiesel	-	-	-	-	-	62	62	10^3t/year
Glycerin	-	-	-	-	-	8	8	10^3t/year
Corn anhydrous ethanol	-	-	-	175	175	175	175	10^3t/year
Surplus DDGS	-	-	-	94	48	94	48	10^3t/year
Corn Oil	-	-	-	12	12	12	12	10^3t/year
Meat	14	15	15	40	40	40	40	10^3t/year
Land use								
Total	105.3	111.5	55.7	306.3	153.2	306.3	153.2	10^3 ha
Sugarcane	52.6	52.6	52.6	52.6	52.6	52.6	52.6	10^3 ha
Corn/Soybean	-	3.1	3.1	100.5	100.5	100.5	100.5	10^3 ha
Pasture	52.6	55.7	-	153.2	-	153.2	-	10^3 ha

3.3.2. Economic feasibility of integrated and conventional systems

Agricultural costs to produce biomass and cattle are presented in Table S11. They include costs with inputs purchase and transportation, fuel consumption, machinery, labor, and depreciation, among others. There is a slight difference (1-2%) on sugarcane costs when comparing scenarios with and without integration (i.e., “a” and “b”) that can be explained by different urea application that is partially replaced by cattle manure in approaches “b”. The small differences in sugarcane costs comparing scenario 1b with scenarios 2b and 3b, are also explained by different manure rates applied in the sugarcane field, considering they have different amount of cattle in feedlot. Larger area led to higher transportation costs in the case of corn and soybean comparing scenarios 1 with scenarios 2 and 3. Cattle production in pasture is about 18% more expensive than in feedlots, because all costs associated with agricultural inputs, transportation of inputs, fuel consumption and land rental are considerably reduced when cattle is finished in feedlots. There is a slight difference on cattle costs in scenarios 1b, 2b and 3b due to different feed costs. Feed costs are presented in Table S12 from Supplementary Material.

Economic results are presented in Table 6, divided in costs, operational surplus, breakdown of investments, and parameters to assess economic feasibility. Compared to conventional system (base scenario) scenarios 2b and 3b resulted in a payback time 43% lower, a 5-fold increase in ratio of NPV to initial investments, and IRR 10 percentage points higher. Scenario 2b and 3b presented basically the same IRR, but the latter presented a NPV that was 16 M USD larger due to a bigger gross revenue. Although total CAPEX and OPEX are higher in scenarios with corn ethanol and biodiesel production, they are balanced with larger revenues from their associated products, with high market prices (Figure S2 and S3, Supplementary Material). These larger revenues led to higher IRR and NPV, and lower payback time for scenarios 2b and 3b. Integrated scenarios with inclusion of soybean and corn presented better ratio of NPV per unit of investment results than scenarios 0 and 1, which means their inclusion improved overall techno-economic feasibility of these systems.

BLI scenarios presented lower total operational costs when compared to conventional scenarios, which can be explained by larger costs to produce cattle in pasture systems. Investments are also larger when no feed is produced, because the CHP requires larger equipment and is a plant sector with higher investment costs (Souza et al., 2019). A detailed breakdown of biorefinery investments is presented in Figure S1 (Supplementary Material). Sugarcane plant accounted for highest investments in all scenarios, from about 38% to 55%. In scenarios without corn ethanol production, CHP unit had the second largest investment costs, that ranged from 38% to 41% in the assessed scenarios. In integrated scenarios, CHP investments are smaller due to bagasse being used as animal feed. Investments for the corn ethanol plant represented the second largest shares in scenarios 2 and 3, ranging from 28 to 30%, considerably high, since part of sugarcane equipment is used by the corn plant during offseason. Biomethane production via anaerobic biodigestion of all produced vinasse account for 5-7% of total biorefinery investments. Feed production represented less than 1% of total investments in all assessed scenarios and soybean oil extraction was less than 1% in scenarios 1a and 1b. Relatively high soybean investments are presented when comparing scenario 1 to scenarios 2 and 3 due to larger soybean production in the latter two scenarios.

Table 6: Economic results for the conventional and BLI scenarios

Scenarios	**Base**	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**Unit**
Costs, gross profit and revenues								
Revenues	261.46	272.41	264.61	651.38	629.53	664.20	642.33	M USD/year
Total operational costs	164.59	171.64	159.83	403.03	379.61	408.68	385.44	M USD/year
Gross profit	96.87	100.77	104.78	248.35	249.92	255.52	256.88	M USD/year
Investments								
Total	376.75	379.49	357.44	541.79	510.00	557.19	525.36	M USD
Sugarcane + feed	343.57*	343.56*	326.21	292.41	273.55	292.18	273.27	M USD
Soybean	-	0.79	0.79	25.69	25.69	41.32	41.32	M USD
Corn	-	-	-	127.14	127.14	127.14	127.14	M USD
Cattle	33.18	35.13	30.43	96.56	83.63	96.56	83.63	M USD
Economic feasibility								
IRR	14.99	15.42	16.76	24.01	25.28	24.02	25.24	%
NPV	88.01	101.84	136.64	576.54	609.33	593.37	625.35	M USD
NPV/investment	0.23	0.27	0.38	1.06	1.19	1.06	1.19	-
Payback	5.40	5.26	4.84	3.27	3.08	3.27	3.08	years

*Scenarios Base and 1a have no feed production

3.3.3. Life Cycle Assessment of conventional and integrated systems

Climate change impacts are presented in Table 7. Feedstock production (i.e., sugarcane, corn, and soybean) contributed most to biofuel production, ranging from 80% to 95%.

Sugarcane climate change impacts vary depending on the amount of manure applied on the field that varies between scenario 1b and scenarios 2b and 3b, since more cattle heads are finished in feedlots in the latter ones, consequently more manure is available to replace urea. Corn and soybean production system and production area are the same in scenarios 1a and 1b, and in scenarios 2a, 2b, 3a and 3b, and the associated GHG emissions are equivalent in these scenarios. Lower total GHG emissions in scenarios 1a and 1b are explained by smaller areas of corn/soybean production. Climate change impacts from meat production were reduced by 23% when cattle were finished in feedlots mostly due to shorter life cycle comparing feedlots (120 days) with pasture (365 days), as well as by smaller agricultural inputs and transportation on pasture area.

Comparing climate change impacts from sugarcane ethanol and electricity outputs in approaches “a” and “b”, “b” had a carbon intensity which was 12% lower in scenario 1, 22% lower in scenario 2, and 20% lower in scenario 3, because total impacts are allocated also to bagasse and yeast that composes feed. For the outputs of corn and soybean plant, smaller differences in approaches “b” compared to “a” can be explained by lower carbon intensities associated with sugarcane electricity, that is used in both soybean and corn plants. Scenario 1b presented the highest potential to avoid GHG emissions per hectare, that is 2 times higher than conventional systems (Base scenario). This is mostly due to more outputs using less land, and higher sugarcane biofuel yields, when comparing to corn ethanol and soybean biodiesel. As more products were produced in scenarios 2 and 3, they presented higher total GHG emissions than scenarios Base and 1. Comparing approaches “a” and “b”, integration reduced total GHG emissions in 25%, mostly due to lower livestock impacts.

Table 7: Climate change impacts for the conventional and BLI scenarios

Scenarios	Base	1a	1b	2a	2b	3a	3b	Unit
Sugarcane plant								
Sugarcane	39.2	39.2	39.4	39.2	39.6	39.2	39.6	$kgCO_2eq/t$
Ethanol	18.9	18.9	16.7	19.9	15.6	19.5	15.6	gCO_2eq/MJ
Electricity	67.9	67.9	60.1	71.7	56.1	70.2	56.1	gCO_2eq/kWh
Bagasse for feed	-	-	152.3	-	142.2	-	142.3	gCO_2eq/kg
Yeast for feed	-	-	252.7	-	236.0	-	236.1	gCO_2eq/kg
Feed								
Feed	-	-	195.5	-	198.1	-	198.8	gCO_2eq/kg
Soybean plant								
Soybean	-	155.3	155.3	161.8	161.8	161.8	161.8	$kgCO_2eq/t$
Soybean meal	-	123.6	123.4	128.8	128.3	147.9	143.7	gCO_2eq/kg
Soybean Oil	-	308.0	307.5	320.9	319.8	-	-	gCO_2eq/kg
Biodiesel	-	-	-	-	-	10.0	9.7	gCO_2eq/MJ
Glycerin	-	-	-	-	-	145.7	141.5	gCO_2eq/kg
Corn plant								
Corn	-	246.8	246.8	253.2	253.2	253.2	253.2	$kgCO_2eq/t$
Ethanol	-	-	-	21.6	21.4	21.5	21.4	gCO_2eq/MJ
DDGS	-	-	-	353.9	351.5	353.6	351.5	gCO_2eq/kg
Corn Oil	-	-	-	797.6	792.1	797.0	792.1	gCO_2eq/kg
Livestock								
Meat, live weight	19.0	19.0	14.6	19.0	14.6	19.0	14.6	gCO_2eq/kg LW
General								
Avoided emissions	7.8	7.4	16.8	3.5	9.1	4.2	10.4	tCO_2eq/ha
Total emissions	0.7	0.7	0.6	1.8	1.4	1.8	1.4	$MtCO_2eq$

In Figure 4a, lower GHG emissions of sugarcane ethanol in integrated scenarios are mainly due to allocation to feed ingredients, as opposed to conventional scenarios. Most of sugarcane ethanol emissions are caused by fertilizer production and application on the field; whereas agrochemicals represented less than 1% of it. Although VB accounts for detailed inventory of agricultural machinery on the fields and inputs of chemicals in the industrial stage of ethanol production, they resulted in only 3% and 2%, respectively, of total emissions in all scenarios. In terms of GHG emissions per kg of sugarcane before allocation (Figure S4, Supplementary Material), integrated scenarios presented slightly lower emissions than conventional systems, due to lower emissions associated with construction materials and LCM burnt in approaches "b" compared to "a". This happens mostly because of smaller CHP units, considering no animal feed is produced. In Figure 4b, GHG emissions from meat production in BLI and conventional systems are presented. It is worthwhile mentioning that the emissions related to calf production are equal in all scenarios (i.e., 11.9 gCO_2eq/kg of meat, in live weight). Even with additional GHG emissions from feed production, approaches "b" presented considerably lower results than approaches "a", mostly due to no emissions associated with pasture management (i.e., soil correctives, transportation); also, reduced slaughter time decreased enteric fermentation and manure handling emissions. In terms of methane emissions, from 148 gCH_4/ kg meat LW in conventional systems, emissions were reduced to around 28 gCH_4/kg meat LW in BLI, representing an 81% reduction. Breakdown of emissions are shown in detail in Table S13, from Supplementary Material.

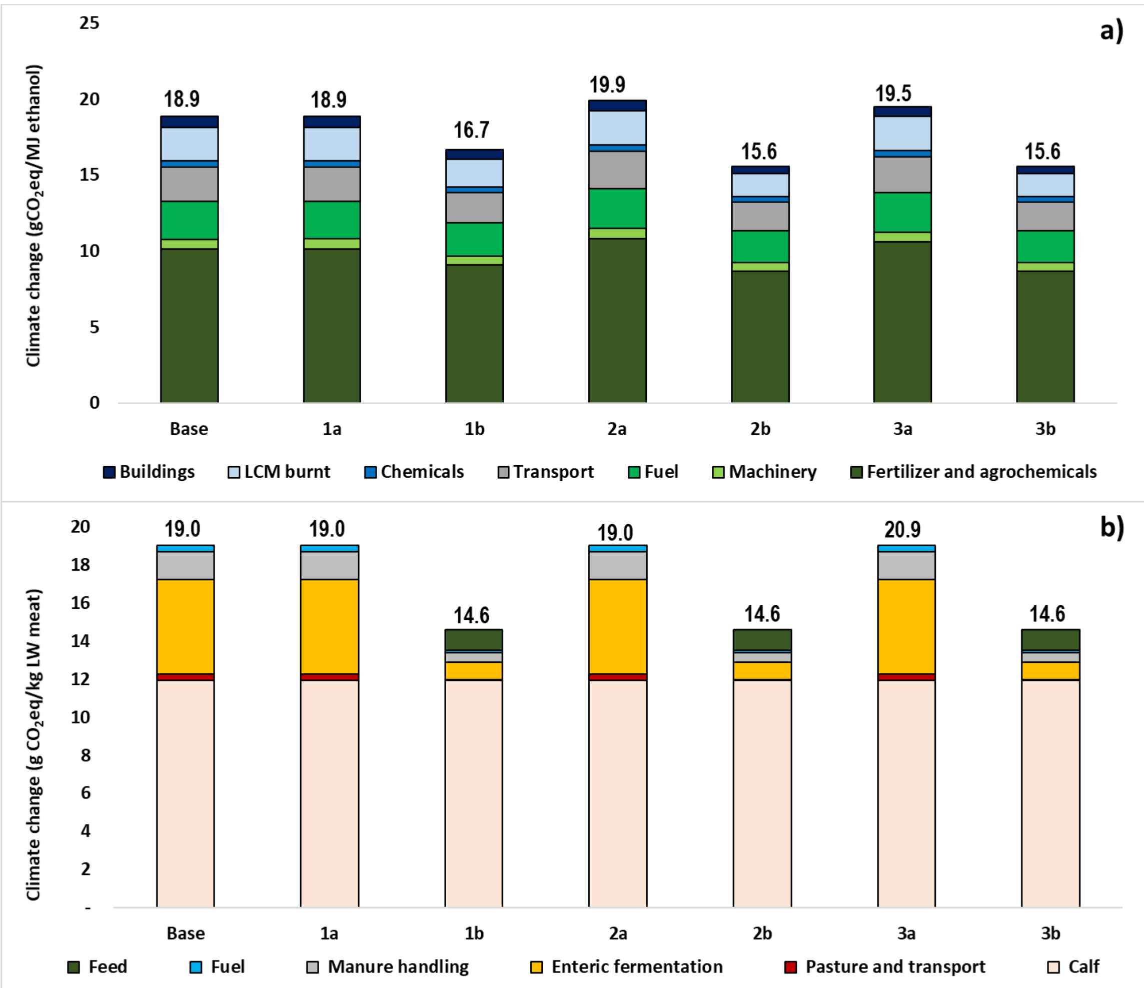

Figure 4: Panel a) Breakdown of climate change impacts of sugarcane ethanol production in conventional and BLI scenarios, after allocation. Panel b) Breakdown of climate change impacts of beef meat in conventional and BLI scenarios.

In terms of fossil energy consumption, measure in kg oil eq, scenario Base consumed about 133 kJ of fossil energy per MJ of sugarcane ethanol produced, while in the most integrated scenario (3b), this value is 103 kJ/MJ, a reduction of 30 kJ/MJ. In Souza and Seabra (2014) this reduction was 18 kJ/MJ and in Souza and Seabra (2013) it reached 38 kJ/MJ of biofuel produced in the integrated system.

The life cycle environmental impacts of conventional and BLI systems interpreted under an SDGs context are presented in Figure 5 for sugarcane ethanol and meat, two common outputs in all scenarios. The arithmetic means of results from the four conventional and three BLI scenarios was applied, since differences among them were only 1-4%. Higher impacts mean worse performance towards each SDGs. Absolute LCA values and normalized impacts relatively to the highest results in each category are presented in Table S14 and Figure S5 (Supplementary Material).

For sugarcane ethanol, conventional scenarios presented higher impacts than BLI scenarios in eight out of nine addressed SDGs. In SDGs 2 – Zero Hunger and SDG 3 – Good Health And Well-Being, BLI systems presented lower impacts, mostly due to allocation to more products. Also, because in the industrial stage, higher LCM burnt in boilers contributed to higher terrestrial acidification and higher fine particular matter formation from conventional when compared to BLI scenarios, which can negatively impact on sustainable agricultural production (SDG 2) and on air pollution, possibly leading to respiratory diseases (SDG 3). Higher mineral N fertilizer (i.e., urea) production led to higher freshwater eutrophication in conventional scenarios and can negatively impact on freshwater quality (SDG 6 – Clean Water And Sanitation). In SDG 7 – Affordable and Clean Energy, conventional scenarios had a higher use of non-renewable resources, resulting in a higher fossil resource scarcity due to higher urea production and transportation. In SDG 11 – Sustainable Cities and Communities, conventional scenarios performed worst due to higher ozone formation during urea production, leading to a possible reduction in air quality. Comparing mineral resource scarcity, the indicator for SDG 12 – Responsible Consumption and Production, conventional scenario presented higher impacts due to larger CHP units, which demanded more building materials, since no LCM is diverted for feed purposes. As discussed in Figure 3a, sugarcane ethanol presented lower GHG emissions when compared to conventional systems, having a better performance in SDG 13 – Climate Action than conventional ones due to allocation of overall emissions to feed components. SDG 14 – Life Below Water is the only SDG where conventional systems performing better than integrated ones, and it happens mostly because of higher N-related emissions from manure application on sugarcane fields that led to higher marine eutrophication, what can impact on marine life. Since there is no BLI integration in conventional systems, all animals are finished in pasture management and more land is occupied, leading to higher impacts in SDG 15 – Life On Land.

Some tradeoffs were observed comparing livestock in pasture (conventional) and in feedlots (integrated). From the nine SDGs assessed in this work, conventional meat production presented higher impacts in SDG 11 and 13, mostly due to longer cycle duration (365 days), intensified usage of fertilizers and soil correctors, agriculture machinery and fuel consumption to agricultural operations on pasture. However, integrated systems increased impacts associated with four other SDGS due to higher terrestrial acidification (SDG 2), freshwater eutrophication (SDG 6), marine eutrophication (SDG 14), and mineral resource scarcity (SDG 12) due to increased crop production and other inputs in feed composition. In SDG 3, 7 and 15, both systems scored fairly the same, once the reduction in agricultural operations in large areas of pasture was compensated by feed production.

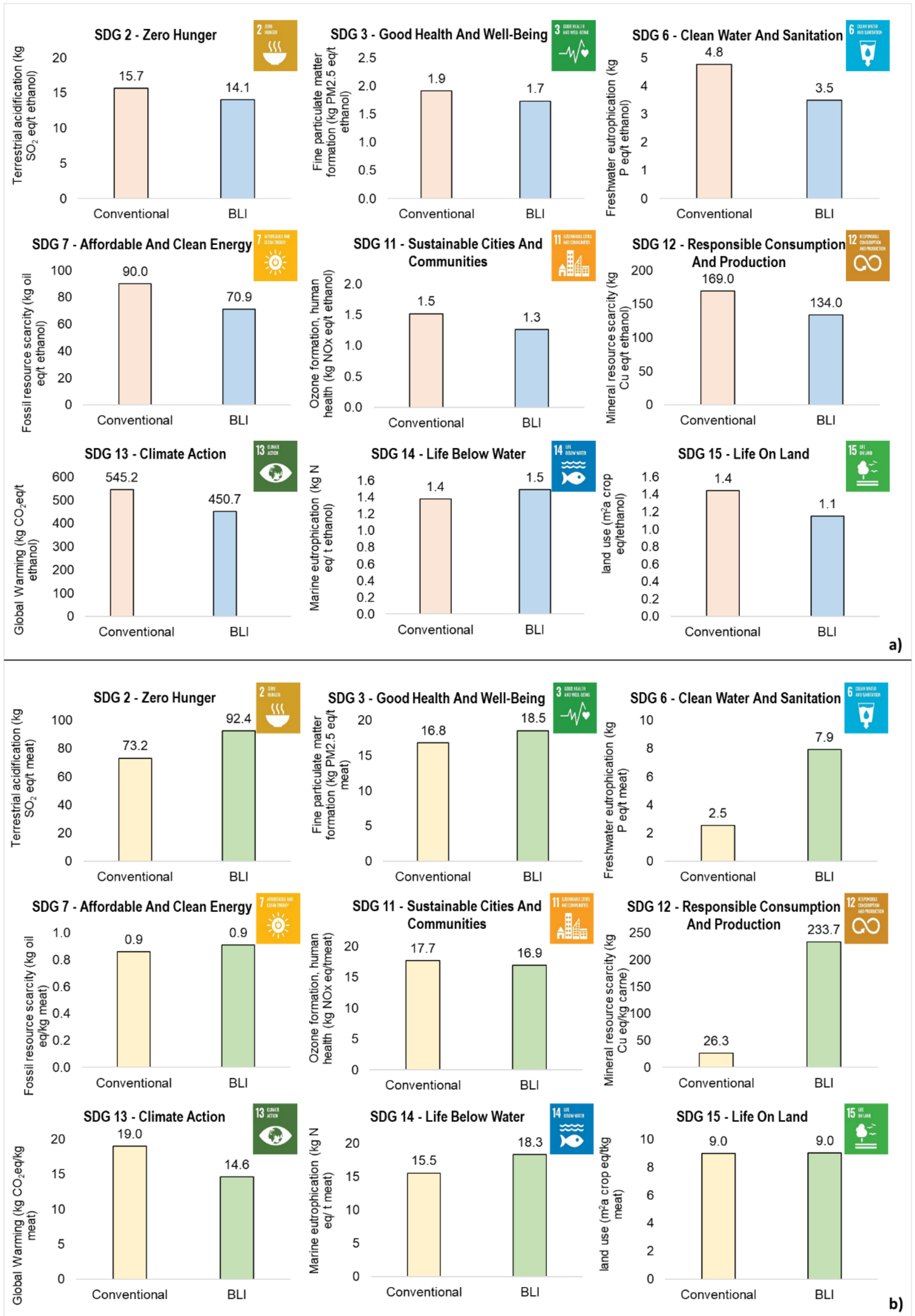

Figure 5: Conventional and BLI systems impacts of sugarcane ethanol on Sustainable Development Goals (a); Conventional and BLI systems impacts of beef meat on Sustainable Development Goals (b). “Conventional” is an arithmetic mean of results from scenarios Base, 1a, 2a and 3a, while “BLI” is the arithmetic mean of results from scenarios 1b, 2b and 3b.

3.3.4. Sensitivity analyses

Figure 6 presents revenues with CBIOs in two approaches: considering CBIO generation only from avoided GHG emission when replacing fossil fuels with the respective biofuel (e.g., ethanol replaces gasoline, biodiesel replaces diesel) in accordance with RenovaBio directives (panel a); and a second approach showing the potential if all avoided GHG emissions (Table 6) could generate CBIOs (panel b). The sugarcane related CBIOs (panel b) increased 2 to 3 million USD per year when considering avoided emissions also from electricity. Meat CBIOs represented 13%, 23% and 20% of total CBIOs in scenarios 1b, 2b and 3b respectively. The inclusion of corn during sugarcane offseason and the production of biodiesel can increase CBIO generation in the two approaches considered. Scenario 3b has the highest potential to generate extra revenues in both approaches. From the 9 million USD per year of scenario 3b in the first approach, sugarcane electricity and meat could contribute to an additional 1.6 and 2.7 million USD, respectively, totalizing 13.38 million USD of CBIO revenues.

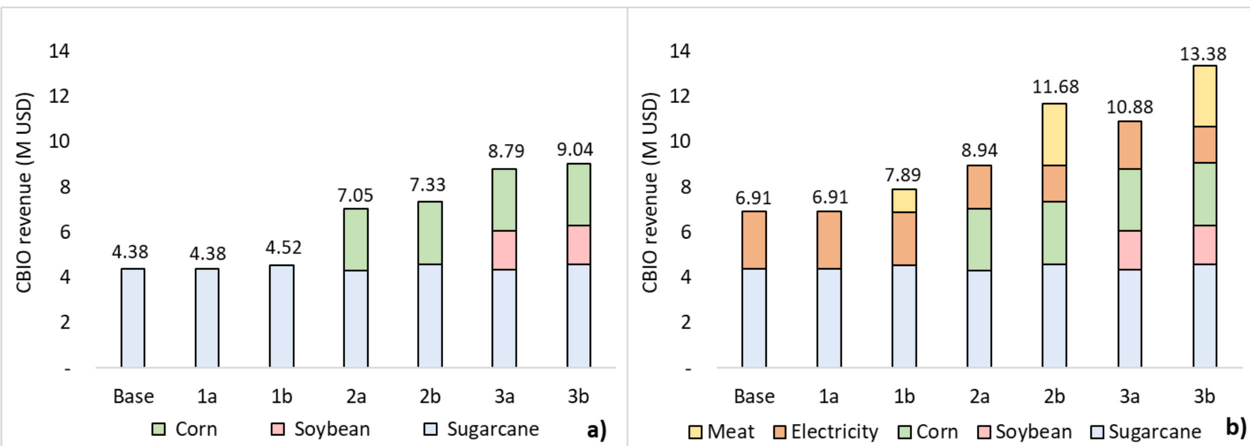

Figure 6: Panel a) CBIO revenues considering only avoided emissions from biofuels; Panel b) CBIO revenues considering all avoided emissions.

When replacing all diesel demand for agricultural operations and transport in scenario 3b and considering no costs and emissions are allocated to this product that is internally produced and consumed, there is a positive impact on techno-economic and GHG mitigation potential of this BLI system (Figure 7). Although there is a 52% decrease on biodiesel sales and a slight increase in biodiesel carbon intensity (7%), all remaining parameters presented positive results. Biodiesel GHG emissions increased since all soybean-related emissions are allocated to less biodiesel being sold. Replacing diesel with biodiesel on agricultural operations reduced GHG emissions of sugarcane ethanol, electricity, corn ethanol and meat in 12%, 12%, 3% and 1%, respectively. Operational costs and payback time decreased 14% and 16%, respectively, purchase of fossil diesel was not required. For the same reason, gross profit, IRR and NPV increased 21%, 15% and 35%, respectively.

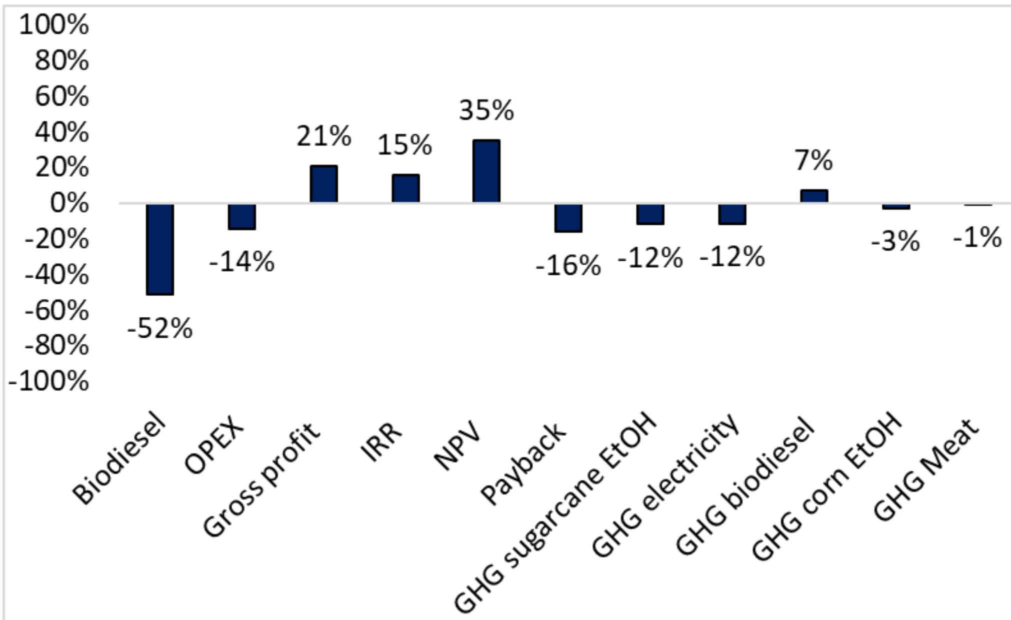

Figure 7: Impacts of diesel replaced with biodiesel on economic feasibility and GHG emissions

Accounting for LUC emissions of sugarcane and soybean/corn expansion on pastureland could increase or decrease total GHG emissions from the BLI scenarios, depending on the approach considered (Figure 8). These differences happened due to different standard soil organic carbon (SOC) and pasture condition before biofuel expansion. Corn and soybean are annual crops and are reported to have a lower SOC than pasture in all LUC changes accounting approaches. Therefore, expansion of these crops in pasture area are likely to cause relatively higher LUC compared with sugarcane expansion. Here, different approaches were applied to account for soil carbon calculation and to show how this would impact on BLI emissions. Approach 1 following European Commission guidelines, approaches 2 and 3 considering crops expansion on degraded pastureland and severely degraded pastureland, respectively, and approach 4 considering sugarcane expansion on extensive pasture management. However, LUC emissions strongly depend on site-specific edaphoclimatic conditions of the current and previous land uses (Lal, 2010) and require a deeper and more detailed assessment to be performed in future work.

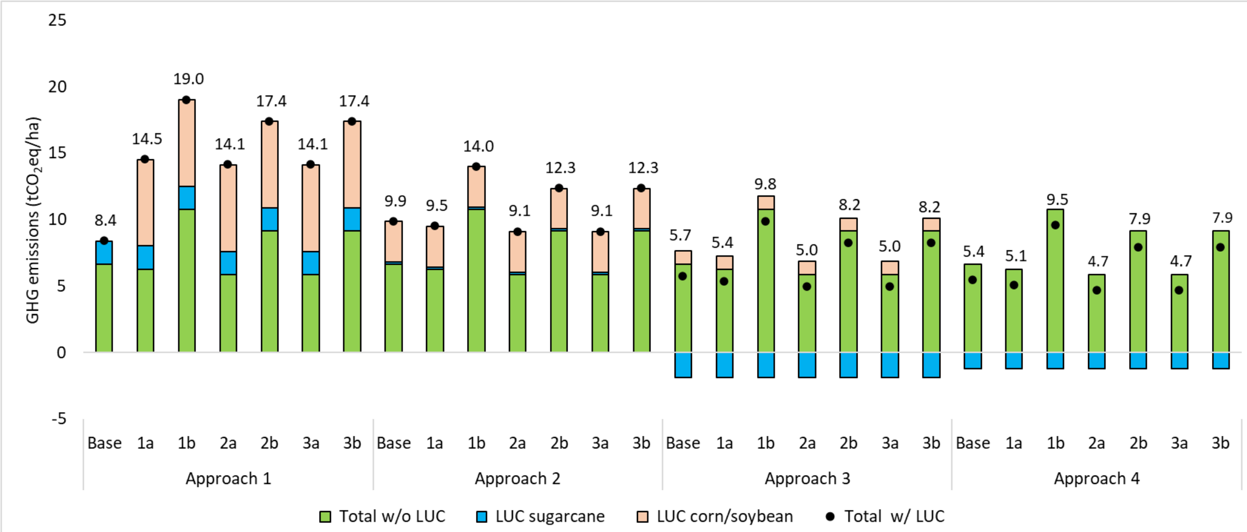

Figure 8: Total GHG emissions of BLI systems considering LUC emissions

Finally, Figure 9 shows the impacts of varying parameters on BLI techno-economic and environmental performance of scenario 3b (highest level of integration). From the seven key parameters, variation of sugarcane yield contributed the most to all outputs considered. Bagasse content on feed, on the other hand, had almost no impact in five out of the six outputs considered, it only considerably impacted on surplus electricity sold to the grid, once more bagasse for feed means less LCM available for CHP. The same effect holds true for variable stocking rate, since more cattle heads per hectare means more bagasse for feed and less for CHP. Cattle stocking rate also impacted on total land use, as higher stocking rates means lower land demand. As expected, higher carcass yields produced more meat and reduced GHG emissions associated with it, however these parameters did not affect other outputs. Average daily gain (ADG) slightly impacted on GHG emissions of sugarcane ethanol because lower feedlot duration allowed a higher production of electricity, and more emissions were allocated to it. When more electricity is produced NPV/investments increases as well. Variation in total investments had impacts on NPV/investments ratio, the lower the total investment, the higher was this ratio. Recovery of N on manure application on the field had almost no impact in all assessed outputs.

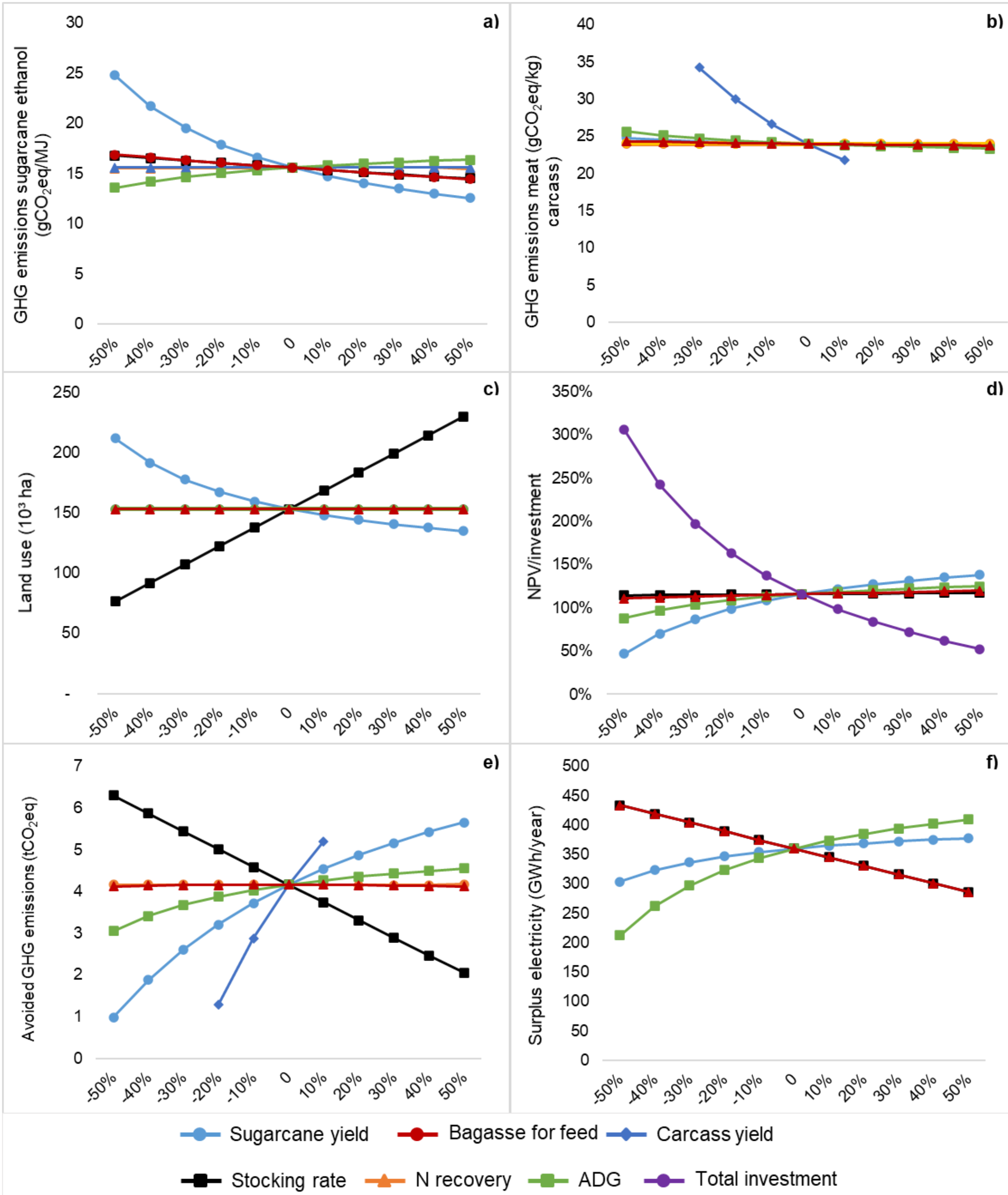

Figure 9: Impacts of variation of key parameters on GHG emissions from sugarcane ethanol (a); on GHG emissions of meat (b); on land use (c); on NPV/investment ratio (d); on avoided GHG emissions (e); and on surplus electricity generation (f). "0" on axis X represents the default values.

3.3.5. BLI limitations and uncertainties

Although Souza et al. (2021) discussed the BLI potential to be broadly implemented in Brazil and to contribute to future energy demands and mitigation targets, their work indicated that a quantitative sustainability assessment would help to address many potential sustainability issues related to BLI. Here, BLI systems have presented the potential to improved techno-economic and environmental feasibility when compared to conventional systems, highlighting improvements in land use and consequent increase in avoided GHG emissions per unit of production area.

However, these results are limited by the assumptions considered in this study. From an environmental perspective, future studies could explore LCA, such as performing consequential assessments (Moreira et al., 2020) and considering credit generation of co-products used as animal feed (Anderson et al., 2018; Popp et al., 2016). This study shows that under the conditions considered, BLI scenarios could be economically feasible, but high uncertainties are associated with the integration (Souza e Seabra 2014). A minimum acceptable rate of return per year of 12% was considered, any NPV above 0 represents the economic feasibility, which happened in all scenarios. Furthermore, and fast paybacks are desirable in any enterprise. However, this 12% is acceptable for the sugarcane sector in conventional production pathways (Watanabe et al., 2016). Detailed economic feasibility studies should assess rates that more closely represents integrated systems. In addition, more economic perspectives should be explored, including incremental (brownfield) assessment of integrated systems in existing biofuel refineries, or horizontal assessment considering livestock and biofuel as two different enterprises, as in Souza et al. (2019).

Uncertainties associated with BLI systems are a) it is likely that not all cattle can be fed in feedlots, as cow-calf system has limitations to be raised in feedlot systems (Souza et al., 2019; USCG, 2012); b) feedlot system can lead to pollution of water sources and bad odor if manure is not well-managed (Cardoso et al., 2016). A comprehensive uncertainty analysis would improve the robustness of BLI modelling presented in this study.

Although not considered in this study, a promising option for releasing pasture area for bioenergy crops production is the recovery of degraded pastures by intensifying livestock production (Silva et al., 2017). This approach can increase carbon sequestration, decrease overall GHG emissions per unit of meat produced, and avoid deforestation (Cardoso et al., 2016; Silva et al., 2017; Figueiredo et al., 2017).

Finally, bioenergy sustainability impacts depend on regional and local characteristics (Hiloidhari et al., 2017). A spatially explicit assessment of BLI can account for site specific characteristics that can strongly influence in the sustainability impacts presented here (Hiloidhari et al., 2017; Humpenöder et al., 2018), such as biomass availability and yields, land use conditions, climatic variables, among others (Field et al., 2020; Granco et al., 2019; Zullo et al., 2018). A better understanding of implications of BLI systems towards water use and water availability, on biodiversity and on biomes are key to a broader sustainability assessment.

3.4. Conclusions

Bioenergy-livestock integrated systems are particularly interesting for Brazil, as they are an important option for future land use management strategies, can optimize land use requirements, and reduce climate change and other environmental impacts in comparison to single value chains. In addition, BLI can help to meet future demands of food and energy in a more sustainable way. This study provided a better understanding of the technical, economic and environmental impacts of BLI scenarios highlighting the synergies among the different value chains and those related to land use and economic effects of using bioenergy by-products as animal feed.

Scenario 3b, the most complex BLI, presented the best techno-economic feasibility among all scenarios, with a payback time 43% lower, NPV/investment 5 times higher, higher revenues, and IRR 10 percentage points higher than Base scenario. On the other hand, scenario 1b presented the highest avoided GHG emissions per hectare, almost 2 times higher than the base scenario, mostly due to higher sugarcane yields to produce biofuel and the possibility of producing more outputs using less area. Methane emissions were reduced by 81% in the BLI system compared to conventional one. Regarding fossil energy consumption, scenario 3b presented a reduction of 30kJ of fossil energy per MJ of sugarcane ethanol produced, compared to base scenario. Sugarcane ethanol from BLI system had better performances towards almost all SDGs compared to conventional systems (SDG 2, 3, 6, 7, 11, 12, 13 and 15). This was due to manure application on sugarcane fields that led to lower urea production, application, and transportation. In a meat perspective, agricultural production of corn and soybean, that compose feed ingredients, would increase acidification and eutrophication of soil and waters from meat produced in feedlots negatively impacting on SDG 2, 6, and 14, and increasing mineral resource scarcity (SDG 12). On the other hand, meat produced in feedlots would reduce associated impacts on SDG 11 and 13, mostly due to shorter cycle duration (120 days), lower fertilizer and soil corrector usage, agricultural machinery and fuel consumption to agricultural operations on pasture. In the other SDGs, both systems presented similar results.

Costs associated with agricultural inputs, transportation of inputs, fuel consumption and land rental are considerably higher when cattle are produced on pasture, which led to an 18% difference when compared to feedlots. Biorefinery investments are also higher in conventional scenarios due to larger CHP units, when no feed is produced. Comparing scenarios 1, 2 and 3, even with higher CAPEX and OPEX, scenarios 2 and 3 present higher revenues which lead to higher economic feasibility compared to scenarios 1 ("a" and "b"), which means inclusion of corn and soybean is techno-economically feasible from a process perspective. Additionally, producing biodiesel (scenarios 3a and 3b) is techno-economic feasible, as investments represented only 4% of the total biorefinery investments.

Possibilities for improving the techno-economic and environmental performance of BLI systems include replacing diesel with biodiesel and considering additional revenues from carbon credit generation. These results are expected to contribute to the challenges of land-based climate change mitigation strategies and growing demand of food, feed, and energy in Brazil and globally. This study can facilitate the design of public policies regarding biofuel production in Brazil and other countries. Further studies should include social impacts and a spatially explicit sustainability assessment of BLI expansion in Brazil to account for site-specific crop yields, effects on soil organic carbon and land use change emissions.

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Supplementary Material to: Techno-economic and environmental assessment of bioenergy and livestock integrated systems in Brazil

1. **Parameters to simulate BLI value chains**

Table S1: Literature to build the inventories of BLI production costs and emissions

	Costs	Emissions
Agricultural		
Sugarcane	CanaSoft® database	CanaSoft® database
Corn	CanaSoft® database	Matsuura and Picoli (2018)
Soybean	CanaSoft® database	Matsuura and Picoli (2018)
Beef cattle	Souza et al. (2019)	Souza et al. (2019); Picoli (2017); Matsuura and Picoli (2018)
Industrial		
Sugarcane ethanol	Souza et al. (2019)	Souza et al. (2019); VB database
Sugarcane straw washing and processing	Mantelatto et al. (2020)	VB database
Anaerobic digestion	Junqueira et al. (2016); Moraes et al. (2014)	Junqueira et al. (2016); Moraes et al. (2014)
Soybean oil extraction	Rost (2013)	Bonomi et al. (2019), VB database
Biodiesel	Olivério et al. (2014)	Bonomi et al. (2019), VB database
Corn ethanol	Dias et al. (2016); Milanez et al. (2014)	Dias et al. (2016); Milanez et al. (2014)

Table S2: Industrial inventory for BLI

Inputs	Value	Unit
Sugarcane		
Quicklime	0.61	kg/t sugarcane
Sulphuric acid	0.42	kg/t sugarcane
Phosphoric acid	60.00	g/t sugarcane
Flocculant	4.08	g/t sugarcane
Antibiotic	1.10	g/t sugarcane
Soybean		
Hexane	1.10	kg/t soybean
Citric acid	0.12	kg/t soybean
Ethanol	45.00	kg/t soybean
Sodium methoxide	1.45	kg/t soybean
Hydrochloric acid	0.02	kg/t soybean
Sulphuric acid	0.01	kg/t soybean
Sodium hydroxide	0.04	kg/t soybean
Corn		
Alfa amilase	0.18	kg/t corn
Glucoamilase	0.50	kg/t corn
Ammonia	3.16	kg/t corn

Table S3: Manure and urea application per scenario

	Base	1a	1b	2a	2b	3a	3b	Unit
Manure	-	-	15.37	-	42.24	-	42.24	kgN/ha
Urea	101.25	101.25	92.59	101.25	77.44	101.25	77.44	Kg/ha

Table S4: Feed composition. Based in Souza et al. (2019)

Feed ingredient	Value	Unit
Total bagasse	12.83	kg/head.day^{-1}
Hydrolyzed bagasse	11.93	kg/head.day^{-1}
Bagasse *in natura*	0.90	kg/head.day^{-1}
Wet yeast	4.89	kg/head.day^{-1}
Molasses	0.39	kg/head.day^{-1}
Corn grain	2.53	kg/head.day^{-1}
Soybean meal	0.91	kg/head.day^{-1}
Urea	0.08	kg/head.day^{-1}
Mineral salt	0.28	kg/head.day^{-1}
Total	**21.91**	**kg/head.day^{-1}**

Table S5: Selected LCA indicators and their relationship with the SDGs

LCA indicator – Recipe 2016	Unit	SDG
Terrestrial acidification	kg SO_2 eq	2
Fine particulate matter formation	kg PM2.5 eq	3
Freshwater eutrophication	kg P eq	6
Fossil resource scarcity	kg oil eq	7
Ozone formation, human health	kg Nox eq	11
Mineral resource scarcity	kg Cu eq	12
Global warming	kg CO_2 eq	13
Marine eutrophication	kg N eq	14
Land use	m^2a crop eq	15

Source: Based on Cavalett and Cherubini (2018) and Souza et al. (2022)

Table S6: Lower heating values used for energy allocation

Product	Value	Unit	Reference
Anhydrous ethanol	28,3	MJ/kg	ANP (2019)
Electricity	3,6	MJ/kWh	-
Bagasse	9,1	MJ/kg	NASEM (2016)
Yeast	15,2	MJ/kg	Martins et al. (2013)
Soybean meal	14,8	MJ/kg	NASEM (2016)
Soybean Oil	37.0	MJ/kg	Lima et al. (2011)
Biodiesel	37,7	MJ/kg	ANP (2019)
Glycerin	14,6	MJ/kg	Lima et al. (2011)
DDGS	16,4	MJ/kg	NASEM (2016)
Corn Oil	37.0	MJ/kg	Lima et al. (2011)

1.1. Livestock emissions

CH_4 emissions from enteric fermentation

CH_4 from enteric fermentation was calculated according to IPCC Tier 2 (IPCC, 2006) and Brazilian parameters from Matsuura and Picoli (2018), with Equation S1 and Table S7:

$$\mathrm{CH_4E_i} = \frac{\mathrm{GE_i}}{\mathrm{EC_{CH4}}} * \mathrm{DMI_i} * \mathrm{Ym_i} * \mathrm{Days_I} \qquad \text{Equation S1}$$

Where:

- CH_4E_i is the enteric fermentation CH_4 emission factor in finishing system i (pasture or feedlot), in kg.year^{-1}.animal^{-1}
- GE_i equals to 18.45 is the energy intensity of feed, IPCC default value, in MJ.kg^{-1}
- EC_{CH4} equals to 55.65 is the energy value of CH_4, IPCC default value, in MJ.kg^{-1}
- DMI_i is the average Dry Matter Intake of animal in in finishing system i (pasture or feedlot), in kg.day^{-1}.animal^{-1}
- Ym_i is the average methane conversion rate, in %
- $Days_i$ is the number of days per year each animal stay in finishing system i (pasture or feedlot), in days.year^{-1}.

CH_4 emissions from manure management

CH_4 from manure management was calculated using Equations S2 and S3, and Table S7 according to IPCC guidelines (IPCC, 2006) and Brazilian parameters from Matsuura and Picoli (2018):

$$\mathrm{CH_4M_i} = CF_{CH4} * \mathrm{Bo} * \mathrm{MCF} * VS_i * \mathrm{Days_I} \qquad \text{Equation S2}$$

Where:

- CH_4M_i is emission factor for CH_4 from decomposition of manure in finishing system i (pasture or feedlot), in kg.year^{-1}.animal^{-1}
- CF_{CH4} equals to 0.67 is the conversion factor of m^3 CH_4 to kg CH_4

- Bo is the maximum production capacity of methane by manure, in $m^3CH_4.kg^{-1}$
- MCF is the methane conversion factor, in %
- VS_i is daily volatile solid excreted for animal in finishing system i (pasture or feedlot), $kg.animal^{-1}.day^{-1}$
- $Days_i$ is the number of days per year each animal stay in finishing system i (pasture or feedlot), in $days.year^{-1}$

$$VS_i = DMI_i * (1 - DE + UE) * (1 - ASH) \qquad \text{Equation S3}$$

Where:

- DMI_i is the average Dry Matter Intake of animal in in finishing system i (pasture or feedlot), in $kg.day^{-1}.animal^{-1}$
- DE is the digestibility of the feed, in %
- UE is the urinary energy, as a fraction of gross energy intake
- ASH is the ash content of manure, as a fraction.

<u>N_2O emissions from manure management</u>

N_2O from manure management was calculated using Equations S4 and S5, and Table S7 according to IPCC guidelines (IPCC, 2006) and Brazilian parameters from Matsuura and Picoli (2018):

$$N_2O_{i=} \frac{44}{28} * (F_i * ED_i + E_N * N_i) \qquad \text{Equation S4}$$

Where:

- N_2O_i is the annual direct and indirect N_2O emissions from manure in finishing system i (pasture or feedlot), in $kg.year^{-1}.animal^{-1}$;
- F_i is the annual amount of N from manure in finishing system i (pasture or feedlot), in $kg.year^{-1}.animal^{-1}$;
- ED_i is the N_2O-N (i.e., N in N_2O) direct emission factor for manure in finishing system i (pasture or feedlot).
- EN is the N_2O-N indirect emission factor for N that volatilizes as NH_3 and Nox from manure.
- N_i is the fraction of N from manure that 104mbiental104104 as NH_3 and Nox in finishing system i (pasture or feedlot).
- 44/28 is the conversion factor from kg N_2O-N to kg N_2O.

$$F_i = \frac{1}{1000} * Nex * W_i * \frac{Days_i}{365} \qquad \text{Equation S5}$$

Where:

- F_i is the annual amount of N from manure in finishing system i (pasture or feedlot), in $kg.year^{-1}.animal^{-1}$
- Nex is the excretion rate of N per 1000 kg of animal live weight, in kg $N/1000\ kg.day^{-1}$

- W_i the average live weight of animals in finishing system i (pasture or feedlot), in kg.animal^{-1}
- $Days_i$ is the number of days per year each animal stay in finishing system i (pasture or feedlot), in days.year^{-1}.

NH_3 emissions to air

NH_3 emissions were calculated according to parameters from Matsuura and Picoli (2018), according to Equation S6 and Table S7:

$$NH_{3\,i} = \frac{17}{14} * F_i * 0.6 * 0.6 \qquad \text{Equation S6}$$

Where:

- NH_{3i} is the emission of ammonia from of animals n finishing system i (pasture or feedlot), in kg.year^{-1}.animal^{-1};
- F_i is the annual amount of N from manure in finishing system i (pasture or feedlot), in kg.year^{-1}.animal^{-1};
- 17/14 is the conversion factor from kg NH_3-N in NH_3

Table S7: Parameters to calculate livestock emissions

Parameter	Unit	Feedlot	Pasture	Reference
GE_i	MJ/kg	18.45	18.45	IPCC (2006)
DMI_i	kg DM/animal.day^{-1}	11.17*	9.6	Picoli (2017)
Ym_i	%	3	6	IPCC (2006)
$Days_i$	-	120	365	Souza et al. (2019)
Bo	m^3CH_4/kg	0.1	0.1	IPCC (2006)
MCF	%	1.5	1.5	Matsuura and Picoli (2018)
Vsi	kg/animal/day^{-1}	2.47	4.1	calculated
DE	%	80	56.3	IPCC (2006); Matsuura and Picoli (2018)
UE	%	4	4	Matsuura and Picoli (2018)
ASH	%	8	8	IPCC (2006)
F_i	kg/year.head^{-1}	20.74	51.84	calculated
E_D	N_2O-N	2%	2%	IPCC (2006)
En	%	1%	1%	IPCC (2006)
Np	%	30%	20%	IPCC (2006)
Nex	kgN/1000kg.day^{-1}	0.36	0.36	IPCC (2006)
Ws	Kg, live weight	480	480	Souza et al. (2019)

*Calculated based on feed formulation of Table S5

Table S8: Prices of external inputs

Inputs	**Value**	**Unit**	**Reference**
Hexane	0.68	USD/kg	COMEXSTAT (n.d.)
Sodium methoxide	2.11	USD/kg	COMEXSTAT (n.d.)
Hydrochloric acid	0.14	USD/kg	COMEXSTAT (n.d.)
Citric acid	1.20	USD/kg	COMEXSTAT (n.d.)
Sodium hydroxide	0.55	USD/kg	COMEXSTAT (n.d.)
Sulphuric acid	0.04	USD/kg	COMEXSTAT (n.d.)
Glucoamilase	3.89	USD/kg	COMEXSTAT (n.d.)
Alfa amilase	5.40	USD/kg	COMEXSTAT (n.d.)
Ammonia	0.82	USD/kg	COMEXSTAT (n.d.)
Mineral Salt	0.02	USD/kg	COMEXSTAT (n.d.)
Calves	1.35	USD/kg, LW	Agrolink (n.d.)

2. Sensitivity analyses

2.1.Land use change emissions

Land use change emissions were calculated according to IPCC (2006) guidelines in equation S7, where CO_{2LUC} is the emissions in CO_2 eq per unit of area, considering the difference in the former carbon soil stock (Csa), with the current carbon soil stock (CSb), both in tonnes of C per hectare (t C/ha); 44/11 is the conversion factor from C to CO_2 eq and 1/20 is the factor of linear depreciation of soil carbon stock, in years.

$$CO2_{LUC} = (CS_a - CS_b) * \frac{44}{12} * \frac{1}{20} \qquad \text{Equation S7}$$

Current and former carbon stock (CS) are calculated applying equation S8, where SOC is soil organic carbon, in t C/ha; Cveg is above and below ground vegetation carbon stock, in t C/ha; and A is the factor scaling to the area considered, in hectares.

$$CS_i = (SOC + C_{veg}) * A \qquad \text{Equation S8}$$

SOC, in tC/ha, is calculated applying equation S9, where SOCst is a standard soil organic carbon in the 0-30 centimeter topsoil layer, in tC/ha; F_{LU} is the land use factor reflecting the difference in soil organic carbon associated with the type of land use compared to the standard soil organic carbon; F_{mg} is a management factor reflecting the difference in soil organic carbon associated with the principle management practice compared to the standard soil organic carbon; F_i is an input factor reflecting the difference in soil organic carbon associated with different levels of carbon input to soil compared to the standard soil organic carbon.

$$SOC_i = SOC_{st} * F_{LU} * F_{mg} * F_i \qquad \text{Equation S9}$$

Values for Equations S7, S8 and S9 are detailed in Table S9, considering the four approaches applied.

Table S9: Parameters to calculate land use change emissions of BLI scenarios

		1		**2 and 3**				**4**		
	Unit	**S**	**P**	**C/Soy**	**S**	**Degraded P**	**Severely degraded P**	**C/Soy**	**S**	**Extensive P**
CS_i	t C/ha	52.00	61.44	25.94	50.47	51.35	40.09	34.75	52.08	45.40
SOC	t C/ha	47.00	53.34	25.94	39.67	40.45	29.19	29.75	42.68	37.30
C_{veg}	t C/ha	5.00	8.10	-	10.80	10.90	10.90	5.00	9.40	8.10
SOC_{st}	t C/ha	47.00	47.00	47.00	41.70	41.70	41.70	41.70	38.45	38.45
F_{LU}	-	1.00	1.00	0.48	0.82	1.00	1.00	0.58	1.00	1.00
F_{MG}	-	1.00	1.17	1.15	1.16	0.97	0.70	1.23	1.00	0.97
F_i	-	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.11	1.00

S = Sugarcane, P = Pasture, C/Soy = Corn in rotation with soybean

2.2.Key parameters for sensitivity analysis

Table S10: Key parameters for sensitivity analysis

Parameters	**Unit**	**-50%**	**-40%**	**-30%**	**-20%**	**-10%**	*****	**10%**	**20%**	**30%**	**40%**	**50%**
Sugarcane yield	t/ha	40	48	56	64	72	**80**	88	96	10	112	120
N recovery	%	35	42	49	56	63	**70**	77	84	91	98	-
Stocking rate	animal/ha	0.5	0.6	0.7	0.8	0.9	**1.0**	1.1	1.2	1.3	1.4	1.5
Carcass yield	%			39	44	50	**55**	61	-	-	-	-
Average daily gain (ADG)	$kg/animal.day^{-1}$	0.5	0.6	0.7	0.8	0.9	**1.0**	1.1	1.2	1.3	1.4	1.5
Bagasse for feed	$kg/animal.day^{-1}$	6.4	7.7	9.0	10.3	11.5	**12.8**	14.1	15.4	16.7	18.0	19.2
Total investments	M USD	1080	1295	1511	1727	1943	**2.159**	2375	2591	2807	3023	3239

*Default values

3. Techno-economic results

Table S11: Feedstock costs in for the conventional and BLI scenarios

Scenarios	Base	1a	1b	2a	2b	3a	3b	Unit
Sugarcane	23.45	23.45	23.27	23.45	22.96	23.45	22.96	(USD/t)
Straw	27.31	27.31	27.31	27.31	27.31	27.31	27.31	(USD/t)
Soybean	-	177.68	177.68	181.92	181.92	181.92	181.92	(USD/t)
Corn	-	133.87	133.87	138.10	138.10	138.10	138.10	(USD/t)
Cattle	1.86	1.86	1.52	1.86	1.54	1.86	1.53	(USD/t, LW*)

*Live weight

Table S12: Costs of feed ingredients

Feed ingredient	1b	2b	3b	Unit	Reference
Internal					
Bagasse	0.024	0.022	0.022	USD/kg	calculated
Yeast	0.024	0.022	0.022	USD/kg	calculated
Corn grain/DDGS[1]	0.134	0.151	0.151	USD/kg	calculated
Soybean meal	0.182	0.185	0.192	USD/kg	calculated
External					
Yeast	0.024	0.024	0.024	USD/kg	MFRURAL (2019)
Molasses	0.273	0.273	0.273	USD/kg	COMEXSTAT (n.d.)
Urea	0.246	0.246	0.246	USD/kg	COMEXSTAT (n.d.)
Mineral salt	0.022	0.022	0.022	USD/kg	COMEXSTAT (n.d.)
Proteic supplement	0.353	0.353	0.353	USD/kg	Souza et al. (2019)
Total	**0.049**	**0.051**	**0.051**	**USD/kg**	

[1]Scenarios 2b and 3b

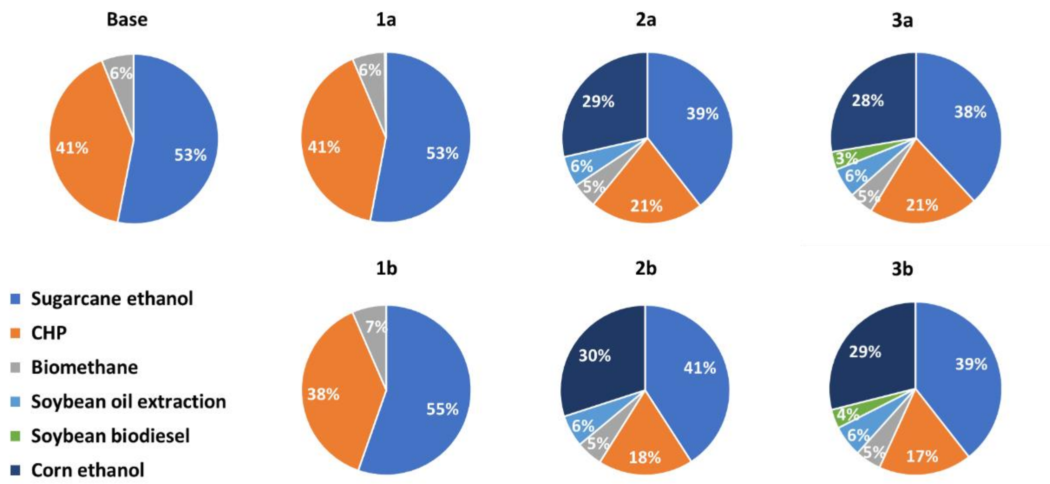

Figure S1: Breakdown of biorefinery investments for the conventional and BLI scenarios

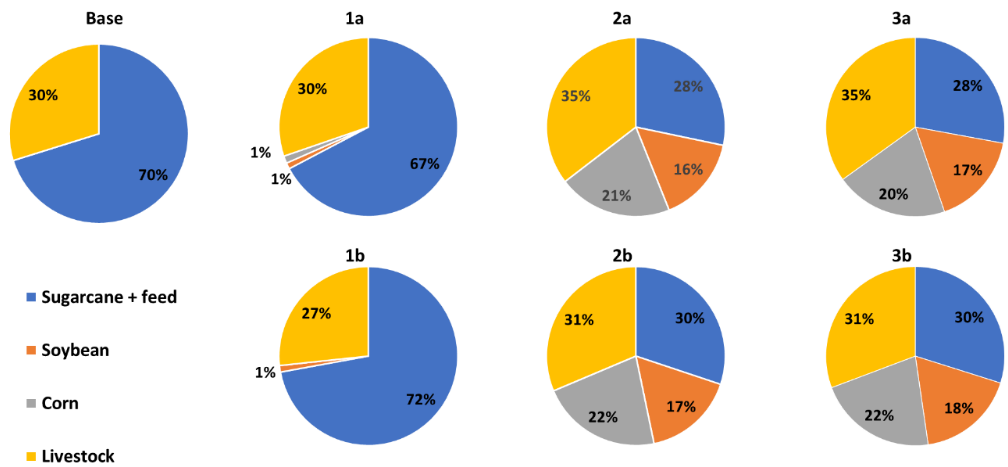

Figure S2: Breakdown of costs for the conventional and BLI scenarios

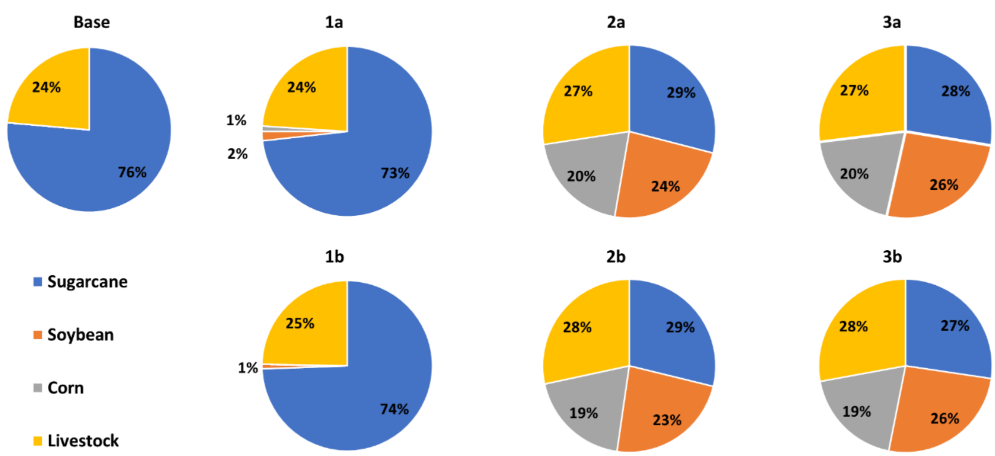

Figure S3: Breakdown of revenues for the conventional and BLI scenarios, without CBIOs

4. Life Cycle Assessment results

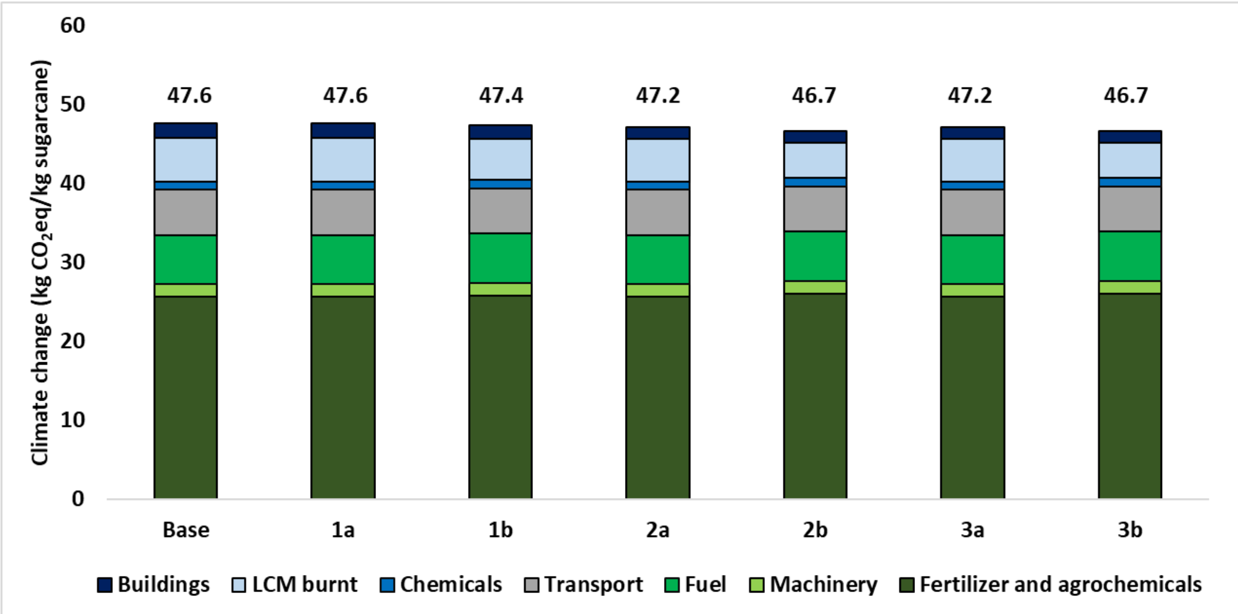

Figure S4: Breakdown of GHG emissions per kg of sugarcane in all scenarios before allocation

Table S13: Breakdown of GHG emissions of meat production

Scenarios	**Base**	**1a**	**1b**	**2a**	**2b**	**3a**	**3b**
Sugarcane ethanol, in gCO_2eq/MJ							
Fertilizer and agrochemicals	10.1	10.2	9.1	10.8	8.7	10.6	8.7
Machinery	0.6	0.6	0.6	0.7	0.5	0.7	0.5
Transport	2.3	2.3	2.0	2.4	1.9	2.4	1.9
Fuel	2.5	2.5	2.2	2.6	2.1	2.6	2.1
Chemicals	0.4	0.4	0.4	0.4	0.3	0.4	0.3
LCM burnt	2.2	2.2	1.8	2.2	1.5	2.2	1.5
Buildings	0.7	0.7	0.6	0.7	0.5	0.7	0.5
Total	**18.9**	**18.9**	**16.7**	**19.9**	**15.6**	**19.5**	**15.6**
Meat, in gCO_2eq/kg meat, live weight							
Calf	11.92	11.92	11.92	11.92	11.92	11.92	11.92
Pasture and transportation	0.37	0.37	0.05	0.37	0.05	0.37	0.05
Enteric fermentation	4.94	4.94	0.94	4.94	0.94	4.94	0.94
Manure handling	1.46	1.46	0.49	1.46	0.49	1.46	0.49
Fuel	0.33	0.33	0.14	0.33	0.14	0.33	0.14
Feed	-	-	1.07	-	1.09	-	1.09
Total	**19.02**	**19.02**	**14.61**	**19.02**	**14.62**	**19.02**	**14.63**

Table S14: Selected environmental impacts categories of sugarcane ethanol, electricity and meat produced in all scenarios

		Global warming	Ozone formation, Human health	Fine particulate matter formation	Terrestrial acidification	Freshwater eutrophication	Marine ecotoxicity	Land use	Mineral resource scarcity	Fossil resource scarcity
		kg CO_2 eq	kg NO_x eq	kg PM2.5 eq	kg SO_2 eq	kg P eq	kg 1,4-DCB	m^2a crop eq	kg Cu eq	kg oil eq
Base	Sugarcane ethanol	5.3E-01	1.5E-03	1.9E-03	1.5E-02	4.7E-03	1.4E-02	1.4E-03	1.7E-01	8.8E-02
	Electricity	6.8E-02	1.9E-04	2.4E-04	1.9E-03	6.0E-04	1.8E-03	1.8E-04	2.2E-02	1.1E-02
	Meat, LW	1.9E+01	1.8E-02	1.7E-02	7.3E-02	2.5E-03	1.9E-01	9.0E+00	2.6E-02	8.6E-01
1a	Sugarcane ethanol	5.3E-01	1.5E-03	1.9E-03	1.5E-02	4.7E-03	1.4E-02	1.4E-03	1.7E-01	8.8E-02
	Electricity	6.8E-02	1.9E-04	2.4E-04	1.9E-03	6.0E-04	1.8E-03	1.8E-04	2.2E-02	1.1E-02
	Meat, LW	1.9E+01	1.8E-02	1.7E-02	7.3E-02	2.5E-03	1.9E-01	9.0E+00	2.6E-02	8.6E-01
1b	Sugarcane ethanol	4.7E-01	1.3E-03	1.7E-03	1.4E-02	4.0E-03	1.2E-02	1.2E-03	1.5E-01	7.6E-02
	Electricity	6.0E-02	1.7E-04	2.2E-04	1.8E-03	5.0E-04	1.5E-03	1.6E-04	1.9E-02	9.7E-03
	Meat, LW	1.5E+01	1.7E-02	1.9E-02	9.2E-02	9.1E-03	2.0E-01	9.0E+00	2.7E-01	9.2E-01
2a	Sugarcane ethanol	5.6E-01	1.6E-03	2.0E-03	1.6E-02	4.9E-03	1.4E-02	1.5E-03	1.7E-01	9.3E-02
	Electricity	7.2E-02	2.0E-04	2.5E-04	2.1E-03	6.2E-04	1.8E-03	1.9E-04	2.1E-02	1.2E-02
	Meat, LW	1.9E+01	1.8E-02	1.7E-02	7.3E-02	2.5E-03	1.9E-01	9.0E+00	2.6E-02	8.6E-01
2b	Sugarcane ethanol	4.4E-01	1.2E-03	1.7E-03	1.4E-02	3.3E-03	1.0E-02	1.1E-03	1.3E-01	6.8E-02
	Electricity	5.6E-02	1.6E-04	2.2E-04	1.8E-03	4.2E-04	1.3E-03	1.4E-04	1.6E-02	8.7E-03
	Meat, LW	1.5E+01	1.7E-02	1.9E-02	9.2E-02	7.9E-03	2.0E-01	9.0E+00	2.3E-01	9.1E-01
3a	Sugarcane ethanol	5.5E-01	1.5E-03	1.9E-03	1.6E-02	4.8E-03	1.4E-02	1.5E-03	1.6E-01	9.1E-02
	Electricity	7.0E-02	2.0E-04	2.5E-04	2.0E-03	6.1E-04	1.7E-03	1.9E-04	2.1E-02	1.2E-02
	Meat, LW	1.9E+01	1.8E-02	1.7E-02	7.3E-02	2.5E-03	1.9E-01	9.0E+00	2.6E-02	8.6E-01
3b	Sugarcane ethanol	4.4E-01	1.2E-03	1.7E-03	1.4E-02	3.3E-03	1.0E-02	1.1E-03	1.3E-01	6.8E-02
	Electricity	5.6E-02	1.6E-04	2.2E-04	1.8E-03	4.2E-04	1.3E-03	1.4E-04	1.6E-02	8.7E-03
	Meat, LW	1.5E+01	1.7E-02	1.9E-02	9.2E-02	7.9E-03	2.0E-01	9.0E+00	2.3E-01	9.1E-01

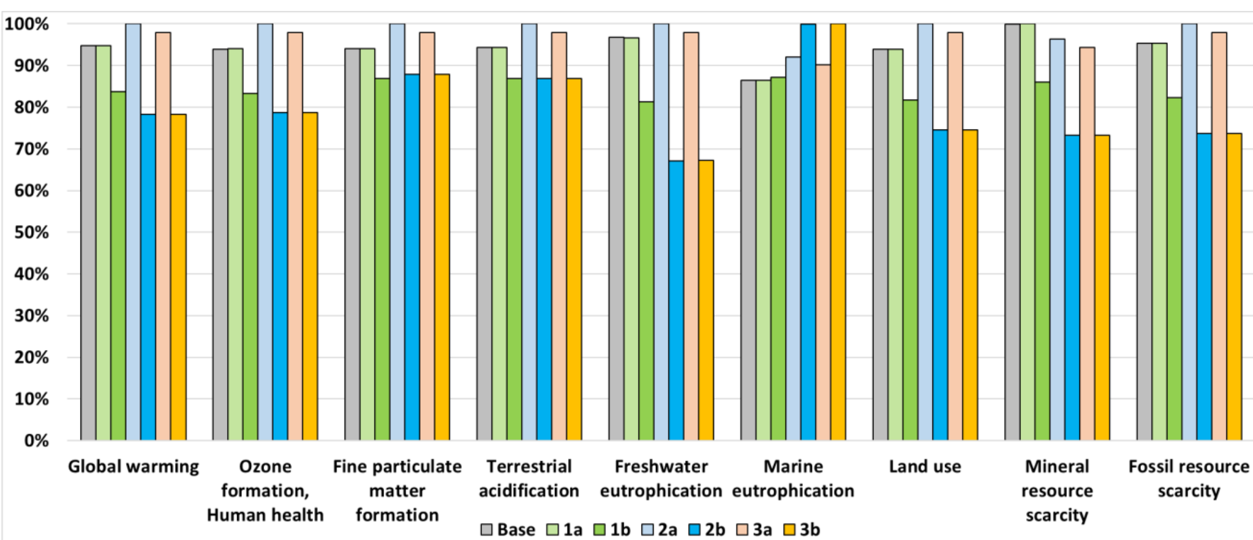

Figure S5: Relative environmental impacts categories for sugarcane ethanol production in all scenarios

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Chapter 4

Spatially explicit assessment of economic impacts and GHG emissions of bioenergy-livestock integrated systems

This chapter is a draft of a research paper for a scientific journal by Nariê Rinke Dias de Souza[1,2], Tassia Lopes Junqueira[1,2] and Otávio Cavalett[1,3].

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Abstract: Future projections indicate an expansion in food and energy demands, which can increase pressure on land use, at the same time that here is an urgent global need for climate change mitigation. Bioenergy is foreseen as key option to meet future energy demands and reduce greenhouse gas (GHG) emissions. However, the sustainability of biofuels depends on the availability of biomass, logistics and impacts on ecosystems, that are largely dependent on locations and regional characteristics. This study presents a bottom-up approach to assess spatially explicit sustainability aspects of bioenergy-livestock integrated systems (BLI) in Brazil and shed light on their contribution to future energy demands, to climate change mitigation targets, and their impacts on selected ecosystem services, including bioenergy production, climate change mitigation, no direct deforestation and reduction of food competition. The proposed integration considers livestock intensification and use of biofuels by-products as animal feed supplement, taking advantage of synergies between these two value chains. Three different technological options were considered: an autonomous sugarcane plant producing ethanol, electricity, and animal feed; integration of corn processing during sugarcane offseason, producing ethanol, corn oil and animal feed (DDGS); addition of a soybean processing unit, producing biodiesel and soybean meal. Techno-economic and environmental implications of the three BLI technological options were modelled using the Virtual Biorefinery, a sustainability assessment tool developed at LNBR/CNPEM. After exclusion of biodiversity hotspots, protected biomes (such as Pantanal and Amazon) and scattered areas for feedstock production, 16 million hectares of pasture inside Sugarcane Agroecological Zoning are available for BLI expansion. The first technology (processing only sugarcane) has the highest potential among the assessed options for bioenergy production producing 89 billion liters of ethanol, as well as climate change mitigation with 139 million tonnes of avoided CO_2eq emissions, while also presenting the highest economic returns. Expansion of the BLI system in Brazil could contribute to meet future bioenergy demands and mitigation targets in the country while also alleviating pressure on land use for food and energy purposes, and without expanding on biodiversity hotspots and protected biomes. These results might help to support more assertive public policies regarding biofuel expansion in Brazil and contribute to achieve the ambitious targets stipulated in the Paris Agreement.

Keywords: integrated value-chains, supply-chain assessment, spatial analysis, techno-economic analysis, life cycle assessment

4.1. Introduction

Future projections indicate an increase in food and energy demands (Bauer et al., 2017; Popp et al., 2017; Riahi et al., 2017), intensifying pressure on land resources, at the same time, there is an urgent global need for land-based climate change mitigation options (Roelfsema et al., 2020; van Soest et al., 2021). In this context, production systems that can optimize land-based outputs under climate change mitigation scenarios are key to meet future food and energy demand in a sustainable way. Intensification of livestock production is one of the main measures that would allow to release land for bioenergy production, without compromising animal protein production (Berndes et al., 2016; Cardoso et al., 2016; Santos et al., 2020). Besides, cattle intensification can minimize associated GHG emissions while also being cost-effective (Cardoso et al., 2016; Silva et al., 2017). Among production systems that can intensify land use in sustainable way while also mitigating climate change impacts, the bioenergy-livestock integration seems particularly attractive for Brazil (Souza et al., 2021a). This system can be implemented by increasing cattle stocking rate or by finishing cattle in feedlots; this integration happens due to nutritional content as animal feed of bioenergy by-products (e.g., bagasse, yeast, distillers' grains, meal) (Souza et al., 2019; 2021a).

Bioenergy is foreseen as potential key option to meet future energy demands and contribute to climate change mitigation (Daioglou et al., 2019; Frank et al., 2021; Jaiswal et al., 2017). However, the sustainability of bioenergy production depends on availability of biomass, logistics and impacts on the ecosystem, that are largely dependent on location and regional characteristics (Hiloidhari et al., 2017; Humpenöder et al., 2018; Creuzig et al., 2015). Biomass productivity, previous and current land uses, biodiversity status, soil and crop characteristics and climatic conditions are strongly dependent on local conditions and demand site-specific assessment (Field et al., 2020; Granco et al., 2019; Zullo et al., 2018). Sustainability science is increasingly moving towards more spatially explicit assessments considering regionalized life cycle impact assessment methods (Huijbregts et al., 2017; UNEP/SETAC, 2016; 2019). In an economic perspective, the biomass spatial distribution can generate high costs of procurement and transportation (Hiloidhari et al., 2017). Georeferenced sustainability impacts can be assessed integrating Life Cycle Assessment (LCA) with Geographic Information Systems (GIS) (Hiloidhari et al., 2017), and through spatially explicit optimization of supply chains of bioenergy production, that can assess both economic and environmental impacts, such as costs and climate change impacts (Jong et al., 2017; Kim et al., 2018; Laasasehano et al., 2019).

Additionally, future bioenergy demands of projection studies rely largely on second generation (2G) ethanol (Andrade Jr et al., 2019; Jaiswal et al., 2017) and of bioenergy with carbon capture and storage (BECCS) technologies (Rogelj et al., 2018; Huppmann et al., 2018). However, both cellulosic biofuel and BECCS are still not widely applied worldwide (Köberle et al., 2020; Rogelj et al., 2016). To meet the future bioenergy demands with conventional biofuel production would require a large area, what could cause negative land displacement and impacts on natural vegetation and food production, often associated with large scale deployment of bioenergy (Cherubin et al., 2021; Frank et al., 2021; Humpenoder et al., 2018).

In a context of need of systems that can optimize land-based outputs under climate change mitigation, and bioenergy as key option to mitigate GHG emissions, bioenergy-livestock integrated systems (BLI) have huge potential to a broader implementation in Brazil, due to its considerably consolidated bioenergy and livestock production (CONAB, 2021, ANP, 2021; IBGE, 2021a). However, it is still unclear the potential contributions of these integrated systems to future energy demands and climate change mitigation targets in Brazil, and the impacts on ecosystems services associated with this potential expansion. In this context, the research questions addressed in this study include assess potential contributions of the integrated systems to future energy demands; assess the impacts of BLI on the climate change mitigation targets in Brazil; and assess the impacts of BLI expansion on selected ecosystems services. The main goal for this study was to identify best locations to expand BLI while maximizing economic returns and minimizing GHG emissions and to assess the potential contribution of BLI to future energy demands. For that, we performed a spatially explicit sustainability assessment of BLI expansion in Center-South region in Brazil considering land use restrictions (e.g., considering only pasture areas inside sugarcane agroecological zoning, no displacement of livestock). This assessment provided insights to identify potential locations and impacts associated to the technological options of BLI in Brazil, which were designed to have zero direct deforestation and to reduce food competition and avoid possible biodiversity losses.

4.2. Methodology

This study was performed as a bottom-up approach to assess the potential contribution of BLI to future energy demands derived from the narratives of Shared Socioeconomic Pathways

(SSPs) in Brazil (Andrade Jr. et al., 2019). By identifying potential locations to implement BLI in Brazil, this study assessed the impacts of BLI expansion on selected ecosystem services such as bioenergy production, climate change mitigation, preservation of forests and of food production.

The integration considered beef cattle intensification and use of biofuels by-products as animal feed supplement, taking advantage of synergies between these two value chains, and it was built upon encouraging experiences from pioneer projects in Brazil and in other countries (e.g., USA). As a model definition, all crops for cattle feed and for bioenergy production are produced inside the integration boundaries to avoid land use change and/or displacement of cattle production. Data for BLI modelling, and environmental and economic parameters were collected from literature, complemented with interviews with experts and producers. Figure 1 represents the schematic diagram of the tools, methods and models applied in this study and their outputs. The spatially explicit assessment was performed using ArcGIS software to derive potential available area to expand BLI in Brazil and using the Crop Assessment Tool (CAT), detailed in the next Section. Then, spatially explicit assessment of BLI production, GHG emissions and profits (or economic returns) were modeled using the Virtual Biorefinery (VB) framework (Bonomi et al., 2016).

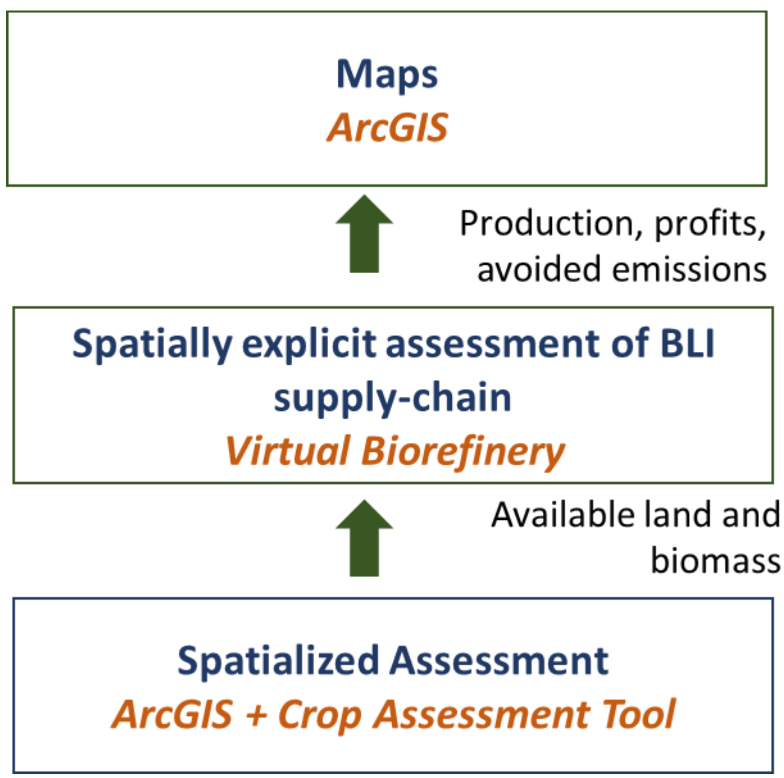

Figure 1: Schematic diagram of the methodology proposed in this study

4.2.1. Spatialized assessment of available biomass and land for BLI expansion

Six Brazilian states were identified as potential locations to expand BLI in Brazil in Souza et al. (2021a): São Paulo, Mato Grosso, Mato Grosso do Sul, Paraná, Minas Gerais and Goiás (Figure S1, Supplementary Material). These states are responsible for 94% of corn produced in rotation with soybean (named second season corn), 90% of sugarcane production, 67% of soybean production, and 54% of beef cattle production (IBGE, 2021a; 2021b; 2021c).

Within these six states, there was an exclusion of (a) biodiversity hotspots and (b) Amazon and Pantanal biomes, (c) considered only pasture areas inside Sugarcane Agroecological Zoning (SAEZ) as potential for expansion, and (d) excluded scattered areas smaller than 40 hectares. Biodiversity hotspots are based on MMA (2007; 2017) classification of areas with considerably importance for nature and biodiversity conservation. An update based on the study of Hernandes et al. (2021) is implemented, considering a more recent land use in Brazil, to account for what is still pasture inside SAEZ. The current use and occupation of the remaining areas of the SAEZ were classified according to the maps provided by the MapBiomas network (MapBiomas, 2020). The SAEZ was developed in 2009 taking into consideration climate, hydrological and soil aspects (Manzatto et al., 2009) to identify areas suitable for sugarcane production. It excludes land with a slope greater than 12%; areas with native vegetation cover; the Amazon and Pantanal biomes; areas of environmental protection; indigenous lands; forest remnants, dunes, mangroves, escarpments and outcrops of rock, reforestation, urban and mining areas; and areas already with sugarcane production.

Sugarcane yields are modelled using the CAT model (Souza et al., 2021b) that implements the Agroecological Zone methodology (AZM) developed by the Food and Agricultural Organization (FAO) (Allen et al., 1998), considering climatic data from 35 years (1980-2015) in a spatial resolution of 27 km x 27 km (Xavier et al., 2015). Availability of sugarcane straw to be recovered for electricity generation is based on the suitability map developed in Souza et al. (2021c), considering 120 kg of straw (dry basis) per tonne of sugarcane (wet basis) (Menandro et al., 2017).

A preliminary assessment was performed carrying out aggregation of grid cells to determine potential sites for implementation of new biorefineries, respecting some restrictions, as exclusion of cells with relatively low and scattered production of biomass in several regions of the study area. We considered a maximum average radius allowed for the plant (approximately 40 km), which restricted the maximum number of grid cells to be clustered (up to 5), and minimum and maximum processing sizes (2 to 8 million tonnes (wet) of sugarcane processed annually). This aggregation routine was carried out using ArcGIS and python programming.

4.2.2. Modelling and simulation of BLI supply-chains

The agricultural production and transportation stages inputs were simulated in CanaSoft® (Cavalett et al., 2016), that is part of VB, for sugarcane, for second season corn produced in rotation with soybean, and for beef cattle production. Data for double cropping of corn and soybean production is based on Matsuura and Picoli (2018), beef cattle modelling is based on Souza et al. (2019), Matsuura and Picoli (2018) and Picoli (2017). Modelling of biofuels industrial conversion stages are based on simplified models VB simulations (Souza et al., 2019; Bonomi et al., 2019; Milanez et al., 2014; Moraes et al., 2014; Junqueira et al., 2016; Dias et al., 2016). The complete assessment of the supply-chain of BLI is performed on the VB (Bonomi et al., 2016), developed by the Brazilian Biorenewables National Laboratory (LNBR/CNPEM). This platform simulates techno-economic and environmental impacts of production chains of present and future biorenewable alternatives, combining georeferenced data from the spatialized assessment, mathematical models, and simulation tools of the entire production chain (i.e., agricultural, industrial, logistics, and product use phases). In this study, GHG emissions and economic impacts of the BLI supply-chain are determined using VB framework, considering agriculture production (e.g., sugarcane, corn, soybean and cattle), logistics from agricultural to industrial plants (e.g., transportation of inputs, feedstocks and residues), and industrial conversion (e.g., ethanol, electricity, biodiesel).

The VB was adapted to the georeferenced assessment, considering each grid cell as a candidate site for biorefinery, with varying process capacity of feedstock and lignocellulosic material (LCM). Techno-economic and environmental inventories were built per candidate site considering site-specific characteristics derived from the dataset generated during the spatialized assessment. The framework generated the necessary economic and environmental inventories to perform the spatially explicit sustainability assessment, considering the regional characteristics to produce biofuels.

4.2.3. Technological options of BLI systems

Three different technological options were considered based on Souza et al. (2021d): Tech1_Sugarcane; Tech2_Corn and Tech3_Soybean. Tech1_Sugarcane considers an autonomous sugarcane plant producing ethanol, electricity, and animal feed. Sugarcane cannot be stored and is operated only part of the year. Thus, in Tech2_Corn, additionally to the autonomous sugarcane plant, corn is processed during sugarcane offseason, producing ethanol, corn oil and animal feed (DDGS). Finally, Tech3_Soybean considers the same configuration of Tech2_Corn, with the addition of a biodiesel plant integrated with sugarcane plant. As definition, nutritional requirements of all cattle in the available area per grid cell must be met with feed containing biofuels by-products, which means each grid cell has specific technical configuration and plant sizes.

A detailed description of these three technological options is presented in Table 1 and in Figure 2. Main biorefinery industrial parameters are based on Chapter 3 and presented in Table 2. In the agricultural phase of all options, manure from cattle on feedlots is applied on sugarcane field to replace part of N fertilizer (Matsuura and Picoli, 2018). Feed production and composition is based on Souza et al. (2019). Considered corn and soybean yields are presented in Table S1 from Supplementary Material. Cattle stocking rate before integration was assumed to be 1 head per hectare for the considered study area, and each hectare of expanded crop must meet the nutritional requirements of one cattle head. The feedlot parameters are based on Souza et al. (2019).

Sugarcane plants are autonomous and operate 200 days per year. The processing capacity depends on available area and modelled sugarcane yields. The main product is anhydrous ethanol, while electricity is produced using biomethane from vinasse anaerobic digestion (Moraes et al., 2014; Junqueira et al., 2016) and lignocellulosic material (LCM) (i.e., sugarcane bagasse and straw) burnt in boiler of combined heat and power generation (CHP) unit. After the sugarcane milling, part of the bagasse is diverted to feed production. The remaining bagasse is sent to the CHP with straw. Electricity generation varies depending on the site-specific sugarcane straw recovery rate. The plant produces feed only if there is enough LCM material to meet the main plant energetic demands. Second season corn is always produced in rotation with soybean. In Tech1_Sugarcane, corn and soybean production is only to meet the necessary corn and soybean meal requirements of cattle feed.

In Tech2_Corn and Tech3_Soybean, CHP unit from sugarcane plant provides heat and electricity to operate soybean plant (e.g., soybean oil extraction and/or transesterification plant), and corn during sugarcane offseason. Corn and soybean processing capacity depend on available LCM from sugarcane plant, after meeting sugarcane plant and cattle feed requirements. Corn plant capacity is also limited by sugarcane daily ethanol production, as part of sugarcane equipment is used by corn plant during offseason, and by a maximum of 130 days operation. An iterative calculation was performed to adjust the sugarcane and corn plant sizes under the available land and biomass conditions and to meet these restrictions in order to share the available area for corn/soybean and sugarcane. The sugarcane plant size defines the corn processing, and the corn processing defines the necessary area to produce corn, that defines available area for sugarcane production. In cases where there was enough LCM to operate corn for more than 130 days, the plant was set to process corn up to 130 days, the remaining LCM was burnt on CHP to generate surplus electricity to be sold to the grid. In some candidate sites, the corn plant operates less than 130 days when the mentioned restrictions could not be met. This process considers the dry grind pathway, with ethanol, dried distillers' grains with solubles (DDGS) (i.e., animal feed), and corn oil production.

In Tech2_Corn and Tech3_Soybean, necessary corn in cattle feed is replaced by DDGS in a proportion of 1:1 (Hoffman and Baker 2011). In Tech3_Soybean, oil extraction and transesterification plants operate integrated with the sugarcane plant 200 days per year, using ethanol in the process (Olivério et al., 2014).

Table 1: Definition of the three assessed scenarios

	Tech1_Sugarcane	**Tech2_Corn**	**Tech3_Soybean**
Description	Sugarcane plant production cattle feed. Cattle finished in feedlots.	Sugarcane ethanol plant, with corn processing during sugarcane offseason. Cattle finished in feedlots.	Sugarcane ethanol plant, with corn processing during sugarcane offseason. Soybean biodiesel production integrated with sugarcane plant. Cattle finished in feedlots.
Main products	Sugarcane ethanol.	Sugarcane and corn ethanol.	Sugarcane and corn ethanol.
Co-products	Surplus animal feed (soybean meal),	Surplus animal feed (soybean meal and	Surplus animal feed (soybean meal and

	soybean oil, electricity, beef meat.	DDGS), soybean oil, corn oil, electricity, red meat.	DDGS), soybean biodiesel, corn oil, electricity, red meat.

Table 2: Main parameters of BLI

Parameters	**Value**	**Unit**
Sugarcane plant		
Electricity from biomethane	3	kWh/t sugarcane
Steam yield	2	kg steam/kg LCM, 50% moisture
Steam consumption	350	kg/t sugarcane
Energy consumption	30	kWh/t sugarcane
Energy consumption (straw)	25	kWh/t straw
Ethanol yield	85	l/t sugarcane
Soybean oil extraction plant		
Soybean oil yield	190	kg/t soybean
Soybean meal yield	800	kg/t soybean
Steam consumption	271	kg/t soybean
Energy consumption	35	kWh/t soybean
Soybean biodiesel plant		
Biodiesel yield	956	kg/t soybean oil
Glycerin yield	117	kg/t soybean oil
Steam consumption	300	kg/t soybean oil
Energy consumption	15	kWh/t soybean oil
Corn ethanol plant		
Ethanol yield	403	l/t corn
DDGS yield	171	kg/t corn
Steam consumption	345	kg steam/t corn
Energy consumption	106	kWh/t corn
Cattle on feedlot		
Duration	120	Days
Feed	22	kg/head.day^{-1}
Meat yield	55	%, mass basis
Slaughter weight	480	kg

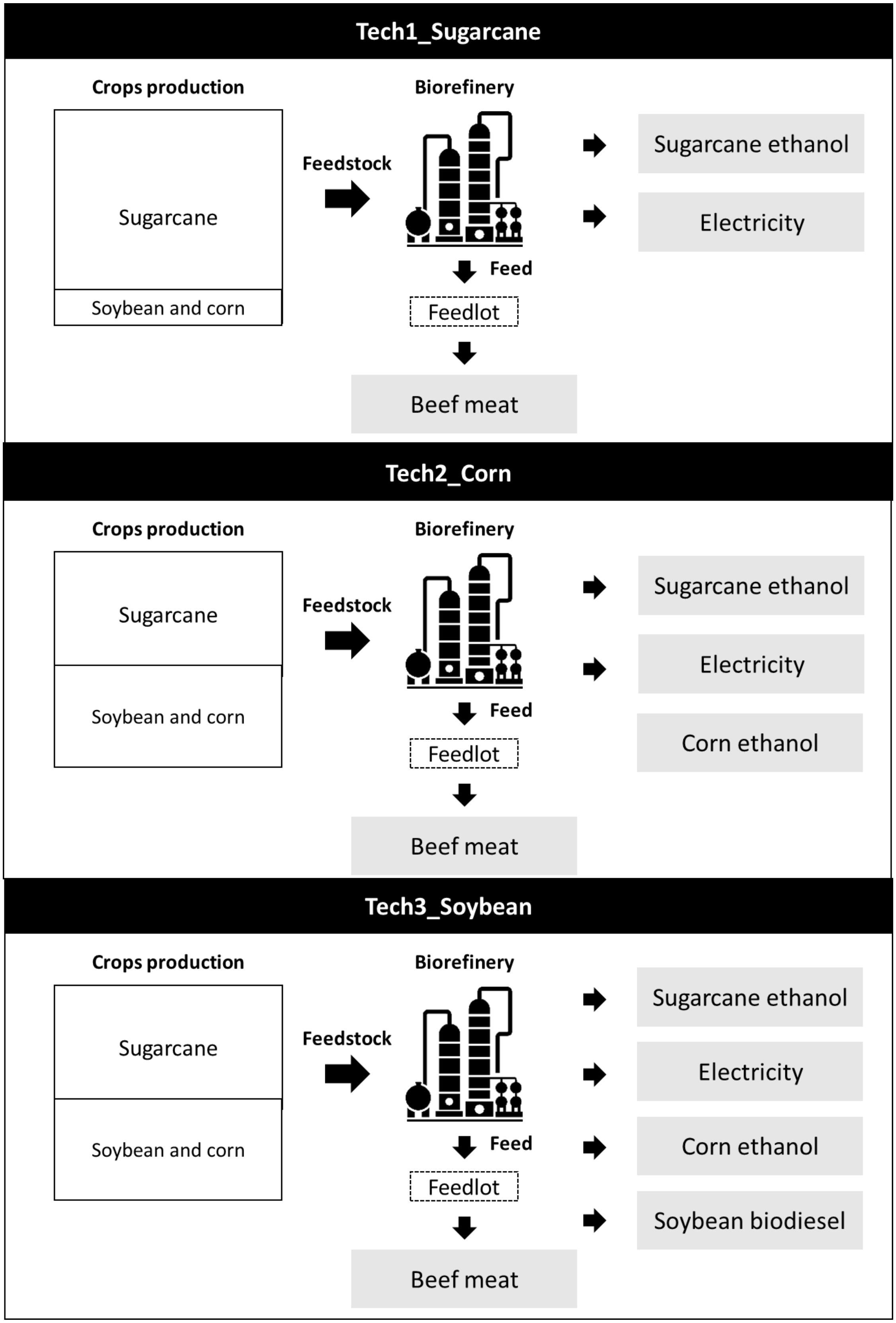

Figure 2: Overview of three technological options of BLI

4.2.4. Supply-chain GHG emissions and profits

The GHG emissions for the integrated systems are calculated using a Life Cycle Assessment (LCA) methodology, using inventories generated by VB framework. The focus of this study was on the quantification of GHG emissions of BLI technological options. The functional unit is 1 MJ of ethanol in a cradle-to-gate approach, using energy allocation among products. To avoid allocation, subdivision of the process is used whenever possible. When not possible, emissions were allocated based on energy content (Table S3, Supplementary Material) of outputs (e.g., sugarcane electricity, ethanol; corn ethanol, oil and DDGS; soybean oil, soymeal, glycerin, and biodiesel), following RenovaBio directives (Matsuura et al. 2018). Global Warming Potential in a time horizon of 100 years is used as climate metric (measured in CO_2eq.). Avoided emissions of biofuels are determined as the difference among carbon intensities of ethanol and gasoline (carbon intensity of gasoline equals to 87.4 gCO_2eq/MJ), and of biodiesel and diesel (carbon intensity of diesel equals to 86.5 gCO_2eq/MJ) (MME, 2018), according to RenovaBio directives (Matsuura et al., 2018). We also considered possible avoided GHG emissions from cattle production in feedlots compared to conventional meat in pasture (20.9 gCO_2eq/kg meat, in live weight), and from sugarcane electricity compared to GHG emissions from natural gas electricity, equals to 500 gCO_2eq/kWh (Ecoinvent, 2018).

CanaSoft® tool is used to generate the life cycle inventory that includes emissions to air, soil, and water from the agricultural production systems. These emissions are from fuel production and use on agricultural operations; machinery production and use; production and application of NPK fertilizers (nitrogen, phosphate, and potassium), soil correctives, and agrochemicals; and application of agro-industrial residues on the field (e.g., sugarcane vinasse, filter cake, ashes). Industrial biorefinery life cycle inventories considers the use of inputs, such as chemicals, biomass (e.g., sugarcane bagasse and straw) burnt in boilers, and building materials.

The economic impacts are calculated using the inventories derived from the VB framework, relying on a cash flow analysis. The cash flow analysis depends on capital expenditures (CAPEX), including investment in buildings, equipment, cattle herd, working capital, etc; operating costs (OPEX) including costs associated with feedstock, labor, maintenance, inputs, utilities, feed, etc.; and on the revenues that are based on market prices of main outputs such as ethanol, sugar, electricity, beef cattle, and others (Table S2). The annualization of CAPEX is performed considering 25 years of expected plant lifetime and a discount rate of 12% per year.

Economic values consider December 2019 as reference, when the exchange ratio between US dollars (USD) and Brazilian Real was 4.11 R$/USD. The feedstock and transportation costs vary depending on the site location. Sugarcane plant investments are calculated on VB framework and were adjusted to varying processing capacities of feedstock. Profits were calculated considering overall revenues of the integrated system, discounting the operational costs and annualized CAPEX (defined here as gross profit). Revenues with carbon credits generation were also considered, considering the carbon credit from RenovaBio program, named CBIO (MME, n.d.). Each CBIO is equivalent to 1 tonne of avoided GHG emission and its average price in 2020 was 8.4 USD (B3, 2020).

4.2.5. Future ethanol demands

The future ethanol demands are based in a study from Andrade Jr. (2019) that interpret future projected demands for SSP1, SSP2 and SSP3 narratives for Brazil (Table 5). The SSPs provide a comprehensive understanding of potential future global projections for the economic sectors. They take into consideration narrative storylines of challenges to adaptation and mitigation of climate change that combines social, economic, and environmental trends (e.g., future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources) (O'Neil et al., 2017, 2014; Riahi et al., 2017).

Table 5: Future ethanol demands up to 2050 in Brazil considering different SSPs

	2020	**2030**	**2050**
SSP1 (EJ)	0.9	1.4	1.5
SSP2 (EJ)	0.7	1.0	0.8
SSP3 (EJ)	0.6	0.7	0.5

Source: Andrade Jr. et al. (2019)

4.3. Results and discussion

4.3.1. Available area for BLI expansion

After excluding the biodiversity hotpots, Amazon and Pantanal biomes, and considering current pasture areas inside SAEZ, the results indicate about 18 million hectares suitable to expand BLI systems, which are represented in Figure 3. Results are divided in 1696 grid cells. Each grid cell has a specific available area for expansion, sugarcane, corn and soybean yield, and straw recovery rate. Average results for available area, sugarcane yield and straw recovery rate per grid cell are 50 million hectares, 75 tonnes per hectare and 43%, respectively.

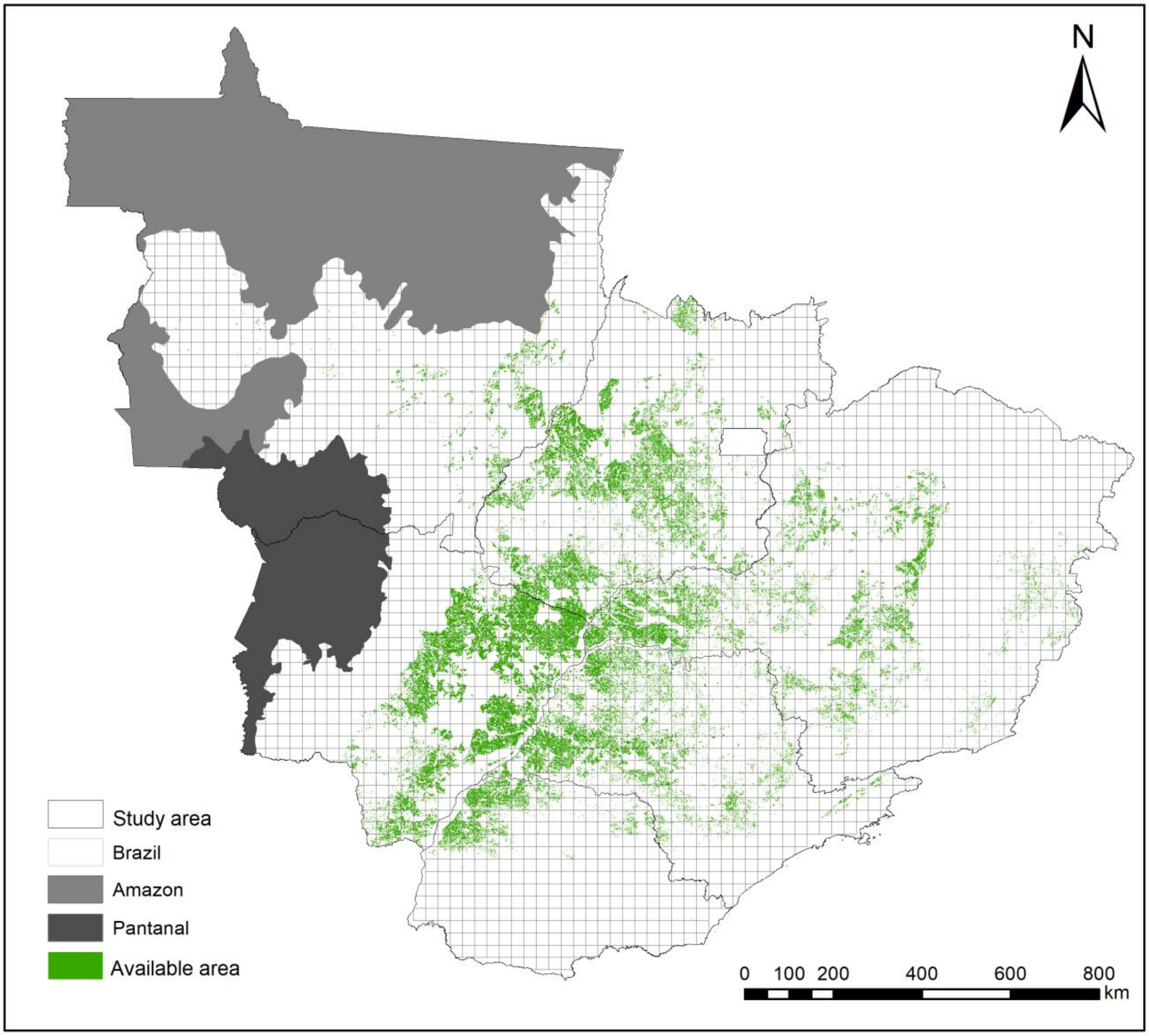

Figure 3: Available area for BLI expansion and considered ethanol demand points in Brazil.

4.3.2. Spatially explicit assessment of BLI supply-chain

At first, it was calculated how much sugarcane could be produced in each grid cell. The result is presented in Figure S2 and identifies that only 14% of total grid cells could produce more than 2 million tonnes of sugarcane per year (the considered cut off value for minimum processing capacity). In most of grid cells less than 1 million tonnes of sugarcane can be produced per year, meaning biomass supply would be too scarce to justify one sugarcane biorefinery in that area.

The grid cells were aggregated as described in Methodology section. The aggregated sites were then considered as 316 candidate sites for BLI implementation. From the initial total 18 million hectares, after aggregation, 2 million hectares were excluded as they represent grid cells that were isolated (mostly in the state of Mato Grosso) and could not meet the maximum radius restriction. In Figure 4 there is the visual representation of the spatially explicit sugarcane production in technological options 1, 2 and 3, respectively in the total 316 candidate sites. In the case of BLI, not only sugarcane is produced in the available area, but all feedstocks for cattle feed also need to be produced within the available area, as definition to avoid displacement of land. In the case if Tech1_Sugarcane, only a small portion of the area is used for corn production in rotation with soybean, and most of candidate sites produce around 3 to 5 million tonnes of sugarcane per year. However, for Tech2_Corn and Tech3_Soybean, more land is used to produce corn and soybean and less sugarcane is produced, as illustrated in Figure 4b, where sugarcane production is less than 2 million tonnes per year in most of candidate sites. This means that in order to have higher sugarcane processing capacities, which are more common for new facilities installed in Brazil, more grid cells should be combined for Tech2_Corn and Tech3_Soybean, or corn should come from outside of BLI boundaries. However, for a better comparison, the same amount of candidate sites and available area per site were considered for all technological options.

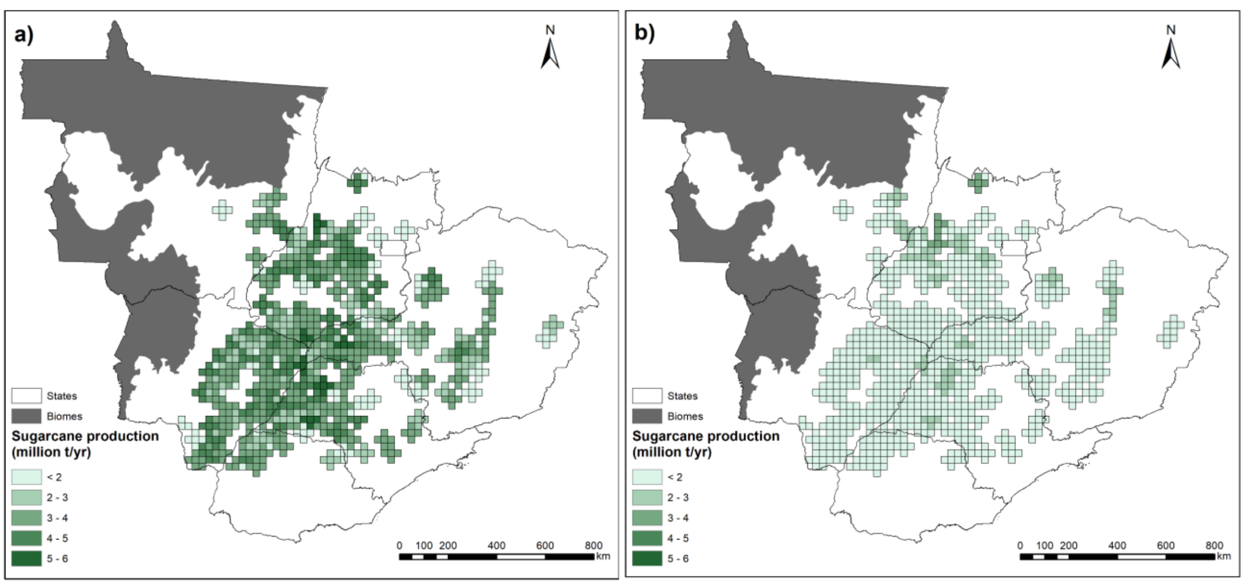

Figure 4: Spatially explicit sugarcane production in candidate sites for Tech1_Sugarcane (panel a); and for Tech2_Corn and Tech3_Soybean both in panel b).

In Figure 5, the total production of biofuels (i.e., sugarcane and corn ethanol and soybean biodiesel) is shown in the study area. In Tech1_Sugarcane, a large amount of candidate sites produces more than 350 million liters of ethanol per year (Figure S3, Supplementary Material), while in Tech2_Corn and Tech3_Soybean (Figures S4 and S5, Supplementary Material), this value is around 200 million liters of total ethanol. Although Tech2_Corn has corn ethanol to complement sugarcane ethanol production, when comparing corn and sugarcane ethanol in the same area, less corn ethanol is produced, because of lower agricultural yields of the latter. Corn average agricultural yield (about 5 t/ha) is too small compared to sugarcane average yield (75 t/ha). Lower corn ethanol production also occurs because there is not enough sugarcane LCM available to operate corn plants during the 130 days of sugarcane offseason, with an average of only 108 days in operation. When comparing Tech2_Corn and Tech3_Soybean (Figures S5 and S6, Supplementary Material), a relatively small amount of ethanol is used in the transesterification pathway to produce biodiesel, hence less ethanol is available in this latter option, but this difference is considerably small as has been visualized in the maps. In Figure 5c, there is an increase in biofuel production compared to Tech2_Corn due to additional biodiesel production. Potentials for surplus electricity generation in the three technological options are presented in Figure S6, from Supplementary Material. Tech1_Sugarcane can export considerably more electricity to the grid compared to the two other technological options, as it does not need to provide energy to corn and soybean plants.

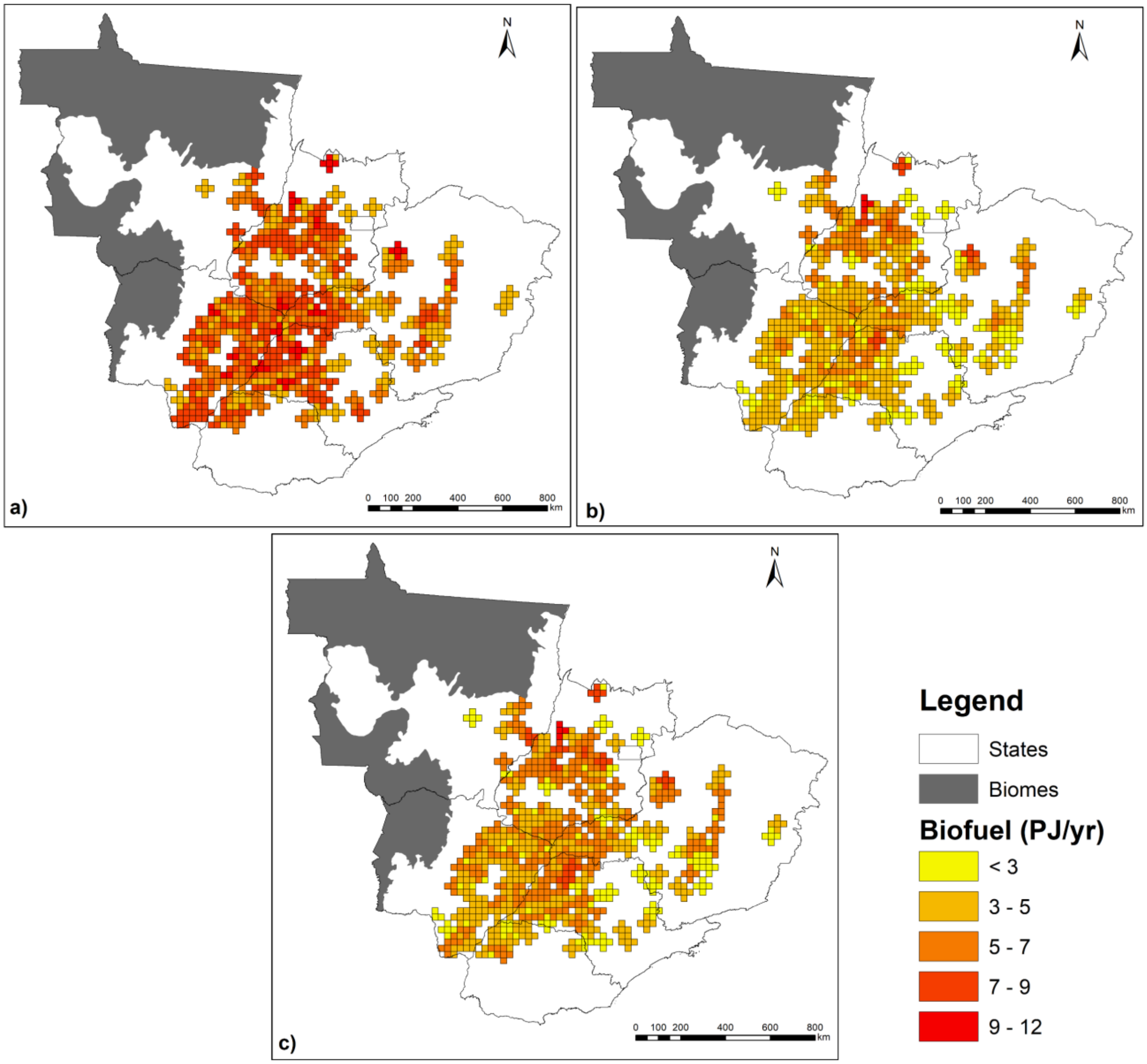

Figure 5: Spatially explicit potential of biofuel production in Tech1_Sugarcane (panel a), Tech2_Corn (panel b) and Tech3_Soybean (panel c).

When considering potentials of avoided GHG emissions only from biofuels, Tech1_Sugarcane has the highest potentials (Figure 6a), of around 0.4 to 0.8 million tonnes of avoided CO_2eq per candidate site. Again, since considerably less ethanol is produced in Tech2_Corn, this technological option presented lower potential (Figure 6b), with average avoided emissions of around 0.3 million tCO_2eq. per candidate site. However, when comparing Tech2_Corn and Tech3_Soybean, the latter presents slightly higher potential since biodiesel is also produced (Figure 6c). Sugarcane ethanol carbon intensity ranged from around 12 to 23 gCO_2eq/MJ in the three technological options. Brazilian average carbon intensity of first generation (1G) sugarcane ethanol is around 21 gCO_2eq/MJ (Sampaio et al., 2019). The lowest values could be found in candidate sites with high sugarcane yield and high straw recovery rates. Average carbon intensity of corn ethanol was 23.8 gCO_2eq/MJ and of biodiesel was 10.0 gCO_2eq/MJ.

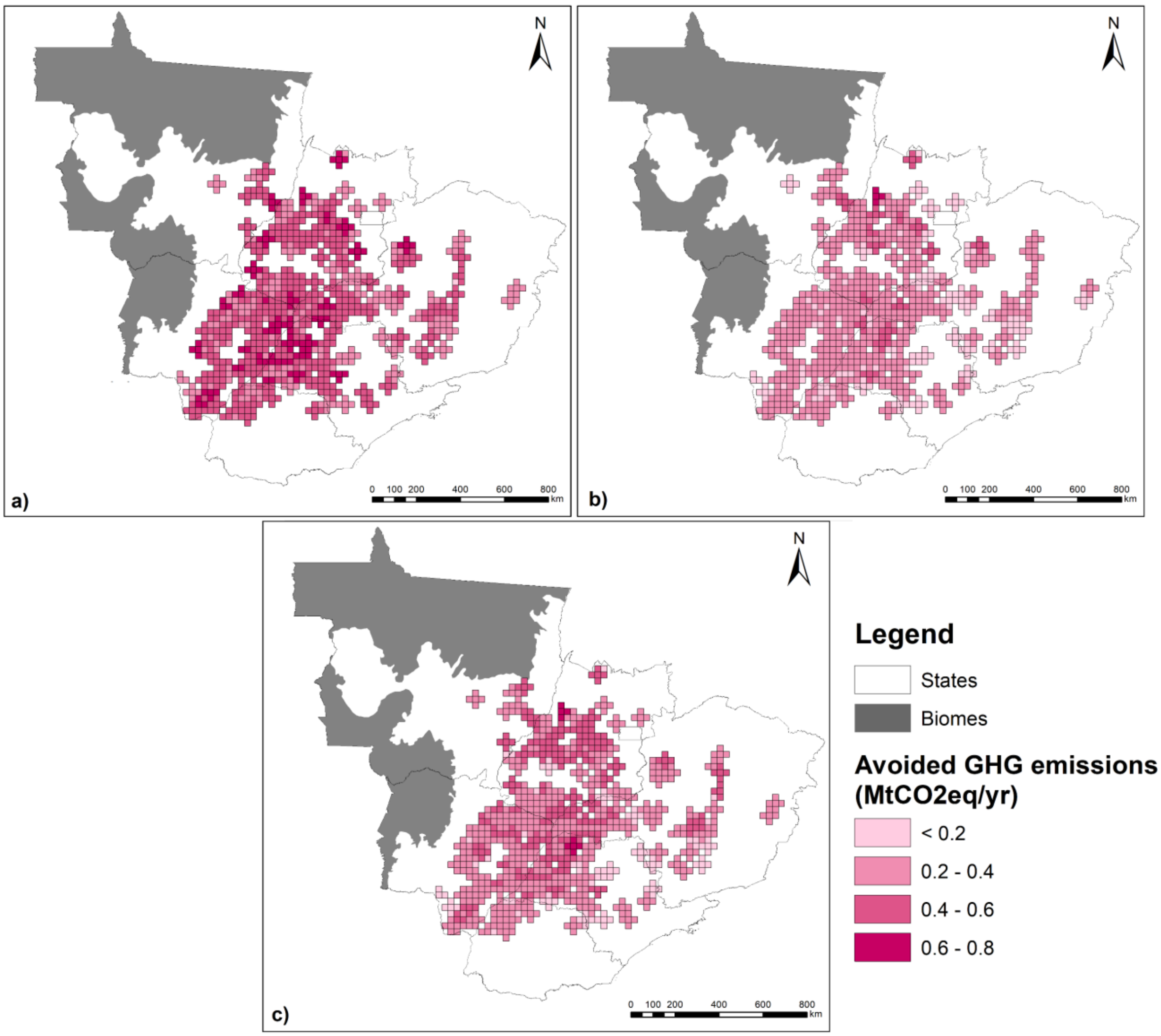

Figure 6: Spatially explicit potential of GHG avoided emissions in Tech1_Sugarcane (panel a); Tech2_Corn (panel b); Tech3_Soybean (panel c)

Finally, comparing the potential profits of all candidate sites considering revenues with CBIO from biofuels, Tech1_Sugarcane presents the highest values in comparison to the other options (Figure 7a), however it is very similar to Tech3_Soybean (Figure 7c), because of a high market value for biodiesel compared to soybean oil. In Tech1_Sugarcane (Figure 7a), most of candidate sites would have profits of around 50 to 90 million USD. Due to lower biofuel production, Tech2_Corn (Figure 7b) presents the lowest profits compared to the other options.

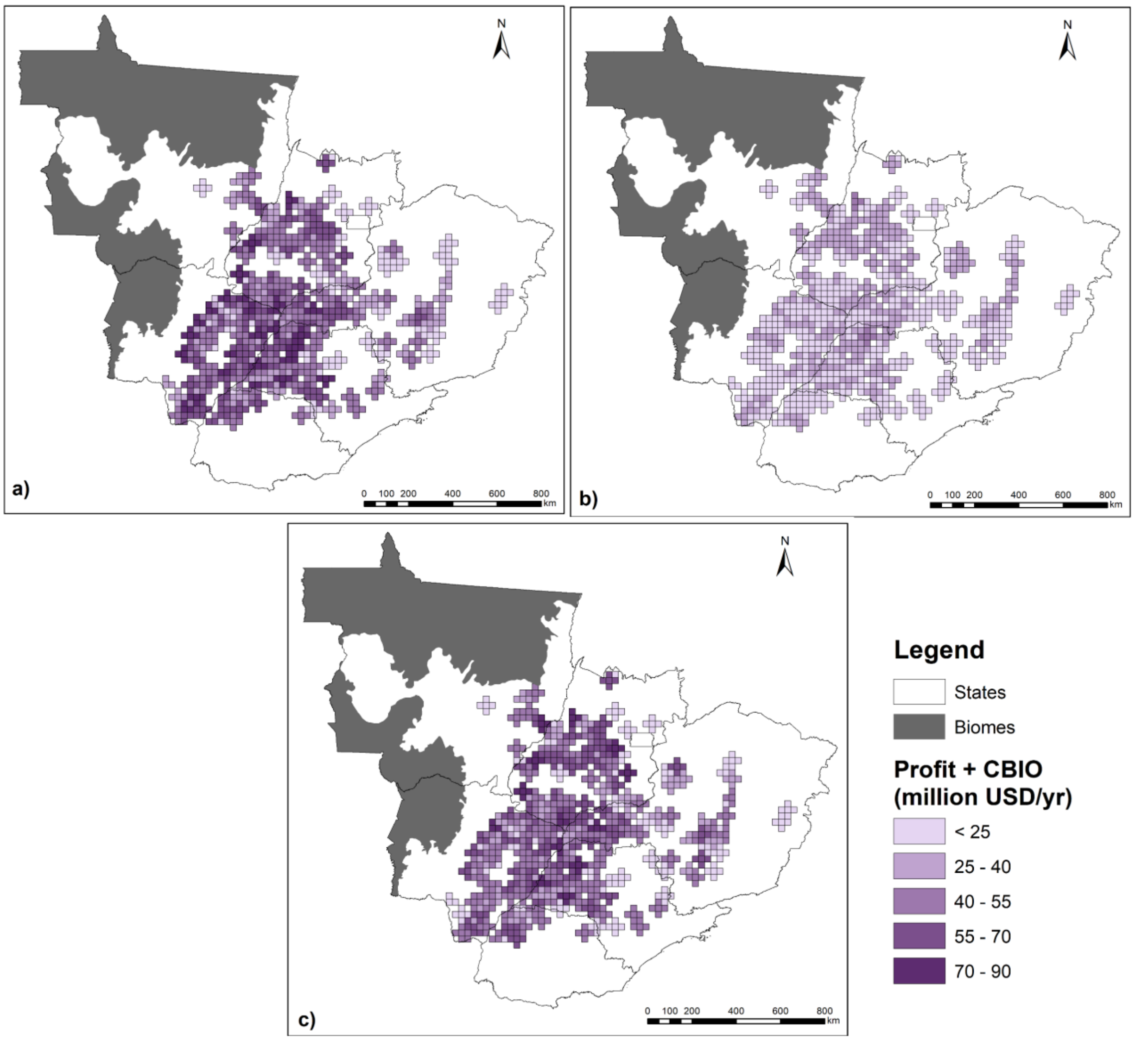

Figure 7: Spatially explicit potential of profits in Tech1_Sugarcane (panel a); Tech2_Corn (panel b); Tech3_Soybean (panel c)

Figure 8 presents the sum of total potential of biofuels production, avoided GHG emissions and profits per technological option. Biodiesel production could increase overall biofuel production, but it was still not sufficient to reach the same level of production for Tech1_Sugarcane (Figure 8a). Since a large share of available LCM is used for animal feed, to operate the soybean and corn plants during sugarcane offseason, surplus electricity in Tech2_Corn and Tech3_Soybean, 49.5 TWh and 49.2 TWh, respectively, are considerably lower than Tech1_Sugarcane, that generated a total of 181 TWh. However, the increase in biofuel production from corn and soybean biofuels was not enough to compensate this 70% reduction in electricity production in Tech2_Corn and Tech3_Soybean. Avoided GHG emissions can considerably increase by considering carbon credits generated when comparing meat produced in feedlot and conventional pasture system, and sugarcane electricity with natural gas one, this increase could be of around 70% in Tech1_Sugarcane, 48% in Tech2_Corn, and about 41% in Tech3_Soybean. Profits slightly increase when considering CBIO revenues from biofuels (about 7-11%), or from meat and electricity avoided GHG emissions (about 3-6%).

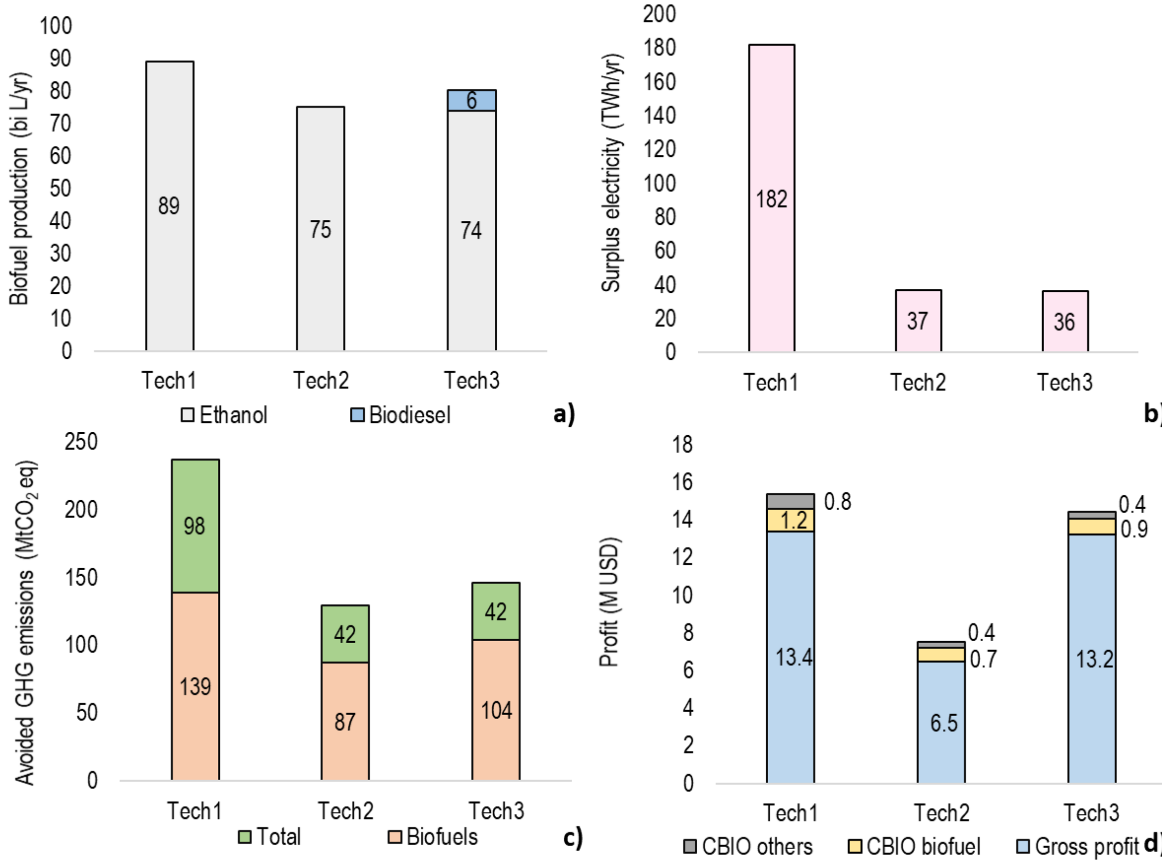

Figure 8: Comparison of the three technological options for biofuel potentials, considering: a) sugarcane and corn ethanol and soybean biodiesel; b) surplus electricity exported to the national grid; c) avoided emissions from biofuels and from other products; d) profitability considering revenues with CBIOs from biofuels and from other products.

4.3.3. Potentials of BLI to meet future biofuel demands and GHG mitigation targets in Brazil

All technological options can meet at least 50% of the demands projected by different SSPs in 2030 and 2050 (Figure 9, panel a and b, respectively), even without considering current biofuel production in Brazil. The highest ethanol demand is projected by SSP1 in 2050, with around 1.5 EJ. The 89 billion liters produced in Tech1_Sugarcane (or 1.98 EJ) are around 1.3 times more than necessary in this scenario, while Tech2_Corn could produce only 55% of the projected demand. The lowest ethanol demand was from SSP3 for 2050, and ethanol production in Tech1_Sugarcane exerts this demand in a factor of 4, and Tech3_Soybean in a factor of 2, even being the options with the least ethanol surplus. Ethanol produced in Tech1_Sugarcane is 1.4 times more than the volume demanded by SSP1 in 2030. Even considering the expansion of Tech3_Soybean, that has the lowest potential among the options, 56% of SSP1 demand for 2030 could be met. For ethanol demands in 2050, Tech2_Corn could meet up to 98% of SSP2 demand and Tech3_Soybean up to 95%. These values do not consider the contribution of the current ethanol production of around 30 billion liters (CONAB, 2020). Expansion of Tech1_Sugarcane in the study area could meet all projected Brazilian ethanol demands from SSPs 1, 2 and 3 in 2030 and 2050, and additional possible external demands from other countries. Tech2_Corn and Tech3_Soybean could also export ethanol in SSP3 in 2030 and 2050. These ethanol exports could be possible without affecting Amazon and Pantanal biomes and biodiversity hotspots.

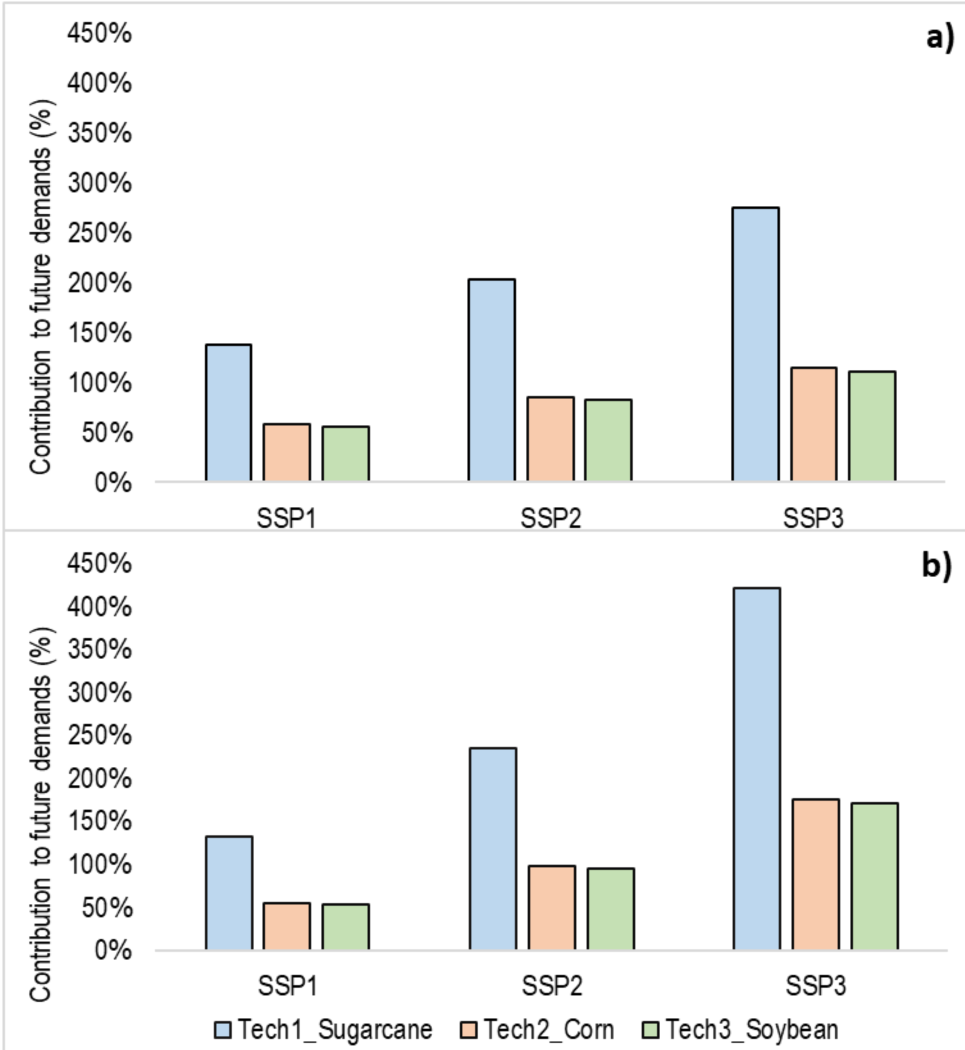

Figure 9: Contributions of three BLI technological options to future ethanol demands of SSP1, SSP 2 and SSP3 in a) 2030 and b) 2050.

Regarding potential to mitigate GHG emissions, Tech1_Sugarcane represents 15% of the total 900 million tonnes of CO_2eq that are intended to be mitigated by 2030 according to Brazilian NDC (MMA, 2015). When comparing Tech2_Corn and Tech3_Soybean, it is possible to observe biodiesel production increased potential avoided emissions, but when comparing Tech1_Sugarcane to Tech3_Soybean, the production of biodiesel was not enough to surpass Tech1_Sugarcane potentials to avoided GHG emissions. It can be explained because the comparison of technological options was carried out considering the same area and sugarcane ethanol has the highest yields, thus more biofuel is produced.

It is worthwhile mentioning that the straw recovery had a key role in the implementation of BLI systems, once it allows to meet sugarcane energy demands and also cattle feed requirements, corn operation during offseason and soybean plant operation. Considering only sugarcane bagasse would not satisfy the BLI requirements of feed and energy.

All candidate sites presented techno-economic feasibility in all 3 technological options, however, Tech1_Sugarcane presented the best performance, producing more biofuel within the available area, with increased avoidance of GHG emissions and higher profits. It is possible to highlight three important regions among the six considered as promising locations to implement BLI under the conditions considered in this study for techno-economic and environmental feasibility. These three areas are west of São Paulo state, east of Mato Grosso do Sul and middle of Goiás state. The indication of these strategic regions is essential to guide BLI expansion in Brazil, as they have great potential to meet future ethanol demands and GHG mitigation targets. BLI systems can also contribute to avoid deforestation, preventing land use displacement (Souza et al., 2019). It can also provide reduction on land competition for food and energy production due to the use of bioenergy by-products as animal feed that replace or reduce grazing and crop production for feed purposes (Moreira et al., 2020; Popp et al., 2016). Studies have suggested that after pasture intensification, 37 to 50 million hectares could be available for bioenergy expansion without causing land use displacement (Alkimin et al., 2015; Lossau et al., 2015).

The results presented here show the large potential of the available area for expansion to meet future ethanol demands and GHG mitigation targets, as well as the spatially explicit avoided GHG emissions, supply chain profits, revenues and their variability according to locations. A spatially explicit sustainability assessment of BLI is key to help to produce bioenergy without compromising feedstock availability, food security, land use, biodiversity, among others.

4.3.4. Uncertainties and limitations

The results presented in this study do not consider impacts of pasture conditions (e.g., level of degradability) on agricultural yields. Sugarcane modelled yields consider climatic characteristics of each region. We assumed a fixed cattle stocking rate of one cattle head per hectare in all study area, a spatially explicit beef cattle yield could influence the results, since all cattle heads should be fed with crops and by-products produced inside the integration boundaries, which means more animal feed production would be demanded in sites with higher stocking rates. Future studies should include spatially explicit and modelled yield for corn, soybean and cattle stocking rate, and possible climate change impacts in crop yields.

The environmental sustainability impact was focused on calculation of GHG emissions in comparison to fossil reference systems. Regarding impacts on biodiversity, we excluded biodiversity hotspots for the available area for BLI expansion, however no assessment was carried out to consider biodiversity losses and/or gains due to the replacement of pasture with crops (i.e., sugarcane, corn, soybean). Although carbon stocks associated with land use change emissions can have significant contribution to overall life cycle emissions (Bordonal et al., 2015; Figueiredo et al., 2017), it was not considered in this study. Also, questions regarding soil organic carbon emissions (SOC) and impacts of BLI on water availability were not performed. Future studies should include such aspects in a georeferenced assessment.

The integration as presented here happens with beef cattle at the final stage of production cycle (Souza et al., 2019, Picoli, 2017), where all cattle heads can be finished in feedlots. Detailed modelling should be carried out to understand the integration at all production cycle, such as cow and calf system. This initial stage of cattle production has limitations on the use of biofuels by-products as animal feed, and less land could be released.

This study indicated potential areas to expand BLI systems in Brazil to meet future energy demands and mitigation targets under the site-specific conditions considered. Optimization procedures could be further applied to define the best biorefinery configuration (e.g., how much LCM should be diverted to feed and electricity purposes to optimize costs and emissions) and to identify the best location to meet such demands taking into consideration supply-chain design, transportation infrastructure, hotspots of ethanol demands or even transportation to ports for possible exportation to other countries. Differently from fossil fuel supply-chain, challenges related to sparse spatial biomass production, logistics, costs, and emissions associated with biomass/product transportation, distribution and use phases are faced by bio-based supply-chains (Yue et al., 2014). Optimization models can combine detailed site-specific characteristics and impacts of biomass production, with variation in demand, biomass yields, carbon prices, among others. Optimization of biofuel supply-chain was successfully implemented worldwide by Harahap et al. (2020), Khatiwada et al. (2016), Jong et al., (2017) and it could be used to optimize technological configurations and location to implement new biorefineries to meet certain environmental constraints, such as stipulated greenhouse gas emission reduction targets, taking into consideration site-specific characteristics of their study region. These aspects are included as suggestions for future work.

4.4. Final remarks

After excluding the biodiversity hotpots, Amazon and Pantanal biomes, considering only current pasture areas inside SAEZ, and excluding scattered areas, 16 million hectares are available for BLI expansion. When considering the expansion of BLI technological options in all this area, Tech1_Sugarcane had the largest potential to produce ethanol (89 billion liters per year), to mitigate GHG emissions (139 tCO_2eq per year) and highest profits (13 million USD). Even considering site-specific sugarcane yields, land availability and sugarcane straw recovery rates, carbon intensity of sugarcane ethanol was not negatively affected and ranged from around 12 to 23 gCO_2eq/MJ in the three technological options, very close to the Brazilian average of around 21 gCO_2eq/MJ.

Bioenergy-livestock integrated systems are an important land-based climate mitigation option for future land use management strategies in Brazil and have great potential to meet future bioenergy demand and GHG mitigation targets without land use displacement, biodiversity loss and competition with food production. All technological options can meet at least 50% of SSP demands in 2030 and 2050, without considering the current biofuel production in the country. The highest future ethanol demand projected by SSP1 in 2050 and Tech1_Sugarcane could produce 1.3 times more. The lowest ethanol demand is projected by SSP3 in 2050, and Tech3_Soybean, which has the lowest potential, could produce almost 2 times more than this volume. Tech1_Sugarcane has potential to meet all internal ethanol demand and possible international markets.

This study may support decision makers and encourage the formulation of enhanced public policies for the bioenergy sector based on the potentials to meet future energy demands and GHG mitigation targets, and to alleviate pressure on land use. Assessment of potential areas for implementation of BLI was presented, indicating that their implementation would be possible in the Center-South region of Brazil. These results might help to support more assertive public policies regarding biofuel expansion in Brazil and contribute to achieve the ambitious targets stipulated in the Paris Agreement. Future studies should address uncertainties in the spatially explicit assessment of BLI expansion in the country, such as refine crop and cattle yield, account for carbon stocks, impacts on water use, and consider the complete cycle of beef cattle production.

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Supplementary Material to: Spatially explicit assessment of economic impacts and GHG emissions of bioenergy-livestock integrated systems

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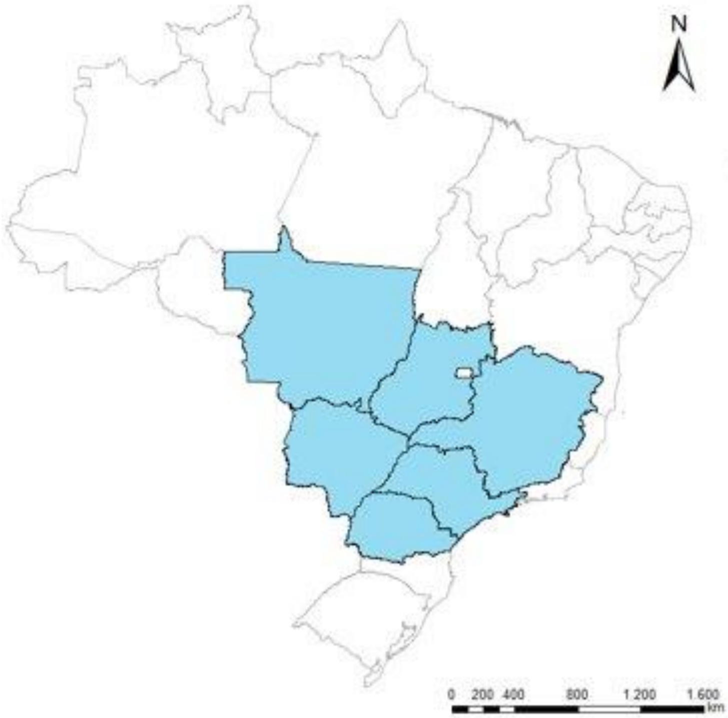

Figure S1: Study area in Brazil considering six states from Center-South region

Table S1: Average corn and soybean yields on the different states of the study area

Yield	**Soybean (t/ha)**	**Corn (t/ha)**
Paraná	3.3	5.4
Mato Grosso do Sul	3.2	4.8
Mato Grosso	3.2	5.7
São Paulo	3.2	4.8
Minas Gerais	3.1	5.1
Goiás	3.1	5.9

Source: IBGE (2021a; 2021b; 2021c)

Table S2: Considered market prices for products and co-products of BLI

Products	Price	Unit	Reference
Anhydrous ethanol	0.47	USD/L	(CEPEA, 2019)
Electricity	51.37	USD/MWh	(CCEE, 2019)
Soybean meal	0.40	USD/kg	COMEXSTAT (n.d.)
Soybean oil	0.66	USD/kg	COMEXSTAT (n.d.)
Biodiesel	0.86	USD/kg	COMEXSTAT (n.d.)
Glycerin	0.54	USD/kg	COMEXSTAT (n.d.)
DDGS	0.17	USD/kg	(Milanez et al., 2014; Moreira et al., 2020)
Corn oil	0.67	USD/kg	COMEXSTAT (n.d.)
Cattle, LW	2.40	USD/kg	Agrolink (n.d.)
US dollar exchange rate	4.11	R$/USD dec-2019	(Banco Central, 2021)

Table S3: Lower heating values used for energy allocation

Product	Value	Unit	Reference
Anhydrous ethanol	28,3	MJ/kg	ANP (2019)
Electricity	3,6	MJ/kWh	-
Bagasse	9,1	MJ/kg	NASEM (2016)
Yeast	15,2	MJ/kg	Martins et al. (2013)
Soybean meal	14,8	MJ/kg	NASEM (2016)
Soybean Oil	37.0	MJ/kg	Lima et al. (2011)
Biodiesel	37,7	MJ/kg	ANP (2019)
Glycerin	14,6	MJ/kg	Lima et al. (2011)
DDGS	16,4	MJ/kg	NASEM (2016)
Corn Oil	37.0	MJ/kg	Lima et al. (2011)

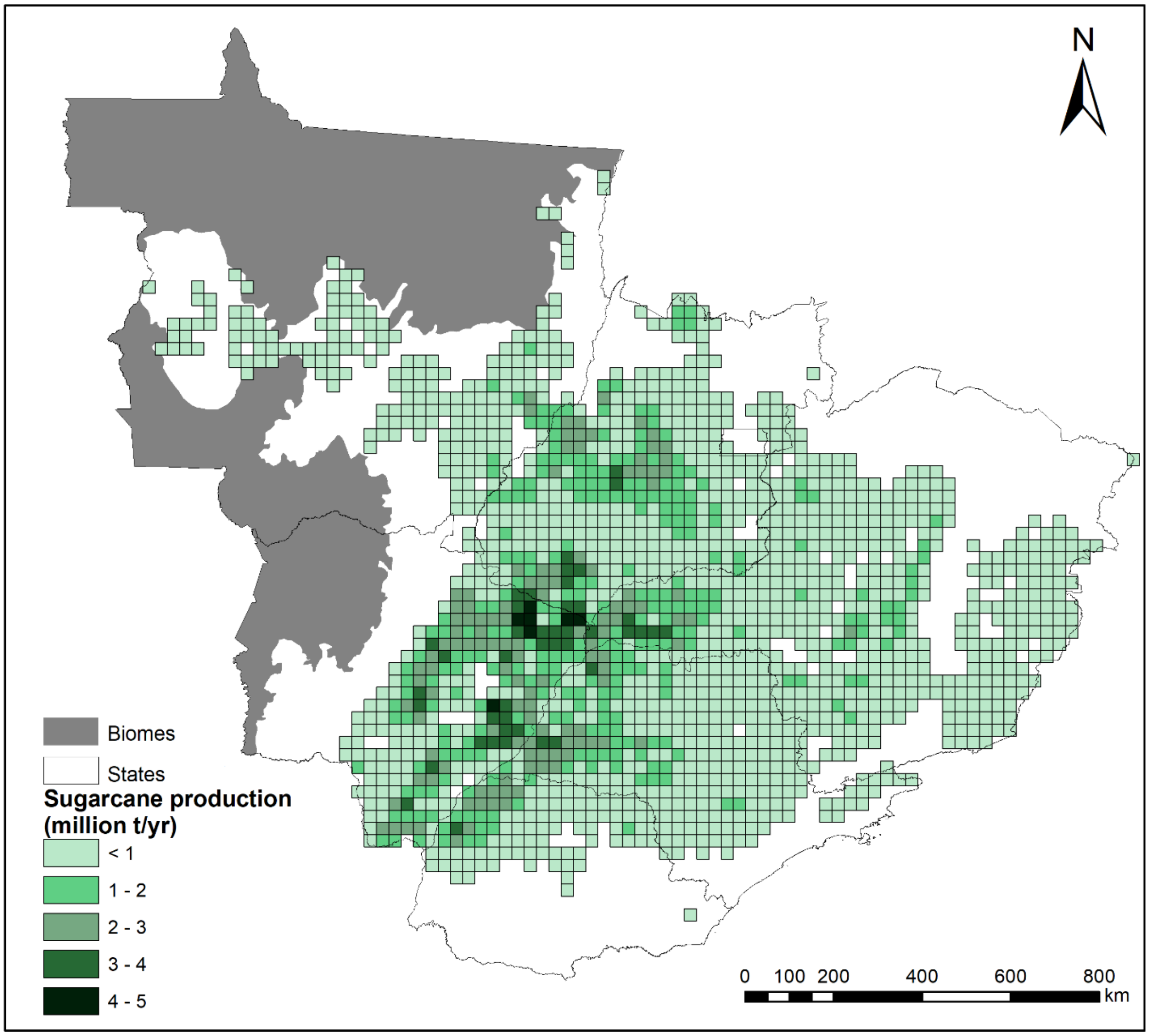

Figure S2: Spatially explicit sugarcane production in total available area for expansion

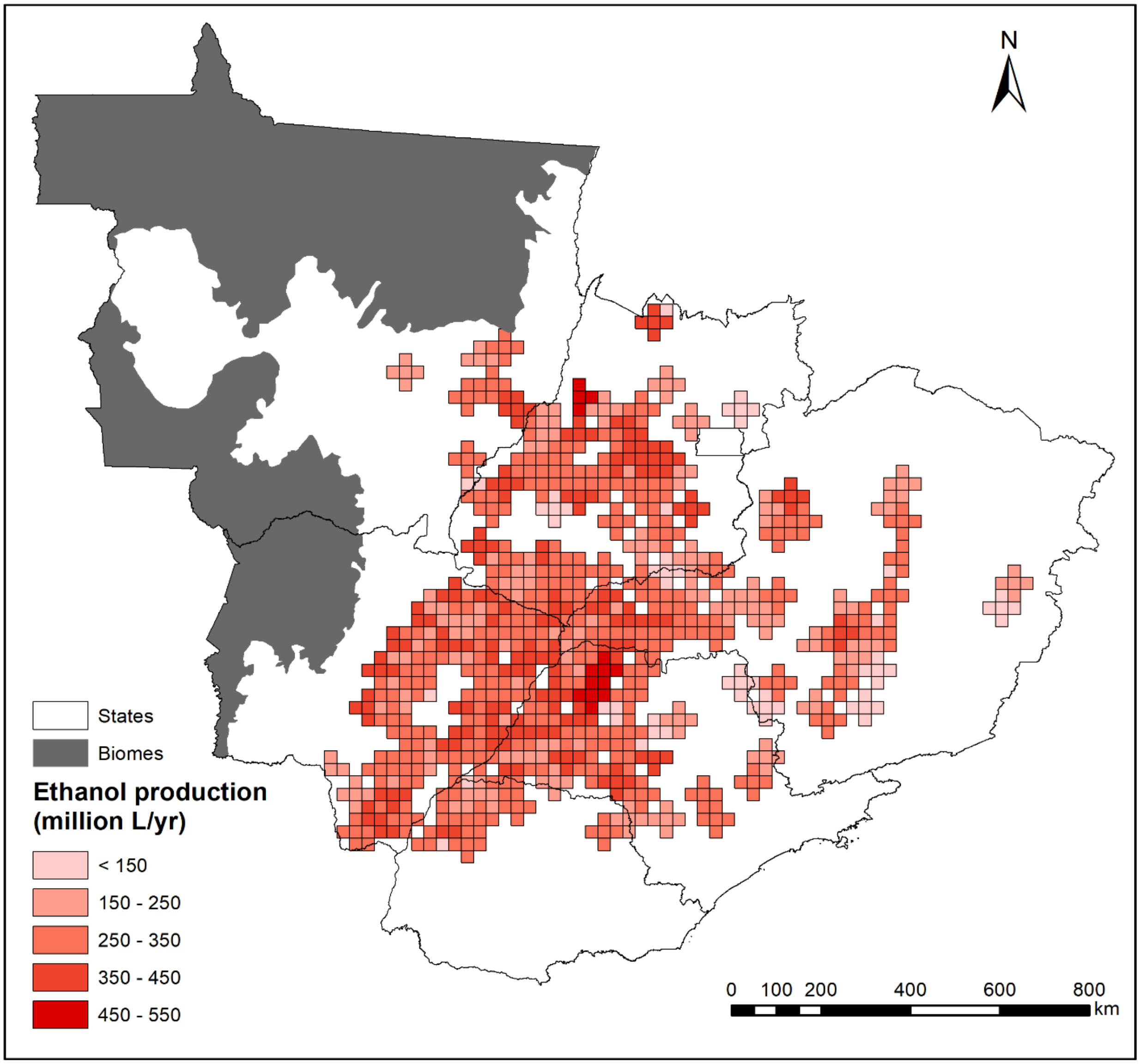

Figure S3: Ethanol output in Tech 1_Sugarcane

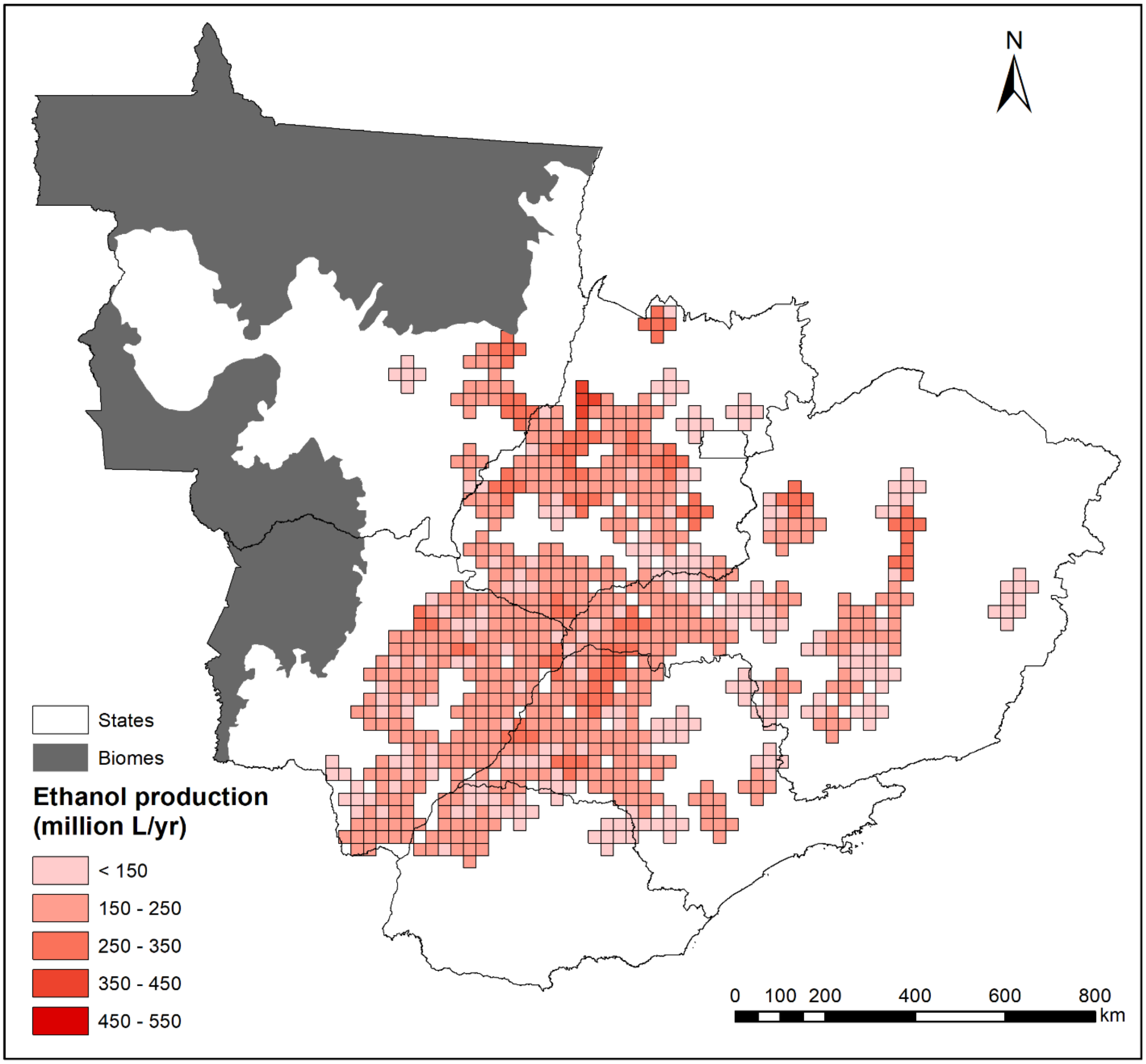

Figure S4: Ethanol output in Tech 2_Corn

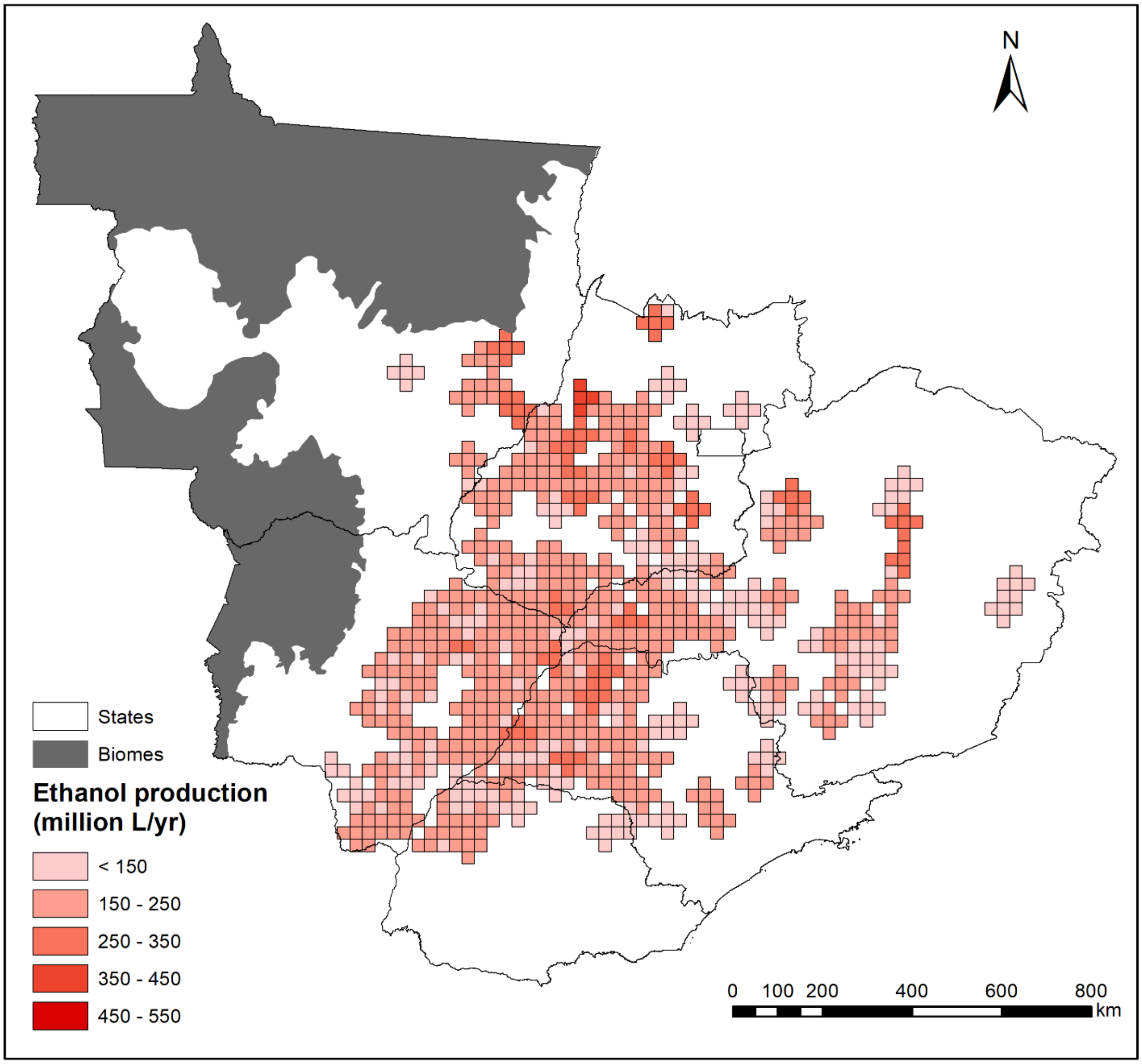

Figure S5: Ethanol output in Tech 3_Soybean

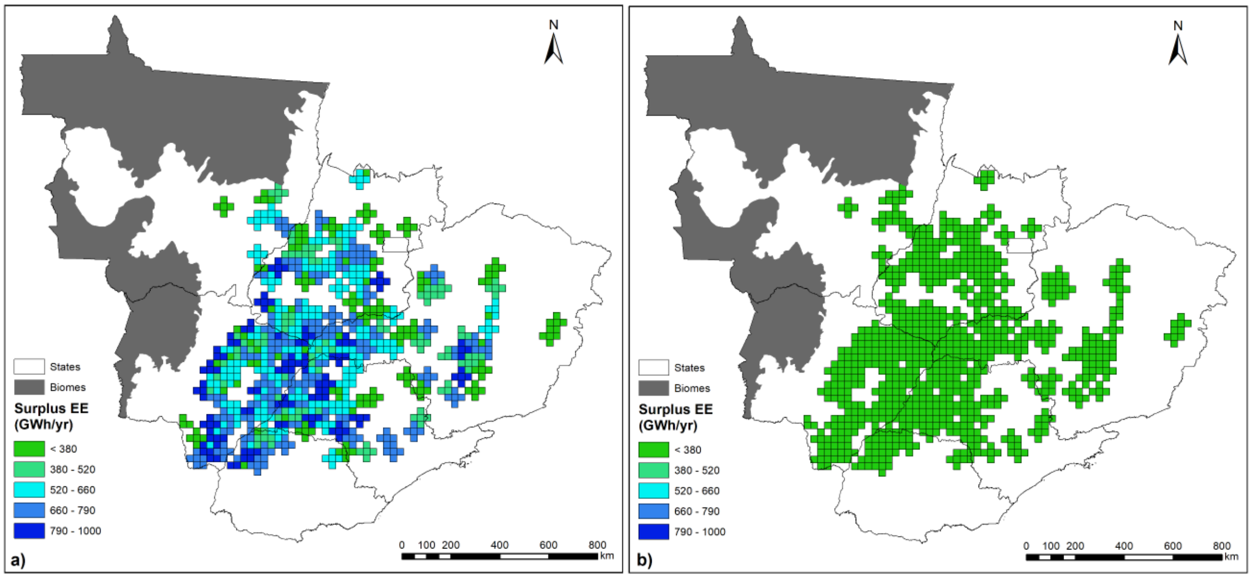

Figure S6: Surplus electricity on Tech 1_Sugarcane (panel a) and on both Tech2_Corn and Tech3_Soybean in panel b)

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Chapter 5

General Discussion

5.1.Techno-economic and environmental aspects of BLI systems

Worldwide, accounting for biofuels by-products as animal feed can improve land use efficiency and reduce greenhouse gas emissions associated with biofuels production (Anderson et al., 2018; Popp et al., 2016; Souza et al., 2019). By-products can reduce or replace grains in the animal feed composition, which can improve land use by decreasing dedicated area for grains production (Buchspies and Kaltschmitt, 2016; Corré et al., 2016; Mumm et al, 2020). In the US, corn ethanol is a consolidated production chain and by-products from both dry-grind and wet-grind pathways can be used as livestock feed, including poultry, swine, beef, and milk cattle (Popp et al., 2016; Mumm et al., 2020). In Europe, ethanol from wheat, corn or sugar beet can produce different by-products with high nutritional value as animal feed (Popp et al., 2016; Buchspies and Kaltschmitt, 2016). In Brazil, sugarcane and soybean are consolidated as main feedstock for ethanol and biodiesel production, and corn ethanol is facing a rapid expansion, mostly in the states of Brazilian Midwest region. The by-products from biofuels produced with these three crops can be used to produce animal feed (Egeskog et al., 2011; Popp et al., 2016).

There is a robust body of literature discussing associated land use and GHG emissions of biofuels by-products as animal feed from a biorefinery perspective (Popp et al., 2016; Anderson et al., 2018; Moreira et al., 2020), but few studies assess the whole picture as integrated systems, and the techno-economic feasibility and other possible environmental impacts from bioenergy-livestock integrated systems.

In Chapters 2, 3 and 4, it was presented and discussed that bioenergy-livestock integrated systems (BLI) in Brazil can co-produce energy and food, alleviating pressure on land resources in both bioenergy and livestock sectors (Souza et al., 2021b). The results presented in Chapter 3 showed that integrated systems could deliver the same amount of products using 50% of land when compared to conventional systems. In Sparovek et al. (2009), released land after integration ranged from 35% to 60%.

A diversified portfolio brings economic benefits to the biorefineries and necessary investments to produce feed are relatively small and feasible, as discussed in Chapter 2 (Souza et al., 2021b). In Chapter 3, BLI systems outperformed conventional systems regarding techno-economic feasibility, cutting payback time almost in half, raising internal rate in 10 percentage points, and resulting in ratio of net present value (NPV) to initial investment 5 times higher. Inclusion of corn ethanol plants operating during sugarcane offseason improved techno-economic feasibility when compared to conventional sugarcane plants, as similar results indicated by Dias et al. (2016). In Souza et al. (2019), BLI investments compared to conventional sugarcane ethanol production were 2% lower, in Chapter 3, this reduction was about 5%, mostly due to smaller combined heat and power (CHP) units. Investments for feed preparation represented only 0.3% of total investments in Souza et al. (2019) and 0.3% to 0.5% in Chapter 3. Corn plant represented 28 to 30% of biorefinery total investments in this study, while in Milanez et al. (2014) it ranged from 17% to 41% of the sugarcane plant investment, in Dias et al. (2016) it represented around 42% and in Iglesias and Sesmero (2015) around 34%. Producing biodiesel was techno-economically feasible and investments represented only 4% of total biorefinery investments. In Chapter 3, integrated systems resulted in cattle production costs 18% lower than conventional ones, due to reduced costs associated with agricultural inputs, transportation of inputs, fuel consumption and land rental. The replacement of diesel with biodiesel produced within integration boundaries reduced greenhouse gas (GHG) emissions of BLI outputs and improved economic feasibility. Accounting for CBIO revenues (Renovabio's carbon credit) only slightly improved revenues from BLI systems. However, such revenues considered CBIO average price in 2020 that was only 8.4 USD, substantially lower than carbon taxes considered in the Shared Socioeconomic Pathways (SSPs), for example, that can reach up to 260 USD in 2050 in SSP 2.6 (Riahi et al., 2017).

The potential to avoid GHG per hectare was two times higher in BLI compared to a conventional system in Chapter 3, largely due to more outputs being produced per land used and the possibility of replacing mineral fertilizer with cattle manure. A considerable reduction of GHG emissions due to cattle manure replacing mineral fertilizer was also reported by Picoli (2017). GHG emissions associated with sugarcane ethanol production were reduced by around 16% in Souza et al. (2019), while in Chapter 3 reduction reached 13 to 28%. For meat, integrated systems reduced associated GHG emissions by 23% in Chapter 3; in Souza et al. (2019) this reduction was 16% and in Picoli (2017) 32%. In all these studies, such reduction happened mostly due to reduced lifetime of cattle and improved carcass yields per hectare.

It is worthwhile mentioning that Brazil just committed to reduce methane emissions during United Nations' Climate Change Conference (COP 26) (CNN, 2021), and BLI systems decreased overall methane emissions in 81% when compared to conventional systems in Chapter 3. BLI systems also improved the energy balance in sugarcane ethanol production, reducing fossil energy consumption from about 133 kJ per MJ of sugarcane ethanol produced in conventional system to about 103 kJ/MJ in the integrated system (Chapter 3). In Souza and Seabra (2014) this reduction in integrated systems was 18 kJ/MJ and in Souza and Seabra (2013) it reached 38 kJ/MJ.

Impacts towards Sustainable Development Goals (SDGs) were in majority lower for sugarcane ethanol produced in BLI systems, except for SDG 14 due to higher agricultural inputs for cultivation of feed ingredients. Meat produced in integrated systems had better performance in SDGs 11 and 13 due to lower finishing cycle and no pasture related impacts, such as application of fertilizers and soil correctives and fuel consumption on agricultural machinery, however increased impacts on SDGs 2, 6, 12 and 14 due to feed production, and scored similar to conventional systems in SDGs 3, 7 and 15.

Although sustainability assessment going beyond climate change impacts was presented in Chapter 3, the spatially explicit assessment of environmental impacts was restricted to GHG emissions in Chapter 4. Even considering site-specific sugarcane yields, land availability and sugarcane straw recovery rates, carbon intensity of sugarcane ethanol was not negatively affected and ranged from 12 to 23 gCO_2eq/MJ in the three technological options assessed in this Chapter, similar to the Brazilian average of around 21 gCO_2eq/MJ (MME, 2018).

In Chapter 4, BLI options considering only sugarcane biofuel had the best economic feasibility and best GHG mitigation potential. Although corn inclusion is techno-economically feasible from a process perspective (Chapter 3), when considering restrictions of land use (i.e., every output should be produced within integration boundaries), inclusion of corn reduced economic feasibility and avoided GHG emissions per candidate biorefinery. This is mostly due to lower crop yields and because in some locations there was not enough sugarcane lignocellulosic material (LCM) to operate the corn plant during the 130 days of offseason, consequently not reaching the full techno-economic potential of corn ethanol production. The inclusion of corn is not the best option in a context of limited area for bioenergy-livestock integration, where crops expand on pasture and all cattle heads must be fed with biofuel by-products and available sugarcane LCM. However, corn brings several advantages to the biofuel and animal feed production, such as the possibility of being stored for long periods and transported for long distances. A possible solution would be to allow biomass coming outside of integration boundaries, such as imports of eucalyptus chips and corn produced elsewhere or close to BLI in Brazil. In this regard, improved sustainability certification schemes would be important to ensure the sustainable supply of the biomass resources from other areas.

A better understanding of site-specific environmental implications of BLI systems, highlighting detailed impacts on water use and water availability, on biodiversity and on biomes would be key to a broader sustainability assessment. As discussed in Chapter 3, land use change (LUC) emissions vary accordingly to the approach and assumptions considered. Depending on the location and pasture conditions, sugarcane expansion on pasture areas can even slightly reduce carbon stocks (Bordonal et al., 2017). Further studies should include detailed carbon stocks of crops and pasture and account for GHG emissions associated with land use changes. In addition, other economic contexts of BLI could also be explored such as variation in input prices and transportation costs, incremental assessment of feed production in existing biorefineries, fluctuation on cattle cycle, and site-specific costs for fuels and fertilizers.

5.2. BLI potentials to meet future energy demands and climate mitigation targets

The large-scale deployment of bioenergy to meet future energy demands and projected climate change mitigation targets must take place in a sustainable way, which includes strategic land use management that does not negatively impact on food production, GHG emissions, human health, biodiversity loss and deforestation, among other potential issues. Implementation of BLI in Brazil could contribute to future energy demands projected by RenovaBio program and the SSPs, and to climate change mitigation targets committed in the Paris Agreement, as discussed in Chapters 2 and 4.

In Chapter 2, a qualitative assessment showed BLI systems present great potential to meet future ethanol demands from RenovaBio in 2030, by using less than 20% of considered available area for that expansion. In Chapter 4, a detailed spatially explicit assessment of available area to expand BLI in Brazil was carried out, considering exclusion of Amazon and Pantanal biomes, biodiversity hotspots and expanding BLI only on current pasture areas of Sugarcane Agroecological Zoning (SAEZ). The performed spatially explicit assessment also considered site-specific crop yields and sugarcane straw recovery rates. The results showed these systems have a considerably high potential to meet future energy demands and up to 89 billion liters of ethanol could be produced annually in the expansion area, in addition to the current ethanol production. This volume represents twice the total ethanol demanded by RenovaBio in 2030, 1.4 and 1.3 times more than projected SSP1 demand in 2030 and 2050, respectively. All BLI options considered in Chapter 4 can meet at least 50% of all SSP demands in 2030 and 2050. Regarding GHG emission, BLI could mitigate up to 139 $MtCO_2eq$. per year, corresponding to 33% of today's energy emission in Brazil (SIRENE, 2020) or 15% of the 900 million tonnes of CO_2eq expected to be mitigated by 2030 according to Brazilian Nationally Determined Contributions (MMA, 2015).

These potential benefits could be achieved considering the conservative assumptions of available pasture area for BLI expansion, of around 16 million hectares (Chapter 4). Other studies suggest that up to 50 million hectares of pasture could be released for biofuel production (Alkimin et al., 2015; Lossau et al., 2015), however they do not take into consideration the exclusion of biodiversity hotspots and Amazon and Pantanal biomes, and expansion only pasture areas in the SAEZ, as performed in the present study. As presented in Chapter 2 (Souza et al., 2021b) and Chapter 4, potential areas to BLI expansion are mostly concentrated in six states of Center-South region Mato Grosso, Mato Grosso do Sul, Goiás, São Paulo, Minas Gerais and Paraná, highlighting west of São Paulo, east of Mato Grosso do Sul and middle of Goiás, that resulted in better techno-economic feasibility and higher potential of biofuel production and mitigation of GHG emissions.

BLI systems can be a great opportunity to achieve GHG mitigation targets to limit global warming to 1.5°C and the future bioenergy demands based on consolidated technologies, since studies projecting these demands account for large deployment of cellulosic biofuels (Andrade Jr et al., 2019; Jaiswal et al., 2017) and of bioenergy with carbon capture and storage (BECCS) technologies (Rogelj et al., 2018; Huppmann et al., 2018). However, both cellulosic biofuel and BECCS are still not widely applied worldwide (Köberle et al., 2020; Rogelj et al., 2016). Large-scale deployment of conventional bioenergy systems would demand considerably higher amount of land, what could cause negative impacts due to land displacement (Cherubin et al., 2021; Frank et al., 2021; Humpenöder et al., 2018).

Although economic feasibility is key for wide application of BLI, until these systems are fully developed and robust, the environmental advantages (e.g., GHG and methane mitigation) should boost BLI systems in the country. Further synergies of BLI could be explored to improve BLI potential in Brazil, such as codigestion of sugarcane vinasse and cattle manure, inclusion of alternative industrial crops such as macauba, sweet sorghum, energy cane and short rotation eucalyptus coppice, that can be grown in more difficult environments (Souza et al., 2021b). In addition, it would be interesting to explore techno-economic and environmental feasibility of BLI with other biofuel pathways, such as thermochemical and second-generation pathways.

5.3. Main challenges, barriers, and uncertainties of BLI systems

Among the challenges and limitations discussed in Chapter 2 to a broader application of BLI systems in Brazil are possible competition of sugarcane bagasse for feed, electricity and 2G purposes, necessity of financial incentives, operational complexity and required specific know-how, due to the additional value chains involved and the diversified portfolio of products (Souza et al., 2021b).

Future studies could perform a detailed assessment considering site-specific potential to finish cattle in feedlots. This could deliver more accurate potentials to release land for biomass production, since results presented here are limited to national cattle stocking rates. Also, detailed modelling of BLI going beyond the finishing stage of beef cattle, including other livestock and more stages of cattle life cycle could also be performed. To keep finishing cycle of beef cattle on grass-fed system and release land for crops production through pasture intensification could also be considered, as it has the potential to decrease GHG emissions and spare land use (Cardoso et al., 2016; Silva et al., 2017; Figueiredo et al., 2017). Although some studies stated that expansion of biofuel crops on pastureland can provide soil carbon sequestration, soil carbon cycling, soil nutrient provision, water regulation and socioeconomic development (Khatiwada et al., 2016a; Oliveira et al., 2019), they require a detailed site-specific assessment.

Chapter 6

General Conclusions

6.1. Final remarks

In a context of increasing energy demands and mitigation of GHG emissions, Brazil has a large potential to decarbonize its transport sector by increasing biofuels production. Despite the biofuel sector being fairly consolidated in Brazil, there is still room to explore synergies and opportunities on integrating food and bioenergy value chains. Bioenergy-livestock integrated systems can be techno-economically feasible and can have positive environmental impacts compared to conventional systems. In this work, BLI systems had a 5-fold increase of the net present value to investment ratio, while reducing payback time by half compared to conventional systems.

BLI systems can help to meet future energy demands, while also contributing to GHG mitigation, without land use displacement, biodiversity loss and competition with food production. GHG emissions were reduced by 13-28% for biofuel production and by 23% for meat production. The integration can also have positive impacts on fossil resource scarcity, mineral resource scarcity, terrestrial ecotoxicity, freshwater eutrophication and terrestrial acidification. BLI systems can produce twice the total RenovaBio demand of 2030, and up to 1.3 and 1.4 times more than SSP1 demands for 2030 and 2050, respectively. It is worthwhile mentioning SSP1 storyline has the highest ethanol demands. Avoided GHG emissions represented up to 33% of Brazilian emissions from the energy sector and 15% of the total GHG reduction target by 2030 committed in the Paris Agreement.

This study might help to support decision makers and encourage the formulation of assertive public policies for the bioenergy sector based on the potentials to meet future energy demands, contribute to achieving the ambitious targets stipulated in the Paris Agreement and to reach the Sustainable Development Goals.

6.2. Suggestions for future work

There is still room to explore BLI implementation in Brazil and to refine spatially explicit assessments of their possible expansion in the country, such as site-specific livestock yield, account for carbon stocks and emissions from land use change, impacts on water use, synergies with complete cycle of livestock production, co-digestion of vinasse and cattle manure, inclusion of alternative crops (e.g., macauba, sorghum, energy cane, eucalyptus), and thermochemical and second generation biofuels.

This work explored techno-economic and environmental aspects of BLI systems in Brazil, however, a broader sustainability assessment should include social effects of integrated systems compared to conventional approaches. Future studies could apply methodologies of social and socioeconomic assessment, such as Social Life Cycle Assessment (S-LCA), input-output analysis (IOA), hybrid S-LCA and IOA, among other, and possibly consider the inclusion of BLI systems into the Integrated Assessment Models (IAMs).

Optimization models could be implemented to deliver optimal shares of lignocellulosic material diverted to electricity and/or animal feed production, taking into consideration the seasonality of feed demand and electricity prices. Also, best locations and technological options of BLI systems to be applied in Brazil under environmental and economic constrains, considering supply-chain design, transportation infrastructure, and hotspots of biofuel demands.

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Annex 1

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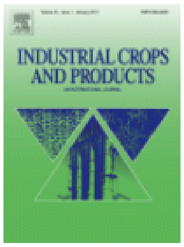

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