ABSTRACT

Title of Dissertation:	THE WATER-ENERGY-LAND NEXUS OF BIOENERGY PRODUCTION IN BRAZIL
	Raul Munoz Castillo, Doctor of Philosophy, 2020
Dissertation directed by:	Professor, Laixiang Sun, GEOG

Biofuels play a critical role in the Paris Agreement to help achieve climate change mitigation targets. However, a significant increase in production of biofuels might potentially be realized at the expense of overusing natural resources, particularly land and water. Understanding the tradeoffs between the development of biofuels and its impacts on land and water is a critical issue for sustainable development. This *energy-water-land nexus* might be particularly important for Brazil, given its position as top exporter and second top producer of bioenergy. Furthermore, Brazil itself has set up its own Intended Nationally Determined Contribution agenda with a significant growth of biofuel production by 2030.

The aim of this research is to quantitatively characterize the nexus of biofuels production with the overall appropriation of land and water resources at the subnational level in Brazil by answering the following questions: (i) How will the

implementation of international climate mitigation commitments adopted by Brazil impact water and land use and therefore water and land stress in Brazil?; (ii) what will be the geographical distribution of such impacts at subnational level? ; (iii) will increase competition among economic sectors aggravate such impacts?; and (iv) how will other socio-economic and physical drivers of change affect those impacts combined with INDC related policies implementation?.

To answer these questions, I developed a set of socio-economic, policy and climate scenarios through an environmentally extended input-output approach that represents socio-economic activities in the 27 Brazilian states, allowing comparison of the resulting water and land demands among main competitive users under different scenarios. I also introduced the use of water scarcity and land stress as environmental impact indicators.

My study confirms that to properly understand the impacts of biofuel production in Brazil on land and water and its “nexus”, the consideration of resource scarcity and its spatial variability are key to ensure sustainable planning of biofuel production. Moreover, I found that the mitigation policies committed by Brazil and its role as top global provider of biofuel will take a significant toll in both water and land consumption in the country, leading to increasing competition among food production, energy generation and human consumption, especially in the most vulnerable and already environmentally stressed states.

THE WATER-ENERGY-LAND NEXUS OF BIOENERGY PRODUCTION IN BRAZIL

by

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Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park, in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
2020

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Preface

Research in this dissertation has been previously published, or has been accepted for publication, in peer-reviewed journal articles. Specifically, the material presented in Chapters 2 and 3.

Dedication

To my son,

Enrique

Acknowledgements

I would like to thank committee members Drs. Klaus Hubacek, Kuishuang Feng, Laixiang Sun, and Fernando Miralles-Wilhelm for their continuous support.

I am particularly thankful to my advisor, Dr Klaus Hubacek and my co-advisor Dr. Kuishuang Feng, for supporting me in conducting my research. I would like to thank you both for your continued guidance and trust in me as a student and PhD candidate, and for the flexibility you gave me to work on my dissertation. The academic conversations with you were always inspiring, challenging, and refreshing. In addition to great advisors, I always found two genuine confidants with whom to discuss personal matters. Thank you Klaus for always giving a broad vision to my research and trying to align it with relevant and leading issues in the area of environmental sustainability. Thanks for the dedicated and in-depth reviews of my manuscripts and for your honest and straightforward opinion. Thank you Kuishuang for your continued technical assistance, for your patience and for the unconditional support. In you, I found a friend who I gained through this process. I am also very grateful to Dr. Laixiang Sun, who always supported with practical, sharp and to the point solutions that were key to advance my research. It has been a luxury for me to have the opportunity to have worked with you and I hope to be able to continue collaborating in the future with this outstanding research team. You always made me feel part of it.

Very especially I would like to deeply thank Dr Fernando Miralles. Beyond committee member, colleague and friend. For having inspired me to enter the academic world, for having guided me along the way, for having supported me on the

process and for encouraging me in the most difficult moments of this long journey of the doctorate. Thank you also for always opening a door to optimism. Also, for some glass of good scotch and some tasty Venezuelan tapas around which to exchange ideas. Thank you.

Even while working on a Ph.D., life continues. While joining UMD as PhD student, I continued to be employed full-time and became father. Special thanks also to my son Enrique. Who came into my life halfway down this path, which is the doctorate. For having made it more challenging, richer and above all more inspiring. Achieving this without you in my life would not be the same, nor would it be so rewarding. You represent the hope of a better and more sustainable world deserved by new generations, which is just what science and research are ultimately pursuing.

Finally, I would like to thank my mother. Who taught me the value of perseverance, hard work, and effort as core values of her life. Always with a smile on her face. Thanks mom.

Thank you all.

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Chapter 1: Introduction, Literature Review and Conceptual Framework

Basic scientific understanding of the interdependencies between food, energy, and water systems (FEWS) is growing in importance as the challenges of ensuring the sustainable and securing provision of these vital resources increase. Several regions of the world are already experiencing FEWS security challenges. Further, there is already evidence of the effects of climate change on the availability of water and demand for food, energy, and water, especially in fast-growing countries[1]. For example, estimates by IEA suggest that emerging economies, like Brazil and India, will double their energy consumption in the next 40 years. In Asia, primary energy production will almost double, and electricity generation will more than triple by 2050; and in Latin America, the amount of electricity generated is expected to increase fivefold in the next 40 years and the amount of water needed will triple[2]. Cities in developing countries must meet the food, energy, and water demands of 70 million more people each year over the next 20 years[3]. By 2030, we will need 45% more water just to meet our food needs[4].

These ongoing examples around the world suggest a pressing need for integrated planning of FEWS development and management to achieve sustainability and security in the coming years. Despite growing concern over the trends and scenarios envisioned for potential developments of FEWS over the near future[5], decision-makers often remain ill-informed about these systems and ill-equipped to deal with the range of plausible outcomes. ***The complexity of the FEWS nexus requires a more systematic approach that takes into account the existing (evident and quantifiable) interactions and dependencies between sectors.***

The bioenergy sector is at the core of the land-energy-water nexus. The synthesis of biofuels from plant biomass (mostly crops) offers an alternative to fossil fuels for energy generation. In recent years, rising interest in biofuel production has resulted from both an increase in oil prices and the new US and EU energy policies mandating a certain degree of reliance on renewable energy as a strategy to curb greenhouse gas (GHG) emissions from the transport sector[6,7]. Biofuels may contribute to the enhancement of energy security in countries lacking direct access to fossil fuel deposits, the reduction of GHG emissions, and a more profitable use of crops than in the food market[7].

The production of biofuel crops, however, can also have negative impacts on the environment, particularly through land use change and deforestation[8,9]. Moreover, biofuels require water and land resources[10,11] that could otherwise be used for the production of food [12] and ecosystem goods and services. Therefore, the competing needs for land and water resources by food and biofuel production are at the forefront of the energy-food debate [13,5], which is fueled by recent food crises and associated spikes in food prices[14] .

According to Gerbens-Leenes et al. (2012)[11], the global biofuel water footprint will increase more than tenfold in the period 2005-2030, reaching up to 5.5% of the totally available blue water for humans, causing extra pressure on fresh water resources in China, Brazil and the US, contributing together half of the global biofuel water footprint. In the longer term, the impacts may be even higher according to other sources. For instance, Bonsh et al. (2016)[15] found that under certain mitigation scenarios, producing 300 EJ/yr of bioenergy in 2095 from dedicated energy crops is likely to double agricultural water withdrawals if no explicit water protection policies are implemented. On the other hand, if irrigation is limited to avoid negative impacts of bioenergy crops cultivation on water resources, bioenergy land requirements will substantially increase (41% according to their study).

Thus, to evaluate the impacts of biofuels on land, energy and water resources, the nexus of biofuel production with the overall appropriation of land and water resources - including impacts on water quality[16]- needs to be investigated, particularly to assess those impacts from large-scale bioenergy production that will require policies that balance associated water and land requirements.

1.1. The study area: Biofuel production in Brazil

Brazil plays a major role in the global biofuel economy as the world's second largest producer and consumer, and the largest exporter of ethanol[17]. The production of sugarcane-based ethanol in Brazil was boosted after the oil crisis in the 1970s thanks to the "Proalcool" Program launched by the Brazilian government with the aim of promoting the use of ethanol within the transportation sector. Through the implementation of this Program, sugar cane dedicated cropland increased from 4.3 million ha in 1990 to 10.2 million ha in 2013 (IBGE, 2017)[18]. Energy from sugarcane biomass has surpassed hydropower generation, representing 15.4% of all energy produced in 2012 compared to 13.8% from hydropower, and 39.2% from petroleum[19]. In 2014, a total of 27 million m^3 of ethanol was produced in Brazil, with an estimated average yield of 7,500 liters of ethanol per planted hectare[20]. According to the IBGE's statistics in 2006 the cropland dedicated to sugarcane was 10 million hectares (ha) equivalent to the 13.3% of the total cropland in Brazil.[21]

There are two main producing areas in Brazil for sugarcane where the production plants for ethanol are also concentrated: the Center-West, Southeast and South, responsible for 88% of the production; and the Northeast and North region where the remaining share is planted. These regions have very different hydro-climatic and socio-economic conditions. The irrigation infrastructure is also unevenly distributed among these areas.

While the issue of land use change associated with biofuels in Brazil has been addressed in several studies[17,22,23], less attention has been given to water resources and consumption. In Brazil, the increased supply of sugarcane is mainly attributed to an increase in acreage. Scarpare et al. (2016)[24] assessed land and water resources use in the sugarcane expansion areas in Brazil, finding that irrigation management has great potential for increasing yields and reducing land needed for sugarcane expansion. However, because sugarcane is a highly water-intensive crop compared to other food and feed crops, its expansion would be relatively larger in regions where irrigation water is available. Guimaraes et al. (2014)[17] analyzed the potential for expansion of sugarcane and ethanol production in Brazil; they identified regional irrigation water constraints that would affect land use requirements.

Currently, sugarcane is still largely produced without irrigation in Brazil. Irrigation could lead to significant productivity gains making sugarcane economically more attractive in larger parts of the country[25,26]. Brazil's irrigated agriculture is around 29 million hectares (ha), equivalent to 61% of the current total cropland, which was estimated to be 45.5 million ha in 2009[27]. However, formal irrigation infrastructure has been developed on only 5.4 million ha of land in 2007 (ANA 2012). Irrigation consumed approximately 24 billion m^3 of water, of which more than 14 billion m^3 or 60% were used by sugarcane (Carneiro et al. 2014, based on FUNARBE 2011)[17,28], followed by rice, a more water intense crop, which takes about half of this share (30%). Therefore, an expansion of sugarcane acreage could pose serious challenges due to the high water-use intensity of this crop and limited water availability for irrigation. Increased water scarcity created by expanded irrigation for biofuels could also adversely affect other energy sources, including hydropower.

Brazil is considered a well-endowed country in terms of water availability with an average of 33,000 $m^{3/}$cap/yr, however, water availability in the country exhibits a high temporal and spatial variability. The lowest value of water per habitant is found in the Atlantic North East hydrographic region, with less than 1,200 m^3/cap/year on average and with values lower than 500 m^3/cap/year in some of the main watersheds of the region. In the semi-arid areas of these basins (Atlântico Leste, Parnaiba, São Francisco), the situation is critical due to severe droughts affecting local populations who suffer intermittent and limited access to water resources for household use, livestock or irrigation. These areas rely heavily on water regulation infrastructure (dams, channels, diversions…). There are other regions where higher population density and higher levels of economic activity lead to critical situations as well. That is the case of the Alto Tiete Basin with values lower than 500 m^3/cap/year, and the cases of basins or other watersheds close to big urban areas in the Atlántico South East or the Parana hydrographic regions. An aggravating factor in these basins is the impairment of water quality, especially in areas close to urban agglomerations, which leads to an increase in treatment costs and restricts the uses of water (ANA, 2011)[29].

When considering the relationship between water demand and availability, the Eastern and Northeast Atlantic region are the ones with the most critical conditions. Almost all the sub-basins exhibit a water scarcity (ratio of demand volume to renewable supply volume) higher than the critical threshold of 40% (see Section 3.1). Some basins of the Eastern Atlantic also present serious difficulties in meeting demands, such us the rivers Vaza-Barris, Itapicuru and Paraguaçu. In less stringent conditions, but still with some supply problems, are basins near urban centers in the Atlantic Southeast, Atlantic South and Parana regions. Finally, some basins in the

South, such as those located in the Uruguay Region, require intense management and interventions, mainly due to multiple water demands competing with irrigation (ANA, 2011)[29].

In light of these regional differences of water availability, investments in irrigation and regional infrastructure development would allow for greater expansion of sugarcane production, but needs to take into account regional or local water availability, as increased water demand for irrigation would put pressure on other users, which could intensify conflicts in water-scarce regions such as Northeastern Brazil[17].

Given the potential increase of external demand driven by on-going international commitments for climate change mitigation, it becomes critical for Brazil to consider regional differences in water availability, demand and scarcity when evaluating how their different regions, states and watersheds can accommodate the potential growing demand for bioenergy production. This is needed to avoid transferring the environmental and economic impacts of meeting international bioenergy mandates to the producing regions, potentially aggravating already complex water resource problems there[30] .

Yet most previous analyses have considered the overall water availability at the national level, ignoring potential impacts on water resources at state or local levels driven by future increased biofuel production. This is especially relevant in more water-stressed regions and states with increasing competition for water use among the main economic sectors. It is also critical to consider that these impacts are not just on water resources, but also on land use, as while irrigated bioenergy production can reduce the pressure on land due to higher yields, associated irrigation water requirements may lead to impacts on water availability and quality.

Additionally, it is worth noting that most of the preceding literature on the water footprint of ethanol in Brazil focuses on blue water driven by sugarcane production. However, it is key to include the green water footprint into the analysis because water footprint accounts show water allocation in volumetric terms and rainwater used for biofuels cannot be utilized for other crops[11]. Introducing the green water footprint allows to account for the water footprint associated with irrigated and rainfed sugarcane production, which ultimately is an indicator of the tradeoffs between water and land impacts of sugarcane production. Also, by including the grey water footprint in the overall water footprint assessment, it is possible to consider limiting availability of water to other crops or sectors due to water quality impacts of bioethanol production.

Finally, previous assessments on bioenergy production in Brazil have covered the water footprint of the agricultural stage of the bioethanol supply chain but there is still the need to uncover which fraction of this water footprint is actually driven by ethanol, sugar or other products that needs sugarcane or its byproducts for their production.

1.2. Conceptual framework

A fundamental challenge in the management of FEWS is that these systems are tightly linked, and the decisions about them are often made independently by decision-makers focusing on each system in isolation or with only minimal consideration of the other systems. Similarly, modeling in support of these decisions is also frequently focused on single systems with only minimal consideration of the other systems. While the multifaceted interactions between food, energy and water are often framed as threats or stresses of one system upon the other(s)[31], basic understanding of the dynamics, interactions, and feedbacks is also useful for identifying synergies and potential efficiencies.

For my research, I will consider a Food-Energy-Water Nexus framework having the biofuels playing a central role within the Nexus interactions and connections and in which these multiple stressors are explicitly identified (See **Figure 1**). This will support my research in different ways by: (**i**) assisting me in situating my research within prior literature and theory, while drawing attention to the specific interplay of biofuels with land and water use that are as yet not fully known and that I want to study; (**ii**) guiding me in the selection of the variables, processes and stressors; (**iii**) necessitating consideration of interactions with other sectors outside of the land-energy "box"; and (**iv**) defining the modeling framework that will guide application of methods and data collection (see Section 3 for Research Design, Methodology and Analysis).

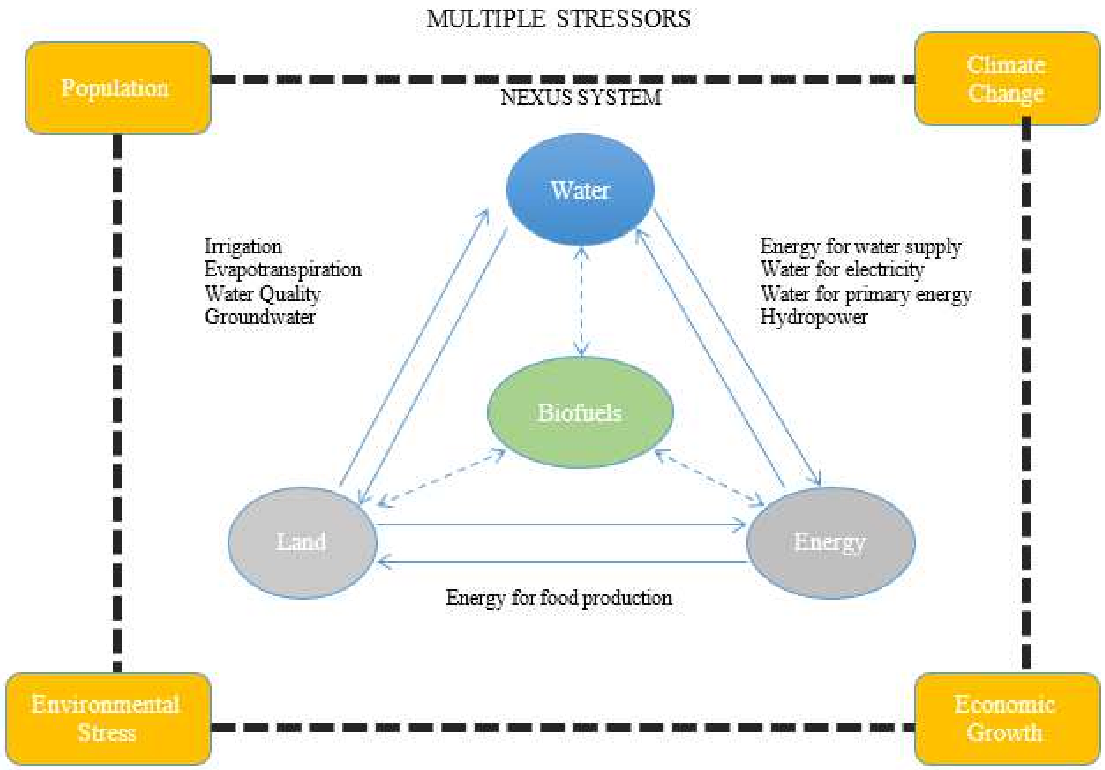


Figure 1-1: Conceptual framework: Biofuels and the Land, Energy, and Water Nexus System under multiple stressors

1.3. Research questions and dissertation structure

1.3.1. Research objectives

Given this context, this proposed research aims to quantitatively characterize the nexus of biofuels production with the appropriations of land and water resources at the subnational level in Brazil, which as the second largest producer of bioenergy, and plays an important role in the global biofuel production and potentially significant environmental, economic and social impacts domestically and globally. This analysis will explore biofuels production driven by both domestic and global demand and the competition with water and land as part of the FEWS use under present and future growth demand scenarios (i.e. closely linked to international climate change agreements) and other physical and socioeconomic relevant drivers for the Brazilian bioenergy production context.

More specifically, the aim of this work is to contribute to the existing literature by answering the following core questions:

With respect to the implementation of international climate mitigation commitments adopted by Brazil, specifically the INDCs in the 2015 Paris Convention: (i) How will the committed climate mitigation actions impact water and land use and therefore water and land stress in Brazil? (ii) what will the geographical distribution of such impacts at the subnational level be? (iii) how will the biofuel expansion increase competition among economic sectors and aggravate impacts on natural resources? and (iv) how other socio-economic and physical drivers of change will affect those impacts combined with INDC related policies implementation?

To answer these core questions, I will address the following research objectives:

i. estimate the virtual and total water footprints (green, blue and grey) associated with sugarcane-based ethanol production in Brazil;
ii. estimate the virtual and total scarce water footprint (green, blue and grey) associated with sugarcane-based ethanol production in Brazil;
iii. estimate the virtual and total land footprint associated with sugarcane-based ethanol production;

iv. estimate the virtual and total land stress associated with sugarcane-based ethanol production;

v. assess the tradeoffs of water and land impacts of bioenergy production in Brazil;

vi. evaluate the future impacts on water and land ant its tradeoffs by the increase of bioethanol production in Brazil by 2030 under different climate and socio-economic scenarios.

1.3.2. Dissertation outline

I am structuring my dissertation in three clearly defined phases which will allow me to produce three different chapters:

Chapter 2: Assessment of the water impacts of biofuel production in Brazil (Paper #1). In this chapter I answer core questions (i), (ii) and (iii) regarding impacts on water use and scarcity, including impacts driven by exports to global markets from Brazil (virtual water). I am contributing to the existing literature with the first assessment on water scarcity driven by sugarcane based ethanol production in Brazil at the state level and with the introduction of an economic comparative advantage indicator to assess the competition among bioethanol and other sectors. As a result of this assessment, I produced Paper #1, which was published in the journal Sustainability (https://www.mdpi.com/2071-1050/9/11/2049)

Chapter 3: Assessment of the land impacts of biofuel production in Brazil (Paper #2): To answers core questions (i). (ii) and (iii) regarding land stress impacts and the associated trade-offs with water scarcity related impacts, in this chapter I study land appropriation and environmental impacts (land stress) in the country driven by ethanol production. The main contribution from this paper will be the first subnational assessment at the state level of land stress driven by bioethanol production in Brazil, including the first analysis of the combined impacts on land and water stress and the associated trade-offs to inform national planning of sugarcane and bioethanol production. This includes also the first combined analysis of socio-economic impacts by the use of an economic competitive advantage assessment and the introduction of a water to land stress ration for bioethanol production. The result of this study was a paper published in 2018 in the Journal of Cleaner Production (https://www.rug.nl/research/portal/publications/the-landwater-nexus-of-biofuel-production-in-brazil(0e516d72-1522-47f2-bb89-d340dad1cf53).html)

Chapter 4 (Paper #3): Assessment of the tradeoffs of water and land impacts and the implications of future demand growth in Brazil driven by international climate mitigation commitments (INDCs). In this chapter I develop different future biofuel production scenarios and to assess their environmental impacts. By doing so I answer core question (i). The main contribution from this paper will be the first integrated assessment of water and land footprint of biofuel at the state level in Brazil as well as the first estimation of such impacts driven by the Paris Agreement in Brazil, along with other climate change and socio-economic scenarios by 2030 by the integration of an MRIO model and the GIS-based spatial explicit Global Agro-Ecological Zones (GAEZ) model. The methods, data and results from this paper are presented in this chapter and as a result I produced a journal paper which is being submitted to a peer-reviewed journal for publication by Fall 2020.

Finally, Chapter 5 summarizes and concludes the entire body of work. I revisit the key findings of Chapters 2-4, and discuss how each chapter improves the understandings about the FEW nexus associated with bioethanol production in Brazil and the outlook under future policy, climate and socio-economic scenarios. This chapter also mentions the limitation of this dissertation, and develops topics for future research.

To sum-up, the overall contribution of my research to literature resides mainly on: (i) uncovering water and land footprint of bioethanol production in Brazil; (ii) the introduction of the Nexus approach, by the assessment of the water-land nexus tradeoffs and synergies at the state level; and (iii) the combined assessment of both physical and socio-economic dimensions of biofuel production by linking the MRIO model with a quantitative index of comparative advantage ratio.

Chapter 2: Uncovering the Green, Blue and Grey Water Footprint and Virtual Water of Biofuel Production in Brazil: A Nexus Perspective [1]

2.1. Abstract

Brazil plays a major role in the global biofuel economy as the world's second largest producer and consumer and the largest exporter of ethanol. Its demand is expected to significantly increase in the coming years, largely driven by national and international carbon mitigation targets. However, biofuel crops require significant amounts of water and land resources that could otherwise be used for the production of food, urban water supply, or energy generation. Given Brazil's uneven spatial distribution of water resources among regions, a potential expansion of ethanol production will need to take into account regional or local water availability, as an increased water demand for irrigation would put further pressure on already water-scarce regions and compete with other users. By applying an environmentally extended multiregional input-output (MRIO) approach, I uncover the scarce water footprint and the interregional virtual water flows associated with sugarcane-derived biofuel production driven by domestic final consumption and international exports in 27 states in Brazil. My results show that bioethanol is responsible for about one third of the total sugarcane water footprint besides sugar and other processed food production. I found that richer states such as São Paulo benefit by accruing a higher

[1] https://www.mdpi.com/2071-1050/9/11/2049

share of economic value added from exporting ethanol as part of global value chains while increasing water stress in poorer states through interregional trade. I also found that, in comparison with other crops, sugarcane has a comparative advantage when rain-fed while showing a comparative disadvantage as an irrigated crop; a tradeoff to be considered when planning irrigation infrastructure and bioethanol production expansion.

2.2. Introduction

The interdependency between land, energy, and water systems has gained increasing interest as demand for these vital resources is growing around the world, leading to resource scarcity and adverse environmental impacts [32]. At the same time, there is increasing competition for these resources from other economic sectors, domestically and from abroad. The stress on these resources is further enhanced through their vulnerability to climate change. Several world regions are already experiencing security challenges in FEWS, adversely affecting sustainable development [32].

In this context, the bioenergy sector is at the core of the energy-water nexus. Biofuels, mostly based on crops, may contribute to the enhancement of energy security in countries lacking direct access to fossil fuel deposits, the reduction of GHG emissions, and a more profitable use of crops than in the food market [7]. However, the production of biofuel crops requires water and land resources [11,33] that could otherwise be used for the production of food (FAO, OECD) and other important ecosystem goods and services. Therefore, *the competing needs for land and* *water resources by food and biofuel production are at the forefront of the energy-food debate* [16]. For example, the global biofuel water footprint is estimated to increase more than tenfold in the period 2005–2030, reaching up to 5.5% of the totally available blue water for humans, placing extra pressure on fresh water resources in China, Brazil, and the US, which contribute about half of the global biofuel water footprint [11]. In the longer term, the impacts may be even higher, especially given climate change [34].

The water footprint (WF) [35,36] serves as a framework for assessing the link between human consumption and the appropriation of freshwater. The WF of a product (or service) represents the total amount of water used during all production steps required to produce the product (or service), and is expressed in water volume per unit of product (e.g. m^3/ton). The blue WF is defined as the volume of surface and groundwater consumed (evaporated) during production. The green WF refers to the amount of rainwater consumed. The grey WF is the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards [36]. Blue water is generally scarcer and has higher opportunity costs than green water. In addition, blue water can substitute for green water and therefore, a comprehensive assessment of WF requires a consideration of both green and blue water footprints [36].

As the world's second largest producer and consumer, and the largest exporter of ethanol, Brazil saw the production of sugarcane-derived ethanol boosted by the oil crisis in the 1970s thanks to the "Proalcool" Program launched by the Brazilian government with the aim of promoting the use of ethanol in the transportation sector.

The existing literature assumes that Brazil will be a major supplier of bioenergy to international markets under future climate mitigation scenarios given its assumed abundance of water resources. For instance, an assessment of the global blue and green water footprint of road transport in 2030 concluded that only Brazil has sufficient available water resources to meet targets for 2030 since the other three large producers (the US, India, and China) would suffer from water shortages, and would not even be able to sustain their own biofuel production in a self-sufficiency scenario [3].

While Brazil is indeed a well-endowed country in terms of water availability with a national average of 33,000 $m^{3/}$cap/yr [29], it is at the same time subject to high temporal and spatial variability. The lowest value of water per capita is found in the Atlantic Northeast hydrographic region, with less than 1200 m^3/cap/year, and values lower than 500 m^3/cap/year in some of the main watersheds. These watersheds also suffer from water quality problems which further restrict the uses of water [29]. In light of these regional differences of water availability, investments in irrigation and regional infrastructure development would allow for a greater expansion of sugarcane production, but need to take into account regional or local water availability, as an increased water demand for irrigation would put pressure on other users, which could intensify conflicts in water-scarce regions such as Eastern and Northeastern Brazil [17,29]. On the other hand, limiting irrigation for bioenergy will substantially increase land requirements.

Sugarcane and ethanol productions negatively affect water quality and aquatic systems in Brazil. One of the main causes of such impacts is sedimentation downhill across the landscape from sugarcane fields that is deposited into wetlands, streams, rivers, and reservoirs. The severity of the problem of sedimentation is aggravated even further by the transport of contaminants such as pesticides and heavy metals used for sugarcane cultivation to aquatic systems [37]. As over-fertilization for sugarcane is a usual problem in Brazil, consequent losses of nutrients to aquatic systems (mainly Nitrogen, but also Phosphorus and Potassium) are one of the main causes of impacts on water quality associated with its production, leading to eutrophication in water bodies and aquatic systems. The industrial processing of ethanol is another important source of pollution through the generation of wastewater and vinasse (liquid byproduct of ethanol), produced from the distillation process, both rich in organic matter and therefore increasing the BOD (biochemical oxygen demand) of the water bodies [37].The pollution of watercourses and bodies not only impacts the ecological equilibrium of the receiving ecosystems, but also affects other water uses downstream, limiting the access to freshwater to other users and increasing treatment costs.

Given the potential increase of external demand driven by on-going international commitments for climate change mitigation, it becomes critical for Brazil to consider regional differences in water availability. This is needed to avoid transferring the negative environmental impacts of meeting international bioenergy mandates to the producing regions, potentially aggravating already complex water resource problems [30].

Previous analyses considering the overall water availability at the national level have largely ignored potential impacts on water resources at state or local levels driven by future increased biofuel production. This is especially relevant in more water stressed regions and states with increasing competition for water use among economic sectors along their national and global supply chains. This is echoed by [38], who assessed the direct and indirect impacts on water consumption of the power sector in major emitting economies, including Brazil, under the Nationally Determined Contributions (NDCs) and longer-term mitigation scenarios and concluded that in light of geographically uneven water scarcity, climate policy decisions concerning the biofuels sector should consider not only on-site water demands, but also the virtual water input from upstream sectors, as well as the virtual water embedded in goods that move in national and international trade.

Another important shortcoming of the literature on the water footprint of biofuels in Brazil is their main focus on blue (irrigation) water driven by sugarcane production. However, it is key to include the green water footprint in the analysis because of the competition for rainwater between crops [11]. Introducing the green water footprint allows one to account for the water footprint associated with irrigated and rainfed sugarcane production, which ultimately is an indicator of the tradeoffs between water and land impacts of sugarcane production. Also, the expansion of biofuel crops may lead to water pollution, thus limiting the availability of water to other crops or sectors due to water quality impacts of the utilization of fertilizers and pesticides.

This study analyzes the spatial distribution, at the state level, of virtual water flows and the water footprint associated with sugarcane-derived ethanol production and consumption in Brazil. By applying an environmentally extended MRIO approach, I estimate the water footprint, including blue, green, and grey water; the scarce water footprint; and the interregional virtual water flows across Brazil at the state level driven by ethanol production and international exports. I also use a comparative advantage ratio to assess the competitiveness of sugarcane compared to other crops in terms of the value added per unit of water consumption.

2.3 Materials and Methods

Using MRIO analysis, I calculated production and consumption-based WF and scarce water footprints (SWF) of bioethanol and associated virtual water flows associated with interregional and international trade. The SWF is the original WF weighed by the water scarcity in the catchment (aggregated to the state level) where the WF is located; this provides a water-scarcity weighted WF that reflects the potential local environmental impacts of water consumption [39]. Through this analysis, I explored the comparative advantage of using water to produce sugarcane (the major crop for biofuel production in Brazil) versus other agricultural crops and other economic sectors across Brazil.

2.3.1 Data Sources

I used an MRIO table for Brazil for the year 2011 at the state level (27 states). The MRIO tables were built based on 27 state I-O tables and estimated inter-regional trade flows [40–42]. The database offers a highly detailed description of the economy with 149 sectors, including 18 agricultural sectors; three primary energy sectors; seven power generation sectors; and two biofuel production sectors, including one for sugarcane-based ethanol, providing more detail than previous studies.

To estimate the green, blue, and grey water footprint for the agricultural sectors, I combined state-level water consumption factors in m^3/ton from the Water Footprint Network [43], linked to crop data from the National Census of Agriculture [18] including 35 permanent and 31 temporary crops that I aggregate to match the MRIO sectors.

In this way, I was able to capture both rainfed and irrigated agriculture, compared to previous studies in Brazil, which have focused on water consumption associated with irrigation and therefore are limited to the blue water footprint. For the remaining sectors, I focused our analysis on the blue water and grey water footprint, assuming that the green water footprint applies specifically to agricultural sectors.

For the livestock sectors, I calculated the direct water consumption coefficient by using the methodology of the ONS (National Operator of the Electrical System) [44], for different species and combined with the production of municipal livestock statistics from the Brazilian Institute for Geography and Statistics (IBGE) [21]. To convert from water withdrawal to water consumption (blue water), we adopted the return flow ratio proposed by the ONS for all species (0.2). To calculate the grey water footprint, I applied the blue water/grey water ratios for different livestock species in Brazil from Mekonnen and Hoekstra [45].

For the water supply and sanitation sector, I obtained the water withdrawals at the state level by combining the per capita water consumption rate (l/person/day) from the National Environmental Sanitation Secretariat (SNSA) [46], combined with the equivalent population per state according to the 2010 Census [47], from which I discounted the distribution losses per state according to SNSA [46]. To convert into water consumption (blue water), I applied 0.8 as the return flow rate according to the Brazilian Association of Technical Standards (ABNT) [48]. To estimate the grey water footprint for the domestic water supply, I applied the relation factor blue/grey water footprint for Brazil from Mekonnen and Hoekstra [49].

Regarding primary energy, I used the water consumption factors by source from Gleick [50], which were combined with the production values from the Oil National Agency (year 2011) [51] in the case of oil and gas sectors and from the National Department for Mineral Production [52] for coal (year 2010). For the bioenergy production sectors, I used the water consumption coefficients from the Foundation Bank of Brazil (FBB); MMA: Foundation to support the Federal University of Vicosa [28] for the sugarcane-based ethanol and from the US Sandia National Laboratories for biodiesel [53] in the case of the non-ethanol biofuels sector. In relation to the power generation sectors, the amount of blue water was calculated by multiplying the power generation by source and state from the Brazilian Energy Research Institute [54] by the consumption coefficients for each technology from NREL [55]. For the specific case of hydropower, I used the consumption (evaporated) water coefficient for Brazil [56]. The grey water footprint was considered negligible for these sectors compared to agricultural and urban wastewater pollution. See **Table 2-1** for an overview of data sources and steps.

As this research intends to address the competition for water resources among biofuel production, agriculture and livestock (food production), energy and electricity, and urban water supply, it is important to clarify that I did not include the water footprint assessment for other sectors (such as mining and industry), which provides a limitation of this study and an underestimate of the potential water impacts.

Table 2-1. Explanation of data collection and compilation for sectoral level water consumption.

Sector	Green Water	Blue Water	Grey Water	Data Sources
Agriculture -crops	WF Factor (m3/ton) × Production (ton)	WF Factor (m3/ton) × Production (ton)	WF Factor (m3/ton) × Production (ton)	IBGE Water Footprint Network
Agriculture -livestock	N/A	Number of heads × average weight per animal (Kg/unit) × (1/1000) (ton/Kg) × WF factor (m3/ton) × return flow rate (%) [Per livestock category]	Blue WF-Grey WF ratio (%) × blue water (m3)	IBGE ONS Water Footprint Network
Water and sanitation	N/A	Withdrawal rate (l/person/day) × population (person) × distribution losses ratio (%) × returns flow rate (%)/1000 (l/m3)	Blue WF-Grey WF ratio (%) × blue water (m3)	IBGE SNSA ABNT Water Footprint Network
Primary Energy	N/A	WF Factor (m3/ton) × Production (ton)	Negligible	ANP FBB, Funarve DNPM US Sandia

				Laboratories Gleick, P.H. (1994)
Electricity	N/A	Power Generation (MWh) x WF ratio (m3/MWh)	Negligible	ANEEL NREL

To estimate water scarcity, I used Raskin's definition of water scarcity [57] as the ratio of total water withdrawal (TWW) to total water availability (TWA). The water scarcity index (WSI) is thus given by WSI = TWW/TWA. This concept is referred to in the literature as the *withdrawal-to-availability* (WTA) index and the *water resources vulnerability index* (WRVI). I used the water balance database provided by the National Water Authority (ANA) [58] to calculate the WTA at the state level. In this database, the WTA is detailed at the micro-watershed level, with a total of 558,699 watersheds. To make this data compatible with the spatial detail of the MRIO table, the state WTA was obtained by aggregating the value of the micro-watersheds within each state boundary by using GIS. The state's fresh water consumption was then multiplied by the state WTA index to obtain the scarce water consumption at the state level. According to ANA, the proposed categorization for the WTA thresholds follows that adopted by the European Environment Agency and the United Nations, as follows: (**i**) excellent conditions for a WTA < 5%; (**ii**) comfortable conditions when 5% < WTA < 10%; (**iii**) worrisome conditions when 10% < WTA < 20%; (**iv**) critical conditions for 20% < WTA < 40%; and (**v**) very critical conditions when WTA > 40%.

2.3.2 Multiregional Input-Output Model

MRIO analysis is a widely used modeling approach, which enables analysts to explore the entire supply chain and the associated ('embodied') emissions or natural resource use. At its core, it is an accounting procedure relying on regional economic input-output (IO) tables and inter-regional trade matrices, depicting the flows of money to and from each sector within and between the interlinked economies, and thus revealing each sector's entire supply chain. The MRIO modeling approach has been frequently used in water footprint and virtual water studies by utilizing the IO ability to quantify direct and indirect (upstream supply chain) water consumption for sectorial production at regional, national or global scales [59–64].

In this study, I apply the MRIO approach to assess virtual water flows across 149 sectors and 27 Brazilian states. The MRIO database for Brazil contains the intermediate consumption matrix **Z**, the final consumption matrix **Y**, the value added vector **v**, and the international export vector **e**. To estimate the virtual water in the intra- and inter-regional supply chain to satisfy final consumption including international exports in each state, I extended the MRIO framework with a water coefficient matrix **K**, which covers green, blue, and grey water coefficient vectors, in addition to water scarcity-weighted water coefficients to account for scarce water. To distinguish the consumptive water and water scarcity-weighted consumptive water, I refer to them as fresh water and scarce water, respectively.

To calculate virtual water flows ($\mathbf{VW}$), I extended the MRIO system based on Leontief's demand-drive model, Equation (1), with the water coefficient matrix, as follows:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}(\mathbf{y} + \mathbf{e}) \tag{1}$$

where $\mathbf{x}$ is a vector of the gross output of the 3969 industry sectors; $\mathbf{I}$ is an identify matrix; $\mathbf{A} = \mathbf{Z}/\hat{\mathbf{x}}$, is a technical coefficient matrix describing inputs into the production of industry sectors to produce one unit output of these sectors and the hat symbol denotes the diagonalization of gross output vector **x**; $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix which captures the total input requirement to produce one unit of final consumption product; and **y** is the summation of rows for final consumption matrix **Y**.

By incorporating the water coefficient **k**, I may derive a water multiplier matrix, which can be used to calculate total virtual water flows in Brazil:

$$\mathbf{VW}_{dom} = \hat{\mathbf{k}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \tag{2}$$

where $\mathbf{VW}_{\mathbf{dom}}$ is a matrix containing virtual water flows from the industry sectors in different states to satisfy their own final consumption (e.g. household consumption, governmental expenditure, capital investment) and other states' final consumption (e.g. exports of final products to other states); $\hat{\mathbf{k}}$ is a matrix with water coefficients on its diagonal; and $\hat{\mathbf{k}}$ may be used as the water coefficient matrix for green, blue, or grey water and scarce green, blue, or grey water.

To calculate virtual water in international exports from Brazil to foreign countries, I replaced the final consumption matrix **Y** with the international export vector **e:**

$$\mathbf{VW}_{\mathbf{exp}}^{\mathbf{r}} = \hat{\mathbf{k}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{e}^{\mathbf{r}} \tag{3}$$

Where, $\mathbf{VW_{exp}^{r}}$ is a vector of virtual water from different sectors in different states that is consumed for the production of international exports in state $\mathbf{r}$.

The total WF at the state level in Brazil can then be calculated by the summation of domestic virtual water flows ($\mathbf{VW_{dom}}$) from all industry sectors associated with the final consumption of water in each state using Equation (4).

$$\mathbf{WF} = \sum_{i} \mathbf{VW_{dom}} \tag{4}$$

where $\boldsymbol{i}$ indicates each industrial sector in a given state.

Since I do not have the physical data for the share of sugarcane for biofuel, sugar production, and others, I separated the water consumption of sugarcane production into these three categories using the shares of each one from the MRIO database. In the MRIO table, there are separate sectors for sugar production and biofuel production.

2.3.3 Total Water Footprint

To provide a comprehensive and complete overview of freshwater appropriation by biofuels, there is a need to consider consumptive water uses, as well as water pollution. The pollution of freshwater resources not only poses a threat to environmental sustainability and public health, but also increases the competition for freshwater [65].

I used the green, blue, and grey water footprint of crops estimated by [43]. Their database details the green, blue, and grey water footprint of 126 crops in a 5 by 5 arc minute grid expressed in m^3 ton^{-1}. To estimate the green, blue, and grey water footprint for each of the crops detailed in the MRIO table, I multiplied the aggregated value of the water footprint (blue, green, and grey) at the state level by the respective sectorial production in tons for the given state. I then incorporated the estimated water footprint for each sector and state into our model through the row vector for water consumption to obtain consumptive blue, green, and grey water footprints. It is important to highlight that these water footprint factors reflect the water consumptive uses of water and not water withdrawals.

2.3.4 Comparative Advantage Ratio

I used a comparative advantage ratio aggregated to the state level to assess the competitiveness of sugarcane compared to other crops in terms of the value added per unit of water consumption.

This ratio is given by the following relation:

$$CA_j = (VA_{sc} / VA_{sx}) / (WF_{sc} \, / \, WF_{sx}) \tag{5}$$

where CA_j is the comparative advantage ratio for a given state j, VA_{sc} is the added value for sugarcane, VA_{sx} is the added value for the sector or crop compared with sugarcane production, WF_{sc} is the water footprint driven by sugarcane production, and WF_{sx} is the water footprint due to the production of the crop. I obtained the added value for each crop from the MRIO table.

The purpose of using this ratio is to assess the water footprint of sugarcane driven by ethanol production from a broader nexus perspective. I evaluated the competing uses of water with other crops or agricultural sectors, focusing on total water consumption and the added value of sugarcane. Since the core of the ethanol water footprint is associated with the agricultural stage of the supply chain, I assumed that any potential growth in bioethanol demand, either domestic or international, will drive the demand for sugarcane production and thus will increase the demand for water.

For the purposes of this investigation, I compared the production of sugarcane with other main crops cultivated in Brazil, namely rice, corn, and soybean. In addition, I also compared sugarcane to the total agricultural production (the sum of all agricultural sectors of the MRIO table). A *CA* value above 1.0 implies that the production of sugarcane in this specific state is more competitive in terms of the value added per unit of water consumption than the production of other crops. I applied this ratio separately for the consumptive uses of water; green and blue water footprint.

2.4. Results

2.4.1 Inter-State Water Flows

In 2010, the total water consumption of sugarcane production in Brazil was estimated as 101 billion m^3, of which 54 billion m^3 was virtually traded across Brazil. Over 2.5 billion m^3 of virtual blue water associated with sugarcane production was traded across Brazil. In addition, the virtual green and grey water flows were 48 billion m^3 and 4.1 billion m^3, respectively. It is worth noting that the grey water footprint triggered by sugarcane production is 64% higher than its blue water footprint, a significant amount that has to be taken into account when comprehensively assessing total water appropriation due to water pollution by sugarcane and ethanol production.

Figure 2-1 shows the virtual water traded by the top exporters and importers of virtual water associated with sugarcane production. São Paulo, the richest state in Brazil and the largest producer of ethanol, responsible for 51% of the production, shows a higher production-based water footprint than its consumption-based water footprint, which leads the state to be a net exporter of green, blue, and grey water. Just by itself, this state has a consumption-based green water footprint of 36.6 billion m^3 (41% of the national), 1.5 billion m^3 (36%) of blue water footprint, and 3.1 billion m^3 (41%) of grey water footprint. On the other hand, the state has a production-based green water footprint of 48 billion m^3 (55%), 1.7 billion m^3 (39%) of blue water footprint, and 4.2 billion m^3 (55%) of grey water footprint.

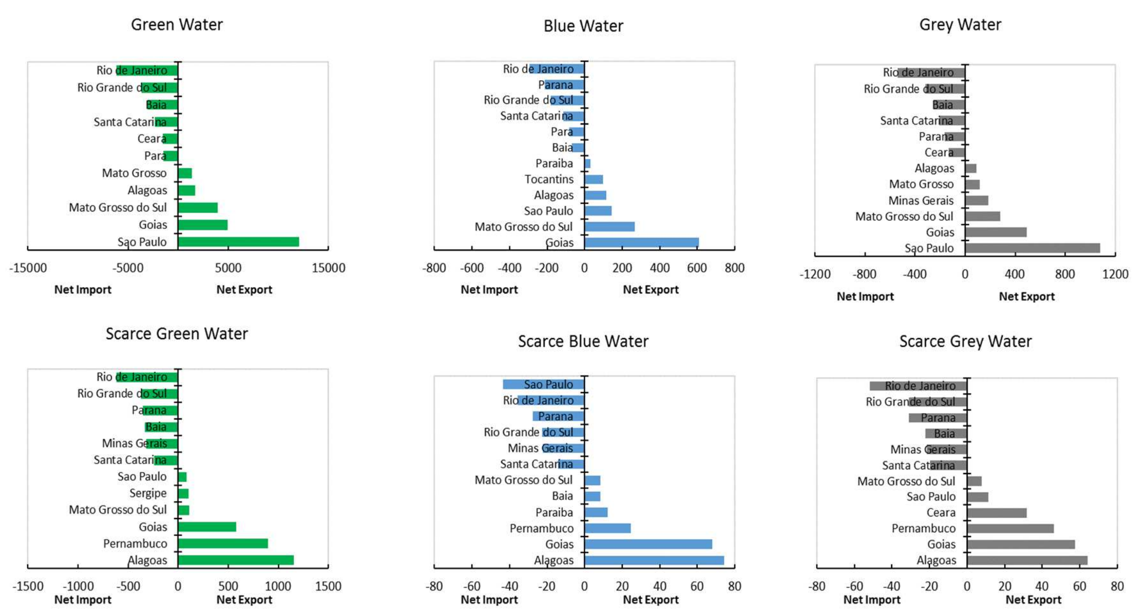


Figure 2-1. Top net virtual water exporters and importers of sugarcane production driven by the final demand of Brazilian states, units in million m^3). Negative values in the x-axis show net imports of virtual water and positive values represent net exports of virtual water.

However, in terms of blue water, the top exporters are Goiás and Matto Grosso do Sul with 0.607 billion m^3 (46%) and 267 billion m^3 (20%), respectively, followed by

São Paulo and Alagoas, in the arid Northeast, with 114 million m^3. This can be explained by the fact that most of the production in São Paulo state is rain-fed, while more than half of the irrigated sugarcane production occurs in the dry Northeast [17], Goiás, and Matto Grosso do Sul.

The major importers of virtual green water associated with sugarcane production are Rio de Janeiro with 6.2 billion m^3 (25%), followed by Rio Grande do Sul with 3.7 billion m^3 (15%), Bahia with 3.1 billion m^3 (12%), Santa Catarina with 2.4 billion m^3 (9%), Ceará with 1.5 billion m^3 (6.2%), and Pará with 1.4 billion m^3 (5.8%) of green water. Rio de Janeiro is also the largest importer of blue water and grey water with 300 m^3 and 350 million m^3, respectively, followed by other Southern states such as Parana, Rio Grande do Sul, and Santa Catarina. For these states, their total consumptive water footprint is much larger than their local water consumption, due to the large import of ethanol, sugar, and other products from sugarcane for domestic consumption.

Thanks to the level of disaggregation of the MRIO table, I was able to uncover the water consumption by sugarcane for ethanol production vs. the total water footprint of sugarcane production. The blue water footprint of sugarcane production driven by ethanol was 1 billion m^3, (23% of the total blue water footprint driven by sugarcane and 6.5% of total agricultural blue water footprint in Brazil), which is 4.7 and 4.6 times higher than the blue water footprint of power generation and primary energy sectors, respectively. The green water footprint was 21.7 billion m^3 and the grey water footprint 1.8 billion m^3.

Figure 2-2 shows the distribution of the regional water footprint among sugar, bioethanol, and "others" for the top 10 states with the highest blue and green water footprint. On average, the largest share of the total footprint from sugarcane is due to sugar production accounting for 64%, whereas ethanol production is responsible for 24%, equivalent to 24.5 billion m^3 total water footprint.

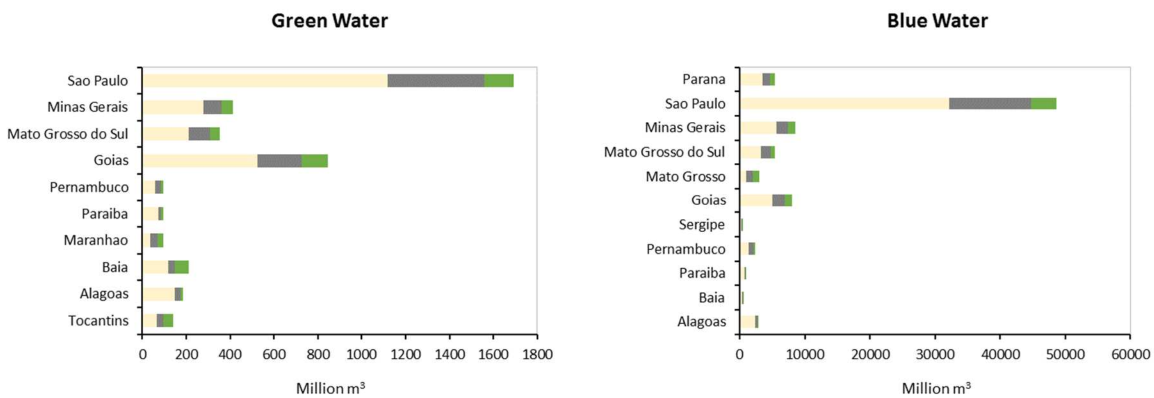


Figure 2-2. Water footprint (WF) distribution of sugar production, ethanol, and "others" (other sectors) for the top 10 states with the largest blue and green water footprint (units in million m^3).

My results also show that 13.5 billion m^3 of virtual total water, including green, blue, and grey water, were traded across the 27 Brazilian states, representing 54% of the total water footprint driven by ethanol production. **Figure 2-3** presents the top water and scarce water importers and exporters in Brazil due to ethanol production. With regard to the virtual blue water footprint, the states with higher rates of irrigated sugarcane production lead the ranking. Goiás is the top exporter of blue water with 45% of the total, followed by Mato Grosso do Sul (23%) and São Paulo (16%). The top importers are Rio de Janeiro with 22% of the total, and the Southern states of Parana (16%), Rio Grande do Sul (13%), and Santa Catarina (8%). São Paulo is the largest exporter of green water with 52%, together with Goiás (18%), Mato Grosso (17%), and Mato Grosso do Sul (8%). The major importers of green water are Rio de

Janeiro with 24% of the national, followed by Rio Grande do Sul (14%) and Bahia (12%).

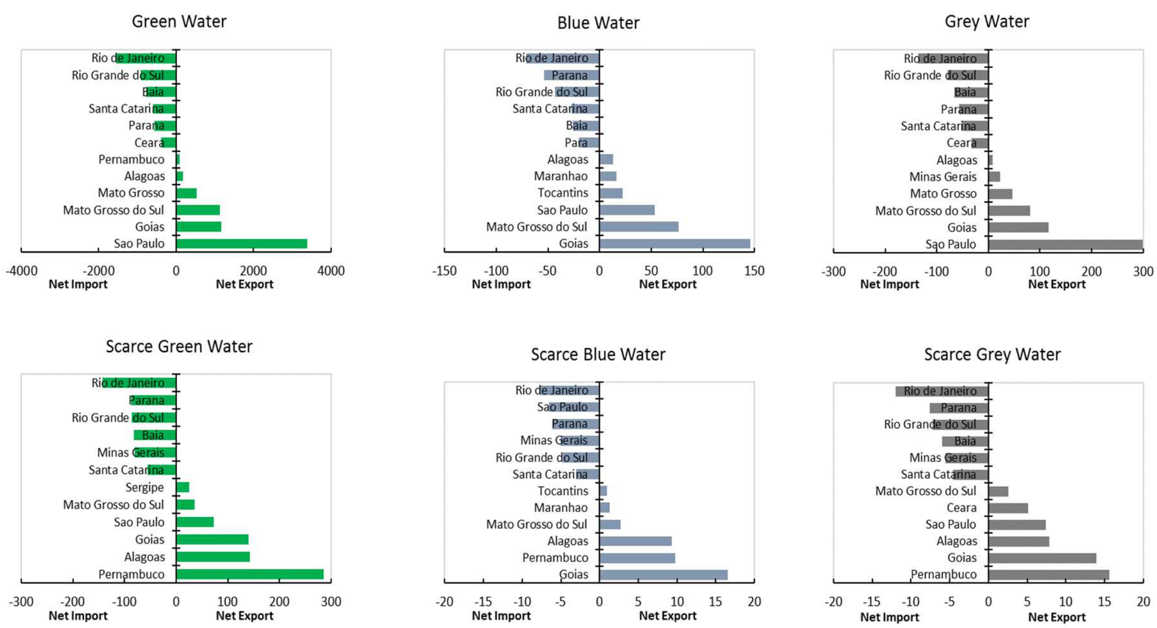


Figure 2-3. Net virtual exporters and importers of freshwater and scarce water from sugar cane production for ethanol (units in million m^3) driven by the final consumption of Brazilian states. Negative values on the x-axis show net imports of virtual water and positive values represent net exports of virtual water.

In terms of virtual grey water associated with bioethanol production, as could be expected, São Paulo was the largest exporter (52%), while from the import side, Rio de Janeiro was the largest importer (24%).

In general, some of the major virtual water importers like Rio Grande do Sul, Bahia, and Ceará, which face severe to critical water scarcity conditions, are benefitting from importing virtual water from main producer states, alleviating the potential pressure on their own water resources if the equivalent production of ethanol would have to be produced domestically.

The distribution of virtual water flows changes significantly when I focus on the scarce water footprint and virtual scarce water. A total of 6.7 billion m^3 of virtual scarce water associated with sugarcane production was traded across Brazil. This amount represents 12% of the total scarce water footprint of sugarcane, equivalent to 10.5 billion m^3, and around 63% of the total freshwater footprint of sugarcane production. Regarding bioethanol, as shown in **Figure 2-3**, in 2010, a total of 1.5 billion m^3 of total virtual scarce water was traded across Brazilian states driven by ethanol production, accounting for 63% of the total scarce water footprint of 2.3 billion m^3. This value represents 11% of total virtual water traded at the national level due to ethanol production, and importantly, most of the flows originated in states with critical or highly critical water scarcity. Therefore, accounting for the production-based versus consumption-based water footprint at these states might become relevant when assessing the impacts of bioethanol production and considering competing uses of water resources with other users or other crops at the local scale. For instance, in Alagoas, a critically water-stressed state, the export of virtual scarce blue water from ethanol production to other states was equivalent to 71.9% of the total blue freshwater exported to other states.

The top exporter of virtual scarce green water from bioethanol production is Pernambuco with 40%, followed by Alagoas (20%) and Goiás (19%). The main importers of green scarce water are Rio de Janeiro (20%), Parana (12%), and Rio Grande do Sul (12%). My results indicate that water-rich states impose water pressure on water-scarce states through importing virtual scarce green water for ethanol production, from states with limited water availability.

Similarly, for virtual blue water exchanges, three water-scarce states are ranked as the top exporters associated with ethanol: Goiás with 39%, followed by Pernambuco (23%) and Alagoas (22%); whereas the top six net virtual water importing states are Rio de Janeiro at the top with 18% of the total followed by São Paulo (15%), Parana (14%), and Minas Gerais (12%). The distribution for virtual scarce grey water follows a similar pattern.

Figure 2-4 traces the start to endpoint of virtual water and virtual scarce water via inter-regional trade across Brazil. When looking at the scarce blue water flows from ethanol, Goiás, Pernambuco, and Alagoas are the main exporters, mostly to other water-rich states. São Paulo, as the second top net importer after Rio de Janeiro, is driving the largest flows from other water-scarce states in the semiarid Northeast. Goiás is virtually exporting the largest flow of 52 million m^3 to São Paulo and to others states in the center and the southeast regions such as Minas Gerais, Parana, Rio Grande do Sul, or Santa Catarina.

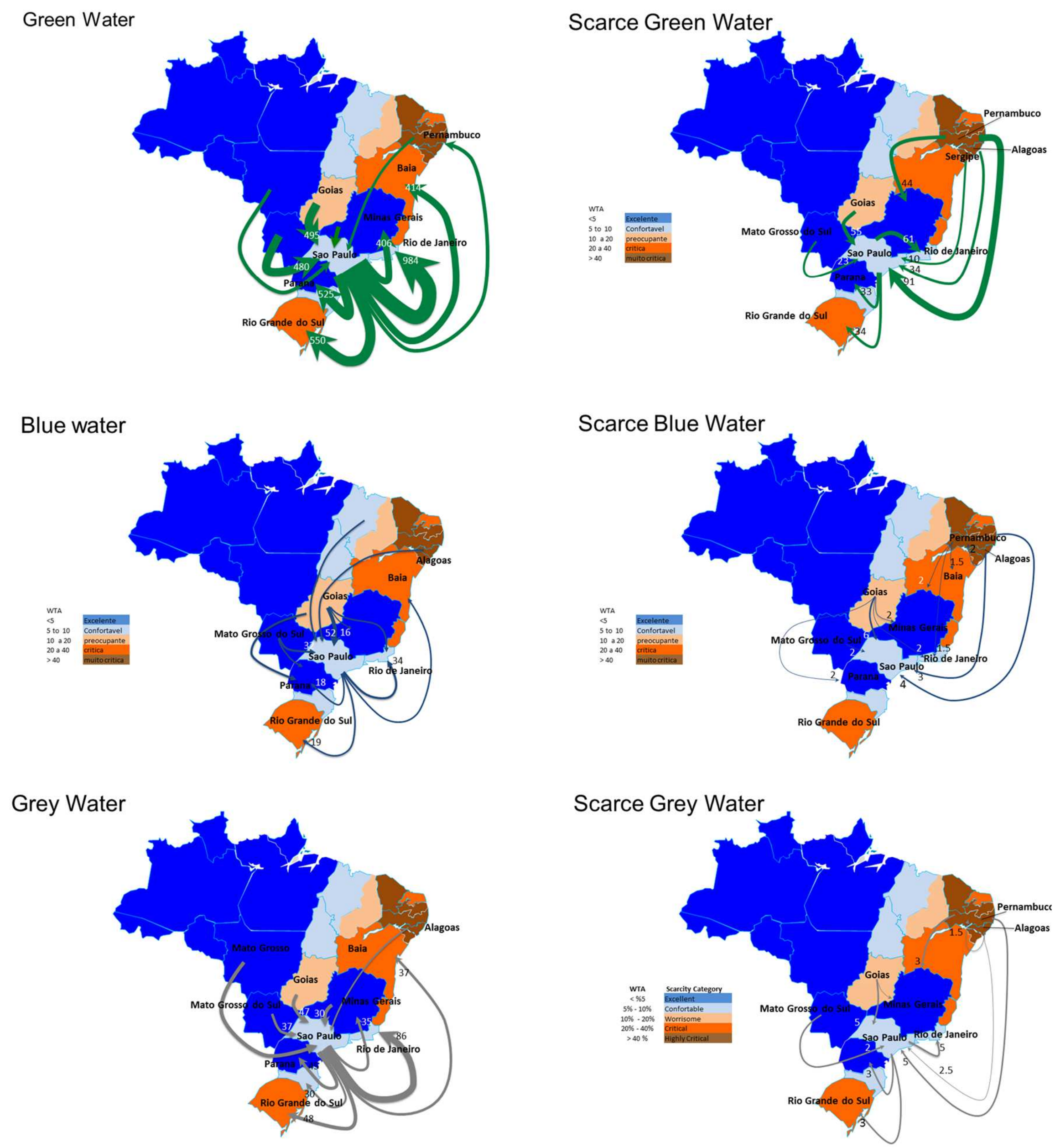


Figure 2-4. Virtual blue, green, and grey water and scarce water of sugarcane production for ethanol traded across Brazilian states (units in million m^3).

Regarding scarce green water flows driven by ethanol, the same three states are the net exporters driven by the demand from São Paulo, but also from other water abundant states such us Minas Gerais, Parana, Rio de Janeiro, Santa Catarina, or Mato Grosso do Sul. São Paulo is the top exporter with the greatest flow of 990 million m^3 to Rio de Janeiro, equivalent to 18% of its total virtual water exports to other states.

The flow distribution for virtual grey scarce water driven by ethanol is similar to the one for scarce blue water, but São Paulo is the net exporter, with its highest export flow to Rio de Janeiro and driving the same time virtual water flows from other states, including the top three water-scarce exporters. Alagoas, in the semi-arid Northeast, as in the case of the virtual blue water, remains a net exporter of grey water.

2.4.2. Virtual Water and Scarce Water Flows Driven by International Trade

Given the importance of Brazil in the global markets for biofuels and the expected increasing demand in the upcoming years, especially in the context of ongoing international climate change mitigation like the INDCs, it is also important to assess the proportion of the water footprint driven by international exports of ethanol. **Figure 2-5** shows net importers or exporters of virtual water triggered by Brazilian exports of ethanol. **Figure 2-6** displays the distribution for the water footprint of international exports and the domestic consumption by the top six production-based water consumer states for both total freshwater and scarce water. The total blue water associated ethanol consumption triggered by international export is 290 million m^3 (29% of the total blue water footprint of ethanol). The total green water footprint driven by ethanol exports is 3.5 billion m^3 (16% of the total green water footprint of ethanol), from which only 17% were traded among states. The total grey water totals 306 million m^3 (16% of the ethanol's total grey water footprint).

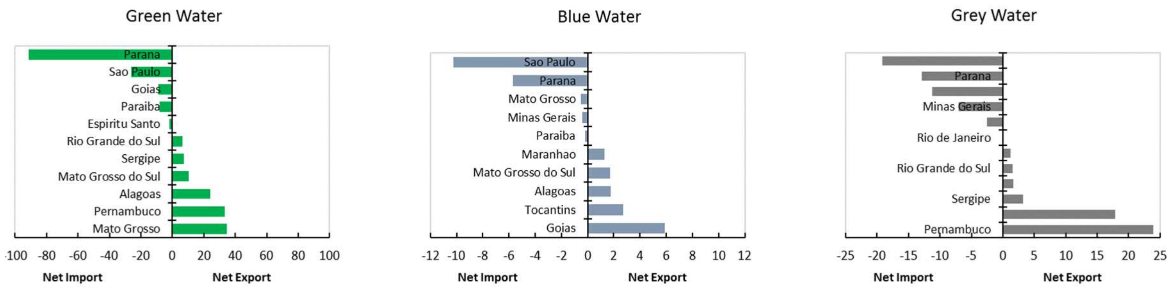


Figure 2-5. Top net exporting and importing states of virtual water driven by Brazil's international exports of ethanol (units in million m^3).

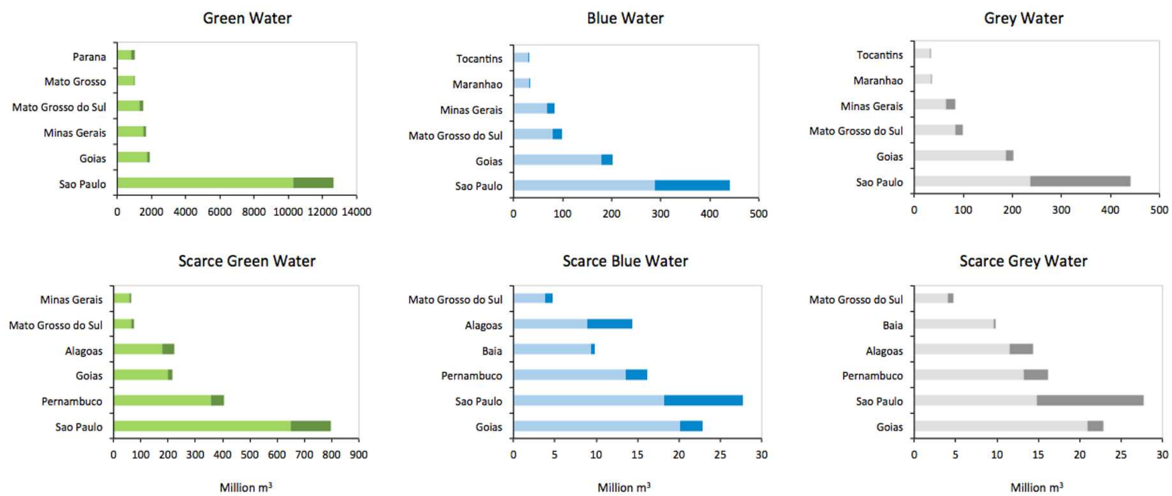


Figure 2-6. Water footprint of ethanol driven by domestic consumption and international exports. Light color shows the share driven by domestic demand and, and the dark color shows the share driven by international exports (units in million m^3).

Overall, São Paulo, Brazil's biggest economy and the top exporter in Brazil, has the largest water footprint driven by international exports associated with ethanol production. São Paulo is responsible for 39% of the total blue water footprint, 70% of the total green water footprint, and 54% of the total grey water footprint associated with ethanol for the production of the international export of goods and service. Ethanol consumption associated with international exports accounts for 19% of green, 34% of blue, and 46% of the grey water footprint for São Paulo's ethanol total footprint.

Ethanol exports also drive the water footprint in other important producer states. However, as shown in **Figure 2-5**, most of the water footprint by exports in these states is induced by São Paulo, which is the top net importer of virtual water driven by international exports and thus triggers a significant water footprint in other states through importing ethanol to re-export or as an input to produce other export goods. In contrast, in terms of the value added triggered by its international exports, São Paulo received 85% of the total value added, while other virtual water exporter states such as Pernambuco, Bahia, and Alagoas received just 0.1%, 0.06%, and 0.7%, respectively. Rio de Janeiro, another important virtual water importer, retains over 8.8% of the total value added by international exports of ethanol.

This is particularly relevant to consider for highly water-stressed states such as Goiás, Pernambuco, Bahia, and Alagoas, which, as shown in **Figure 2-6**, are among the top six states with the highest shares of green, blue, or grey scarce water footprint associated with international exports but receive a low share of value added in return. In other words, richer states such as São Paulo benefit with a higher economic value added from exporting ethanol or products that use ethanol as part of their production chain while also impacting water availability in poorer states through importing virtual scarce water from them.

2.4.3 Water Scarcity and Comparative Advantage of Sugarcane Production

Finally, in order to have a more comprehensive and nexus (energy-food) perspective, I evaluated the competing uses of water with other crops and sectors through a comparative advantage assessment that relates the water footprint with the value added by different competing crops and sugarcane production. In **Table 2-2**, I summarize the results for the comparative advantage assessment between the production of sugarcane and other crops for the top 10 states with the largest production-based water consumption. The results in **Table 2-2** show the values for the CA coefficient referred to in Equation (5).

Table 2-2. Comparative Advantage results (CA values) for green and blue water of sugarcane production versus: total agriculture, rice, corn, and soy.

Green Water				
State	**Total Agriculture**	**Rice**	**Corn**	**Soy**
São Paulo	0.93	1.06	2.27	2.03
Minas Gerais	0.89	0.55	2.13	1.47
Goiás	1.08	0.73	3.98	1.03
Mato Grosso do Sul	2.27	1.32	54.01	1.65
Parana	1.47	1.75	4.53	1.26
Mato Grosso	1.11	1.13	54.74	0.94
Alagoas	1.08	3.09	1.58	151.32
Pernambuco	0.56	0.16	0.44	42.28
Paraíba	0.47	0.10	0.07	26.41
Bahia	1.40	0.58	4.28	1.99
Blue Water				
State	**Total Agriculture**	**Rice**	**Corn**	**Soy**
São Paulo	0.71	1.32	0.01	0.03
Goiás	0.24	0.04	0.00	0.00
Minas Gerais	0.42	0.26	0.03	0.01
Matto Grosso do Sul	0.32	2.73	0.00	0.02
Rio de Janeiro	0.29	0.31	0.01	0.01
Bahia	0.17	0.09	0.02	0.00
Alagoas	0.93	2.02	0.01	1.09
Tocantins	0.11	0.23	0.01	0.00
Pernambuco	1.15	3.77	0.04	0.01
Paraíba	0.45	0.12	0.13	0.03

Table 2-3. Comparative Advantage results (CA values) for blue water of sugarcane production versus water & sanitation, livestock, power generation (excluding bioethanol-based generation and hydropower), and primary energy sectors (excluding bioethanol production).

	Blue Water			
State	**Water & Sanitation**	**Power Generation**	**Primary Energy**	**Livestock**
São Paulo	1.76	0.25	0.01	0.38
Goiás	0.32	0.01	N/A	0.09
Minas Gerais	1.68	0.16	N/A	0.37
Matto Grosso do Sul	0.89	0.05	N/A	0.36
Rio de Janeiro	3.23	0.46	0.009	0.48
Bahia	6.91	0.04	0.003	0.07
Alagoas	58.22	0.05	0.05	0.7
Tocantins	0.05	N/A	N/A	0.06
Pernambuco	3.11	0.21	N/A	0.25
Paraíba	0.78	0.0001	N/A	0.08

When looking at the results for the green water footprint, six out of the 10 selected states show a comparative advantage for sugarcane production compared to other crops (CA higher than 1.0). The states with the lowest values of CA are for two extremely dry and water stressed states, Pernambuco and Paraíba.

In contrast, when focusing on the results relative to blue water consumption, all the selected states, with the exception of Pernambuco, show a relative competitive disadvantage for sugarcane production compared to other crops (CA lower than 1.0). Only when compared to rice, I find four states - São Paulo, Mato Grosso do Sul, Alagoas, and Pernambuco - where producing sugarcane has a higher relative comparative advantage; explained by the higher blue water intensity of rice cultivation.

The inter-state comparison provides some interesting results. With regard to the green water footprint, Mato Grosso do Sul has the highest CA value (2.27) compared to all crops, while it has one of the lowest CA rates (0.32) for blue water. Mato

Grosso do Sul is among the top 10 agricultural states in Brazil but has lower rates of irrigated agriculture than other main producers such as Goiás, Minas Gerais, or Mato Grosso, so the CA values indicate that sugarcane production has a higher competitive advantage in this state and could be favored over other crops when not depending on a new irrigated area and thus water for irrigation should be limited to crops with a higher comparative advantage. Goiás and Alagoas, two of the main sugarcane producers that also cope with worrisome and very critical water stress conditions, present similar values.

The opposite situation can be found in Pernambuco, where CA values for green water are among the lowest (0.56), but it is the only state with a CA value (1.15), indicating that even though the state is critically water-stressed, sugarcane could still be prioritized over other crops when assigning limited water resources for irrigation.

When focusing on intra-state results, it is interesting to see how São Paulo, where sugarcane production is predominantly rain-fed, has a comparative advantage over rice (1.06), corn (2.27), or soy (2.03) when considering the results for the green water footprint, and only over rice production (1.32) when assessing the CA related to the blue water footprint. On the other hand, Alagoas is the only state with a competitive advantage for sugarcane production over soy cultivation relative to blue water consumption, in contrast to the results against total agricultural production, explained by higher rates of irrigated agriculture with sugarcane as the dominant irrigated crop.

In light of these results, when focusing on the competitive advantage related to the green water footprint, the production of sugarcane has a competitive advantage over the cultivation of rice, corn, or soy in some of the Brazilian states, whereas its production has a clear competitive disadvantage when considering the results for the blue water footprint. Taking into consideration that the green water footprint is usually associated with rainfed crops while the blue water footprint is commonly related to irrigated agricultural production, this implies that the production of sugarcane as a rainfed crop is more competitive than other food or feed crops in some of the states, while irrigated sugarcane is less competitive than other crops such as rice, corn, or soybean. For irrigated agriculture, more competitive crops than sugarcane should be prioritized when planning the expansion of new agricultural systems.

Overall, the results seem to show a clear tradeoff between water footprint and land use expressed by the opposite general trends of green water and blue water results. While favoring rain-fed agriculture for sugarcane and potentially having a positive impact in terms of a lower water consumption through irrigation, this may also imply the need for greater land areas dedicated to sugarcane, appropriating land that could be used for pastures or other crops.

Finally, I compared the CA values of sugarcane production with other economic sectors than crops to have a broader vision from a nexus perspective. For that purpose, I assessed the results for the blue water footprint, as water for irrigation is the agricultural consumptive use competing with other non-agricultural uses of water, through the use of infrastructure that withdraws water from the environment. As could be expected and shown in **Table 2-3**, the sugarcane production has a clear competitive disadvantage when compared to most non-agricultural sectors as primary energy, power generation, or livestock. Only, with a few exceptions (Goiás, Matto

Grosso do Sul, Tocantins, and Paraíba), when compared to the water and sanitation sector, does it have a competitive advantage. It can be explained by the nature of the residential water supply as a public service, which is often subsidized and in most cases is not associated with any economic activity.

2.5 Discussion and Conclusion

Given the uneven spatial distribution of water availability and scarcity in Brazil, decision-making related to biofuel sector planning and climate change policy should take into consideration not only on-site water demand by bioenergy production, but also the virtual water traded across the country and its spatial distribution. This is especially relevant under ongoing international climate change mitigation negotiations and agreements that may very well increase the demand of biofuel production in Brazil as a major player in the global biofuel markets.

By using an environmentally extended MRIO model through the incorporation of water consumption and water scarcity, I uncover the green, blue, and grey water footprints of sugarcane-based ethanol production in Brazil and its interregional virtual water flows spatially distributed at the state level. This work contributes to the existing literature on virtual water research on biofuels in Brazil by providing a comprehensive account of the total appropriation of water by biofuel production, including the associated water pollution discharges to the environment. In addition, this research allows disaggregation at the sectoral level from sugarcane to ethanol production, and to track flows of virtual water and scarce water from production to consumption within the supply chains across Brazilian states. My results show that the major share of the water footprint of sugarcane production is driven by sugar and other processed food production, while ethanol is responsible for less than one third of the total sugarcane water footprint.

According to my estimates for 2010, 54 billion m^3 of total virtual water driven by sugarcane production was traded across Brazil, accounting for 54.3% of the total water footprint. From this total, the green water footprint accounted for 48 billion m^3, the blue water footprint for 2.5 billion m^3, and the grey water footprint for 4.1 billion. It is worth noting that the grey water footprint was 64% higher than the blue water footprint, which supports my initial argument about the importance of including the grey water footprint in water footprint assessments in order to avoid an underestimation of actual water appropriation by a given sector or economic activity.

From the water footprint of sugarcane, I uncovered the total water footprint of sugarcane-based bioethanol. I found that São Paulo is the largest exporter of green and grey water, with the biggest flows to its neighbor state, Rio de Janeiro, which is the largest importer of virtual water. At the same time, São Paulo is a net importer of water from other water-stressed states such as Goiás and Alagoas. Regarding the blue water virtual flows, I found that Goiás, a water-stressed state, is the largest exporter with its biggest flow to São Paulo, which is benefiting by the use of scarce blue water from Goiás for its economic activities.

I also found that inter-regional flows of virtual water associated with bioethanol production are significantly different when considering water scarcity. My results show that the three water stressed states of Goiás, Pernambuco, and Alagoas led the rank of scarce green, blue, and grey water, which is mainly driven by consumption and production activities in São Paulo and other water abundant states in the southern-center region. Rio Grande do Sul, the only water-scarce state in the southern region, with a richer economy, is a net importer of scarce water from Goiás and from other poorer and critically water-stressed states in the semi-arid northeast such as Alagoas and Pernambuco.

Interestingly, when focusing on the water footprint driven by international exports, I found that most of the virtual water is driven by São Paulo, which, as the main producer and exporter of ethanol, is triggering significant water consumption in other states through importing ethanol to re-export or as an input to produce other goods for export. However, the main share (85%) of the economic added value associated with these exports remained in São Paulo, while Pernambuco and Alagoas received in return only 0.1% and the 0.7% of the added value triggered by the international exports of ethanol, respectively.

Finally, I used the model to assess the competitive advantage of sugarcane production compared to other crops relative to the value added per unit of green and blue water footprint. By doing so, I evaluated the production of sugarcane from a broader land-energy-water nexus perspective to better understand the competition for water use among sugarcane and other crops. I show that producing sugarcane has a competitive advantage over the cultivation of soy, corn, or rice in some of the states related to the use of green water, while related to the blue water footprint, the production of sugarcane is less competitive in most cases in terms of the value added per cubic meter of blue water consumed. This could be a critical part of water management in Brazil given the potentially significant expansion of biofuel production at the national level. This is especially pertinent in the context of the southeast, particularly in the state of São Paulo where 90% of the sugarcane production occurs, which is mostly rain-fed, where land and water are being used fully and therefore there is very limited expansion possibility in that region. This may imply that any potential expansion of sugarcane in other regions such as the northeast, where half of the production is already irrigated due to the lack of available cropland and limited water availability, will occur by expanding irrigation systems increasing the competition for water between sugarcane and other suitable crops, as well as residential consumption, as shown by my results for the comparative advantage with non-agricultural sectors. This important potential implication merits further investigation.

As a final concluding remark of this study, to better inform biofuel-related policies and planning in Brazil, further research is needed to further understand the tradeoffs between water and land use impacts of bioenergy production in Brazil; to explore how future policy scenarios for biofuel production and global demand scenarios under international climate mitigation agreements could aggravate these impacts; and to develop deeper and finer resolution analyses of those impacts and tradeoffs in water scarcer regions with greater potential for bioenergy expansion to enhance efforts in sustainable water infrastructure and irrigation planning.

Once I have explored the implications of biofuel production in water use and its impacts on water scarcity, to answer the main question and to meet the overall goal of my proposed dissertation there is still the need to understand better the impacts on land use and its interrelations with water use to advance in the assessment of the water-land nexus of biofuel production in Brazil. To do so I will need to study the land footprint of biofuel production at state level as well as its environmental impacts in terms of land stress, and carry out a comparative analysis of impacts on land and water, its tradeoffs and synergies, and more importantly to further study the different impacts between irrigated and rain-fed ethanol production and its geographical distribution across Brazilian states as the promotion of irrigated versus non-irrigated ethanol production is one of the main issues discussed around the bioenergy policy planning in Brazil. This is key to explore spatial patterns in Brazil of this land-water nexus that may be use to inform national planning for expansion of bioenergy in Brazil, by uncovering these tradeoffs among consumer and producer states in Brazil while considering their respective environmental conditions for the sustainable use of both resources.

I will contribute to these needs with the assessment introduced in the next chapter.

Chapter 3: The Land Water-Nexus of Biofuel Production in Brazil: Analysis of Synergies and Trade-offs Using a Multiregional Input-Output Model [2]

3.1 Abstract

Biofuels play a critical role in the Paris Agreement to help achieve climate change mitigation targets. However, a significant increase in production of biofuels might potentially be realized at the expense of overusing natural resources, particularly land and water. Understanding the tradeoffs between the impacts on land and water arises as a critical issue in the development of biofuels. This *energy-water-land nexus* might be particularly important for Brazil, given its position as top exporter and second top producer of bioenergy. Furthermore, Brazil itself has set up its own Intended Nationally Determined Contribution agenda with a significant growth of biofuel production (18%) by 2030. Most studies on environmental impacts of biofuel production have either focused on land use or water use, but very few studies assessed both. Using an environmentally extended MRIO approach, this study analyzes the current water-land nexus of bioenergy production in Brazil by quantifying the distribution of tradeoffs and synergies between land and water use for bioethanol production and its environmental consequences across Brazilian states. My results show a clear tradeoff of water and land impacts and significant differences between irrigated and rain-fed ethanol production. When including water and land

[2] http://pure.iiasa.ac.at/id/eprint/15653/

scarcity in the analysis, the results are significantly different, uncovering very different tradeoffs and synergies between bioethanol producer and consumer states that could inform the expansion of bioenergy in Brazil. Compared to other crops, sugarcane has a higher comparative advantage relative to land than to water.

3.2. Introduction

Today, biofuels play a critical role in the international agreements for climate change mitigation as the Paris Agreement was signed by the "parties" in 2016 and translated into the Intentional Nationally Determined Contributions (INDCs) pledged by the signatory countries. The synthesis of biofuels from plant biomass (mostly food crops) offers an alternative to fossil fuels [66]. According to the International Energy Agency (IEA), a major opportunity to reduce fossil CO_2 emissions is the transition to renewable energy sources such as biomass from forests or agricultural crops [67].

However, a significant increase in production of biofuels might potentially be achieved at the expense of other natural resources, particularly land and water [8]. A number of studies have investigated these impacts. For example, Fisher et al. [68] studied the nexus of biofuels and food security and found that global expansion of first-generation biofuels will threaten food security in developing countries. In this context, a number of relevant questions have emerged such as how many people could be fed by the crops used for biofuels; the extent to which these crops, if used for food consumption in the producing countries, could alleviate malnutrition; and whether bioenergy production entails an important displacement of land use through international trade of feedstock or vegetable oil [69]. Several recent studies on assessing the impacts of further expansion of biofuel production in Brazil found that the reduction in GHG emissions by using ethanol in the country had been at the expense of accelerated water consumption and land use. According to Nunez et al. [70], the potential expansion of sugarcane cultivation (a major source for biofuel production in Brazil) would lead to a conversion of two million hectares (ha) of cropland from pastures. Current targets of biofuel expansion could therefore result in additional deforestation, defeating one of its primary goals of contributing to climate change mitigation. Biofuel expansion may put biodiversity at risk through land conversion. Understanding the tradeoffs between the impacts on land and water arises as a critical issue [71]. While irrigated bioenergy production can reduce the pressure on land due to higher yields, associated irrigation water requirements may lead to degradation of freshwater ecosystems and conflict with other potential users of water resources [15].

Thus, the *water-land nexus* turns out to be relevant for Brazil, as the country is the top exporter of biofuels and the second largest producer. Furthermore, Brazil is likely to continue to be the main supplier of biofuels to global markets, driven by international low-carbon commitments, due to its relative abundant water and land resources. Brazil itself has set up its own INDC agenda with a significant growth of biofuel production by 2030 *(INDC Document of the Federative Republic of Brazil, 2015)*[72].

Sugarcane is still largely produced without irrigation in Brazil. Thus, significant productivity gains could potentially be achieved with irrigation, making sugarcane economically more attractive in many regions of the country [25,26]. For example, Scarpare et al. [24] assessed land and water use in the sugarcane expansion areas in

Brazil and concluded that irrigation management has great potential for increasing yields and limiting sugarcane expansion. On the other hand, Carneiro [17] warned that regional water constraints may limit the intensification and expansion of sugarcane production. They also concluded that the conversion of pasturelands to cropland and expansion of the dedicated sugarcane areas would be larger in regions where irrigation demand is lower, such as the southeast of the country.

Most studies on environmental impacts of biofuel production in Brazil have either focused on land use or water, but very few studies assessed both. In addition, the existing ones have primarily focused on irrigation (blue) water use. A combined assessment of land use and water footprint from a "nexus" perspective, which considers the total appropriation of water (blue, green and grey water) by biofuel production vis-à-vis other water consumers and water availability is needed to provide a more comprehensive picture of the overall impacts on water. Another gap in the literature is the impact on land or land stress created through expansion or intensification of biofuel production. In general, rainfed agriculture in semiarid regions occupies more land than irrigated cultivation [73], and often agriculture can either expand to areas with productive natural ecosystems in humid areas or onto irrigated marginal lands [74] increasing the stress on land resources. This is of special interest in the case of Brazil, where one of the expected areas for agricultural expansion of sugarcane for bioethanol production is the semi-arid Northeast, which already faces severe water stress conditions, and where suitable land for sugarcane production is already in use. Therefore, further expansion would have to occur in less suitable areas [17], or other states in the southeast or the center-west with lower levels of water scarcity but higher levels of land stress due to agricultural production. However, existing studies have not taken into account land stress when assessing land use impacts from biofuel production.

In addition, most research on land use impacts of biofuel production in Brazil focused on direct "on-site" impacts, without considering indirect impacts emanating throughout the supply chain. Muñoz et al. (2017) assessed the direct and indirect water footprint of sugarcane-based bioenergy along global and domestic supply chains. They found that richer states such as São Paulo benefited more than other states by accruing a higher share of economic value added from exporting ethanol as part of global value chains while increasing water stress in poorer states through interregional trade.

Finally, to improve the understanding of the energy-water-land nexus of biofuel production in Brazil, the literature is missing an integrated assessment of land and water impacts of bioenergy in Brazil including the economic comparative advantage of producing sugarcane for bioethanol versus using the same water and land resources for the production of other crops or livestock. This is highly relevant for Brazil, a country with high geographic and socio-economic variability, to properly assess the regional distribution of economic gains in exchange for the use of natural resources for bioenergy production.

In this study, I analyze the current water-land nexus of bioenergy production in Brazil by quantifying the spatial distribution, at the state level, of tradeoffs and synergies between land and water use of bioethanol production and its environmental consequences. I apply an environmentally extended MRIO approach to estimate the land footprint, the land stress footprint, and the interregional virtual land flows across Brazil driven by ethanol consumption and international exports. In addition, I assess the comparative advantage of sugarcane compared to other crops, livestock and forestry.

3.3. Materials and Methods

3.3.1. Environmentally extended Multiregional Input-Output Analysis

With the environmental extensions, the MRIO modeling approach has been applied in numerous water footprint and virtual water studies because of its ability to quantify direct and indirect (supply chain) water consumption of sectorial production to satisfy the final demand at regional, national or global scales [59,60,62–64,76,77]. MRIO has also recently been applied to study the resource nexus ([78],(Munoz Castillo et al., 2017)[7980]).

Using MRIO analysis, I calculated production- and consumption-based land footprints (LF) and scarce land footprints (SLF) of bioethanol and associated virtual land flows associated with inter-regional and international trade. The scarce land footprint is the land footprint weighted by land stress in a catchment (aggregated to the state level). This provides a land stress weighted footprint that reflects the potential local environmental impacts of land use [39]. Through this analysis, I explored the comparative advantage of using land to produce sugarcane (the major crop for biofuel production in Brazil) versus other agricultural crops and other economic sectors across Brazil. I applied the MRIO approach to assess virtual land flows across 149 sectors in 27 Brazilian states.

To calculate virtual land flows ($\mathbf{VL}$), I extended the MRIO model for Brazil as follows:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}(\mathbf{y} + \mathbf{e}) \tag{6}$$

where $\mathbf{x}$ is a vector of the gross output of all economic sectors across 27 Brazilian states (149 sectors in each state); $\mathbf{I}$ is the identity matrix; $\mathbf{A} = \mathbf{Z}/\hat{\mathbf{x}}$, is a input coefficient matrix describing inputs from all sectors into the production of economic sectors to produce one unit sectorial output; $\mathbf{Z}$ is the intermediate input matrix and the hat symbol denotes the diagonalization of gross output vector $\mathbf{x}$; $(\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse matrix which captures total input requirements (i.e. including upstream requirements) to produce one unit of final consumption of a product; $\mathbf{y}$ is the total final consumption vector for each Brazilian state**,** including final demand sectors such as household consumption, Government expenditure, capital formation, and change in inventory; $\boldsymbol{e}$ is the international export vector.

To estimate land appropriation in intra- and inter-regional supply chains to satisfy final consumption and international exports in each state, I extended the MRIO framework with a land coefficient vector $\mathbf{k}$**,** which represents both non-weighted land use coefficient and land stressed-weighted land use coefficients (accounting for stressed land as an indicator of land quality). To distinguish the consumptive land and land stress-weighted consumptive land, we refer to them as land and stressed land, respectively.

Thus, I may derive a land multiplier matrix, which can be used to calculate total virtual land flows in Brazil:

$$\mathbf{VL}_{dom} = \hat{\mathbf{k}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \tag{7}$$

where $\mathbf{VL_{dom}}$ is a matrix containing virtual land flows from all economic sectors of Brazilian states to satisfy their own final consumption and other states' final consumption through the intra- and inter-regional supply chain; $\hat{\mathbf{k}}$ is a matrix with land coefficients on its diagonal; $\hat{\mathbf{k}}$ may be used as the land coefficient matrix for either land or stressed land; $\mathbf{Y}$ shows the inter- and intra-regional flows of goods and services from production states and sectors to the final consumers in all states.

To calculate virtual land in international exports from Brazil to foreign countries, I used the international export vector $\mathbf{e}$ for each state r to drive the total land use requirement coefficient matrix ($\hat{\mathbf{k}}(\mathbf{I} - \mathbf{A})^{-1}$) using Equation (3):

$$\mathbf{VL^r_{exp}} = \hat{\mathbf{k}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{e^r} \tag{8}$$

where $\mathbf{VL^r_{exp}}$ is a vector of virtual land from different sectors in different states that is consumed to meet the international exports in state **r**.

The total LF of each state in Brazil can be calculated by the summation of domestic virtual land flows ($\mathbf{VL_{dom}}$) from all industry sectors driven by the final consumption in each state using Equation (4).

$$\mathbf{LF} = \sum\nolimits_{i} \mathbf{VL_{dom}} \tag{9}$$

where $\boldsymbol{i}$ indicates each industrial sector in a given state.

I separated the land consumption of sugarcane production into three categories, sugar production, biofuel production, and others, using the share of each commodity category in the total sugarcane production from the MRIO table.

3.3.2. Comparative Advantage Ratio

A comparative advantage ratio was used to assess the competitiveness of sugarcane compared to other crops in terms of the value added per unit of land use following a similar approach used in Munoz et al. (2017) for water use.

This ratio is expressed as follows:

$$CA_j = (VA_{sc} / VA_{sx}) / (LF_{sc} / LF_{sx}) \quad (10)$$

Where CA_j is the comparative advantage ratio for a given state, VA_{sc} is the added value for sugarcane, VA_{sx} is the value added for the sector or crop compared with sugarcane production, LF_{sc} is the land use driven by sugarcane production, and LF_{sx} is the land use due to the production of the crop (*x*). I obtained the value added for each crop from the MRIO table. The comparative advantage framework has been used in the literature to study the comparative advantage of agricultural production related to the use of natural resources [81].

By using this ratio, I was able to assess the land footprint of sugarcane driven by ethanol production from a broader water-land nexus perspective. I evaluated the competing uses of land with other crops, livestock or forestry sectors, focusing on total land consumption and the added value of sugarcane. I compared the production of sugarcane with other main crops cultivated in Brazil, namely rice, corn, and soybean as well as the main livestock sectors and forestry. A *CA* value above 1.0 indicates that the production of sugarcane in this specific state is more competitive in terms of the value added per unit of land than the production of other crops, and vice versa.

3.3.3. Water/Land Trade-off Coefficient

By using the results of the total water footprint analysis from Munoz et al. (2017), I integrated the two variables of water stress and land stress, through a water/land-use tradeoff coefficient to further understand the relation among water scarcity and land stress driven by biofuel production. Given the tradeoff among irrigated and non-irrigated sugarcane production (more irrigation water might be translated into less land use and more rainfed crops may imply higher land appropriation), I assessed it separately for blue, green and total water footprint through the use of a ratio of water to land impacts (WLR):

$$\mathrm{WLR} = \mathrm{WSF}_i / \mathit{LSF}_i \qquad (8)$$

Where WSF is the water scarce footprint for a given state and LSF is the stressed land footprint for the same state both driven by bioethanol production. This ratio has already been used in previous assessments of tradeoffs among water and land impacts, measured as resource appropriation, of crop production [82]. Considering total crop production for bioethanol production across Brazilian states, the highest values of WLR will show higher relevance of water use compared to land use and vice-versa.

3.3.4. Data

I employed a 2011 MRIO table for Brazil at the state level (27 states). The MRIO tables were built using 27 Brazilian I-O tables and estimated inter-regional trade flows [42]. The MRIO includes 149 economic sectors, including two biofuel production sectors, one of them for sugar-cane based ethanol.

For the purpose of this study and to assess the competition for land of sugarcane production with the main land consuming sectors (and which could be actually displaced by an increase of sugarcane production), I focus on agriculture (11 crops), livestock (five livestock subsectors) and forestry (cultivated and natural) sectors of the MRIO table. I used data from the National Census of Agriculture [21] available for 330 crop types, which I aggregated to the state level to match the sectorial resolution of the MRIO model.

For the calculation of land stress, I used the land stress index database from ETH Zurich [82], which was aggregated to the state level to match my MRIO model. Land stress related to crops, measured in m^2 yr land- equivalents (m^2 yr_{eq} kg^{-1}), is a an indicator of the land "quality" which quantifies loss of natural, productive land in equivalents of the globally most productive areas and is calculated for each grid cell [82].

Similar to water-use related environmental impacts, the impacts due to land occupation vary regionally. Quality of land is a complex concept, comprising a range of ecosystem services. There is no consensus on one single indicator to express land quality. I use the one proposed by Pfister based on the use of net primary productivity (NPP; kg C m-2 yr-1) of the natural reference vegetation as a proxy for potential and quality. This Land Stress Index (LSI) is calculated globally at a resolution of 0.5 x 0.5 degree.

Water consumption accounts used for MRIO analysis were taken from the authors' previous study *Uncovering the Green, Blue, and Grey Water Footprint and Virtual Water of Biofuel Production in Brazil: A Nexus perspective* (Munoz et al. 2017) where water intensity of different crops was collected from the Water Footprint Network (https://waterfootprint.org/en/).

3.3.5 Limitations of my approach

All the recommendations provided in this study are based on a state-level analysis of land and water footprint and thus my approach presents a limitation for more detailed assessment at sub-state levels (i.e. watersheds or municipalities) that will have to consider local socio-economic and environmental contexts. For instance, special attention should be paid to areas in the Amazon basin or in the Mata Atlântica eco-region, both with high levels of environmental sensitivity given their unique values of biodiversity, and which are already critically stressed by human disturbance.

My results provide a basis for a national comparison of water and land use by bioethanol production among Brazilian states, which can help to compare, from a national strategic planning perspective, the environmental impacts of intensification and expansion scenarios of bioenergy in the future and to decide upon where investments in sugarcane production could be more reasonably allocated. However, an improvement of the resolution of my modeling framework is needed to downscale the analysis to sub-state or basin levels in order to provide a more detailed assessment that may support decision-making on water-or-land-resource management strategies for biofuel production at such spatial scales to effectively address scarcity of water or land.

Another area of improvement for my approach would be the quantitative determination of the tipping points for land stress values. Since my results are based on a comparative assessment of land and water stress values for sugarcane production, these tipping points are not relevant for my study but might be needed for further analysis of land stress associated with scenarios on expansion of bioethanol production.

3.4 Results

3.4.1. Land and land stress footprints and inter-regional virtual land flows of bioethanol production

In 2010, the total land footprint of sugarcane production in Brazil was 10 million hectares according to my estimate; 64 % of this land use was for sugar production, 24% for ethanol production, and “other” economic sectors were responsible for 12% of total land use for sugarcane production (**Figure 3-1**).

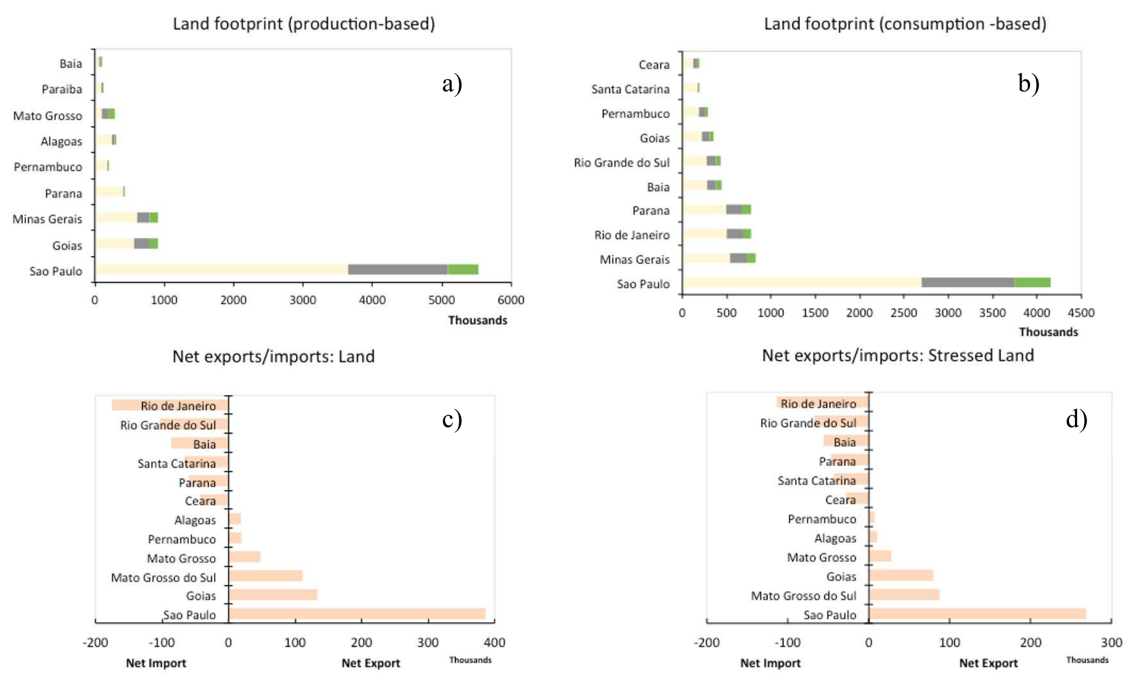


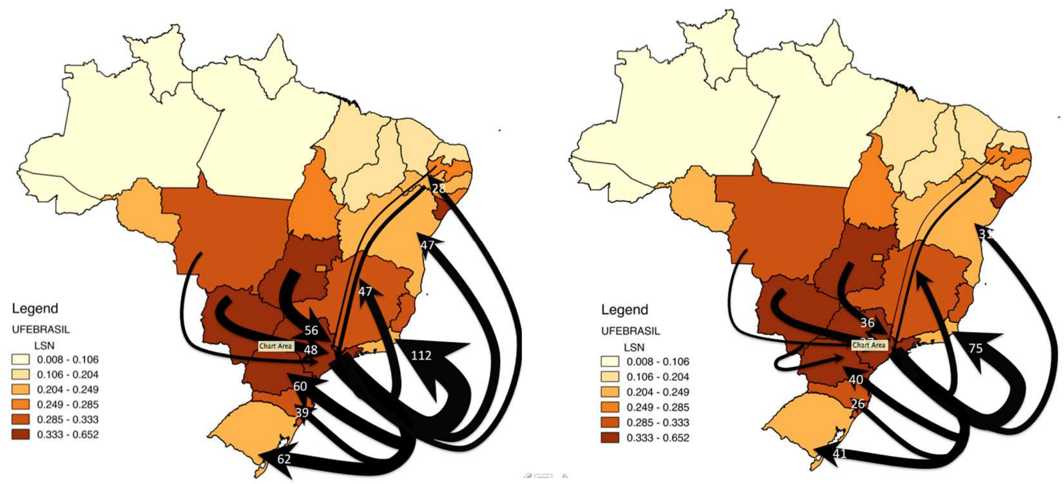
Figure 3-1. Land footprint of sugarcane and net land embodied in domestic trade in Brazil (thousand ha). Above: Land footprint of sugarcane production (a) and consumption (b). Below: Top exporters and importers of virtual land (c) and virtual stressed land (d) of bioethanol in Brazil. Production-based land footprint is the land used for the total sugarcane production of a given state; whereas consumption-based land footprint is the total land for sugarcane production along the entire supply chain needed to meet the final consumption of a state. Color code for a) and b): land footprint driven by sugar (yellow), ethanol (grey) and “other” sectors (green). [Units in ha]

In the same year, 716,000 ha were embodied in inter-regional trade across Brazil driven by ethanol production, which accounted for 29 % of its total land use. From **Figure 3-1** I can see that São Paulo, as the top producer of bioethanol, is the largest exporter of virtual land associated with biofuel to other Brazilian states, followed by other traditional agricultural states in central and southeastern regions such as Goiás, Mato Grosso, MatoGrosso do Sul, and other states in the semiarid Northeast such as Pernambuco and Alagoas. All of them are today under moderate to severe land stress; especially in the case of Mato Grosso do Sul, Mato Grosso, Goiás, and São Paulo. At the same time, Rio de Janeiro, with lower levels of land stress, is the largest importer of virtual land. This can be explained by the fact that most of the production in São Paulo state is rainfed, while more than half of the irrigated sugarcane production (and therefore less land–intensive) occurs in the dry Northeast [17].

In order to verify this positive relationship between rain-fed sugarcane production and land use, and between land use and water consumption, I compared the results with the results for green and blue water footprint of bioethanol production from Munoz et al. (2017). I found a high correlation (0.99) between the green water footprint and the land footprint of bioethanol while blue water footprint and land footprint show a slightly lower correlation (0.8927), as most of water used for sugarcane production is rainfed.

In order to understand the environmental impacts of biofuel production related to land use, it is key to incorporate land stress into the results, through the land stress footprint. In 2010, the land stress footprint of bioethanol production was equivalent to 1.6 Million ha, which accounted for 63% of the total land footprint. According to my estimates, this is equivalent to 74% of the total land used in Brazil for rice production, or 10% of the area dedicated to corn, 5% of the area used for soy, 55% of the area used for beans or 80% of the land used for fruit crops (other than oranges).

Figure 3-2 shows ethanol production related virtual land and virtual land stress traded across Brazilian states driven by regional final demand. When looking at the stressed land flows, I find similar spatial patterns in the virtual land and virtual stressed land flows between Brazilian states. I also observe the share of stressed land virtually traded across the country compared to total land flows. A total of 480,000 ha of stressed land associated with ethanol production were traded across Brazil which accounts for around 30% of its total land stress footprint in the nation. This result indicates that production of bioethanol in central and southeast Brazil has imposed significant environmental impacts in those states since these are already land stressed regions. Thus, an increase of biofuel production in these states through new-dedicated sugarcane crop areas would lead to significant impacts on local ecosystems. This increase in biofuel production could instead be by efficiency gains, among others, based on expansion of irrigation. On the other hand, this might aggravate impacts on water resources, especially in those water stressed states, such as Alagoas or Pernambuco, where bioethanol production is already increasing water scarcity.



Virtual land flows **Virtual Stressed Land Flows**

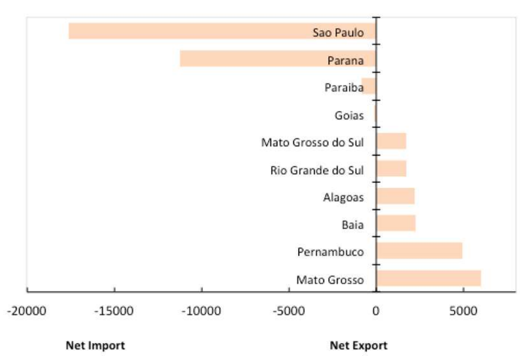
Figure 3-2. Virtual flows of land and stressed land for bioethanol production across Brazilian states (Units thousand ha). (Legend refers to stressed land levels for each state).

3.4.2. Land and stressed land footprints of bioethanol production for exports

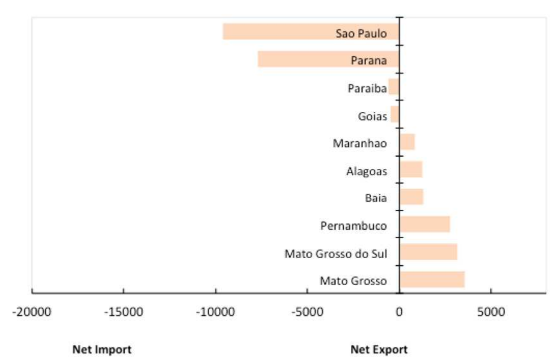
In 2010, the total land associated with ethanol production driven by Brazil's international exports to other economies was 420,000 ha, equivalent to 17 % of the total land footprint of bio-ethanol production, and from which only 7 % were traded among Brazilian states. Compared to the green virtual water footprint of bioethanol driven by international exports (Munoz et al. 2017), which accounted for 17% of the total green water footprint of bioethanol, this number is significantly smaller.

São Paulo, Brazil's biggest economy and the top exporter in the country, is responsible for 70% of the total land footprint of bioethanol driven by Brazil's international exports and is the largest importer of virtual land from other states. São Paulo imports a total of 18,000 ha, equivalent to 6 % of its total footprint and 59% of the total virtual land traded across Brazil driven by international exports. When compared to the share of green water footprint in the same state driven by international exports (19%; Muñoz et al. 2017), the value for land footprint is significantly lower.

The numbers above show that when compared to the water footprint, São Paulo takes up higher shares of land footprint triggered by international exports of bioethanol, as top producer and exporter of bioethanol and due to the fact that the state relies mostly upon rainfed sugarcane crop production. In other words, São Paulo is more self-sufficient in terms of land use to meet its international exports of bioethanol while it is more dependent of virtual water imports from other states for the same purpose, externalizing the environmental impacts related to water consumption (see **Figure 3-3**).



Land footprint



Stressed Land

Figure 3-3. Top exporters and importers of land and stressed land driven by international exports from Brazil to global markets of bioethanol [Units in ha]

3.4.3. Comparative advantage (CA) of bioethanol production considering land and water

In order to have a more comprehensive nexus perspective, I evaluated the competing uses of water and land with other crops and sectors through a comparative advantage assessment that relates the water and land footprints with the value added by different competing crops and sugarcane production. **Figure 3-4** shows the values of the CA assessment for sugar cane production compared to other crops relative to land use, and the results from the same assessment for blue and green water (Munoz et al. 2017). Overall, sugarcane is more productive per unit of land and unit of green and blue water than other crops.

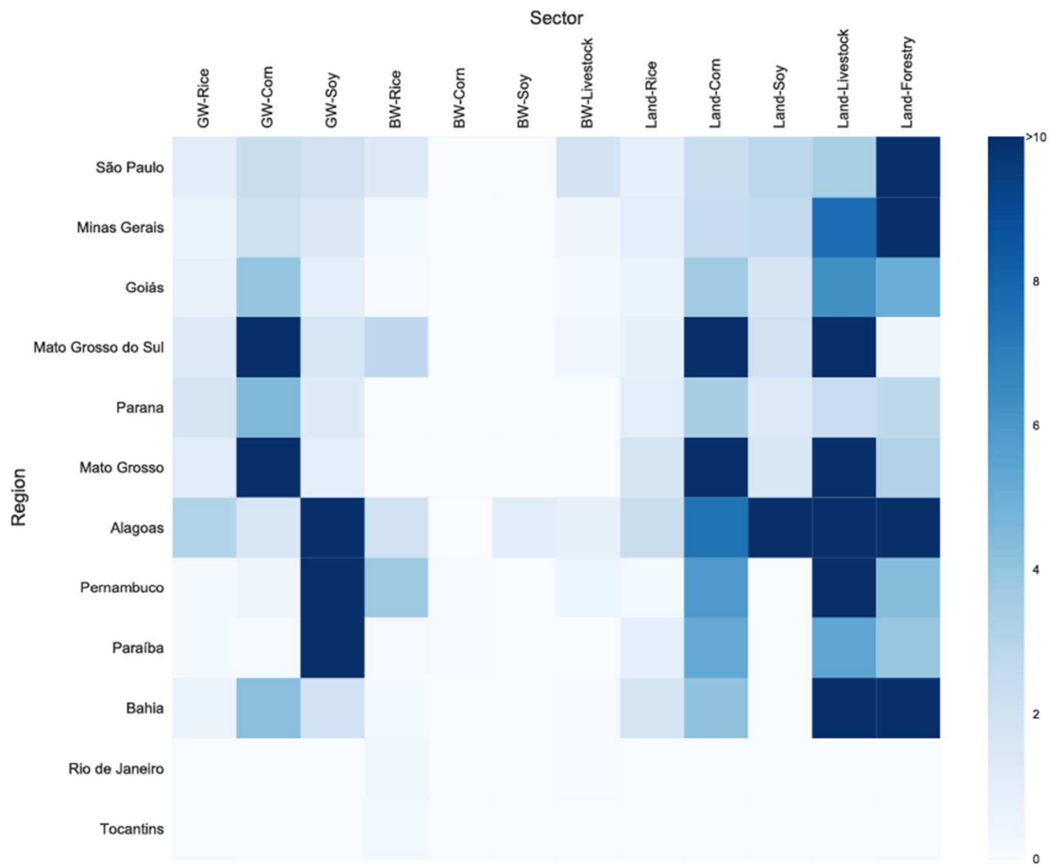


Figure 3-4. Comparative Advantages assessment of sugarcane production versus other crops relative to land and water use. Note: GW is green water; BW is blue water.

I also find that there is an inverse relationship among CA for land use and for water footprint when I consider water and land stress. For instance, I can find lower CA advantage results relative to land use compared to green water for some land stressed states such as São Paulo and higher values of CA for land use in some water scarce states such as Alagoas. When looking at the comparison with rice, a land- and water-intensive crop, I find a competitive disadvantage (CA lower than 1.0) relative to land use in land stressed states (Mato Grosso do Sul, Mato Grosso and Paraná) while finding a competitive disadvantage for water footprint in water scarce states (Pernambuco, Alagoas and Paraíba). Bahia, a water-scarce state but with lower values of land stress compared to these states (MG, MS, PN) shows a competitive disadvantage for land use. For soy, in general, I find higher CA with regard to land use than for water, explained by soy being a green water intensive crop (Munoz et al. 2017). In the case of corn, I find a competitive advantage for the use of green water and a competitive disadvantage relative to water footprint for water stressed states such as Paraíba and Pernambuco.

When doing an inter-state comparison, I find that the only states in which I find a lower CA for land than for water compared to all crops are São Paulo and Pernambuco. This is an interesting finding given the fact that São Paulo is the largest producer of sugarcane and bioethanol in the country at the expense of a high occupation of land for rain-fed sugarcane production. In other words, in São Paulo the use of land for sugarcane production is less cost-effective, expressed in economic added value per unit of resource use (ha of land or m^3 of water), than the use of water when compared to other crops. However, this local impact on the state's land resources is compensated at the same time by São Paulo importing large amounts of virtual land from other states; and thus, externalizing the impact to other states while keeping the largest share of value added (Munoz et al. 2017).

3.4.4. Stressed land versus scarce water: tradeoffs and synergies

The water/land tradeoff ratio in equation (8) has already been used in previous assessments of tradeoffs among water and land impacts (measured as resource appropriation) of crop production [73]. The results of the application of this ratio at the state level are mapped in **Figure 3-5**. I also plotted the results for total water footprint versus the land footprint of bioethanol production for both freshwater to total land and scarce water to stressed land in order to obtain a graph by which tradeoff and win-win outcomes can be readily identified. The first immediate general finding from this exercise is that the relationship among land and water use for biofuel production in Brazil changes significantly if I consider stress for both resources. The distribution presented for the results of freshwater to total land follows a clear linear pattern whereas the distribution for scarce water to stressed land is less correlated. This is explained by the positive correlation of the green water footprint (the biggest share of total water appropriation by bioethanol production) and land footprint and by the negative correlation of scarce water and stressed land in most cases.

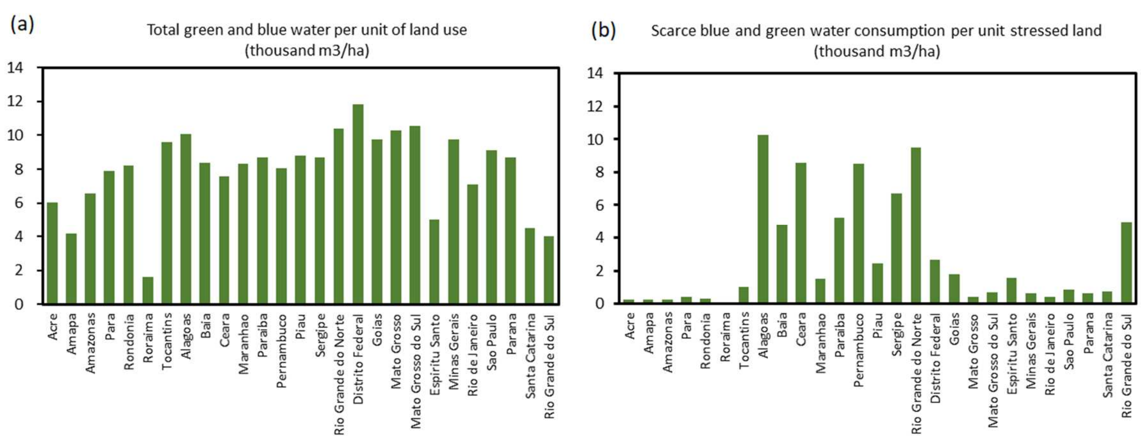
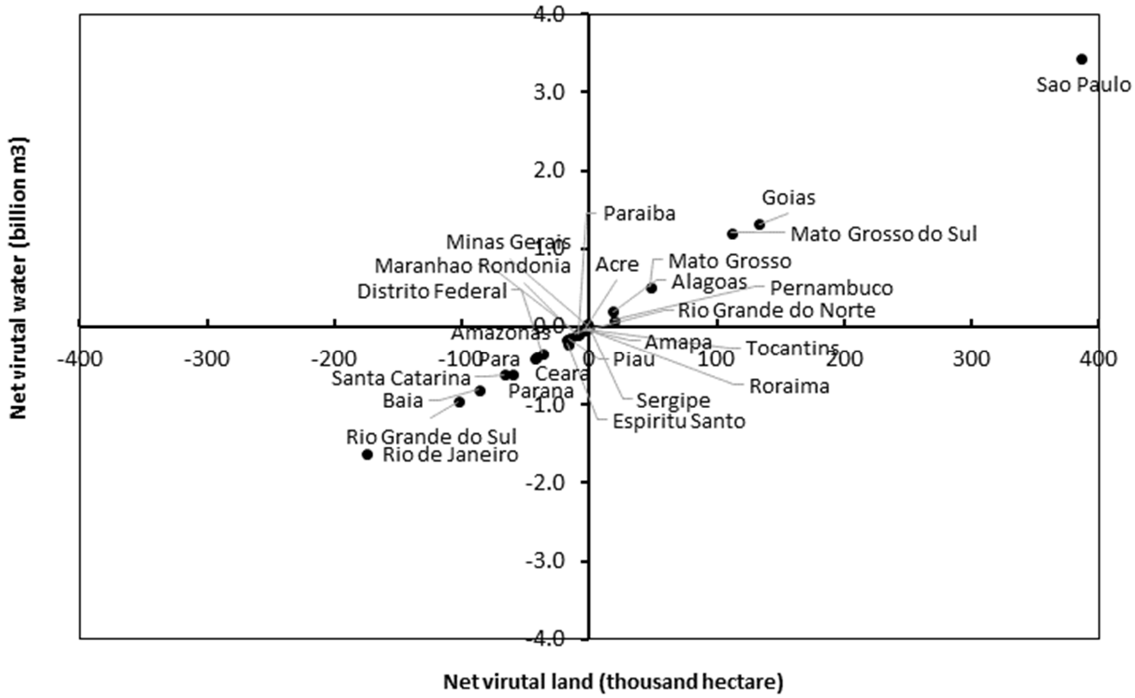


Figure 3-5. Water footprint (million m^3) to land footprint (thousand ha) and scarce water footprint (million m^3) to stressed land footprint (thousand ha)

For instance, when comparing the bar charts in **Figure 3-5** (a) and b) I can clearly see that there is a relative small fluctuation in the ratio (total freshwater to total land) for most states with the exception of a few states which show higher efficiency for the use of water compared to land, or in other words, where the consumption of biofuel production has comparatively higher impacts on land than on water, such as for Espiritu Santo, Roraima, Amapá, Santa Catarina or Rio Grande do Sul. However, when I focus on the bar chart for total scarce water to stressed land (see **Figure 3-5b**), I find a large variation. There are states where the biofuel production has a greater and significant impact in terms of water scarcity, especially for the states in the semi-arid Northeast such as Alagoas (10.3 thousand m^3/ha), Pernambuco (8.5), Sergipe (6.7), Ceará (8.6 Mm3/ha), Bahia (4.8), Rio Grande do Norte (9.5), and Rio Grande do Sul (4.9) in the South, which without considering scarcity had values lower than the average and thus showed more balanced impacts among water and land use. Goiás, the largest exporter of blue water driven by sugarcane production in Brazil (Munoz et al. 2017), shows also higher impacts on water scarcity than on land stress (2 thousand m^3/ha) but remarkably lower than for semi-arid states. This is explained by higher levels of water scarcity in the Northeast, and higher land stress in Goiás, due to higher levels of land occupation driven by crop production.

(a) Net Water vs. Net Land



(b) Net scarce Water vs. Net stressed Land

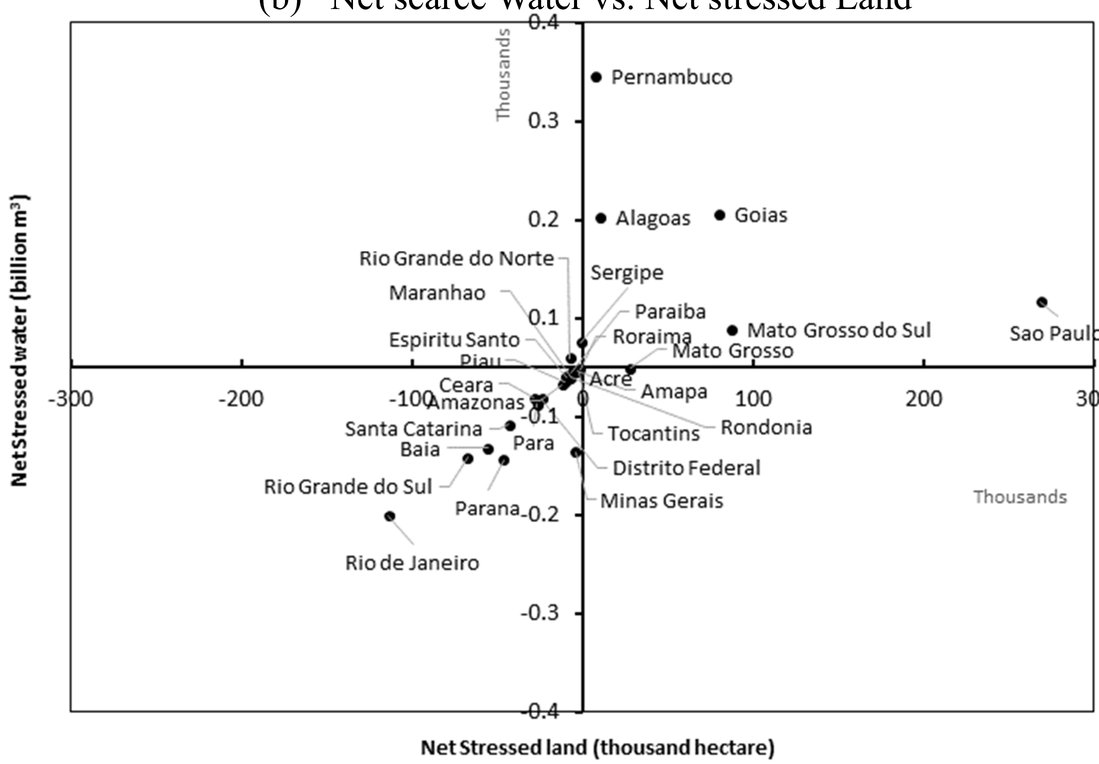


Figure 3-6. Net water to net land in inter-regional trade and net scarce water to net stressed land in inter-regional trade in Brazil.

Figure 3-6 also shows the results of net inter-regional exporters and importers of total freshwater (blue and green water) versus total land (a) and total scarce water (green and grey) versus stressed land (b) driven by sugarcane production. By plotting the results in this way, I obtain a diagram through which I can identify clear trade-off and win-win outcomes among water and land impacts of biofuel production across Brazil. For instance, by focusing on the top-right quadrant, I can identify tradeoffs among states with higher impacts of bioethanol production on land stress (those with higher values closer to the horizontal axis), and states with lower impacts on water stress (those with higher values closer to the vertical axis); as well as by comparing the left-lower quadrant to the top-right quadrant to identify tradeoffs among net exporters and importers of land and water, i.e. the winners and losers of bioethanol in Brazil in terms of impacts on natural resources. Win-win outcomes can be found for states closer to the origin, or in other words, with low impacts on both land and water scarcity.

Again, by comparing **3**-**6(a)** and **3-6(b)**, I clearly see that the story is very different if I incorporate scarcity in the analysis, with a linear distribution for total **3-6(a)** and a non-linear distribution for **3-6(b)**. For instance, according to **3-6(a)** (no stress), São Paulo is the largest exporter of both total water and land to other states, followed by Goiás, Mato Grosso do Sul and Mato Grosso, with all of them having balanced values for the use of both resources (all of then situated along the diagonal axis). Rio de Janeiro is the top importer of both land and water from other states, followed by Rio Grande do Sul, Bahia, and Santa Catarina, also aligned across the diagonal axis. However, when looking at **Figure 3-6(b)**, São Paulo is the largest exporter of stressed land due to bioethanol production, with values over 250,000 ha of stressed land virtually exported, but with lower impacts in terms of water scarce footprint; with Pernambuco being the top exporter of virtual scarce water (around 300 Mm^3), followed by Alagoas and Goais (around 150 Mm^3). Goiás, an already water and land stressed state and top exporter of virtual blue water driven by bioethanol production, displays therefore more balanced impacts in both water and land resources.

When looking at the net importers of both water and land (lower-left quadrant), I see that the variability in the distribution when considering resource scarcity is lower. The most remarkable exceptions are Paraná and Minas Gerais, which are virtually importing relatively more scarce water than stressed land from other states.

Maps in **Figure 3-7** show the results of the water-to-land tradeoff ratio at the state level for biofuel production. This ratio maps higher relevance of water use (green or blue) in red areas, and higher relevance of land use in blue areas. In other words, **Figure 3-7** shows in red the states where the pressure on water resources is higher relative to land use or vice versa in blue. Looking at the map, water use is in general more relevant in arid or semiarid states (northeast), but also in relatively humid areas where intense irrigation and population pressure imply high water impacts, as the case of Goiás or Rio Grande do Sul (relative to green water).

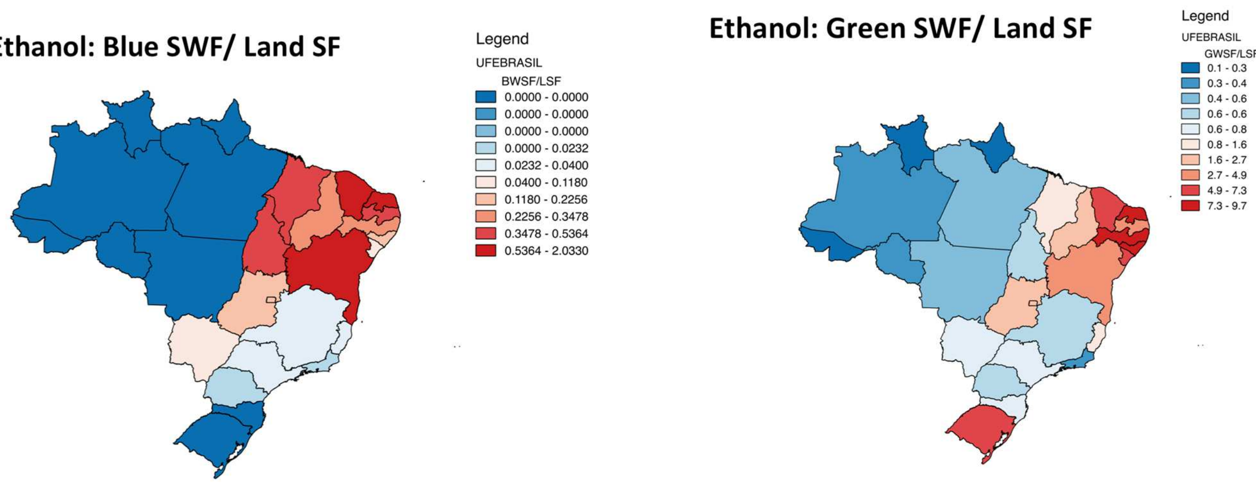


Figure 3-7. Land/water tradeoff ratio mapped at state level

3.5. Discussion and conclusions

Understanding both local land and water (on-site) impacts and virtual land and water impacts traded across Brazil and its spatial distribution is key for a sustainable biofuel sector, especially in the context of ongoing international climate policy and commitments made under the Paris Agreement in 2015. The tradeoffs and synergies between land and water use (the water-land nexus) of bioenergy production in Brazil and its environmental and socio-economic consequences have to be carefully assessed to ensure that further potential bioethanol expansion and associated investments for irrigation do not aggravate the current situation of water and land stress by selecting the most suitable regions in Brazil for expanding sugarcane crop production.

I used an environmentally extended MRIO model through the incorporation of land use and land stress, to uncover the land footprint of sugar-based ethanol production in Brazil and its associated inter-regional virtual land flows spatially distributed at state level. I also quantitatively assessed the spatial distribution of tradeoff and synergies between water and land use of bioethanol production and its associated environmental impacts by incorporating a water to land tradeoff ratio.

This study contributes to the existing literature on research of biofuels in Brazil by disaggregating at the sector level from sugarcane production to sugar, bioethanol and "other" production, in order to uncover the land footprint of biofuel production and to track the virtual flows of land and stressed land from production to consumption across the supply chains in Brazil. I also advanced the understanding by combining the water and land footprints of bioethanol and virtual flows of both water and land as well as water and land stress in Brazil to obtain the total appropriation of water (green and blue water footprint) and land by bioenergy production and its related direct and indirect environmental impacts as well as the tradeoffs and synergies among water and land use of ethanol production. My results show a clear correlation between the land footprint and green water footprint, finding not just lower levels of correlation between land footprint and blue water footprint but even an inverse relationship among them in some states; which confirms a clear tradeoff of environmental impacts on water and land between irrigated and rain-fed-based ethanol production. I also found that when including scarcity for both water and land in the analysis, the results are significantly different, uncovering very different tradeoffs and synergies between producer and consumer states of bioethanol that could inform the expansion of bioenergy in Brazil.

The high share of stressed land reflects the pressure that additional bioethanol production would exert on land resources in Brazil. About one third of the stressed land footprint is for export production. The spatial pattern is similar to the pattern for total virtual land flows, with São Paulo a significant virtual exporter driving imports from other land stressed states, such as Mato Grosso and Mato Grosso do Sul. The situation is even more pronounced for international exports where São Paulo alone is responsible for 70% of the total land footprint driven by the production for exports from Brazil to other economies. While São Paulo is more self-sufficient in terms of land use to meet its demands from global markets for bioethanol, it is more reliant on virtual water imports from other states to meet export demand.

My CA analysis confirms that the use of land for production of sugarcane in some states, such as São Paulo, is less cost-effective (less economic added value in return per unit of land used) than the use of water. However, São Paulo compensates this local impact by importing virtual land from other states to meet its local demand and international export of biofuel while keeping the largest share of value added in exchange; 85% of the value added by international exports from Brazil remains in São Paulo (Munoz et al. 2017).

Finally, I analyzed the spatial distribution of tradeoffs and synergies between land use and water consumption in Brazil for biofuel production by the use of a water-to-land nexus coefficient. My results show a significant change when including land and water scarcity into the analysis. I found different tradeoffs and synergies for land and water use that should be considered when planning bioethanol expansion in Brazil. First, in states such as Pernambuco, Alagoas, Sergipe and Paraíba, development of biofuel may lead to an increase in water scarcity but less impact in in terms of land stress. In these regions, the expansion of biofuel production could rely on expansion of rain-fed cropland or by investments in irrigation efficiency for existing irrigated sugarcane fields. The feasibility of the first option (expanding rain-fed sugarcane fields) would have to be further investigated since the Northeast region has already limited capacity for expanding arable land [7].

Second, some states show an increasing impact on land resources but smaller impact on water scarcity for biofuel expansion. These states are São Paulo, Mato Grosso, and Mato Grosso do Sul. In such regions, expanding bioethanol production should be supported by investments to increase irrigated cropland already dedicated to sugarcane in order to increase productivity gains rather than expanding rain-fed sugarcane production, and thus increasing its land occupation. Third, there are relatively small impacts on both water scarcity and land stress from further expansion of biofuel production: these states would be the best candidates for further sugarcane development if the climate was suitable for that purpose.

Obviously, other limitations should be carefully considered, especially those concerning environmental restrictions related to land use change (for instance, in those states located in the Amazon Basin, such as Amazonas, Amapá or Pará, with greater environmental sensitivity and with specific legal constrains for land occupation). In this category I may find states such as Espiritu Santo, Tocantins, Rondônia, Maranhão and Piauí. Lastly, some states have large impacts on both land stress and water scarcity. In these states there is limited capacity for expanding sugarcane production, for either rain-fed or irrigated cropping, and thus sugarcane development should not be pursued. Goiás falls within this category.

My study confirms that to properly assess the impacts of biofuel production in Brazil on land and water and its "nexus", their mutual synergies and tradeoffs, the consideration of resource scarcity and its spatial variability is key. Therefore, governmental development policies and planning for bioenergy production at national and subnational levels need to carefully consider the tradeoff between land use and water consumption and its respective impacts on both resources; and again, the concepts of virtual water and land as well as water and land stress may serve as suitable tools to balance such tradeoffs.

So far, and by the last two chapters I have assessed both water and land footprint in Brazil driven by bioenergy production and its impacts expressed in terms of water scarcity and land stress. I have also been able to analyze the spatial distribution of the interrelations between impacts in both water and land; or in other words, the spatial distribution of the water-land nexus of ethanol production. However, to effectively inform policy and planning of bioenergy production and to meet the overall goal of my thesis, I need to go a step further to explore how these impacts driven on both land and water and the associated resource competition with other economic sectors might look like in the future under different socio-economic, climate and environmental conditions.

Of special interest for Brazil, and for my dissertation is to explore how new federal policies committed to comply with the Paris Agreement, signed in 2015, could affect water and land demand as the Brazilian NDC heavily relies in the increase of bioenergy production to both meet its own national demand and to meet demand from global markets. Both demands are expected to increase under the international mitigation agreements as biofuels are proposed as one the key means to achieve a global carbon neutral economy.

To answer these questions and to fill this gap on my dissertation, I will explore future climate mitigation scenarios together with other socio-economic and technological scenarios through the next chapter.

Chapter 4: Water and Land Implications of biofuel development in Brazil by 2030 under the Paris Agreement: A Nexus Perspective

4.1 Abstract

As outlined above, Brazil plays a major role in the global biofuel economy. It is the world's second largest producer and consumer and the largest exporter of ethanol, and demand is expected to significantly increase in the future. But with biofuel crops requiring significant amounts of water and land resources - that could otherwise be used for the production of food, urban water supply, or energy generation – the impact on demand for land and water are expected to be significant with NDCs committed by Brazil under the Paris Agreement potentially increasing the demand of biofuel production in Brazil. This study first develops a set of socio-economic development, policy and climate scenarios, and then assess their environmental implications through an environmentally extended input-output approach (including land and water) that represents socio-economic activities in the 27 Brazilian states, allowing comparison of the resulting water and land demands among main competitive users under different scenarios. For the latter (land), (I simulated the sugarcane growth and yield in each state using the Global Agro-Ecological Zones (GAEZ) model) I applied the Global Agro-Ecological Zones (GAEZ) assessment, which is a Geographical Information System (GIS)- based tool to simulate future land suitability and water demand of different crops in each region. Finally, I also look at

the spatial variability of the associated economic value- added of biofuel production across Brazil under different scenarios. Our results shed light on significant impacts that future production of biofuel Brazil will have in both terms of land and water consumption and therefore the implications in terms of increased competition for both scarce resources that could be experienced by other crops or other economic sectors. Even more, my results confirm how climate change and ongoing international climate change mitigation negotiations and agreements will significantly drive a higher consumption of both resources associated to biofuel production and thus significantly enlarge the environmental footprint of biofuel production and potentially increase the competition with food production. More specifically, I found that by 2030 the total land use at the national level in Brazil driven by sugarcane production will experience a net increase by around 191% considering all the driving forces in the scenarios, while blue water consumption will rise by up to 262% compared to the baseline. This confirms that the policies committed by Brazil and its role as a main provider of biofuel within the international climate agreements, and particularly through the signature of the NDCs under the Paris Agreement, will take a significant toll on Brazil in terms of water consumption. Such increase on resources demand may very well increase the competition with food production, energy generation and/or human consumption, especially in the most vulnerable states in terms of water and land availability where the level of economic development is also lower in comparison with other states in the country.

4.2. Introduction

Globally, Brazil is a reference for both food security and abundance in natural capital. It meets most of its domestic demand for agricultural products, plays a major role in the international commodity markets, provides vital global environmental services and has a less-restrictive availability of land, water and top agricultural technology[84]. Moreover, its abundance on natural resources allows Brazil to sustain this role as a key global provider of food and commodities as well to have a high potential for contributing to global climate mitigation in line with the Paris Agreement.

In a world with increasing challenges related to water security, Brazil is well known for being a privileged rich country in terms of water resources, with nearly a fifth of the world's water reserves[85]. For instance, just the Amazon basin, of which 63.9% runs within Brazilian borders[86], is the largest river in the world by flow rate[86] and accounts for 40% of total freshwater of the Latin American Region[87]. However, when looking at subnational or regional levels, the aggregate numbers for the country hide significant regional disparity of water resources availability and more importantly of water scarcity. According to the National Agency of Water[29] when considering the water balance, the relationship between water demand and availability, the Eastern and Northeast Atlantic region are the ones in the most critical conditions for water shortage. Almost all the sub-basins show a water scarcity (ratio of demand volume to renewable supply volume) higher than 40% (considered as the ratio for critical water scarcity conditions). Several watersheds of the Eastern Atlantic also present serious difficulties in meeting demands. In less stringent conditions, but still with some supply problems, are basins near urban centers in the Atlantic Southeast, Atlantic South and Parana regions, where most of the country's population and economic activity resides. A recent example of the increasing conditions of water stress was the water crisis experienced by the State of Sao Paulo during 2014 and 2015 with severe water shortages for urban water supply and significant losses of agricultural production[88]

Moreover, water scarcity imposes significant challenges to energy and food security. Indeed, the sectors that contribute the most to the national and regional economy are also those most dependent on water. For example, 62% of Brazil's electricity is generated through hydropower plants. Water is also essential for agriculture, another important sector of the country's economy. According to the National Water Agency (ANA), irrigation consumes 72% of Brazil's water supply[58].

Brazil is not only well endowed with extensive water resources, but also a rich country in terms of land resources as the fifth largest country in the world with a territory of 853 million hectares. A substantial part of this territory is covered by native vegetation, while agricultural production occupies a relatively smaller part of the territory. In 2006, the last year when comprehensive data is available, only 26% of the territory was used for agriculture, divided between crops (1/4) and (predominantly low productive) cattle raising (3/4)[89]. Considering the country's large land area and the extensive share of this area occupied by pastures, there is substantial physical potential for increasing agricultural production while mitigating GHG emissions through the conversion of degraded pasturelands to croplands. For instance, the country has around 40 million hectares of degraded pasturelands outside the Amazon forest suitable for the production of sugarcane; which equals to over 60% of the total Brazilian cropland[90]

Moreover, even considering the privileged situation of the country in terms of overall availability of land and water, there are increasing pressures driven by both national socio-economic development and global markets, which is going to threaten the sustainable use of both resources. Brazil is the world's second-largest food exporter and agriculture and agro-industry account for 8.4% of GDP. The fast growth of agricultural production resulted in an exponential growth of irrigated land areas over the past decade with fast increasing water consumption. Currently, less than 20% of irrigated lands have access to formal irrigation infrastructure. In the energy sector, hydropower plants will continue to generate most of Brazil's electricity, leading to increasing competition with agricultural production for water use, even with the diversification of energy sources planned over the next two decades.

More specifically, when looking at the energy matrix, there is a strong link among the use of water and land resources (water-land nexus) driven by the central position of biofuels within the country's national strategy towards the expansion of renewable sources. Given Brazil's major role in the global biofuel economy and the "Proalcool" program which saw sugarcane dedicated cropland increase from 4.3 million ha in

1990 to 10.2 million ha in 2013[18], energy from sugarcane biomass has surpassed hydropower generation, representing 15.4% of all energy produced in 2012 compared to 13.8% from hydropower, and 39.2% from petroleum[54]. In 2014, a total of 27 million m^3 of ethanol was produced in Brazil with an estimated average yield of 7,500 litres of ethanol per planted hectare (UNICA, 2015)[20]. According to the IBGE's statistics in 2006 the cropland dedicated to sugarcane was 10 million hectares (ha) equivalent to the 13.3% of the total cropland in Brazil[21].

In addition to the pressure over water and land resources driven by bioethanol's domestic consumption, Brazil is likely to experience higher demand by international markets as a result of international accords for GHG mitigation. For instance, Gerbens-Leenes et al. (2012)[11] studied global water demand related to increasing biofuel use for road transport in 2030 and evaluated the potential contribution to water scarcity, finding that the global biofuel water footprint will increase more than tenfold in the period 2005-2030, reaching up to 5.5% of the totally available blue water for humans, causing extra pressure on fresh water resources. China, Brazil and USA would contribute half of the global biofuel water footprint. Their study concluded that countries should consider water availability when investigating the extent to which biofuels can satisfy future transport energy demand. Rulli et al. (2016)[16] assessed global biofuel crop production and global patterns of biofuel crop/oil trade to determine the associated displacement of water and land use (including Brazil). They concluded that to evaluate the important impacts of biofuels on food security, the food-energy nexus has to be investigated in the context of its linkages with the overall appropriation of land and water resources.

However, even though there are numerous impact assessments of Brazilian bioenergy production on either land or water, there is as yet little literature on the study of both impacts considered jointly and their tradeoffs, synergies and win-win potentials. As a recent example of this holistic approach, Chapters 2 and 3 of this dissertation[91,92] assessed the impacts of bioethanol production on both land and water resources at the state level and their interrelations by using an integrated economic-environmental modeling framework; or in other words, the water-land nexus of sugarcane based biofuel production in Brazil. The results[75] show that in 2010 the total water consumption of sugarcane in Brazil was 101 billion m^3, of which 54 billion m^3 was virtually traded across states in Brazil. Out of this, approximately one third was driven by bioethanol production per se, with a total scarce water footprint of 2.3 billon m^3. These two chapters also found that richer states such as Sao Paulo benefited by keeping a higher share of economic value-added from the exports of ethanol to global markets while aggravating water stress conditions in poorer and water scarcer states. The assessment also showed that compared to other crops, sugarcane has an economic competitive advantage when rain-fed while showing a comparative disadvantage when irrigated.

Related to land use and the tradeoffs with water, Chapter 3 of this dissertation[92] found that in 2010 the total land footprint of bioethanol production was about 2.4

million ha, from which 716,000 ha were traded across states in Brazil, and 1.6 million ha were stressed land. According to these results, there is a clear tradeoff of water and land impacts and significant differences between rainfed and irrigated ethanol production, with a very high spatial variability when including water and land scarcity in the analysis and therefore very different synergies and tradeoffs among producer and consumer states. Compared to other crops, sugarcane has an overall higher economic comparative advantage related to land use than to water consumption.

The overarching question posed in this investigation is how potential demand growth or other contributing factors such as climate change could affect these impacts synergies and tradeoffs, and their temporal and spatial distribution in Brazil. For instance, Brazil is expected to significantly increase its production of bioethanol in the following decades for being able to meet the demands of its internal and global markets. Indeed, according to some sources in the literature, the country is likely to continue to be the major supplier of biofuels to international markets driven by international low carbon agendas and commitments, such as the Paris Agreement. Brazil itself has set up its own INDC agenda with a significant growth of biofuel production by 2030 (INDC Document of the Federative Republic of Brazil, 2015)[72,92]. In addition, internal socio-economic forces, such as population and GDP growth as well as new transport and national energy policies may drive an additional increase of bioethanol demand.

Moreover, climate change may also impact the physical conditions of sugarcane production by affecting yields, water use efficiency and irrigation requirements, thus potentially affecting the spatial distribution of its cultivation in different areas in Brazil. For example, the state of Sao Paulo, which accounted for nearly 60% of total Brazilian sugarcane production in the 2010s, may be heavily affected by climate change as the production is currently rain-fed[93]. In return, efficiency gains or losses of water use will affect land use changes associated to sugarcane production. Regarding the potential expansion of bioethanol production and its geospatial distribution, the increased supply of sugarcane in Brazil is traditionally attributed to an increase in acreage. Scarpare et al. (2016)[24] assessed use of land and water resources in the sugarcane expansion areas in Brazil, finding that irrigation management has great potential for increasing the linear yield relationship, limiting sugarcane expansion and hence, intensifying land use. However, because sugarcane is a water-intensive crop compared to other food and feed crops, its expansion would be relatively larger in regions where irrigation water resources are less-restricted.

As noted above, there are several examples of studies focusing either on water or land impacts of biofuel production in Brazil, but there is little research in the existing literature assessing future impacts of biofuel production in Brazil on both land and water resources at the subnational levels, considering at the same time major climatic, physical and socio-economic dynamics affecting sugarcane cropping and bioethanol production in the country. In order to assess how changes in the economy and society would impact future land use and water demand, it is necessary to combine biophysical, economic, and societal data; and a consistent theoretical framework is key to answer such questions. This study aims to first develop a set of socio-economic development, policy and climate scenarios, and then assess their environmental implications through an environmentally extended input-output model (extended for land and water) that represents socio-economic activities in the 27 Brazilian states. This approach allows comparing the resulting water and land demands among main competitive users for those resources and further assessing how the aforementioned land-water nexus of biofuel production will be impacted under the different scenarios. For land, I create the state-based linkages based on the Global Agro-Ecological Zones (GAEZ)[94] assessment, which is a Geographical Information System (GIS)- based tool used to provide the future land suitability and agricultural water demand in each region. Finally, I also look at the spatial variability of the associated economic value- added of biofuel production across Brazil under the proposed scenarios. More details of the future scenarios can be found in section 4.3.1.

4.3 Materials and Methods

The core of my methodological approach is a MRIO model environmentally extended by a set of natural-resource parameters that represent consumption patterns of water and land for each economic sector (in Mm^3 for water and ha for land) for the 27 states conforming Brazil. The high level of sectoral disaggregation offers a detailed description of the economy, with 149 sectors; including 18 agricultural sectors, three energy primary sectors; seven power generation sectors, and two biofuel production sectors, including one specific sector for sugarcane-based ethanol. The details about this model, data inputs and how the socio-economic structure drives land use and water consumption are already described in Chapters 2 and 3. By using this MRIO model, I estimate the values used in this study for the baseline scenario (2010) for water and scarce water footprint, land and stressed land footprint and economic competitive advantage of sugarcane production compared to other sectors.

In addition, in this chapter I use the GAEZ model to obtain the sugarcane potential yield and blue/irrigation water demand under historical (baseline year 2010) and future (2030) climate and irrigation conditions, to exogenously calculate the coefficients of sugarcane land and blue water demand change during the study period under the different scenarios. For the land coefficients, the GAEZ model simulates the impact of climate and irrigation change to the sugarcane potential yield, which is measured as the ratio of yield under future scenarios to yield under current conditions, in each state. If the yield ratio is greater than 1, then less land will be required to produce the same amount of sugarcane in the future, otherwise, more land will be needed. Then in each state, I use the existing sugarcane land footprint (the value from WFN) divide the yield change ratio to calculate the future land footprint. The calculation of water footprint follows the same logic.

Future land footprint = existing land footprint/(future potential yield/baseline potential yield)

The GAEZ was developed jointly by IIASA and FAO (FAO, 1995) and has been used in numerous global and national studies and subsequently updated and improved in recent years. A detailed description of the GAEZ method and presentation of all its modelling functions can be found in the GAEZ´s site (http://webarchive.iiasa.ac.at/Research/LUC/GAEZ/index.htm. Its basic principles rely on the algorithmic incorporation of well-established scientific information and parameters (e.g. quality of soil, local climate conditions, potential fertilizers and pesticides to be used, machinery, potential crop mix and sequences) in a GIS to evaluate the suitability of a particular land unit for crop production. The model calculates the attainable yields of each grid-cell on a given digital map through suitability assessment. Basically, the GAEZ is a gridded cell-based model which overlays climatic related maps (for instance, climatic belt, thermal zone or length of the growing period), with soil related maps and terrain conditions; each analysis unit is assessed in terms of all feasible agricultural land options. The productivity assessment records expected production of relevant agroecologically feasible crops and agricultural activities for three level of input (low, medium, and high) to be considered.

The added value of using the GAEZ model is its ability to match land quality with the ecological requirements of the respective plants for soil, climate, field management input level (e.g. fertilizer and irrigation) under explicit recognition of the socio-economic conditions. This method allows me to estimate this aspect of the regional differences that is mostly determined by physical or natural factors.

4.3.1. Scenario Development

The development of scenarios is based on previous works by Hubacek and Sun (2001, 2005)[95,96], and Yu *et al*. (2016)[97]. I updated them based on the MRIO for Brazil as used in Chapters 2 and 3[75] and the updating is done step by step as will be introduced in the rest of this section., **Table 4-1** shows the specification of each major driving force.

As the objective of this study is to assess potential changes on water and land use due to bioethanol production in Brazil in the context of climate change adaptation policies (NDC implementation by 2030), I use my MRIO core model for a scenario analysis. Under the assumption of an overall growth of domestic and global demand for biofuel produced in Brazil, a potential increase of water and land use might be expected. In addition, due to the dynamic changes in economy and society, further changes in terms of cropland requirement and water consumption are expected as well for the coming years. Other biophysical changes as those driven by climate change and agricultural management changes represented by irrigated area change may very well also impact the demand for both water and land resources by biofuel production. Towards a comprehensive understanding of the future land and water use dynamics of ethanol, I have identified a number of major driving forces represented by six scenarios (see Table 4-1)

Once I establish scenarios for each of these ¨major driving forces¨, I introduce them step by step to obtain additional or incremental effects. I start from the baseline year (2010), to add a set of scenarios representing each of the major driving forces to show the additional effects on land and water requirements.

More specifically, I first set up different scenarios in climate change conditions, irrigated area change, population growth, household income, climate policy (e.g. change in Energy structure), and export patterns affecting sugarcane water and land demand. Population and economic development will drive the future global consumption of goods and services, including sugarcane and bioethanol production; while technological progress, policy and climate change may impact upon the resource (water and land) use efficiency of different sectors. All of these changes will lead to change in the demand for goods and services through the global supply chain and ultimately impact on water and land demand triggered by the production of bioethanol. The subnational interactions will be systematically featured through national MRIO modeling. By using my core model, I am able to assess the impacts of future demand for goods and services on the resource use which could lead to water and land competition among the main crops and other resource consuming sectors.

Starting from the base year 2010, I then add a set of scenarios to show the additional impacts of each driving factor on land and water requirements. Therefore, the baseline represents data for the base year 2010, with climate, irrigation, population, income, exports and policy scenario (no policy) for 2010. **Scenario 1** then applies the water and land-use coefficients (physical units per unit of economic output) driven by climate change, taking the change in land and water productivity of sugarcane under climate conditions in the baseline climatology of 1981-2010 and climate projections in future climatology of 2021-2050 (the 2030s), but with all the other driving forces remaining the same as in 2010. In **Scenario 2**, I add to **Scenario 1** the additional direct land and water requirements driven by a sub-national sugarcane irrigation strategy in 2030. In **Scenario 3** I include, in addition to **Scenario 2**, the additional water and land consumption due to population growth. **Scenario 4** adds per capita income growth**. Scenario 5** shows effects due to a public policy affecting ethanol production specifically and which in turn will drive additional consumption of land and water through the economy. **Scenario 6** adds change in exports driven by global markets from Brazil. The variables and sources used for the scenario structure proposed here are detailed in **Table 4-1**. The steps of the scenario development are presented in **Table 4-2**.

Table 4-1: Variables and data sources associated with each scenario

Scenario	Variable	Source	Notes
Climate Change	Crop inputs (irrigation and fertilizer) and yield change driven by climate	CRU TS 4.03 (2010) [98]	Inputs of analysis: water (blue) demand and yield
Irrigation	Irrigated area change	GAEZ Munoz R., et al (2017) (Irrigation ratio)	Total irrigated area for Brazil
Population	Population increase	IBGE (2010)	20% average increase for Brazil
Income Change	Income Change (%)	OECD (2018)	Elasticity included
Policy	Structure Change in Energy Matrix	EPE (2016)	Substitution of fossil fuels by biofuel under Brazilian NDC
Exports	Exports increase (%)	EPE (2017)	33% average increase for Brazil

Table 4-2: Proposed scenarios

Scenarios	Climate Change	Irrigation	Population	Income & consumption	Exports	Policy (NDC)
Baseline	1981-2010	2010	2010	2010	2010	2010
S1	2030s	2010	2010	2010	2010	2010
S2	2030s	2030	2010	2010	2010	2010
S3	2030s	2030	2030	2010	2010	2010
S4	2030s	2030	2030	2030	2010	2010
S5	2030s	2030	2030	2030	2030	2010
S6	2030s	2030	2030	2030	2030	2030

Climate change impacts in water demand and crop yield

Climate conditions have a direct impact on the crop's water demand for irrigation and yield which at the same time may impact the total final water demand for sugarcane production. For instance, warmer conditions in some regions of the country may lead to an increase in water demand driven by higher evapotranspiration but might also be compensated by a shorter crop sugarcane growth cycle and less yield, which in turn may lead to less water demand. To account for the uncertainty of the climate change, eight climate scenarios (four Representative Concentration Pathways of CO_2 concentration level × two global climate models) are used to comprehensively estimate their impact on the sugarcane potential yield and blue/irrigation water demand across Brazil.

To build up this scenario, I run the GAEZ model under different future climate projections to the 2030s, which translate into changes on sugarcane irrigation water demand and yield, and cropland inputs such as fertilizer. For the land coefficients, the GAEZ model simulates the impact of climate and irrigation change on the sugarcane potential yield (future scenarios/current conditions) in each state. If the yield ratio is greater than 1, then less land will be required to produce the same amount of sugarcane in the future; otherwise, more land will be needed. Please note that the potential land-use/land-cover change of the sugarcane planting area expansion is not considered in this study. The extra land demand for sugarcane production is calculated based on the future sugarcane demand increase and the average potential yield in each state under different future climate, irrigation and field management scenarios. The calibration of the land and water coefficients and economic inputs of the sugarcane sector for the MRIO analysis are shown in the following equations. The calculation of water footprint follows the same logic.

$$coe\_land_{2030} = \frac{yield_{2010}}{yield_{2030}} \times coe\_land_{2010}$$

$$coe\_water_{2030} = \frac{water_{2030}}{water_{2010}} \times coe\_water_{2010}$$

$$inputs_{2030} = \left(\left(\frac{yield_{2030}}{yield_{2010}} - 1\right)/2 + \left(\frac{water_{2030}}{water_{2010}} - 1\right)/2\right) \times inputs_{2010}$$

Where *coe_land*, *coe_water* refer to land and water coefficients, *yield* and *water* refer to the sugarcane potential yield and blue/irrigation water demand, *inputs* is the economic input of the sugarcane sector in the MRIO table.

Irrigation dynamics

Change of irrigated area will directly impact the total blue/irrigation water demand for sugarcane production. According to the future sugarcane irrigation strategy, irrigated sugarcane area in Brazil will increase from 2 million ha in 2015 to 2.8 million ha in 2030. At the state level, SP will have the greatest increase of 352,731 ha (146%), followed by MG and GO of 180,859 ha (153%) and 136,516 ha (136%) respectively. Seven states will reduce the sugarcane irrigated area by 54,524 ha, especially the semi-arid regions of AL (-25,280 ha) and PE (-18,859 ha). In contrast, irrigation expansion in most states, especially in the major sugarcane production regions, will compensate the negative impact of future climate change or even favoring higher productivity ratio of sugarcane cultivation, thus reducing the future land demand of sugarcane. Because of the lack of a state level sugarcane planting area projection in 2030, I use the maximum potential sugarcane irrigation rate, which assumes a projected irrigated area change in 2030 with no change of total planting area in each state, as the projected irrigation rate in 2030. The sugarcane irrigation rate is used to simulate the sugarcane potential yield and blue/irrigation water demand under both baseline and future climate conditions using the GAEZ model. Results are translated to the land and blue water demand change ratio in each state, and are used to calibrate the land and water coefficients and the GTAP[99] (Global Trade Analysis Project) economic input of the sugarcane sector in 2030 for the MRIO analysis of total land and water footprint in each state.

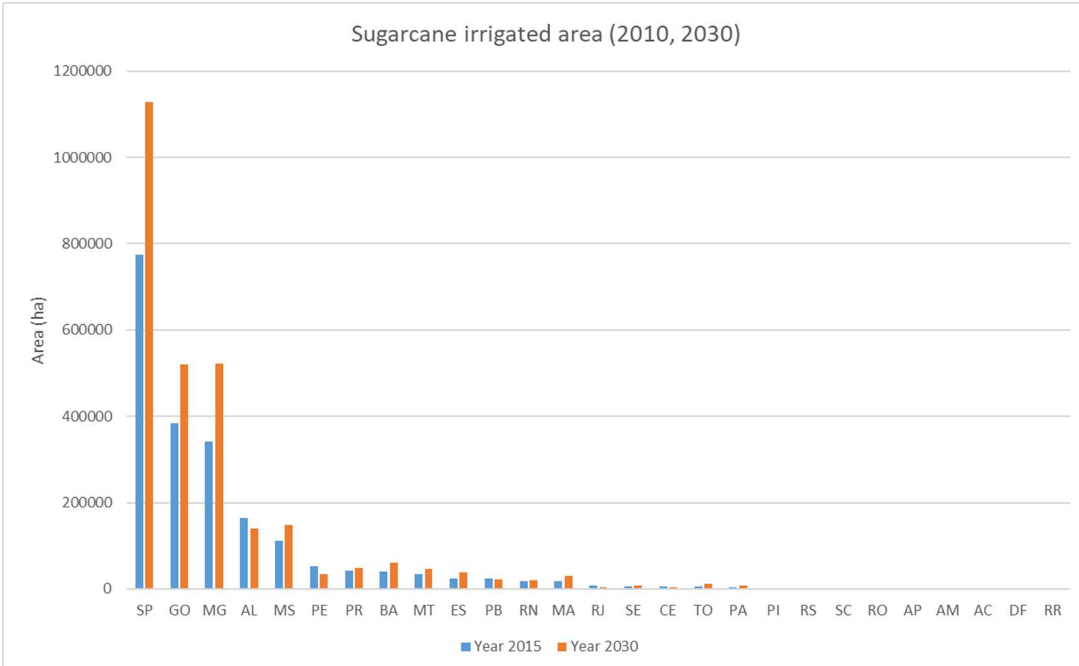


Figure 4-1. Sugarcane irrigation strategy in 2015 and 2030

Population dynamics

Brazil is the Latin-American country with the largest population, with 190m people in 2010 according to the national official census (IBGE)[47]. This population scenario has been developed based on population projections by the national statistics institute (IBGE) for 2030 for each one of the 27 Brazilian states[100]. Population change is then translated to the change in consumption of goods and services, which in turn drive the change in demand of biofuel production in the study regions along the global supply chain through MRIO analysis, which drives water and land demand.

According to this database, the Brazilian population is expected to grow by 20% by 2040. For the purposes of this study, I do not consider changes in urbanization, or lifestyles patterns.

Income growth

There is a strong correlation between income and consumption. As of late 2010, Brazil's economy is the largest of Latin-America and the second largest in the Americas[101]. From 2000 to 2012, Brazil was one of the fastest-growing major economies in the world, with an average annual GDP growth rate of over 5%, with its economy in 2012 surpassing that of the United Kingdom, temporarily making Brazil the world's sixth largest economy.

The World Bank's global consumption database provides household consumption by income groups in rural and urban areas. Brazil, as one the BRICS (Brazil, Russia, India, China, South Africa), is one of the world's major developing countries with the fastest GDP and per-capita income growth in the last few decades. According to the World Bank's database (https://data.worldbank.org/indicator/NY.GDP.PCAP.CD), the Brazilian GDP per capita has increased from 210 US$ in 1960 up to 9,821 US$ in 2017.

Over the past two decades, strong growth combined with remarkable social progress have made Brazil one of the world's leading economies, despite the long recession that began in 2014 and from which the economy is now slowly emerging.

However, inequality remains high and fiscal accounts have deteriorated substantially, calling for wide-ranging reforms to sustain progress on inclusive growth[102]. This inequality is also clearly spatially distributed across the country, with most of the national GDP concentrated in the South-East region. According the IBGE (2016)[103], in 2010 six states alone from the 27 Brazilian states accounted for nearly two-thirds of the GDP: Sao Paulo (32.2%), Rio de Janeiro (11.6%), Minas Gerais (8.9%), Rio Grande do Sul (6.2%) and Parana (6%), which in sum was equivalent to 64.9% of the total national GDP. This spatial variability of the GDP is also translated into the geographical distribution of the natural resources consumption in the country, with relevant virtual flows of water and land across the country associated with the production and consumption of key products and commodities, which in some cases benefits richer states while impacting poorer regions, as demonstrated in Chapters 2 and 3 through the assessments of virtual water and land trade in Brazil driven by ethanol production.

For the purpose of my assessment, and given the lack in the literature of any projections of GDP or income distribution at state level in Brazil for the 27 states, I adopt the baseline distribution of the per-capita income at the state level in Brazil in 2010 (IBGE, 2016)[103] and apply the national projected GDP from OCDE[102] by 2030. I assume no future changes on the current GDP distribution among Brazilian regions.

Exports

Brazil is the 24th largest export economy in the world. In 2016, Brazil exported $191billion and imported $140bn, resulting in a positive trade balance of $50.7bn. In 2016 the GDP of Brazil was $1.8trillion.

As with other Latin-American countries, the Brazilian economy is highly dependent on exports of agricultural products, natural resources and commodities, including sugarcane-based ethanol. According to the World Bank[105], in 2017, Brazil's top five exports were Soybeans ($25bn), Iron Ore ($17bn), Petroleum oils and bituminous oils ($17bn), Raw Sugar Cane ($9bn) and Non-Coniferous Chemical Wood ($6bn). Sugarcane, ranked as the fourth exporting sector, is intrinsically linked to ethanol production as around one third of the agricultural production is dedicated to biofuels (Chapter 2)[91]. Therefore, I assume that an increase on exported raw sugarcane will indirectly imply an increase in the production and export of bioethanol.

Moreover, the global biofuel market has a potential to increase per se according to different sources. Just in 2005 the ethanol global market was around $30-40bn, out of which only $4bn were for internal trade[106]. Brazil is currently the leading ethanol exporting country due to its competitive advantage in biofuel production associated with its optimal climatic conditions for cropping sugarcane and the experience and know-how developed in ethanol driven by the Proalcool Program. This tremendous export potential in Brazil has actually stimulated investments in infrastructure for transporting ethanol from the main producing areas to major ports in Brazil in recent years[107]. It has allowed Brazil to meet the export demand to other markets, which accounted for 15% of the total national production in the last decade. Additionally, as discussed in the introduction section, since the Paris Agreement was signed in 2015, it is expected that the global biofuel market will grow in order to make it possible for most of the signatory countries to meet their mitigation pledges through biofuels. Under this scenario, Brazil has been referred to as the leading supplier to meet the additional demand for biofuels as driven by international markets according to different sources in the literature [16,11].

According to macroeconomic projections for Brazil for 2017-2027 (EPE, 2017)[108], the country's exports volume will grow from \$227bn to \$303bn, equivalent to a 33% increase of total national exports. For my scenario design I assume the annual growth according to the export's final demand vector in the MRIO model, which will drive the additional production of sugarcane-based ethanol itself as exported product and as input for other exporting sectors within the Brazilian economy. I assume no changes to the baseline exports distribution among states will happen and, thus, I keep the structure provided by my MRIO table for 2010.

Policy and energy planning

As discussed above, INDC implementation by Brazil relies heavily on expanding biofuel production to increase its share within the national energy matrix. As stated in the official INDC document submitted by Brazil to the IPCC: *"Brazil intends to* *adopt further measures that are consistent with the 2°C temperature goal, in particular: i) increasing the share of sustainable biofuels in the Brazilian energy mix to approximately 18% by 2030, by expanding biofuel consumption, increasing ethanol supply, including by increasing the share of advanced biofuels (second generation), and increasing the share of biodiesel in the diesel mix".*

This is the focus of my sixth scenario; I consider the increase in total ethanol production from 2015 to 2030 based in the technical note published by the Energy Research Institute (EPE, 2016)[109], *The Brazilian commitment to fight climate change: energy production and use*; which is the official document by which Brazil proposes to implement its INDC commitments. In this study, I assume that all the increased biofuel from sugarcane will be used to replace the current gasoline/petrol. According to this report, the ethanol production is projected to increase 7.2% annually, with the elasticity of 0.76, the total output from the ethanal production in 2030 will be 2.16 times compared with 2010. And all the extra biofuel production will be used to replace the gasoline/petrol sector's output in the Input-Output table in all the Brazilian states.

By introducing this scenario, I am able to estimate the additional land and water resources requirements driven by the Brazilian economy and, thus, I am able to assess how the implementation of the 2015 Paris agreement will increase competition among main economic sectors and aggravate impacts on land and water, as well as what will be the geographical distribution of such impacts at the state level.

4.4. Results

4.4.1. Sugarcane potential yield and blue water demand change

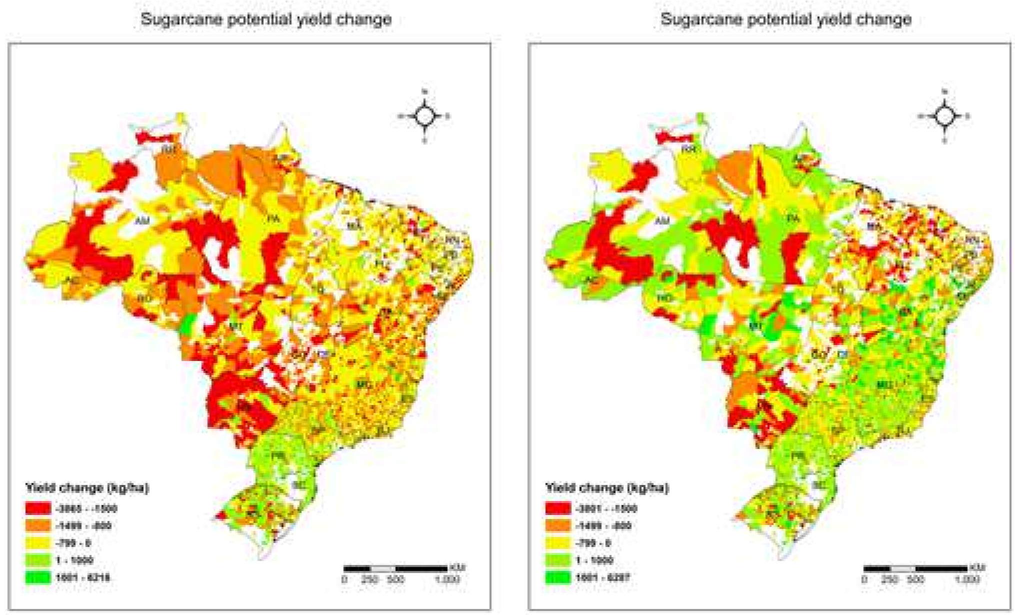


Figure 4-2. Sugarcane potential yield change under climate change (left), and climate and irrigation change (right) in sugarcane cultivated regions.

Climate change and irrigation can directly impact the sugarcane yield and blue/irrigation water demand in the field, thus further influencing the land and water footprint of the sugarcane sector in different regions. I estimated the potential yield and irrigation demand considering climate change and irrigation development scenarios, to exogenously estimate land and water change coefficients for the MRIO modeling.

Figure 4-2 shows the sugarcane potential yield change in the states with sugarcane cultivation under both scenarios. Under the projected climate and irrigation pattern in 2030, most of the tropical regions in the north and central Brazil may suffer a great yield loss and national average sugarcane yield may decrease by 579.79 kg/ha (7.9% of national average potential yield in 2010). This could be explained due to the projected warmer climate which accelerates sugarcane growth and shortens its growing cycle and could lead to yield reductions in most regions, even with the most suitable sugarcane cultivars currently available and with the highest potential yield among all the alternatives that are selected by the AEZ model to fit the changed climate. Besides that, extreme high temperatures can harm the growth and yield of sugarcane in those regions, while in the temperate climate zones of southern Brazil, higher temperatures will favor sugarcane growth and yield.

Under the future sugarcane irrigation plan in 2030, most states will expand their sugarcane irrigation area except for the states that will shrink the sugarcane irrigated area (Alagoas, Ceara, Paraiba, Pernambuco, Piaui, Rio de Janeiro and Rio Grande do Sul). Irrigation will mitigate sugarcane yield reduction under climate change and will lift the potential yield from reduction to increase in many regions in southeast Brazil. The national average sugarcane yield will increase by 254.88 kg/ha (3.5% of national average potential yield in 2010) if such irrigation plan is adopted.

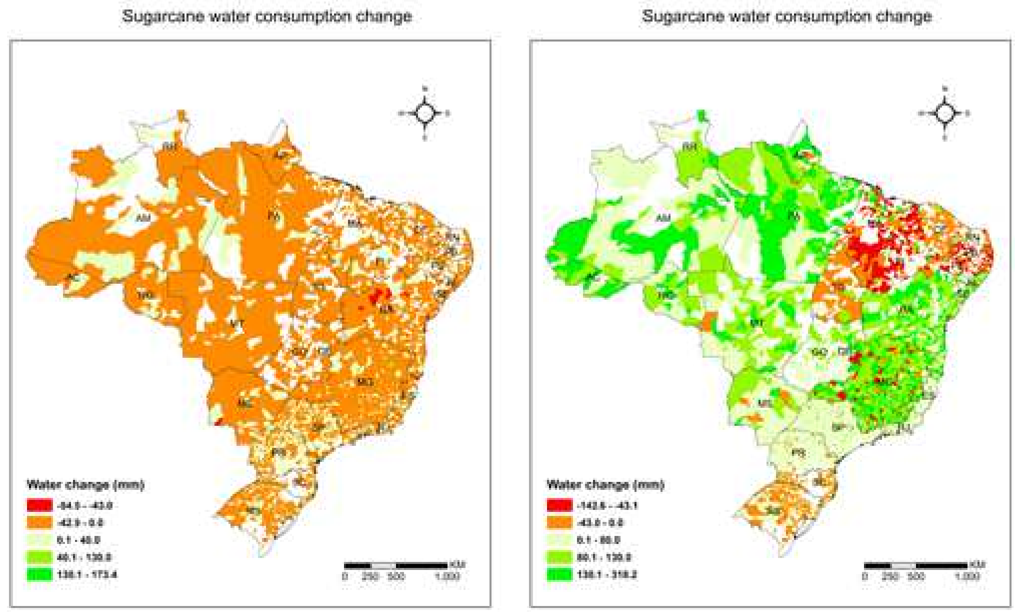


Figure 4-3. Sugarcane blue water demand change under climate change (left), climate and irrigation change (right)

Because of the negative climate change impact on shortening the sugarcane growth cycle and reducing potential yield, sugarcane blue/irrigation water demand will also decrease in most regions of Brazil if the sugarcane irrigation pattern is the same as the baseline. Meanwhile, even if sugarcane potential yield may decrease, a warmer climate will increase soil evaporation and consume more water to maintain the soil moisture for sugarcane growth, which may lead to a higher blue/irrigation water demand in a few counties. Generally, the national average sugarcane blue water demand will decrease by 5.58 mm (3.55% of the national average in 2010) under future climate change scenarios. But if the future sugarcane irrigation expansion plan is adopted, most of the states will consume much more water to meet the sugarcane blue/irrigation water demand under the warmer climate in Brazil. The national average blue/irrigation water demand in 2030 will be 47.97mm (30.5% of the national average in 2010) higher than 2010. Spatial distribution of the results is shown in Figure 3.

4.4.2 Land and water footprint change ratio

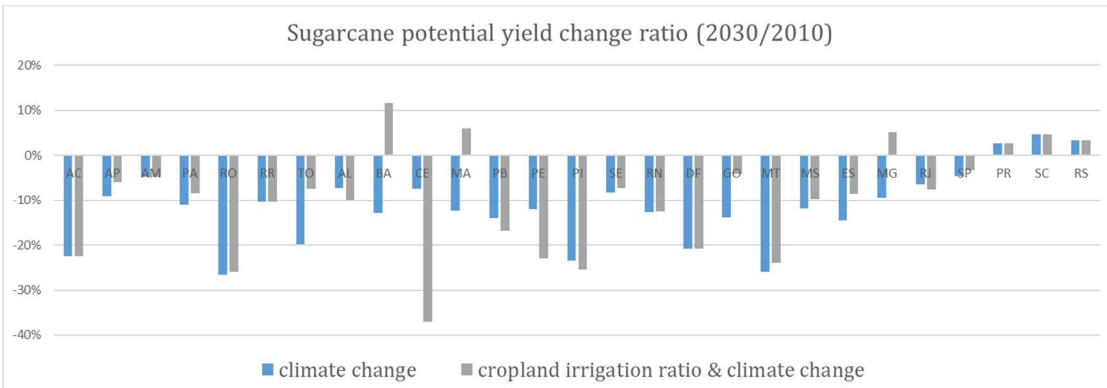


Figure 4-4. Sugarcane yield change ratio in each state

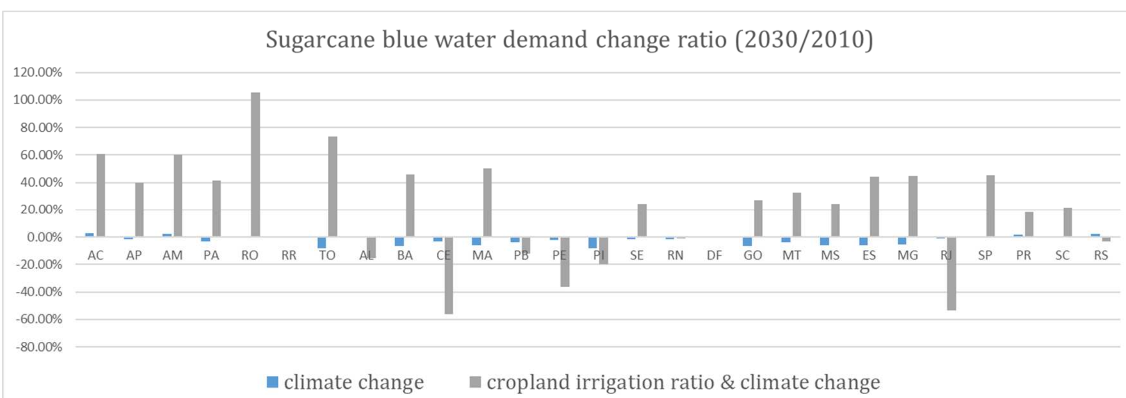


Figure 4-5. Sugarcane water consumption change ratio in each state

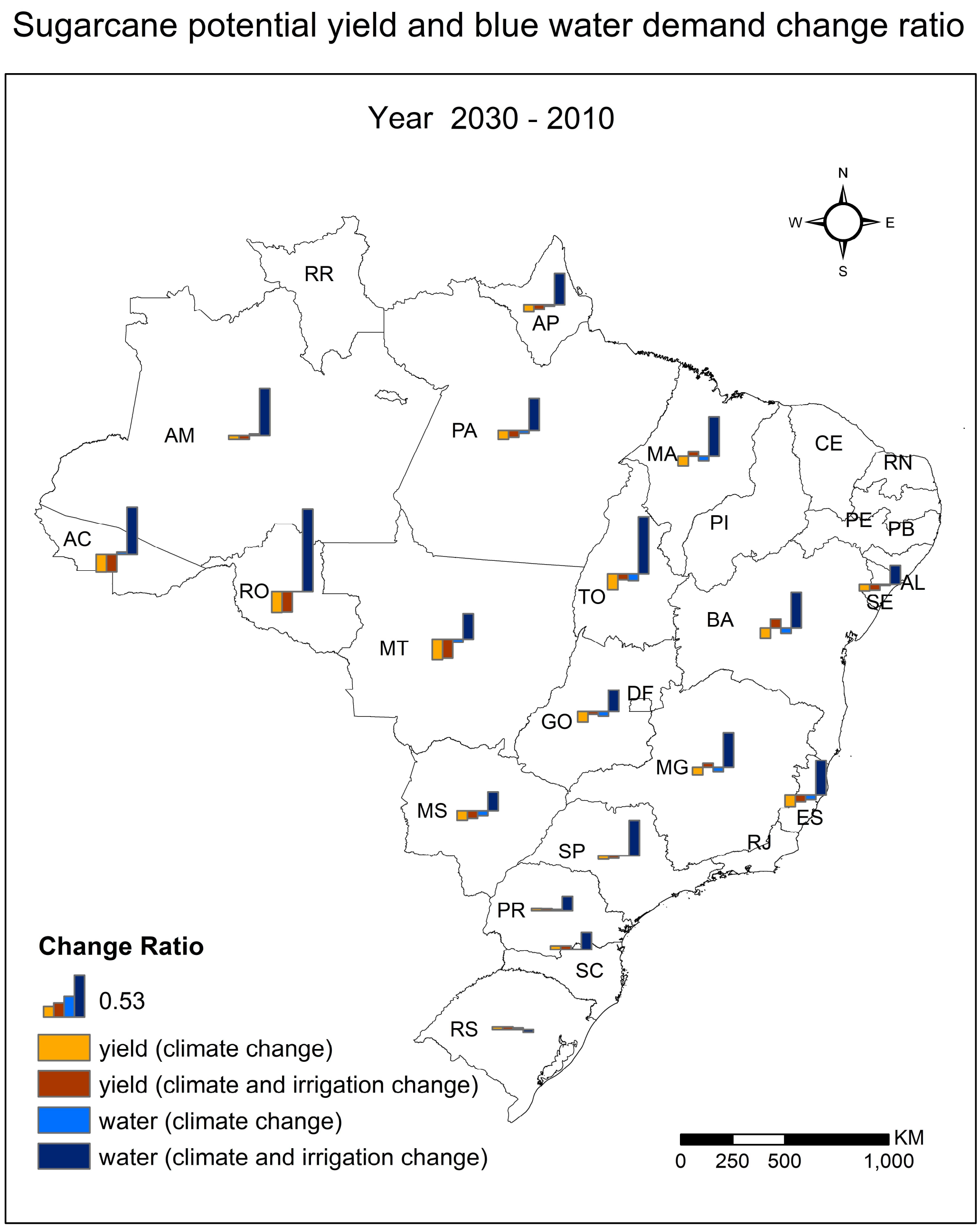


Figure 4-6. Sugarcane potential yield and blue/irrigation water demand change ratio (2030-2010)

I use the GAEZ simulations to calibrate the land and blue water coefficients of the sugarcane sector under different climate and irrigation change scenarios. The change ratio of sugarcane potential production between the 2030s and the baseline climate is used to calibrate the land coefficients, which refers to the land demand to produce per unit weight of sugarcane in different Brazilian states.. Results show that climate change will have a negative impact to yield in most states, except for the states in southern Brazil of PR, SC and RS. It is also obvious that irrigation will greatly mitigate the yield decrease in most of the states, as the sugarcane yield will change from decrease to increase with the irrigation expansion in the states of BA, MA and MG.

Similarly, the water coefficients of sugarcane in each state (Figure 4-5) are calibrated using the irrigation water demand simulated by the GAEZ model. Because all the sugarcane in the state of RR and DF are rain-fed in 2010 and 2030, no irrigation/blue water will be required in these two states. Only five states will experience slight irrigation water increase under the climate change scenario, including AC (3.02%), AM (2.11%), RS (2.03%), PR (1.7%) and SC (0.37%). But under the future sugarcane irrigation plan in each state, almost all the states will experience an irrigation water increase, except for the states with an irrigated area decrease (AL, CE, PB, PE, PI, RJ and RS). The sugarcane irrigated area plays a much more important role in determining the total irrigation water consumption compared with climate change, and the irrigation plan should be carefully designed for the water sustainable agricultural development considering the local water resource.

4.4.3 Sugarcane Input-Output analysis of land and water demand

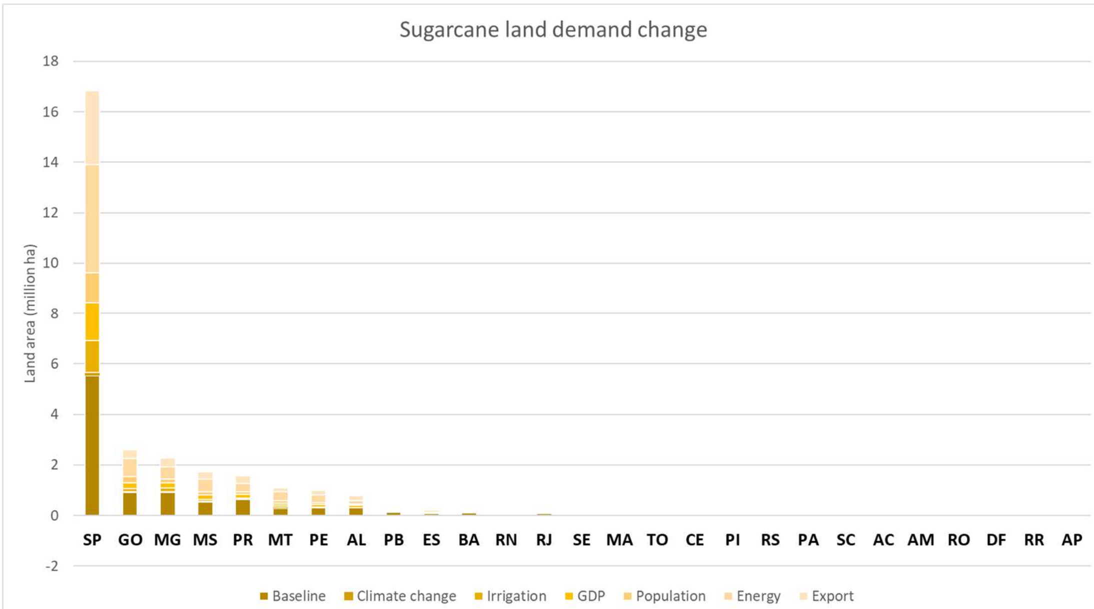


Figure 4-7. Land demand change (ha) of sugarcane from IOA

The total land demand of sugarcane in 2010 is estimated as 10Mha, it would reach 29.4Mha in 2030, according to my projections and considering all the forces driving my future scenario. This is equivalent to a net increase of 191% in the next 20 years. Generally speaking, land requirements of crops are largely determined by local conditions of agro-resources (e.g. climate, land, soil) and agricultural technologies/inputs (e.g. irrigation, fertilizer); and improving crop yield will directly reduce agricultural land demand. However, my results show that the direct driving factors of climate and irrigation only account for 1.6% and 8.8% of the total land demand increase of sugarcane, whereas changes in indirect factors of energy structure and exports will account for 38.4% and 25.7% of the total change in land demand of sugarcane. Thus, the indirect impact of energy structure and exports will largely determine the land demand for sugarcane. The latter will, at the same time, be largely determined by the role Brazil will play in the global market for biofuel supply to other economies under the international climate change agreements. GDP and population will be responsible for 11.4% of the increase of total demand.

As expected, SP accounts for 54.8% of the national total land for sugarcane cultivation in 2010 and will further increase to 57.3% in 2030. In this case, the energy structure, exports and income growth will account respectively for 38%, 25.8% and 13.3% of the total increase. SP is followed by GO (8.9%), MG (7.7%), MS (5.9%), MT (3.7%), PE (3.2%) and AL (2.6%), with much smaller share of sugarcane land demand in 2030.

It is worth noting that in the semi-arid Northeast region, I find PE as the most sensitive state to changes in the energy structure driven by policy and planning, accounting for 49.2% of the corresponding total increase, followed by MA (48.4%), MT (43.1%), RJ (42.2%) and MS (42%).

Exports play an important role at the state level, where some regions will experience a higher increase due to exports than by energy structure change, especially in the Northeast and southern sub-regions of the country. For instance, in RS exports will drive 46% of the total increase (compared to 20% by energy structure changes), 42.5% in AL (compared to 29.3% from energy structure), RJ with 34.9% or

SC with 33.6% of total change (compared to the 5.9% driven by energy structure). Those are followed by PR (32.3%), CE (30.8%) and PB (30.6%).

The natural tradeoff between irrigation expansion and land use is also reflected in my results. In that sense, future planned irrigated area is the driving factor responsible for the highest decrease of land use change per state where the planned area is expected to be reduced. In RJ, the land use is expected to decrease 39% due to changes in the irrigated area by 2030. The state is followed by RO (- 27.3%), AM (-20.9%), AC (-18.9%), AP (-17.8%) and PA (-17.4%)

Climate change has a lower relative influence on the total land demand change than exports, change on energy structure or income growth. The most affected state is DF with 11.8% of its total land consumption increase driven by this force, together with AC (8.4%), PI (7.6%) RO (7.1%), MT (5.5%) and PB (4.4%), affecting mostly states in the Amazon Basin (AC and RO) and in the semi-arid Northeast (PI and PB). The producing states in southern Brazil (PR, RS, SC) show a slight decrease (less than 2.5%) of land use due to climate change; meaning that just considering this driving force, land use would decrease most likely due to a yield gain and the related inputs increase for sugarcane cultivation and irrigation .

Finally, population has an important driving role mainly in those states less populated and less developed in the baseline scenario, such as those in the Amazon basin, with RR with 52.7% and AP with 33.5% of the total land use change drove by population increase.

Table 4-4. Land demand change (ha) of sugarcane from IOA

State	Baseline	climate change	Irrigation	GDP	Population	Energy structure	Export
AC	3568.0	588.3	1324.0	998.0	1271.5	1579.0	1247.7
AP	135.0	5.1	27.2	27.6	51.3	14.8	27.1
AM	3776.0	135.7	1146.3	921.2	1122.4	1046.0	1107.7
PA	13301.0	572.3	3032.0	2768.1	3373.7	3647.9	4043.9
RO	2342.0	431.4	1660.0	747.9	762.8	1621.6	863.2
RR	285.0	16.9	0.0	54.2	153.6	16.9	50.2
TO	36287.0	2612.2	13276.4	9590.8	8980.9	24432.6	14596.5
AL	308006.2	12590.9	-21479.8	83139.9	52820.7	132299.7	191653.8
BA	104708.9	3756.2	12119.2	21247.0	11949.6	27523.1	24396.5
CE	19149.0	437.5	-3308.8	6843.9	5528.9	13612.8	10310.6
MA	47685.0	1739.8	8193.1	11337.1	8195.5	40542.6	13760.2
PB	120504.0	7409.0	-3520.2	34760.3	23094.0	47002.4	48031.0
PE	309487.3	18041.9	-44854.0	105598.9	77372.3	309546.8	163585.7
PI	15022.0	1602.3	-943.9	4444.8	2851.6	6833.1	6201.7
SE	54097.0	2520.4	7282.6	14951.4	12056.2	38629.9	21114.4
RN	59487.1	3835.8	54.2	16771.1	13614.2	37387.8	19351.4
DF	456.0	65.9	0.0	102.9	173.9	102.2	114.0
GO	911847.4	39725.1	107112.5	245909.8	250192.1	685189.7	371800.6
MT	289091.2	44066.5	64877.2	94817.1	99310.9	347579.9	156283.7
MS	545651.2	17766.7	84445.9	159339.6	138215.5	497297.3	287096.6
ES	76683.0	3948.3	18127.3	20801.5	19294.8	57536.0	33012.5
MG	910928.7	20392.6	149844.6	219078.3	147325.7	485174.2	336113.4
RJ	79387.9	2381.3	-22142.0	19398.1	13343.4	23931.2	19811.0
SP	5527566.0	134614.0	1261677.2	1499755.1	1193860.0	4298825.1	2919656.3
PR	626198.9	-3236.5	50953.3	148839.8	117469.4	319438.3	301745.0
SC	8030.0	-168.2	820.1	1581.5	1939.6	404.8	2316.4
RS	19501.0	-118.3	-512.7	3756.2	2649.0	3429.0	7971.6

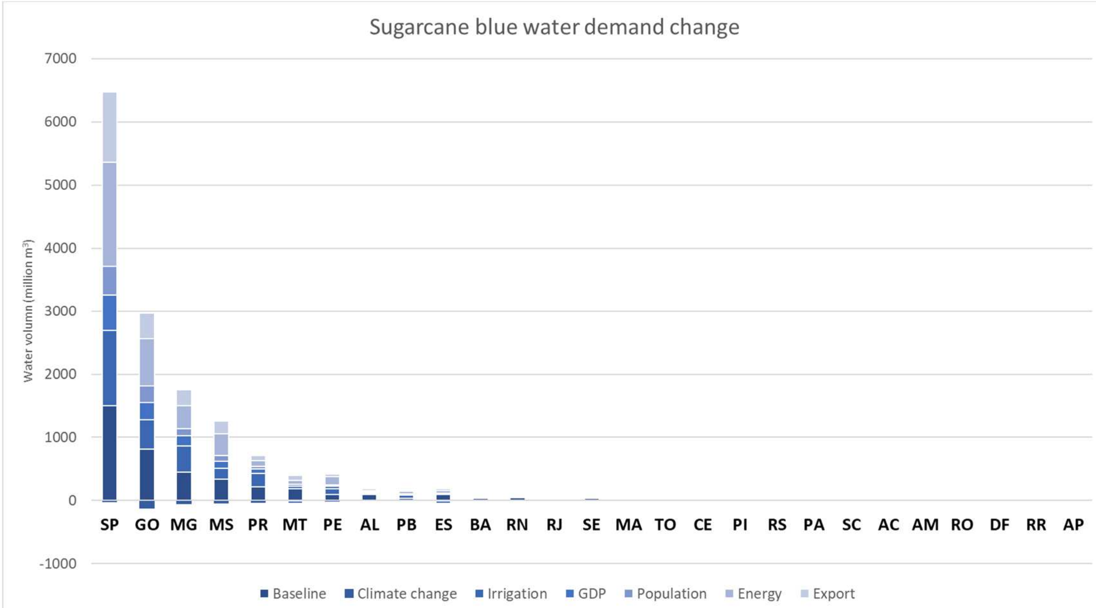


Figure 4-8. Blue water demand change (million m^3) of sugarcane from IOA

Regarding water for irrigation (blue water), the total demand driven by bioethanol production for the baseline was estimated on 3,975 Mm^3, with 14,390 Mm^3 estimated for 2030 the considering all the driving forces of change, which means a 262% of net total increase. Just alone, SP is expected to experience a 328% net increase of its total water consumption driven by sugarcane. Net blue water demand changes by scenario and state are detailed in a Table 4-5 and spatially plotted in Figure 4-9.

An interesting finding of my study is that the total blue water demand of sugarcane will decrease under climate change referred to the national total, which is about -3.4% of the total blue water demand increase in Brazil in 2030. This can be explained by the first direct impact on evapotranspiration needed by any crop as a response to higher temperatures. On the one hand, a projected warmer climate will shorten the sugarcane growth cycle, thus reducing potential yield, total blue water demand, and the related field inputs for the sugarcane growth and irrigation (e.g. fertilizer, energy, infrastructure).

However, interestingly, when isolating the effect of climate change, we can see that climate change is still impacting as a driving force in terms of water consumption net increase with reference to the baseline scenario, with an overall increase of 26.8% country-wise and significantly increase in some states as BA (295%), GO (452%), MA (128%), MS (139%), MG (540%), or even in SP with an 1,504 % net increase.On the other hand, some states planned to reduce the irrigated sugarcane area in 2030, including AL, CE, PB, PE, PI, RJ and RS; this will further reduce the blue/irrigation water demand. Energy structure change is still the largest indirect contributor (34.1%) and exports accounts for 22.1% of total blue water demand increase.

At the state level, RR and DF only have rain-fed sugarcane with no irrigation demand during the study period. SP is the largest sugarcane blue water consumer in both 2010 (37.8% of national total) and 2030 (44.8% of national total). SP is followed by GO, MG, MS and BA with 19.7%, 11.8%, 8.4% and 4.7% of national total blue water demand in 2030 respectively. Almost all the states in Brazil will experience a blue water demand decrease under climate change, as explained above. More specifically, the highest positive impact in terms of water demand (less water needed) will be experienced in the semi-arid states in the Northeast with PI having 55% less water demand driven by climate change, followed by PB (18%), PE (-18

%). The opposite situation, with an increased water demand by changing climate, will be experienced in CE with 35% demand increase and RJ (16%).

Table 4-5. Blue water demand change (million m^3) of sugarcane from IOA

State	Baseline	climate change	Irrigation	GDP	Population	Energy structure	Export
AC	0.0033	-0.0002	0.0033	0.0012	0.0015	0.0018	0.0014
AP	0.0053	-0.0004	0.0037	0.0014	0.0027	0.0008	0.0014
AM	0.0034	0.0000	0.0035	0.0013	0.0015	0.0014	0.0015
PA	0.2693	-0.0280	0.2012	0.0724	0.0883	0.0954	0.1058
RO	0.0285	-0.0037	0.0573	0.0138	0.0140	0.0298	0.0159
RR	0	0	0	0	0	0	0
TO	32.7410	-6.9721	50.0125	13.8990	13.0151	35.4079	21.1533
AL	188.4057	-6.7953	-41.9932	38.6781	24.5731	61.5482	89.1607
BA	211.2521	-31.9914	218.8388	69.6496	39.1719	90.2232	79.9738
CE	34.7369	-2.9019	-23.6334	3.4326	2.7731	6.8277	5.1714
MA	92.1746	-13.5189	98.6787	34.8769	25.2124	124.7234	42.3312
PB	97.3360	-12.0044	-11.8885	20.3360	13.5108	27.4980	28.0998
PE	90.0946	-7.6231	-42.0809	14.8347	10.8693	43.4855	22.9807
PI	5.9408	-1.3440	-0.9192	1.0288	0.6600	1.5815	1.4354
SE	4.0342	-0.2370	1.6564	1.2568	1.0134	3.2471	1.7748
RN	41.3508	-3.5400	0.3398	10.0609	8.1670	22.4287	11.6087
DF	0	0	0	0	0	0	0
GO	813.1659	-126.9025	466.4175	266.4164	271.0559	742.3282	402.8054
MT	6.4368	-1.1443	3.6691	2.1027	2.2023	7.7079	3.4658
MS	341.3078	-48.7826	163.7343	111.2087	96.4654	347.0811	200.3747
ES	11.0009	-1.6743	9.3658	3.9284	3.6439	10.8659	6.2345
MG	447.5718	-54.8322	416.0748	163.2528	109.7842	361.5422	250.4650
RJ	21.2727	-0.9136	-13.4942	2.2227	1.5289	2.7421	2.2700
SP	1504.3876	-29.4972	1185.5305	572.2059	455.4969	1640.1432	1113.9449
PR	31.1523	1.2493	8.3900	9.0036	7.1059	19.3234	18.2531
SC	0.0002	0.0000	0.0001	0.0000	0.0001	0.0000	0.0001
RS	0.0068	0.0003	-0.0006	0.0013	0.0009	0.0012	0.0028

An important finding is that, similarly to the land use results, exports will drive significant shares of the total water demand in some producer states, some already water stressed either by physical conditions as the Semiarido in the Northeast or by exaggerated current demands as in the Southeast. In PI, for instance, just exports alone are driving 59% of the total water demand increase, followed by PE (54%), RS (47%) and by PB (43%).

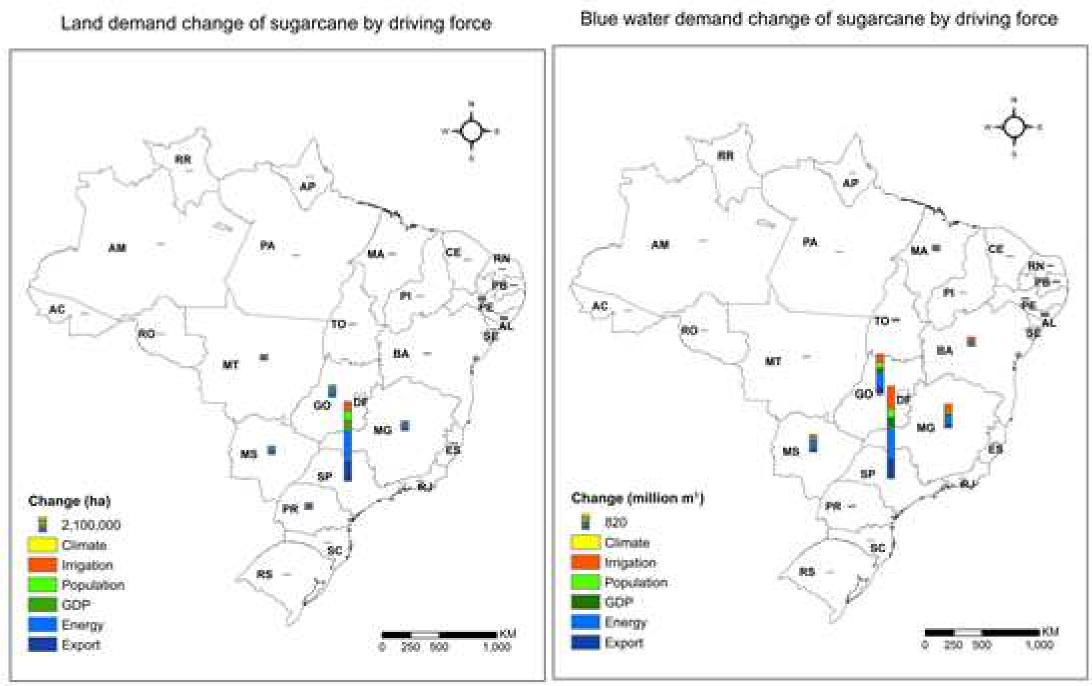


Figure 4-9. Spatial distribution of land (left) and blue water (right) demand change by driving force by 2030.

With respect to population growth, in the case of water demand, there is an increase in some states in less populated areas but also in some of the states that are currently highly populated. For example, AP with a 28% increase or AM (17%), AC (16%) and PA (16%) in the Amazon basin and less densely populated, but also states such as PE with 26% increase or SC (22%) currently more populated and with some of the largest metropolis in Brazil. The difference with land use might be explained by higher levels of biofuel consumption for the local supply chains (energy production and transport) and not just by an increase of the natural resource consumption for sugarcane production (or in other words, more land needed just for direct production).

4.5. Discussion and conclusions

In this chapter, a set of different scenarios have been developed to assess how population and GDP growth, climate change, irrigation expansion, changes in the energy matrix structure, and exports driven by the global market in the decades ahead might affect the demand of water and land driven by bioethanol production in Brazil at the state level.

My results shed light on significant impacts that future production of biofuel in Brazil will have, both in terms of land and water consumption and therefore the implications in terms of increased competition for both scarce resources by rival crops or economic sectors. Even more, my results confirm how climate change and ongoing international negotiations and agreements on climate change mitigation will significantly drive a higher consumption of both resources associated to biofuel production and, as a result, significantly enlarging its environmental footprint and potentially increasing competition with food production. I also found that the driving forces differently impact land and water consumption, with a clear land-water "nexus" tradeoff to be considered when planning policy and infrastructure related to biofuel production expansion as one of the main pillars of the Brazilian INDCs.

According to my estimates, by 2030 the total land use at the national level in Brazil driven by sugarcane production will experience a net increase of around 191% considering all the driving forces in my scenario modeling. Changes on energy structure and international exports will be responsible for 38.4% and 25.7% of the total, followed by income growth with 14.1% of the share. This is an important finding as it confirms that climate mitigation policies related to international agreements in Brazil could have a significant impact in terms of land use change given the leading role of Brazil as a top exporter of bioethanol worldwide. This could aggravate competition for land use with other food producing sectors (crops and pastures), especially in those land stressed areas potentially aggravating deforestation processes and impacting biodiversity and ecosystem services provision if related land-use and environmental protection policies are not properly designed or enforced.

I also found that climate change will have a small effect with just 1.6% total increase in terms of land use change countrywide compared to structural, policy and socio-economic forces. Sao Paulo, as the largest producer, will still account for 57.3% of the total land demand increase by 2030, followed by Goias (GO 8.9%), Minas Gerais (MG 7.7%), Mato Grosso do Sul (MS 5.9%), Parana (PR 5.3%), Mato Grosso (MT 3.7%), and Pernambuco (PE 3.2%).

Exports to global markets will have an even higher land use demand in some states than in SP, the largest producer. This is the case of the Semiarid region in the Northeast, with 42.5% increase for AL, 30.8 for CE, 30% for PB, 29.6 for PI and

26% for PE. This might be especially relevant for these states under current water and land stressed conditions and with traditionally less developed and favored economies than those in the Southeast such as SP, which at the same time is driving most of the domestic imports of biofuel and sugar cane within Brazil.

Another important finding is that in some states, energy structure related changes are the most relevant driving force. This is especially relevant for Pernambuco, for instance, in which this factor will contribute 49.2% of increase on land demand driven by sugarcane production by 2030. Pernambuco is a state that during the past two decades has been experiencing a transformational change towards becoming one of the most consolidated economies of the country and is starting to be considered potentially as one of the future reference manufacturing poles in Brazil. However, the state is facing serious water, land and energy security challenges and both the state and Federal governments are currently working in deep structural and sectorial policy and infrastructure investments with water supply, irrigation, crop planning and biofuel production expansion at its core. Thus, understanding the direct and indirect impacts of biofuel production on land and water resources is critical to inform this process.

Regarding water consumption, my estimates also show a significant increase on total (blue) water footprint/demand of sugarcane production in Brazil, with a 262% net total increase at the national level by 2030 compared to the baseline. Sao Paulo will particularly be impacted in terms of water consumption, with a net total increase of 328%. This can be explained as the state is the largest producer in Brazil, and it is expected to sustain most of the production in the future, but currently the production is mostly rain-fed and land availability is saturated for further crop expansion. Thus, this production growth is expected to be feasible due to expansion of irrigation systems that will promote and stabilize sugarcane yield compared with existing rainfed system, largely impacting the sustainability of water resources and hydrological systems, and aggravating the competition with other crops, energy generation and urban consumption. Furthermore, the state alone is expected to drive 44.8% of the total national blue water footprint of sugarcane production in 2030.

Another important finding related to water is that climate change will have a positive effect in terms of water consumption with a net total decrease of 3.4% of the national blue water demand compared to the baseline. Surprisingly, some drier states, such as RN, PB, AL, PI, PE and CE, will experience a decrease of their blue water footprint due to climate change, as it will shorten the growing cycle of sugarcane and reducing yields. However, a warmer climate could increase evapotranspiration, which would have to be compensated with a higher green water footprint. Additionally, less yield, and given the limited water supply for irrigation in some of these states, might need to be compensated with cropland expansion for sugarcane calculation, which in turn could have a negative impact in terms of land use.

More importantly, and similarly to the case of land requirements, I found that energy-related structural changes and exports are the major driving forces for a total net increase of the blue water footprint of sugarcane production in Brazil, accounting in combination for more than half (56.2%) of the total, with 34.1% and 22.1% respectively. This is also a relevant finding, and one that confirms that the policies committed by Brazil and its role as a main provider of biofuel within the international climate agreements - and particularly through the signature of the NDCs under the Paris Agreement - will take a significant toll in Brazil in terms of water consumption which may very well increase competition with food production, energy generation and/or human consumption, especially in the most vulnerable Brazilian states in terms of water and land availability and for those with less developed economies. This is a critical negative environmental externality at the local level that should be assessed in detail and accounted for in both the national economic and development policies (subsidies for instance) and international commerce agreements for biofuel exports to international markets. This might even become more critical for local water and food security in the context of more aggressive mitigation strategies in Post-Paris Agreement scenarios.

Chapter 5: Conclusion: major findings and further research

5.1. Paper 1

This paper is the first step of my dissertation in assessing what is the status of water and land use and therefore water and land stress in Brazil driven by bioethanol production, the geographical distribution of these uses and stresses at the subnational level, and the extent of competition for the use of water between bioethanol production and other crops and economic sectors in terms of the economic competitive advantage of the use of water.

My results show that ethanol is responsible for less than one third of the total sugarcane water footprint. I found that São Paulo is the largest exporter of green and grey water, with the biggest flows to its neighbor state, Rio de Janeiro, which is the largest importer of virtual water. At the same time, São Paulo is a net importer of water from other water-stressed states such as Goiás and Alagoas. Regarding the blue water virtual flows, Goiás, a water-stressed state, is the largest exporter with its biggest flow to São Paulo.

Interestingly, inter-regional flows of virtual water associated with bioethanol production are significantly different when considering water scarcity. Three water stressed states of Goiás, Pernambuco, and Alagoas led the rank of scarce green, blue, and grey water, which is mainly driven by consumption and production activities in São Paulo and other water abundant states in the southern-center region.

Regarding water footprint driven by international exports, most of the virtual water is driven by São Paulo, which, is triggering significant water consumption in other water stressed states through importing ethanol to re-export or as an input to produce other goods for export. However, the main share (85%) of the economic value- added associated with these exports remained in São Paulo, while Pernambuco and Alagoas received in return only 0.1% and the 0.7%, respectively.

In terms of the competition for water with other crops, I found that producing sugarcane has an economic competitive advantage over the cultivation of soy, corn, or rice in some of the states related to the use of green water, while related to the blue water footprint, the production of sugarcane is less competitive in most cases in terms of the added value per cubic meter of blue water consumed. This could be a critical part of water management in Brazil given the potentially significant expansion of biofuel production at the national level, and Northeast where half of the production is already irrigated due to the lack of available cropland and limited water availability, and where any future growth of bioethanol production will occur by expanding irrigation systems, thus increasing the competition for water between sugarcane and other suitable crops, as well as residential consumption with lower competitive advantage for the use of water as shown by my results. This important potential implication merits further investigation.

5.2. Paper 2

In this paper I advance on the land side of the water-land nexus of the bioethanol production in Brazil, by addressing the following questions: what are the environmental impacts on land use of ethanol production? what is its geographical distribution at the subnational level? how does the competition for land take place between bioethanol production and other crops? and what is the extent of interactions among water and land impacts of biofuel production?

My results show that additional bioethanol production would exert significant impacts on land resources in Brazil, and the global markets play a relevant role on these impacts. About one third of the stressed land footprint is for export production, with São Paulo a significant virtual exporter driving imports from other land stressed states, such as Mato Grosso and Mato Grosso do Sul. Indeed, São Paulo alone is responsible for 70% of the total land footprint driven by the production for exports from Brazil to other economies.

When analyzing the tradeoffs and synergies between land use and water consumption in Brazil for biofuel production and the corresponding spatial distribution within the country, my results showed a significant change when including land and water scarcity into the analysis, revealing different trade-offs and synergies for land and water use that should be considered when planning bioethanol expansion in Brazil.

For instance, in arid states at the Northeast such as Pernambuco, Alagoas, Sergipe and Paraíba, development of biofuel may lead to an increase in water scarcity but less impact in in terms of land stress. In these regions, the expansion of biofuel production could rely on expansion of rainfed cropland or by investments in irrigation efficiency for existing irrigated sugarcane fields.

Some states show an increasing impact on land resources but smaller impact on water scarcity triggered by biofuel expansion. In the cases of São Paulo, Mato Grosso, and Mato Grosso do Sul, the expansion of bioethanol production should be supported by investments to increase irrigated cropland already dedicated to sugarcane in order to increase productivity gains rather than expanding rainfed cropping.

There are other states where I found relatively small impacts on both water scarcity and land stress from further expansion of biofuel production: these states would be the best candidates for further sugarcane development if the climate was suitable for that purpose and considering their respective socio-environmental context and constrains, as those states in the Amazon basin (Amazonas, Amapa, Para or Tocantins). Lastly, some states have large impacts on both land stress and water scarcity. In these states there is limited capacity for expanding sugarcane production, for either rain-fed or irrigated cropping, and thus sugarcane development should not be pursued. Goiás falls within this category.

As a main conclusion of this chapter; my study confirms that to properly assess the impacts of biofuel production in Brazil on land and water, the consideration of resource scarcity and its spatial variability is the key. Therefore, governmental development policies and planning for bioenergy production at the national and subnational levels need to carefully consider the trade-off between land use and water consumption and its respective impacts on both resources,. For this purpose, the concepts of virtual water and land as well as water and land stress may serve as suitable tools to balance such tradeoffs.

5.3 Paper 3

While in chapters 2 and 3 of the dissertation I have uncovered both water and land impacts driven by bioethanol production in Brazil; as well their “nexus”; in this paper I have assessed how these impacts could change under relevant future socio-economic and environmental scenarios.

My results shed light on the significant impacts that future production of biofuel in Brazil will have, both in terms of land and water consumption and therefore the implications in terms of increased competition for both scarce resources with other crops or other economic sectors. Even more, my results confirm how climate change and ongoing international climate change mitigation negotiations and agreements will significantly drive a higher consumption of both resources associated to biofuel production and thus critically worsening its environmental footprint.

According to my estimates, by 2030 the total land use at the national level in Brazil driven by sugarcane production will experience a net increase of around 191% while water footprint/demand of sugarcane production in Brazil could grow by up to 262%. Sao Paulo will particularly be impacted in terms of water consumption, with a net total increase of 328%.

I found that energy related structural changes and exports are the major driving forces for a total net increase of the blue water footprint of sugarcane production in Brazil, accounting in combination for more than half (56.2%) of the total, with 34.1% and 22.1% respectively. Regarding land use, changes on energy structure and international exports will be responsible for 38.4% and 25.7% of the total demand growth.

My findings therefore confirm that the policies committed by Brazil and its role as main provider of biofuel within the international climate agreements - and particularly through the signature of the NDCs under the Paris Agreement - will take a significant toll in Brazil in terms of water consumption which may very well increase competition with food production, energy generation and/or human consumption, especially in the most vulnerable Brazilian states in terms of water and land availability and for those with less developed economies. This is a critical negative environmental externality at local level that should be assessed in detail and accounted for in both the national economic and development policies (as subsidies, for instance) and the international commerce agreements for biofuel exports to international markets; something that might become even more critical for local water and food security in the context of more aggressive mitigation strategies in Post-Paris Agreement scenarios. The study in detail of the major contributing markets demanding biofuel from Brazil in the future and the inclusion of more detailed technology scenarios are proposed here as areas for further research.

5.4 Limitations of my approach and areas of improvement

As the core of my assessment relies on the use of an MRIO model, most of the limitations are related to its application. As a matter of fact, the limitations of input-output modeling have been well documented in the literature. As a reference, Wiedmann (2009), Lenzen *et al.* (2010), Daniels *et al.* (2011), and Wiedmann *et al.* (2011) summarize major MRIO constrains.

MRIO analysis provides only a “static screenshot” of the state of an economy during a given accounting time span, a year in most cases. Moreover, a standard MRIO model commonly face the sectoral aggregation errors, as individual products are usually aggregated into different economic sectors (Chapagain and Tickner, 2012). An alternative approach with higher sectoral resolution – such as the input-output assisted hybrid life cycle assessment (Suh *et al.*, 2004; Li *et al.*, 2012; Feng *et al.,* 2014b). However, given that my research focus on environmental impacts of sugarcane-based ethanol production, and the MRIO used includes sugar cane cropping and ethanol production (industrial phase) as separate sectors, the sectoral aggregation error may only occur when tracing the water and land embedded in upstream supply chains of the sugar cane cooping and ethanol production.

Another key constraint of using MRIO modeling is the level of aggregation and the intrinsic assumption within the data that each economic sector produces a homogenous product output. Products with very different resource consumption (or generated pollution) intensities are mixed together and averaged into one sector, which can distort resource requirements (or pollution concentrations). This can be an additional source of error that might lead to distortions and higher uncertainty levels of results. Averaging natural resource requirements for an economic sector (water or land in this case) may under- or over-estimate the resource requirements and, therefore, the virtual flows (Steen-Olsen *et al.*, 2014; Bruckner *et al.*, 2015), at the state level, in the case of my research.

There is a considerable time-lag for the publications of MRIO datasets. MRIO datasets consist of multiple national input-output tables that require significant effort and time to harmonize. The time lag of the data in the MRIO database is problematic as it may weaken the relevancy of the research aim of present-day issues as well as the policy implications derived from analytical results (Wiedmann *et al.*, 2011; Bruckner *et al.*, 2015). For my research, we use the state-based Brazilian MRIO, which is the latest available at this level, and we thus assume the national economy remains the same for our baseline year, 2010. Additionally, another source of error for my analysis is that for the scenario construction we have used to diverse and heterogeneous data sources to parameterize the environmental coefficients for water and land demand, that we assume all to be referred to 2010.

Another common problem of IO analysis that might also to be considered for my research is in its inability to account for multiple and simultaneous uses of agriculture land. In other words, interpretation problems arise when farming practices include multiple crops or fallow agriculture land following a traditional crop rotation cycle or land serving multiple economic purposes within a single year (Bruckner *et al.*, 2015). This limitation does not affect sugarcane cropping in Brazil, as sugar cane crops in Brazil are replanted every five to ten years[110]. However, this limitation might affect other competitive crops considered in my study and disaggregated at sector level within the MRIO I used.

In this regard, all the recommendations provided in my study are based on a state-level analysis of land and water footprint and thus, may inform decision-making at this scale. However, these recommendations cannot be used to support policy or planning at sub-state levels (i.e. watersheds or municipalities) with specific local socio-economic and environmental conditions. For instance, special attention should be paid in Brazil to areas in the Amazon basin, the Mata Atlântica eco-region or the Pantanal Wetland, with high levels of environmental sensitivity given their unique values of biodiversity, and which are already critically stressed by human disturbance, mainly by cropland and pastureland expansion. Those key biomasses do not match administrative boundaries and they are fragmented and irregularly spread across the countries, often crossing borders between states.

My results provide a basis for a comparison of water and land use by bioethanol production among Brazilian states, which can help to compare, from a national strategic planning perspective, the environmental impacts of intensification and expansion scenarios of bioenergy in the future and to decide upon where investments in sugarcane production could be more reasonably allocated. However, an improvement of the resolution of my modeling framework is needed to downscale the analysis to sub-state or basin levels in order to provide a more detailed assessment that may support decision-making on water-or-land-resource management strategies for biofuel production at such spatial scales to effectively address scarcity of water or land. For instance, further research on the use of applied telescoping on MRIO analysis to zoom-in in specific watersheds could be a new extension of my research to be explored.

Another limitation of my modeling approach is linked to the use of the GAEZ for the scenario assessment. Because the sugarcane demand will soar up under future socio-economic development scenarios, expanding its planting area to meet the extra demand is needed. However, landuse/landcover change simulation requires not only the spatial observation of sugarcane planting area across Brazil, but also future landuse/landcover decisions from climate, social and economic perspectives, which is out of the scope of this study. Considering the complexity and uncertainties of simulating the sugarcane expansion, we use the state-level average potential sugarcane yield and irrigation water demand between historical and projected climate to obtain the land and water demand change ratio, thus adjust the land and water coefficients in each state to feed the MRIO modeling. Although introducing landuse/landcover model to project the sugarcane expansion may improve the land and water demand in the future, its potential uncertainties should be discussed.

In addition, the build-in GAEZ suitability module will optimize the local agricultural adaptation measures and field management to guarantee the potential land productivity, which may have higher levels than farmers' practice and bring uncertainties. However, considering only few or even no large-scale agricultural adaptations in most crop models[111 112–115], climate change impact assessment with automatic adaptations from the GAEZ model will be more feasible. Introducing lower levels of management and adaptation scenarios that closer to local farmers' practice may further improve the performance of the GAEZ simulations for further in-depth research.

Finally, another area of improvement for my approach would be the quantitative determination of the tipping points for land and water stress values. Since my results are based on a comparative assessment of land and water stress values for sugarcane production, these tipping points are not relevant for my study but might be needed for further analysis of environmental stress associated with scenarios on expansion of bioethanol production.

To summarize and considering all above, in practical terms, my model and research results can be used as it is for policy and investment planning related to biofuel production at the national and subnational level (state-based level). For instance, the ministries of finance and planning can use my results to prioritize areas of biofuel production or to inform large regional infrastructure projects which might target, among other competing users, irrigation water demand of future biofuel production. As an example, nowadays some of such large projects are planned to divert water from water rich states to the semiarid Northeast, promoting inter-state water uses related conflicts and environmental impacts. Other alternatives can be explored to promote more rational use of water and land in the Semiarid or to promote the investment in water efficient technologies or mainstreaming the circular economy of water within water management and investment planning.

Finally, my model presents an opportunity for investments and water resource management at basin level to inform investments program design by improving the aforementioned spatial resolution and the capabilities of the MRIO-GAEZ integrated model, including the assessment of climate change impacts. It has potential to be used by national financial institutions (as BNDES) or international financial institutions as multilateral development banks.

Abbreviations

FEWS	Food Energy Water Nexus
WWAP	World Water Assessment Program
UN-DESA	United Nations Department of Economic and Social Affairs
FAO	Food and Agriculture Organization of UN
GHG	Greenhouse Gas
OECD	Organization for Economic Cooperation and Development
IBGE	Instituto Brasileiro de Geoestadistica
EPE	Empresa de Pesquisa Energitca
UNICA	Uniao Nacional da Cana de Acucar
ANA	Agencia Nacional de Aguas
FUNARBE	Fundação Arthur Bernardes
INDC	Intended National Determined Contribution
WF	Water Footprint
MRIO	Multiregional Input-Output Analysis
SWF	Scarce Water Footprint
ONS	National Operator of the Electrical System
SNSA	Secretaria Nacional de Saneamiento Ambiental
ABNT	Brazilian Association of Technical Standards
FBB	Foundation Bank of Brazil
NREL	National Renewable Energy Laboratory
TWW	Total Water Withdrawal
TWA	Total Water Availability
WSI	Water Scarcity Index
WRVI	Water Resources Vulnerability Index
VW	Virtual Water
CA	Comparative Advantage
IEA	International Energy Agency
LF	Land Footprint
SLF	Stressed Land Footprint
VL	Virtual Land
VA	Value Added
WLR	Water to land impact ratio
ETH	Zurich
NPP	Net Primary Productivity
GIS	Geographic Information System
GAEZ	Global Agro-Ecological Zones
WF	Water Footprint
GWP	Global Water Partnership
WB	World Bank
GDP	Gross Domestic Product
WFN	Water Footprint Network
IIASA	International Insitute for Applied Systems Analysis
BRICS	Brazil, Russia, India, China
IOA	Input-Output Analysis
BRAZILIAN STATES ACRONYMS	
AC	Acre

AL	Alagoas
AP	Amapá
AM	Amazonas
BA	Bahia
CE	Ceará
DF	Distrito Federal
ES	Espírito Santo
GO	Goiás
MA	Maranhão
MT	Mato Grosso
MS	Mato Grosso do Sul
MG	Minas Gerais
PA	Pará
PB	Paraíba
PR	Paraná
PE	Pernambuco
PI	Piauí
RJ	Rio de Janeiro
RN	Rio Grande do Norte
RS	Rio Grande do Sul
RO	Rondônia
RR	Rorâima
SC	Santa Catarina
SP	São Paulo
SE	Sergipe
TO	Tocantins

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