UNIVERSITY OF TECHNOLOGY SYDNEY
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WATER–ENERGY–FOOD NEXUS IN SUGARCANE ETHANOL PRODUCTION IN THE STATE OF GOIÁS, BRAZIL: A REGIONAL INPUT-OUTPUT ANALYSIS

by

Rodrigo Augusto Bellezoni

A dissertation submitted in fulfilment of the requirements for the degree
Doctor of Philosophy (Energy Planning and Policy)

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Certificate of Original Authorship

I, Rodrigo Augusto Bellezoni, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Systems, Management & Leadership, Faculty of Engineering and Information Technology at the University of Technology, Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as fully acknowledged within the text. This thesis is the result of a Collaborative Doctoral Research Degree program with Federal University of Rio de Janeiro, Brazil.

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Format of the Thesis

This manuscript consists of a conventional thesis format and it is structured as a continuous series of sections, including:

- an introduction to the research study, a review of the literature and a justification of how it adds to knowledge in the field
- description of and justification for the research approach and methods
- a case study analysis
- presentation of results and discussion
- conclusion.

List of Publications Included

As a partial result of this thesis, an original article on the water-energy-food nexus approach was published in the *Biomass & Bioenergy* journal, as presented below:

Rodrigo A. Bellezoni, Deepak Sharma, Alberto A. Villela, Amaro O. Pereira Jr, 'Water-energy-food nexus of sugarcane ethanol production in the state of Goiás, Brazil: An analysis with regional Input-Output matrix', *Biomass & Bioenergy*, Vol. 115 (2018), pp 108-119.

Please refer to **Appendix XXII:** Publications Included to see this published article and the permission from the copyright owners to include an online version of it in this thesis. Additionally, refer to the appendix to check the contributions of each author to this article.

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Abbreviations/Glossary

ABC	Low carbon emission agriculture program
AEZ	Agro-ecological zoning
ANA	National Water Agency
ANP	National Agency for Petroleum, Natural Gas and Biofuels
BTL	Biomass-to-liquids
CAPEX	Capital expenditure
CBIO	Biofuel decarbonisation credit
CES	Constant elasticity of substitution
CCS	Carbon cost share
CGE	Computational general equilibrium
CGEE	Centro de Gestão de Estudos Estratégicos
CLEWS	Climate, Land, Energy and Water System
CMBC	Committee for the Monitoring of Biofuels and Fuels
CNI	National industry confederation
CNPE	National Energy Policy Council
CO_{2e}	Carbon dioxide equivalent
CONAB	Brazil’s national supply company
COP 21	21st Conference of Parties
CRA	Environmental reserve quota
DLUC	Direct land-use change
EMBRAPA	Brazil's federal agricultural research agency
EPE	Brazilian energy research company
ERQ	Environmental Reserve Quota
ETS	Emissions trading schemes
EVAC	Evaporation coefficient
EVAV	Volume of water lost by evaporation
FAO	Food and Agriculture Organization of the United Nations
FUNARBE	Federal University of Viçosa Support Foundation
GCM	General circulation models
GDP	Gross domestic product
GHG	Greenhouse gases
GIZ	German development agency Deutsche Gesellschaft für Internationale Zusammenarbeit
GO	Goiás State
GWP	Global warming potential
HEFA	Hydro-processed ester fatty acids
HLPE	High-level panel of experts
hm^3	Cubic hectometre
IAEA	International Atomic Energy Agency
IBGE	Brazilian Institute of Geography and Statistics
ICAP	International Carbon Action Partnership
ICIMOD	International Centre for Integrated Mountain Development

ICLFS	Integrated cropland-livestock-forestry system
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IISD	International Institute for Sustainable Development
ILUC	Indirect land-use change
IMB	Mauro Borges Institute
INPE	National Institute for Space Research
IO	Input-output
IOA	Input-output analysis
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
J	Joules
km^2	Square kilometre
LCA	Life cycle analysis
LEAP	Long-range energy alternatives planning
LHV	Lower heating value
LR	Legal Reserve
LUC	Land-use change
LULUCF	Land-use, land-use change and forestry
MAPA	Ministry of Agriculture and Food Supply
MAPBIOMAS	Annual land use and coverage mapping in Brazil
MBRE	Brazilian Emission Reduction Market
MCTI	Ministry of Science, Technology and Innovation
MME	Ministry of Energy and Mines
MSA	Multi-sectoral systems analysis
MuSIASEM	Multi-scale integrated assessment of society and ecosystem metabolism
NDC	Nationally determined contribution
NPCC	National Policy on Climate Change
NWRP	National Water Resources Policy
OPEX	Operational expenditure
PDE	Ten-Year Energy Plan
PMR	Partnership for Market Readiness Organisation
PNPB	Brazilian biodiesel production program
PPA	Permanent preservation area
PPP	Polluter pay’s principle
PRBP	Paranaíba River Basin Plan
PROALCOOL	Brazilian National Alcohol Program
QAV	Aviation kerosene
PSA	Payment for environmental services
RBP	River basin plan
SEEG	Emissions estimating system for GHG
SEI	Stockholm Environment Institute
SHP	Small hydroelectric plants
SIP	Synthesised iso-paraffin

SIRENE	National emissions record system
Tg	Teragrams
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNICA	Sugarcane Industry Association
WCI	Western Climate Initiative
WEAP	Water evaluation and planning system
WEFN	Water-energy-food nexus
WMU	Water management unit
ZAE Cana	Sugarcane agro-ecological zoning

ABSTRACT

WATER–ENERGY–FOOD NEXUS IN SUGARCANE ETHANOL PRODUCTION IN THE STATE OF GOIÁS, BRAZIL: A REGIONAL INPUT-OUTPUT ANALYSIS

by

Rodrigo Augusto Bellezoni

Concerns about the impact of biomass growth for biofuel production emphasise the importance of planning the expansion in energy crops, taking into consideration water, energy and land resources, as well as greenhouse gas emissions (GHG). This research analyses the impacts of first-generation sugarcane ethanol expansion in the Paranaíba basin (Goiás State, Brazil), focusing on how future demand for ethanol could affect the socioeconomic, energy and environmental outcomes in the region. An economic-ecological input-output (IO) framework was applied to develop a water-energy-food nexus (WEFN) analysis on ethanol production. A Leontief IO price framework was also applied to analyse the economic and environmental impacts of changes in factor input prices, resulting from the imposition of a US$10 carbon tax. The results show that sugarcane expansion would apparently have little significant direct impact on land and water availability in the Paranaíba basin, when price change effects (through a carbon tax policy) are not taken into account. Conversely, however, when a US$10 carbon tax policy is applied, the negative environmental impact (of economic changes) of expanding sugarcane crops in Goiás would be 5-fold higher as compared with the non-carbon pricing scenarios; thereby significantly changing the big picture of promoting biofuels expansion in the state when physical and economic models are jointly applied. Therefore, any ethanol scenario under a carbon pricing initiative would turn into a high-impact development option for Goiás, showing much higher environmental impacts when compared to non-carbon-pricing scenarios and the long-term environmental impacts would offset any economic gains. This significant difference between the results of a physical approach and a price approach is an important way of assessing environmental impacts in terms of their economic implications, and a means of aligning both results and policy recommendations more closely to reality. Additionally, the impacts on the return of a sector's value-add show that no Goiás' economic sector would be significantly impacted in carbon price scenarios up to US$10/tCO$_{2e}$, except for the *Agricultural* sector; this would face huge challenges even under 45% and 35% emissions reduction scenarios, with impacts of 17% and 20% in value-added terms, respectively. Finally, the unintended impacts of expanding biofuels, such as the possibility of indirect deforestation and its related GHG emissions, must always be considered before promoting sugarcane expansion in the Paranaíba basin. Therefore, the WEFN analysis is a valuable tool for guiding the sustainable management of natural resources, including water, energy, land use and GHG emissions. In particular, the hybrid extended IO-WEFN framework is useful for designing effective biofuel policies and collectively addressing impacts on environmental, social and economic spheres, in a local or broader context.

Dissertation directed by Professor Deepak Sharma

School of Information, Systems & Modelling (ISM)

1 Introduction

1.1 Background

Debates on energy security, oil price variability and the growing global commitment to address climate change have intensified in the 21st century, motivating increasing investments in renewable energy resources, even though fossil fuels still dominate the global energy markets. Since the *Transport* sector heads up oil consumption worldwide and air, marine and heavy freight transport rely on the high energy density of liquid fuels, the transportation sector is on the lookout for alternative renewable fuel sources.

On a global scale, biofuels accounted for about 3% of the fuel consumed by the transport sector in 2014 (IEA, 2016), and the United States and Brazil lead the world in biofuel production. Brazil accounted for 22.5% of global biofuel production in 2016, which represents 83% of South and Central America's total output. Researchers and planners have focused on liquid biofuels, which in Brazil have long contributed to reducing greenhouse gas emissions (GHG) from the transport sector, besides contributing to agricultural development and reducing oil import dependency.

Besides the energy and environmental aspects, traditional biofuel production may have many social benefits that can help developing countries grow in a more sustainable way. Some studies have highlighted the employment and income generation related to biofuel programs in developing countries and their positive effects on living conditions (Lynd and Woods, 2001; Moraes *et al.,* 2010). Thus, as technological improvements emerge, the potential environmental and economic benefits of biofuels are becoming more evident, making them a promising renewable energy source.

It is noteworthy that biofuels can be produced from different raw materials, generating sources of energy with distinct characteristics. Traditional biofuels use conventional food and feed crops, also known as 'flex-crops' or 'flex-commodities'. Flex-crops are agricultural crops that can be used for food, feed, fuel and industrial material. First-generation biofuels (*1G*) usually refers to ethanol produced from sugar-rich (*e.g.* sugarcane, sugar beet, sweet sorghum) and starch-rich flex-crops (*e.g.* corn, wheat, cassava, rice), and to biodiesel made from oilseed crops (*e.g.* soybeans, rapeseed, sunflower, palm) or animal fat (Gasparatos and Stromberg, 2012; OECD/IEA, 2010). Most of the current global biofuel production is the result of targets and incentives that players such as Brazil, the United States and the European Union have set up to diversify transport fuel supplies, improve energy security and reduce GHG emissions (IRENA, 2016).

Biofuels made from non-edible biomass and cellulose, hemi-cellulose and lignin, biomass-to-liquids (BTL) and bio-synthetic natural gas are called second-generation biofuels (*2G*) (FAO, 2008b; OECD/IEA, 2010). Typical lignocellulosic feedstocks are agricultural by-products (*e.g.* cane bagasse, corn stover, husks, stalks), forestry residues (*e.g.* thinning, treetops and branches), perennial grasses (*e.g.* switchgrass and *miscanthus*), short rotation coppice (*e.g.* eucalyptus, willow, poplar, acacia) and municipal waste (HLPE, 2013). Lignocellulosic feedstocks often do not compete for high-quality land with food crops due to their high yields and growing capacity on land poorly suited to food crops. Before converting sugars into ethanol through the well-known fermentation and distillation stages, firstly the cellulose and hemi-cellulose components of the biomass must be broken down into sugars, typically in a so-called biochemical conversion route (OECD/EIA, 2010; HLPE, 2013; IRENA, 2016). Feedstocks can also be submitted to a high-temperature process (gasification/pyrolysis) to be converted into a synthesis gas via the thermochemical route. This gas can then be transformed into different types of liquid or gaseous fuel, so-called ‘synthetic fuels’ (OECD/IEA, 2010). Most biochemical and thermochemical technologies are currently in a pilot or demonstration phase.

Because of their current early-stage of development, third-generation (*3G*) biofuels are not yet cost-effective and typically refer to algae-based biofuels. *3G* biofuels usually refer to biofuels that are grown on much less land than *1G* and *2G* biofuels and that do not compete with either food crops or with arable lands, while producing a variety of useful co-products. Conversion of algae to biofuel (biodiesel and jet fuel) involves the same steps needed to convert oilseeds to biodiesel, such as extraction of oil, purification and transesterification of lipids. Several countries have now intensified their research and development efforts into both *2G* and *3G* biofuels due to their technical, economic and environmental potential (IRENA, 2016).

Considering the range of variables involved in biofuel production (including the different raw materials, the biofuel crop considered, the scale of production, the land category considered, cultivation practices, water availability, fertiliser application, conversion technologies and the region or country of production, not to mention climate change considerations in future scenarios) viewpoints on socioeconomic and environmental implications of biofuels are likely to vary widely (Ravindranath *et al.*, 2011). In this regard, traditional biofuels have been criticised for two main reasons. The first is that they may compete with food crops for land, water, nutrients and other resources; the second is that they may impact the agriculture itself, food security, food prices, the local environment and the economy (FAO, 2008), all of which frequently offset the positive impacts of reduced GHG emissions.

First-generation biofuel production may result in both direct and indirect land-use change. Direct land-use change (DLUC) occurs when feedstocks for biofuel production are new crops directly established on arable land, forest or grasslands. Indirect land-use change (ILUC) occurs when the feedstocks for biofuel production are not triggering land-use change on-site, but elsewhere due to the need to compensate foregone production now used for biofuels (Lapola *et al.,* 2010; 2014; HLPE, 2013). Switching native ecosystems to biofuel production by deforestation may drastically harm the desired GHG emission reduction, besides threatening biodiversity (Tilman *et al.,* 2009; Fargione *et al.,* 2010; Lapola *et al.,* 2010; Karp and Richter, 2011; FAO, 2013; Dhillon and Wuehlisch, 2013).

A study conducted by the World Bank targeting land investments by resource-poor, capital-rich countries has shown a weak correlation with cultural affinity between countries of origin and countries of destination. Conversely, a strong correlation was observed between high levels of land investment intentions and 'weak land governance and protection of local land rights' (Arezki *et al.,* 2011). According to the International Water Management Institute, water is in fact the key resource behind these investments (Williams, 2012). Water and land resources are subject to independent regulatory systems and different government responsibilities, and this lack of interlinks between agencies and policies has been leading to land deals that do not consider the water implications of large-scale projects, which can lead in turn to water being overdrawn and the diversion and the drying up of water sources (HLPE, 2013). In this context, it is clear that there is a strong link between environmental (resource availability and use) and economic systems. Therefore, any change in price for any resource can directly and indirectly affect both the price and availability of other resources (*e.g.* water, energy, land, food), impacting society's access to key resources on either a local or national scale. However, price change mechanisms and price impacts on key production inputs are frequently not considered in environmental impact analyses; that is, these analyses are strictly physical in that they focus on the physical flow of resources and ignore the economic implications on the system.

Besides the lack of an integrated governance framework, much of the physical impact of biofuel policies and production on water, energy and food security arises from the choice of feedstock and technology for that production. These factors determine the form of competition for food, feed and land, with diverse land and water needs depending on the feedstock (HLPE, 2013). Therefore, governments should assess the amount of biofuel that can be produced sustainably, giving priority to approaches that complement rather than compete with water use and food production, and that use available land with neither direct nor indirect land-use change (IRENA, 2016).

Regarding the feedstock chosen, Brazil is the biggest sugar producer in the world, the biggest sugar exporter (respectively 21% and 58% of the world total) (FAO, 2017) and the second largest producer of fuel ethanol, with a record production of 30.23 hm^3 in 2015 (UNICA, 2017). Global bioethanol output is mainly concentrated in Brazil and in the United States, which combined account for 85% of total production (MME, 2017b). While Brazilian ethanol is produced from sugarcane, US ethanol is produced mainly from corn. The US ethanol is competitive in terms of its production costs, but its energy balance is not as high as sugarcane-based ethanol and its productivity is lower in terms of area. Considering Brazil's large availability of land for energy crops, its sugarcane ethanol is a well-known success story of commercial use of biomass for energy purposes, based on its low 'well-to-wheels' GHG emissions, the crop's very high yield (typical of C4 plants), low water footprint and its low induced deforestation (Goldemberg, 2008; Pereira *et al.,* 2008; La Rovere *et al.,* 2011).

The use of ethanol as an alternative fuel in Brazil expanded after the first oil crisis, with the PROALCOOL[1] Program in 1975. First it was employed as an octane booster to gasoline and later as a complete substitute in properly adapted engines. The program has attracted significant investment in agricultural and industrial processes related to *1G* ethanol production, stimulating sugarcane growing and the construction of ethanol plants in the country. Additionally, an important domestic ethanol market was consolidated through a huge investment cycle focusing on promoting flex-fuel engines, which gives to consumers the choice of fuelling their cars with petrol or ethanol in any proportion, according to their selling prices. Brazilian ethanol can be produced both in autonomous distilleries and in the most common mixed-sugar ethanol plants.

Brazilian ethanol production rose from 10.6 hm^3 in 2000/01 to 17.8 hm^3 in 2006/07, and then to 27.3 hm^3 in 2016/17, with significant increases in agricultural and industrial productivity (UNICA, 2017). In 2016, sugarcane biomass energy accounted for 17.5% of Brazil's internal energy supply, whereas ethanol had a 5.6% share of the final energy consumption (MME, 2017). When considering all liquid fuels used in the road transport sector alone, the share of ethanol accounted for 18% of the total in 2016, led by diesel oil (45.4%) and gasoline (31.2%) (MME, 2017). Currently, anhydrous ethanol is employed as an oxygenated additive to gasoline (from a blend of 18% to 27% blending of gasoline-ethanol, also called gasohol). Hydrous ethanol is employed in dedicated engines or in flex-fuel engines (up to E100).

As stated by Brazil's National Agency of Petroleum, Natural Gas and Biofuels – ANP (ANP, 2017), as of February 2017, the country had 384 ethanol mills, producing about 334,000 m^3 a day, with sugarcane being the feedstock used in 97% of the authorised mills (ANP, 2017). According to ANP (2016), 36.7% of all ethanol produced in Brazil between

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[1] The Brazilian National Alcohol Program – PROALCOOL – was based on several interventions by the federal government. *'Phase 1 (1975 – 1979): Government effort launched with an initial target to blend anhydrous ethanol to gasoline up to 22.4% (by volume). Phase 2 (1979 – 1986): Government support to strong ethanol production increase. Industry agreement to start producing ethanol powered cars. Phase 3 (1986 – 1989): Ethanol production stopped increasing in 1986. Major supply crisis in 1989 reduced the share of ethanol fuelled cars. Phase 4 (1989 – 2003): Ethanol is mixed up to 24% with gasoline. Phase 5 (from 2003 on): New and huge investment cycle. High oil prices, energy security, and climate change concerns stimulate world demand, increasing export opportunities. Domestic demand growth thanks to flex-fuel cars' (La Rovere et al., 2011).*

2008 and 2015 was anhydrous ethanol, while the hydrous ethanol share was 63.3%. In the same period, 95% of all ethanol consumed was for energy purposes (ANP, 2016).

Sugarcane is cultivated in many Brazilian states, being the top crop in terms of raw biomass production and third in terms of area, after soybeans and corn (IBGE, 2017). The largest sugarcane-producing area is the Centre-South region, accounting for more than 90% of the country's production (**Figure 1**); within that region, São Paulo State produces 56% of the total in Brazil (IBGE, 2017; UNICA, 2017). Sugarcane is also the most irrigated crop in the country (it accounts for 30% of total irrigation in Brazil), with about 17,000 km² (ANA, 2012), and the National Irrigation Policy (enacted in 2013) (BRASIL, 2013) encourages the expansion of irrigated areas. However, 98% of that is the so-called salvage irrigation, *i.e.* 20 – 80 mm/year irrigation aiming to partially reduce water stress in the dry season, which corresponds to the application of vinasse in the soil. Vinasse is a potassium-rich ethanol distillation by-product produced in large amounts (about 10 litres for each litre of ethanol) and diluted with water recycled from the process (when necessary) (ANA, 2017). Therefore, despite the significant share of sugarcane in the total irrigated area, it is noteworthy that the water demand per km² is much lower than that of other crops mainly due to low application levels (salvage irrigation) and high water reuse in industrial processes (vinasse application).

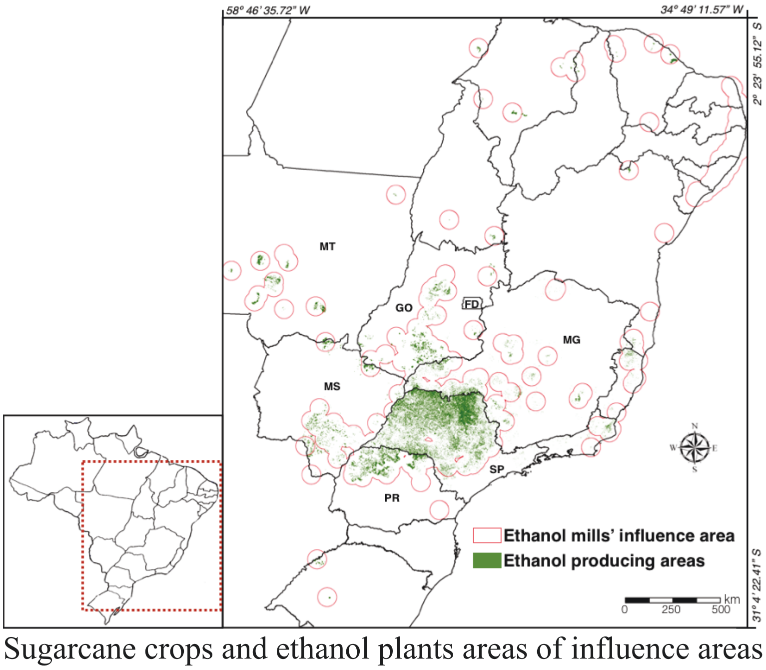

Figure 1. Sugarcane crops and ethanol plants areas of influence areas in Brazil.
Note that the current study focuses on sugarcane expansion in Goiás State (GO), Centre-West region.
Source: Author's adaptation from CONAB (2017).

The projected increase in ethanol consumption in the transport sector over the next decade (about 54 hm^3) (EPE, 2017) includes the expansion of sugarcane production to areas such as the Brazilian Cerrado (a savannah-type biome, located mainly in the Centre-West region) (Manzatto *et al.,* 2009; Fachinelli and Pereira, 2015). There has been rapid growth of sugarcane crop in this region, from about 3,700 km^2 in 2000, to about 19,600 km^2 in 2015, a 5-fold increase (UNICA, 2017). Goiás (50%) and Mato Grosso do Sul (38%) states were the main drivers behind this increase, accounting for 88% of the region's current production (UNICA, 2017). The growing demand for new production sites has led to the exploration of water-stressed areas and it justifies further analysis of the Paranaíba river basin in the state of Goiás, which has recently raised concerns about water and land resource availability.

In this regard, biofuel production has attracted the attention of policymakers and the current debate is largely focused on the environmental and socioeconomic implications of first-generation biofuel crops, since they impact food production, water security and biodiversity (IEA, 2007; Barker *et al.,* 2007; RFA, 2008; FAO, 2008; Fargione *et al.,* 2008; De Fraiture *et al.,* 2008; Lapola *et al.,* 2010; La Rovere *et al.,* 2011; Walter *et al.,* 2011; Ravindranath *et al.,* 2011; Howells *et al.,* 2013; Rulli *et al.,* 2016).

Regarding the important role of Brazil in the global biofuel market and the natural conflicting perspectives on assessing biofuel sustainability, many authors have been investigating the socioeconomic and environmental issues related to Brazil's biofuel production (Macedo *et al.,* 2004, 2005, 2008; Coelho *et al*., 2006; Pousa *et al*., 2007; Goldemberg *et al*., 2008; Garcez and Vianna, 2009; Goldemberg and Guardabassi, 2009; Hall *et al*., 2009; Lehtonen, 2009; Pacca and Moreira, 2009; Kohlhepp, 2010; Rathmann *et al.,* 2010, 2011; Takahashi and Ortega, 2010; Borzoni, 2011; La Rovere *et al*., 2011; Nogueira, 2011; CGEE, 2012; Galdos *et al*., 2013; Nogueira and Capaz, 2013; HLPE, 2013; Herrera, 2013, 2014; Lapola, 2010, 2014; Maroun, 2014; Wilkinson, 2015; UNCTAD, 2016; Carvalho *et al.,* 2016; Watanabe *et al.*, 2016; Obermaier *et al.,* 2017). However, different sustainability analyses frequently use different methodologies and, due to their complexity, which also involves a great number of dependent and independent variables that directly impact on the results, they arrive at very different conclusions. Nor do Brazilian and other international studies on biofuel production usually consider price change effects either when analysing, designing or promoting biofuel policies and their trade-offs in terms of environmental and socioeconomic implications. There is, therefore, an urgent need to include price change effects in traditional environmental analyses to improve the decision-making process with high-quality information.

Thus, there is no consensus on a specific methodology to analyse water, energy and land issues related to biofuel production. In this regard, authors have been studying biofuels through a range of perspectives and by applying distinct methodologies, such as water footprint assessment (Gerbens-Leenes *et al.,* 2009, 2012; Yang *et al.,* 2011; Hernandes *et al.,* 2013; Fachinelli and Pereira, 2015), energy balances (Macedo *et al.*, 2005; Shapouri *et al.,* 2002, 2008), land-use changes (Fargione *et al.,* 2005; Rathmann *et al.,* 2010; Lapola *et al.,* 2010, 2014; Ravindranath *et al.,* 2011; Walter *et al.,* 2011; Howells *et al.,* 2013), GHG emissions (Macedo *et al.,* 2004, 2008; Goldemberg, 2008; Walter *et al.,* 2011; MCTI, 2016), and biofuel sustainability concerns (UNEP, 2009; Sheehan, 2009; La Rovere, *et al.,* 2011; Schaeffer *et al.,* 2011; Mata *et al.,* 2013; FAO, 2013; Castanheira *et al.,* 2014; Rulli *et al.,* 2016; Obermaier *et al.,* 2017). Besides including the aforementioned approaches, examining price change effects may be highly desirable from a policy point of view, because managing physical and economic implications in designing different biofuel policies can be mediated through price change analysis.

Therefore, concerns about the impact of biofuel production highlight the importance of taking into consideration all the resources and socioeconomic effects involved when planning an expansion of energy crops (Berndes, 2008; Gerbens-Leenes *et al.,* 2009; IEA, 2012). In this regard, a water, energy and food nexus approach is currently quite popular in environmental management, finding fertile ground in policymaking and science (Hoff, 2011; Bazilian *et al.,* 2011; Fingerman *et al.,* 2011; Yang and Goodrich, 2014; Al-Said and Elagib, 2017).

Focusing on water, energy and food security simultaneously is often referred to in the literature as the water-energy-food nexus (WEFN). The logic behind the WEFN concept is that it shifts attention from a one-sector view to a more integrated one (Al-Said and Elagib, 2017). Overall, the concerns expressed in the literature emphasise the relevance of water-energy-food (WEF) interlinkages in different time scales for activities that have limited access to water, energy and land resources and for fast-developing regions with rapidly growing demand for all elements of the WEFN (Hoff, 2011; Bazilian *et al.,* 2011; ICIMOD, 2012; WEF, 2011, Rulli *et al.,* 2016).

Two-sector nexus thinking is also not new, particularly when linking water-food, water-land and land-food. Since agricultural irrigation is the activity that makes the greatest demand on water worldwide, knowledge of the water-food linkage is particularly important for water and food policies, especially in countries such as Brazil. Much less has been done on the land-energy, energy-land, energy-water, and energy-food linkages (Ringler *et al.*, 2013). The energy-land linkage is mostly defined by fertiliser applications on land and by fuel use in agricultural machinery. The energy-water and water-energy nexuses have been increasingly investigated, as water (*i.e.* good quality water) is becoming scarcer and energy is becoming less affordable, meaning each of these factors has an impact on the other's development (Pate *et al.*, 2007). At the same time, the rise in water scarcity is increasingly affecting energy production (Van Vliet *et al.,* 2012; Miara *et al.,* 2013).

Despite the growing recognition of WEFN and the existence of a number of examples worldwide, the understanding of how to conduct assessments and tackle complex relationships between the WEFN elements is relatively limited. More innovative frameworks have been developed recently, with a focus on describing the interlinkages in the WEFN, as well as assisting in case studies and, ultimately, identifying policies and actions (IISD, 2013). In this context, most of the nexus studies follow the WEFN mainstream, focusing on physical (flow) analysis and the interdependence between environmental resources (interlinkages). However, these studies do not consider the effects of changes in input prices, such as water, energy, land, etc., on production sectors and, therefore they lack the ability to assess an important variable in the system that could directly affect the policymaking process.

Against this background, Brazil may become again the main player in the global ethanol industry, given its technological capacity, favourable environmental conditions and competitive costs; additionally, examining price effects when promoting future ethanol expansion in the country may be highly desirable from a biofuel policy point of view. The country has great potential for expanding sugarcane production, as well as the logistics required to produce and export ethanol on a large scale (Szklo *et al.,* 2007).

However, this expansion has raised concerns about the sector's sustainability and recently, on food security. For instance, global demands for water, energy and food are estimated to increase by 40%, 50% and 35% respectively by 2030 (US NIC, 2012). Given growing global demand for resources directly involved in ethanol production, such as water, land, energy, labour and capital, the sustainability of Brazilian ethanol has been put at the centre of the country's national policy debates.

Additionally, Brazil has committed to international environmental policies, is a signatory to the Kyoto Protocol and recently submitted its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change – UNFCCC – at the 21st Conference of Parties (COP 21) held in Paris, France, 2015. The country has committed to reducing GHG emissions by 37% by 2025 and has indicated a 43% reduction by 2030, with 2005 emissions as the baseline. Such measures encompass the energy, agriculture, forest, wastes and industry sectors (EPE, 2017b).

Regarding production and use of energy, the commitments include maintaining an 18% share of sustainable bioenergy in Brazil's final energy consumption throughout 2030. This will entail an expansion of biofuel production and consumption, including raising the share of advanced biofuels (*e.g.* second-generation ethanol) and increasing the biodiesel content in diesel blending. The additional biomass is also intended to expand the share of non-hydro renewable sources in power generation to at least 23% by 2030 (EPE, 2017b).

Specifically, the Brazilian NDC aims to achieve a 45% share of renewable energy in the national energy matrix by 2030, with a target of raising *1G* ethanol production to about 50 billion litres[2] (*i.e.*, 50 hm^3 of ethanol), significantly increasing *2G* ethanol production, to 2.5 billion litres (2.5 hm^3) from 2023 onwards, and tripling power generation from biomass, with an emphasis on sugarcane by-products (EPE, 2017b).

Despite this incentive to grow more sugarcane, the crop impacts soil and water through erosion and pollution, and its irrigation requirements can reduce the water available to irrigate food crops, meet human consumption and meet industrial and power generation demands. Water, energy and land are basic resources for any production process, but the

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[2] Brazil's current (2016/17) ethanol production amounts to 27.3 hm^3 (UNICA, 2017).

intensity to which they are being exploited has led to increased environmental impacts. It is also noteworthy that the use of each of these resources affects demand for the others (IAEA, 2009), thereby also affecting their price and availability. Further, water, energy and land use also affects the climate, inducing a negative cycle, since climate change will amplify the challenges of balancing the WEFN elements (Bazilian *et al.,* 2011; Waughray, 2011; IISD, 2013). In addition, when taking climate change concerns and economic aspects into account simultaneously, the impact of carbon pricing on the ethanol sector (and other sectors) can be estimated through the imposition of a fictitious carbon tax policy, for example. As a result, the price of production factors will change according to different carbon prices and these price change estimates may help in designing biofuel policies that consider both the economic and environmental impact of biofuel expansion.

The relationship between water-energy-land resources and their respective policies can be explained briefly. Water policies, for example, are commonly based only on water analysis (elaborated and regulated by a specific agency) and they might have adverse unforeseen effects specially on energy and land resources and the climate. The same happens to energy/land resources, where policies are also based only on analysis of energy/land issues. Since the current policies are based on existing models that usually focus on one resource and ignore interconnections with other resources, better methods and models that consider all the interlinkages among water, energy and land are needed (IAEA, 2009). While this traditional analysis is useful for assessing interconnections through the physical relationships between resources or demand sectors, such physical analyses are not enough to be translated into public policies. That is because they do not include the economic aspects and they will become more useful only if the effects of price changes are taken into consideration as well. Thus, a WEFN approach that considers both the physical and the economic implications of different policy strategies could be a major opportunity for integrated solutions that respond to the interdependencies of water, energy, food and economic systems (IISD, 2013).

1.2 Research Objectives

Against the above background, the main objective of this research is to analyse the wider impacts of the ongoing expansion of sugarcane ethanol production is the Brazilian

Cerrado (specifically in the Paranaíba basin, Goiás State) in order to understand (i) how the interlinkages between the local economic sectors may influence the availability of resources in the region, and (ii) how future demand for ethanol could impact local resource availability, based on current Brazilian ethanol policies and targets. Additionally, this research intends to understand the impact of input price changes (for example, by imposing a carbon tax) on the local economy and environment, including economic arguments that support the physical analysis mentioned above.

Therefore, the main objective of this research is to answer the following questions:

1. Is there room for ethanol expansion in the state of Goiás without significantly impacting water, land and energy resources in the region?
2. What are the economic and environmental impacts when input price changes are considered for this Brazilian case study?

In order to achieve the main objective, five specific objectives have been set. These are as follows:

i) Review biofuel-related policies in Brazil and WEFN studies in order to develop a wider perspective on the environmental and economic impacts of ethanol production in the country

ii) Review the sugarcane ethanol production through the Goiás State case study in order to develop ethanol production expansion scenarios and, ultimately, analyse environmental and economic impacts of ethanol expansion in the state

iii) Develop medium-term ethanol production scenarios for Goiás, taking into account national official forecasts, agro-ecological zoning for sugarcane production, river basin plans and land use in the state

iv) Apply IO concepts to assess the environmental and economy-wide impacts of ethanol expansion in Goiás, assuming an economic-ecological IO framework, and

v) Apply the IO price model to assess the impacts of price changes due to the imposition of a carbon tax policy and analyse the overall impacts on the economy and the local environment.

1.3 Framework, Scope and Significance of this Research

The analysis performed herein is based on the WEFN approach, which is carried out through input-output (IO) model concepts. Since there is no uniform framework to analyse WEFN issues (Leontief, 1970; Isard *et al.,* 1972; Victor, 1972; Bazilian *et al.,* 2011; Fingerman *et al.,* 2011; Howells, *et al.,* 2013; Yang and Goodrich, 2014; Biggs *et al.,* 2015; Al-Said and Elagib, 2017), researchers have been seeking a suitable method to undertake such analysis. Due to its robustness, the IO model is one of the most widely applied methods in economics. It analyses the interdependence of sectors in an economy, showing how the output of a given sector is an input to another, on a national or regional level (Miller and Blair, 2009). IO models can also be expanded to account for energy and environmental impacts (Gay and Proops, 1993; Cruz *et al.*, 2009), by assuming a relationship (*i.e.* proportionality) between the sector's output and the corresponding impact levels. Additionally, some IO model interactions between the Brazilian ethanol sector and the national economic system have been applied to analyse the impact of ethanol and sugar exports (Burnquist *et al.*, 2004; Costa *et al.*, 2006), the impact of adding ethanol manufacturing plants to the ethanol production system (Terciote, 2006), to studies on ethanol demand forecasts (Filho and Filho, 2009) and to socioeconomic analyses of different technological approaches to producing ethanol (Cunha and Scaramucci, 2006; 2006a; Scaramucci and Cunha, 2008). Since most of these studies have focused on the economic aspects of the ethanol sector, they unfortunately could not properly address environmental issues regarding the sector itself and the Brazilian economy.

Conversely, some studies have developed IO analysis that considers the energy and carbon intensities of different ethanol technological routes (Compéan and Polenske, 2011; Figueiredo *et al.,* 2008) and by integrating IO models with life cycle analysis (LCA) to evaluate the economic and GHG emissions of *1G* and *2G* ethanol production in Brazil (Watanabe *et al.,* 2016). Other studies have applied IO models coupled with linear programming approaches to distinct objectives (Hristu-Varsakelis *et al.,* 2010; Tan *et al.,* 2012). Finally, the use of hybrid IO models with multi-objective linear programming

(Carvalho *et al.,* 2015; 2016; 2016a) that analysed the economic-energy-environmental-social spheres coupled with LCA estimates for ethanol production in Brazil was carried out by Carvalho *et al.* (2016a). These authors have concluded that hybrid IO models were useful tools to assess the impacts of changes in the output of economic sectors in ethanol scenarios, highlighting the importance of analysing direct and indirect impacts that result technical and political choices (Carvalho *et al.,* 2016a).

As stated, while IO models have many applications, there has been little investigation of environmental factors (or commodities) in hybrid IO models applied to WEFN (Karkacier and Goktolga, 2005; Hristu-Varsakelis *et al.,* 2010; Li *et al.,* 2012; Holland *et al.,* 2015; White *et al.,* 2017). However, despite some recent relevant studies that use hybrid IO models and focus on analysing the environmental impacts of the Brazilian ethanol system (Watanabe *et al.,* 2016; Carvalho *et al.,* 2015; 2016a), these studies consider only GHG emissions and only one resource in the WEF nexus, *i.e.* they exclude water and land resources. Indeed, studies with hybrid IO models that take GHG emissions and water, energy and land uses into account as variables in the same nexus analysis as explored in this thesis are rare (see White *et al.,* 2017, who have not analysed GDP and employment indicators). Finally, researchers have been doing traditional WEFN analysis, placing much emphasis on the physical elements of the nexus and neglecting input price change impacts. While such analysis is very useful, it is inadequate from a policymaking point of view: physical relationships are not enough to produce high-quality outcomes for the policymaking process and this is the main shortcoming of the traditional nexus analysis. In fact, policymaking demands economic arguments to justify the choice of a specific policy option; these physical interdependences can best be translated into policies when price change effects are included into the analysis.

In this context, we justify the use of hybrid IO models as a WEFN tool to analyse *1G* sugarcane ethanol expansion in the Paranaíba basin, which is located in the Brazilian Cerrado. Additionally, by using IO model concepts coupled with a WEFN approach that focuses on water-energy-land resources, as well as on the GHG emissions and socioeconomic aspects from a river basin/state perspective, this research overcomes the lack of integrated analysis. Additionally, by including price change effects in the analysis, this work also overcomes the criticism related to traditional WEFN analysis (*i.e.* that it is exclusively physical) when applied to the design and promotion of (biofuel) policies. This hybrid IO-WEFN framework was chosen for a number of reasons. The first is its broad potential to assess integrated impacts throughout the economy. Second, it is a reliable decision-making tool for planning purposes and third, it can also be applied to other energy commodities and target sectors, as well as economic systems and regions to promote the sustainability of biofuels and policy integration.

Since the state of Goiás (GO) is one of the leading Brazilian states in sugarcane expansion, it was selected as the case study for analysis in this thesis. The existence of a water resource plan for the important Paranaíba river basin in the state was taken into account when choosing the study area. The Paranaíba basin covers about 220,000 km² in Brazil's Centre-West region and it comprises 63% of Goiás (ANA, 2015). This basin is the second largest river basin in the Paraná hydrographic region, which takes up about 30% of Brazil's entire national water consumption. However, as it has less than 7% of national water availability, there are potential water-use conflicts and even shortages.

The analysis of the issues related to energy was conducted using Brazil's current energy policies, the 'Ten-Year Energy Expansion Plan: 2026 – PDE' (MME, 2017b) and the 'Ethanol Supply and Demand Scenarios – extended version to 2030' (EPE, 2017), both produced by *Empresa de Pesquisa Energética* – EPE (the Brazilian Energy Research Centre, an applied research centre in the Ministry of Energy and Mines – MME). Both Brazil's (MME, 2017) and Goiás' Energy Balance (GOIÁS, 2010, MME, 2016) were analysed and different ethanol supply scenarios were applied to identify future impacts on the availability of resources in the region of study.

Besides the overview of both energy and water regulations, land use was also considered through analysing 'Sugarcane Agro-Ecological Zoning – ZAE Cana' (Manzatto *et al.,* 2009) and data from the public (IMB, 2014; IBGE, 2017, 2017a; CONAB, 2017), private (UNICA, 2017) and third sectors (MAPBIOMAS, 2017).

Due to the multidisciplinary nature of this research, a combination of methodologies is applied, and the overall methodology framework employed is shown in **Figure 2**.

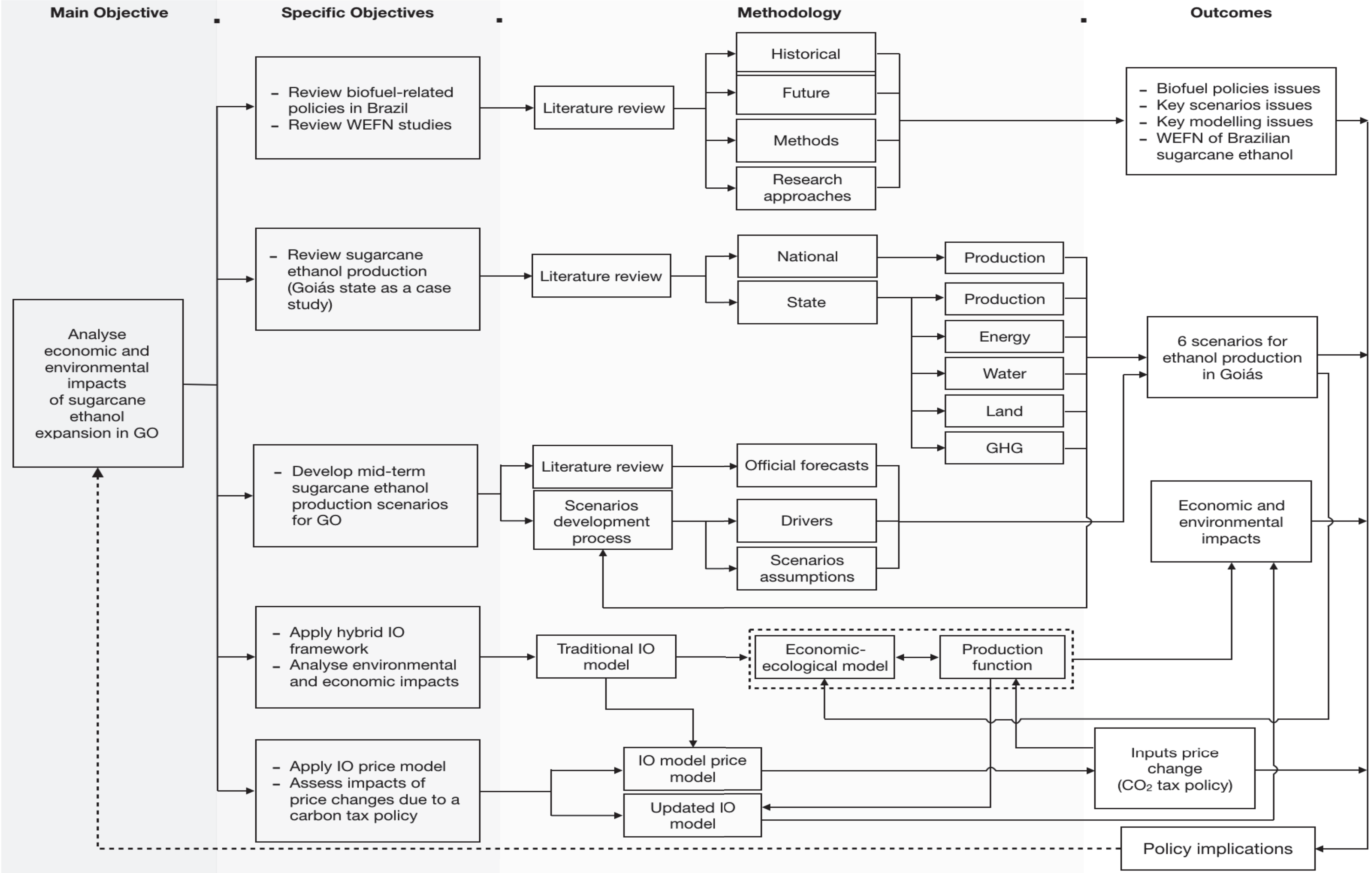

Figure 2. Overview of the research framework

1.4 Organisation of the Thesis

This thesis consists of five sections, namely, *Introduction*, *Biofuel Policies in Brazil*, *Methodology*, *Case Study* and *Conclusions*.

Section 2 presents an overview of the Brazilian national biofuel policy, *i.e.* the *RenovaBio* policy, recently in force in the country and currently in its implementation process. This section also includes a brief historical overview of the Brazilian ethanol program from its inception to the present time, including the motivations for the implementation of the current national biofuel policy, its rationale and future trends. Additionally, the section provides useful insights into the Brazilian Forest Code and the Brazilian Climate Policy, highlighting their interconnections to biofuel production in the country.

Section 3 describes the methodology and scope of this research. It provides an overview of the WEF nexus approach and its applications, as well as different frameworks to analyse the nexus of water, energy and food. This section also describes IO model concepts along with their fundamental formulas, required for the understanding and application of the proposed methodological framework. Regional IO model development and the hybrid IO modelling framework are explored by including water, energy, land-use and GHG emissions as input and output vectors in the original model. Finally, the Leontief price model concepts and the Goiás' economic-ecological IO model are presented; the former, to analyse environmental impacts from sugarcane expansion policies and the latter, to analyse the impacts of input price changes from a carbon tax policy imposition. This section provides all data sources for socioeconomic (employment, GDP and prices) and environmental resources (land, water, energy and GHG emissions).

Section 4 covers the Brazilian sugarcane industry and environmental concerns in the country, and presents the Goiás State case study. Additionally, the Brazilian ethanol outlook and policy scenarios for expanding ethanol production in Goiás are provided. *Section 4.3* presents the results of the case study, including the environmental (local water resources, indirect land-use change, etc.) and economic impacts (on input prices from a carbon tax policy, on sectoral value added, etc.). *Section 4.4*. provides some discussion about the potential impacts of sugarcane crops expansion in the region, highlighting concerns about such impact on local water resources management and indirect land-use change, the impact of price changes on ethanol production and the overall economy, and the lack of integrated policies for WEF and GHG emissions in the country. Finally, *section 4.5* presents some insights into the limitations of this research.

In s*ection 5,* the main conclusions on the WEFN framework applied to the sugarcane ethanol expansion in the state of Goiás are provided, as well as some recommendations for future studies.

2 Biofuel Policy in Brazil

The use of ethanol as an alternative fuel in Brazil expanded after the first oil crisis, with the Brazilian Alcohol Program – PROALCOOL – in 1975, impelling the country to increase the production of *1G* bioethanol based entirely on the fermentation of sugar juice from sugarcane and/or molasses. Ethanol was first employed as an octane booster to gasoline and later as a complete substitute in properly adapted engines. The program has attracted significant investment in agricultural and industrial processes related to *1G* ethanol production, stimulating sugarcane cultivation and the construction of ethanol processing plants in the country. Additionally, an important domestic ethanol market was consolidated through a huge investment cycle focusing on promoting flex-fuel engines, which gives consumers the choice of fuelling their car with petrol or ethanol in any proportion according to their sale price. Brazilian ethanol can be produced in both autonomous distilleries and in most mixed-sugar ethanol plants.

The institutional restructuring of the ethanol industry was established in 1997 with the creation of two important institutions: the National Energy Policy Council (CNPE), and the National Oil Agency (ANP), later renamed the National Agency of Petroleum, Natural Gas and Biofuels. The CNPE is responsible for establishing directives for specific programs for biofuels use while the ANP oversees the regulation, contracting and inspection of biofuel-related economic activities and implements national biofuel policy, with an emphasis on ensuring supply throughout the country and protecting consumer interests in relation to product price, quality and supply.

The PROALCOOL and its subsequent policies (which are not considered formal programs) have been in place now for more than 40 years, setting up Brazil as an important ethanol producer in relation to technological achievements and ethanol use. The PROALCOOL has been analysed in several comprehensive studies that have used different approaches, such as history (Geller, 1985; Goldemberg and Moreira, 1999), policy implementation (Oliveira, 2002), GHG emission reductions (Goldemberg *et al.,* 2004; Szklo *et al.,* 2005; Pousa *et al.,* 2007; Goldemberg *et al.,* 2008), social aspects (Nardon and Aten, 2008; Lehtonen, 2009) and biofuel programs (Hira and Oliveira, 2009; Hall *et al.,* 2009; Garcez and Vianna, 2009; Takahashi and Ortega, 2010, La Rovere *et al.*, 2011, Nogueira and Capaz, 2013).

The Brazilian Biodiesel Production Program (PNPB), launched in December 2004, is a much more recent initiative, and literature and performance history about it are consequently scarcer. In recent years, because of increasing concern about the sustainability of energy systems, as well as the evolution of biodiesel production in Europe, interest in biodiesel has expanded in Brazil. Several institutions have begun to develop activities in this field, and some government actions have been taken.

The PNPB was developed to encourage small producers and farmers from the least developed regions of Brazil to become involved with biodiesel production and to set progressive targets for the mandatory use of biodiesel blends in all diesel oil sold in gas stations. Initially launched with the compulsory addition of 2% in volume to diesel oil (B2), the 2008 PNPB mandate set a target of up to 5% (B5) of biodiesel to mineral diesel. Currently, biodiesel blend accounts for 10% (B10) in almost all diesel oil sold in the country (EPE, 2017b).

From the history of the two programs, it is not difficult to notice the conceptual differences in the motivation for developing each program. The PROALCOOL was first conceived to reduce Brazil's dependency on oil imports and, over time, the program has become a major means to guarantee the sugarcane market and to seek an alternative fuel to gasoline. On the other hand, the PNPB was created mostly on the basis of social inclusion and regional development. Despite this orientation, biodiesel production has developed in Brazil based essentially on extensive soybean production in the Centre-West region, where agroindustry is already well established.

Therefore, government interventions and the focus on value-chain have been very important in increasing ethanol and biodiesel production and use in Brazil, as well as developing their respective technologies during all phases of both programs.

Currently, the Brazilian Energy Research Centre (EPE) publishes an annually-updated Ten-Year Energy Expansion Plan (PDE), which considers the expansion of the Brazilian energy sector and is one of the main tools for planning demand and supply expansion for different energy sources, including biofuels. This report is an important guide from the government to help formulate Brazil's energy policies. The latest report is the PDE 2016-2026 (MME, 2017b), which shows the projected expansion of the energy sector in the decade 2016-2026. Additionally, there are specific publications from EPE/MME regarding ethanol demand and supply scenarios to 2030 (EPE, 2017), as well as the *Demanda da Energia 2050* (*2050 Energy Demand)* technical report (EPE, 2016) that introduces the Brazilian long-term energy targets.

In order to design a national biofuel policy, the Brazilian government has been discussing strategies to implement the *RenovaBio*, a policy that aims to recognise the strategic role of all biofuel sources, *i.e.* ethanol, biodiesel, bio-methane, bio-kerosene, *2G* ethanol and others, in the Brazilian energy matrix. The national biofuel policy, *RenovaBio*[3], focuses on energy security as well as on mitigating GHG emissions from the fuel sector.

The *RenovaBio* does not propose the creation of carbon taxes, subsidies or credits, it does not mandate volume blending of biofuels into traditional fuels and it does not change the existing mandates (such as adding anhydrous ethanol to gasoline and biodiesel to diesel oil). The main goals of the national biofuel policy are:

- to promote a contribution in compliance with the Paris Agreement
- to promote the proper expansion of biofuels in the Brazilian energy matrix, with emphasis on the regularity of fuel supply, and
- to ensure predictability to the fuels market by inducing energy efficiency gains and GHG emission reductions in the production, marketing and use of biofuels.

To meet these goals, the *RenovaBio* has been designed to introduce two basic market mechanisms to recognise the potential of each biofuel in reducing GHG emissions, individually and by each processing plant:

- establishment of national emission reduction targets for the fuel matrix, determined for a 10-year period, whereby national targets will be turned into individual targets. These targets are important for establishing some

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[3] Federal Law n. 13.576, enacted on the 26th of December 2017, 'establish the National Biofuel Policy (RenovaBio) and makes other provisions'. Federal Law available at: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/L13576.htm?TSPD_101_R0=78070d6f3fb51e1519cb38135a4d9fd1r2z00000000000000009fa9deb3ffff00000000000000000000000000005aafcee000bac78138. Presidential Decree n. 9.308, enacted on the 15th of March 2018, 'provides the definition of annual compulsory GHG emission reduction targets for the fuel trade referred to the Federal Law 13.576'. Presidential Decree available at: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2018/Decreto/D9308.htm.

predictability and, therefore, enabling private players to undertake their planning and investment analyses in an environment with less uncertainty, and

- certification of biofuel production with different scores being attributed to each producer (the higher the producer's score, the higher the net energy produced with less CO_2 emissions in the life cycle).

The connection between these two instruments will occur through the creation of biofuel decarbonisation credit (CBIO), a financial asset traded on the stock exchange and issued by the biofuel producer from biofuel sales (invoices). In summary, the *RenovaBio*'s trading scheme is based on national emission reduction targets that, in order to be met, are shared among regulated players, such as fossil fuel distributors; these distributors, in turn, have to meet their individual targets to reduce emissions by purchasing the CBIO credits issued by certified biofuel producers/importers, thus ensuring that the fossil fuel producers themselves contribute to GHG emissions reduction.

2.1 Motivations for the National Biofuel Policy

2.1.1 The Brazilian Biofuel Market

The increased oil production over the decade to 2026 forecast by the Ten-Year Energy Expansion Plan (PDE 2026 (MME, 2017b)), associated with maintaining Brazil's refinery production levels, lead Brazil to being a net crude oil exporter. However, the balance between demand for and supply of the main oil products indicates that the country is likely to continue being a net importer of oil products through to the PDE 2026 horizon, especially due to the large imported volumes of naphtha, aviation kerosene (*QAV*) and diesel oil.

The balance between demand and supply for gasoline A (that, is, gasoline without ethanol) indicates periods when Brazil will vacillate between the threshold of self-sufficiency (*i.e.* about 2,000 m^3/day in 2026) and being a net gasoline importer, despite such *RenovaBio* biofuel policy impacts as bringing important investments in the expansion of ethanol production to the Otto Cycle[4] (EPE, 2017b). In other words, to improve sugarcane ethanol supply and help promote the country's energy security, thereby reducing its dependency on imported oil products, Brazil should expand its ethanol production significantly and improve its sugarcane and ethanol productivity. According to the PDE 2026 (MME, 2017b), the forecasts regarding the Otto Cycle[5] have already considered the impacts of the *RenovaBio* policy and, therefore, in order for these projections to be feasible, *RenovaBio*'s mechanisms should be implemented as soon as possible.

2.1.2 External Dependence on Oil Products

Brazil's dependence on fuel imports has grown substantially since 2010, with net imports surpassing more than 10 hm^3/year, and reaching a maximum of 14.3 hm^3 in 2013 (EPE, 2017b). For comparison purposes, and to indicate the significant size of this dependence, Brazil is the second largest global biodiesel producer, with 3.8 hm^3 produced in 2016 (EPE, 2017b).

External dependence on fuel represents a direct transfer of resources to other countries and a lost opportunity to generate income in Brazil. The country's net expenditure on fuel imports alone surpassed US$10 billion annually between 2011 to 2015. This amount, sent abroad during only six years, would be enough to build more than 500 biodiesel plants or about 130 brand new ethanol mills in the country (EPE, 2017b).

A challenge for the future is to balance the growing external dependence with the expansion of domestic fuel supply. The current deficit will grow in the years to come with the resumption of economic growth and the resulting increase in domestic demand. The solution will include the resumption of investment in ethanol, biodiesel and new biofuels production. However, the lack of a specific public policy until early 2018 and the unpredictability of the ethanol market, coupled with the effects of oil geopolitics, have

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[4] An Otto Cycle is an idealised thermodynamic cycle that describes the functioning of a typical spark ignition piston engine. It is the thermodynamic cycle most commonly found in automobile engines (Chih, 2004).

[5] PDE 2026 (MME, 2017b) also states that electrical vehicles (EV) will account for less than 1% of the total Brazilian fleet by 2026, pointing out some difficulties in introducing this technology into Brazil, such as high EV prices, issues around supply infrastructure, unpredictability of electrical demand, lack of tax incentives due to current budget crisis and public policies that focus mostly on biofuels as the main source of GHG emission reductions in the transport sector.

brought some uncertainty to private enterprise and discouraged market forces from expanding their investment in biofuels.

2.1.3 Observed Growth in Ethanol Imports

There were no significant registered quantities of ethanol imported into Brazil before 2010. However, in recent years, ethanol imports have been increasing, from 0.132 hm³ in 2013/2014, to 1.83 hm³ in 2016/2017 (**Figure 3**). After a long period as a net exporter of ethanol, Brazil became a net ethanol importer in 2017 (*i.e.,* 0.445 m³), just at it is for diesel oil, gasoline and QAV, etc.

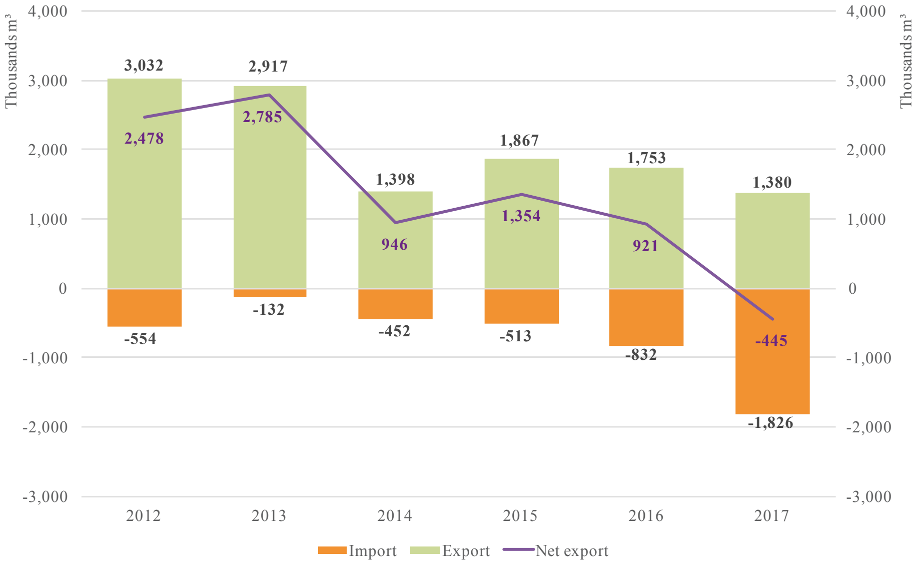

Figure 3. Brazil’s ethanol exports and imports
Source: Author’s adaptation from ANP (2017b).

The excessive growth in all fuel imports is likely to increase in coming years, for two reasons. The first is the resumption of economic growth in Brazil and the second is the lack of any specific policies to encourage both fossil fuel and biofuels production, both of which will involve distribution of imported fuel and that by road transport. In this scenario of inefficiency and the high logistical costs of road transportation, Brazil will impose higher fuel prices on society. In contrast, the option of supporting growth in domestic biofuel supply will contribute to reducing the logistical inefficiency of imports, since biofuels production would be much more decentralised than the production of oil-based fuels.

Regarding other sources of supply, national production of oil products is quite close to the industrial support capacity and the country is already dependent on the foreign market for gasoline and diesel oil. Petrobras refineries, which account for most of the national production, have a high utilisation factor, and no new investment in expanding capacity is envisaged in the short term.

Although ethanol has long contributed to slowing down the growth of gasoline imports, its expansion in the energy matrix has been restricted by several factors, such as few greenfield projects, restrictions on sugarcane expansion areas, the low viability of large-scale *2G* ethanol plants, international interest in Brazilian ethanol, and the economic attractiveness of hydrous ethanol. Therefore, in order to become independent of gasoline and diesel imports, Brazil has no alternative but to increase domestic production by constructing new refineries and revamping existing ones, or through expanding domestic biofuels, *i.e.* ethanol and biodiesel, production.

However, after the 2008/2009 international financial crisis, the Brazilian ethanol industry suffered from a reduction in the sugarcane processing rate compared to previous years. Additionally, sugarcane productivity itself has varied since 2010 (mostly due to producers' financial issues) from 77 t/ha in 2010/2011, to 67.1 t/ha in 2011/2012, 74.8 in 2013/2014, 76.9 t/ha in 2015/2016 and, finally, to 72.6 t/ha in 2016/2017 (EPE, 2017b). There are several reasons for this, stemming largely from financial problems[6]. Gasoline prices pushed down the price of hydrated ethanol, reducing its margins. This margin reduction in an already indebted sector in turn jeopardised investment in the replanting of sugarcane fields, investment that was fundamental to ensuring productivity to meet demand for the coming years. This reduction also jeopardised investment in technological development and in adopting new sugarcane varieties.

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[6] Besides financial issues, sugarcane productivity was also affected by the introduction of compulsory mechanisation in both the harvesting and planting stages. For instance, producers have had difficulty handling machinery that could improve both sugarcane (*i.e.* t/ha) and ethanol productivity (*i.e.* l/t). This is because they had to set an ideal height to cut the cane: if they cut the cane too close to the ground, the cane juice would be contaminated by the soil and this would reduce the total recoverable sugar (TRS); if the cut was too far from the ground line, producers would lose a significant portion of the TRS, since there is a high concentration of TRS in the lower part of the cane stalk. In addition, mechanisation means greater soil compaction and lower density of plants per area since the crops must conform to the specifications of the machines. Finally, climate conditions were not good enough (*e.g.* low rainfall volume and above average temperatures) to improve sugarcane productivity in recent years (EPE, 2015).

Therefore, this became a negative cycle whereby the deterioration in economic and financial conditions could continue into the future. Further, if a policy to help reverse this negative cycle is not implemented, stagnation or declining sugarcane productivity may affect fuel prices, with negative impact on consumers. At the same time, there was an increase in sugarcane production costs, largely due to the introduction of compulsory mechanisation, both in the harvesting and planting stages. Besides damaging current production and the productivity of the next harvests, this environment of financial difficulties was not conducive to new investment in production capacity, and only seven brand new ethanol plants were installed between 2012 to 2017 (EPE, 2017b).

2.1.4 Risks to National Fuel Supply

It is important to consider that the national fuel supply is considered a public utility. Among other objectives of the National Energy Policy, under the terms of § 1º of art. 1º of Federal Law n. 9,847/99, it is the duty of the state to ensure regularity and continuity of supply, protecting the interests of the consumer related to price, quality and product supply (Federal Law n. 9,478/97).

The economic recession experienced in recent years has contributed to mitigating the risk of fuel shortages by reducing fuel consumption in Brazil. However, the resumption of economic growth expected in the coming years will lead to an expansion in domestic demand for fuel. Given the positive correlation between GDP and energy consumption, which includes fossil fuels and biofuels, economic recovery will significantly increase the risk of fuel shortages. However, even under the effects of the economic recession, there are risk factors to the national fuel supply, such as:

- limited refining capacity
- unfavourable scenario for investments in new refineries
- long maturation and construction time of new refineries (at least four years)
- intensification of fuel transportation by road
- exponential increase in fuel imports, raising the country's exposure to the risks of oil geopolitics, and

- lack of both import and handling infrastructure to manage the increasing volumes of imported fuels.

In summary, fossil fuel consumption in the country has increased at high average rates but domestic production capacity has not developed at the same pace and investment in import and storage infrastructure has not been sufficient to ensure a suitable fuel supply. For biofuels, the following risks can be highlighted:

- limited biofuel production capacity
- unfavourable scenario for investment in ethanol production (which has been affecting sugarcane productivity)
- unpredictability for new investment in biofuels
- debt and closure of several ethanol and biodiesel production units
- lack of investment in the sugarcane production cycle
- decrease in sugarcane productivity
- increased dependence on imported ethanol to ensure the mandatory addition of anhydrous ethanol to gasoline, and
- lack of long-term pricing and contracting policies and mechanisms.

Considering the maturity of investment in fuels and biofuels, the inaction of the State represents a risk to society, both in terms of supply (regularity of supply) and price (external exposure and logistic inefficiencies).

Regarding energy security, the *RenovaBio* aims to promote the appropriate expansion of biofuel production and use in the country. Brazil seeks to establish a biofuel policy that takes into consideration the evolution of the market for oil and natural gas products (which is often influenced by exogenous issues) but does not create imbalances in the biofuels industry, given its importance for energy security, GHG emission commitments and national development.

The proper balance of the various markets to which biofuels are related involves taking market failures into account (*i.e.,* externalities, imperfect competition, information asymmetries) and the public good, different business strategies and the influence of external factors such as oil geopolitics. Therefore, balance depends on the reliability of the state in encouraging and regulating economic activity, which requires specific public policies and planning.

Currently, biofuels account for 26% of the Brazilian fuel matrix. Part of this share has been achieved through mandates for blending biofuels into gasoline and diesel, *i.e.* 27% of anhydrous ethanol blending to gasoline (EPE, 2017b) and 10% biodiesel blending to diesel oil (http://mme.gov.br). Despite these mandates, the lack of a national biofuel policy until early 2018, particularly in the case of ethanol (greater volumetric expression), has resulted in a large variation in ethanol's share of fuel consumption in the Otto Cycle.

2.1.5 Volumetric Targets for Biofuels

For nearly 90 years, the Brazilian fuel sector has met mandatory targets for biofuel blends, a successful worldwide example of replacing fossil fuels with renewables. This policy began in the 1930s, with the addition of anhydrous ethanol to gasoline, which was essentially imported at that time.

With PROALCOOL in the 1970s, influenced by the two oil crises and their impact on the Brazilian economy, the production and use of ethanol was developed on a large scale. Anhydrous ethanol was the first product to gain notability in terms of scale, with the increase in its content added to gasoline. As a result, for several years, the minimum anhydrous blend to gasoline was equal to 20%, a percentage that surpasses any other blend in the world. Still in PROALCOOL, a new fuel appeared: hydrous ethanol. It was initially used only in cars with engines dedicated to this biofuel and, as of 2003, in flex-fuel vehicles, which can use any proportion of hydrated ethanol and gasoline. Since their release, sales of flex-fuel vehicles have reached impressive levels, surpassing the sale of gasoline vehicles after just three years (**Figure 4**).

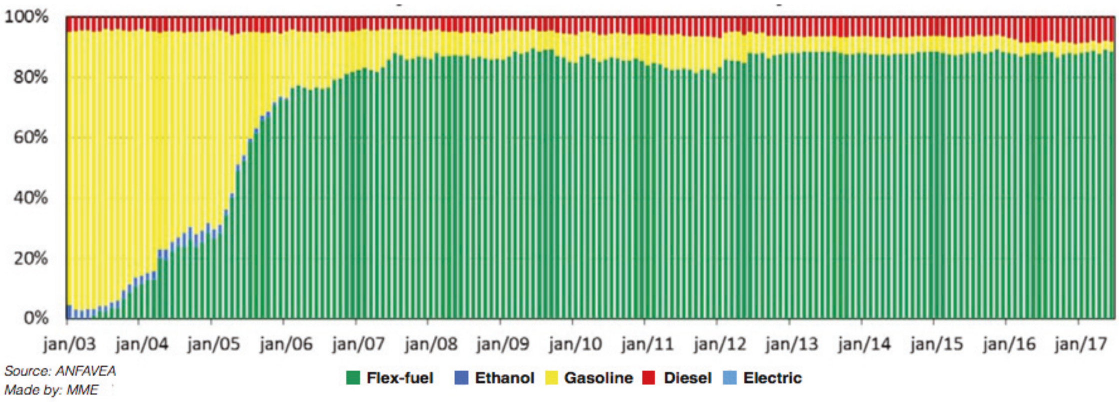


Figure 4. Evolution of car sales in Brazil
Source: Elaborated by MME (2017c), from ANFAVEA data.

In December 2004, the National Program for the Production and Use of Biodiesel (PNPB) introduced biodiesel into the Brazilian fuel matrix. Taking advantage of the experience of adding anhydrous ethanol to gasoline, the PNPB set targets for blending biodiesel with all fossil diesel traded in the country, starting at 2% (blend B2). This percentage was increased until it reached 8% in 2017. The Federal Law n. 13,263/2016, which defined B8 (8% blend), also established the schedule for introducing the B10 blend into the market by March 2019, but CNPE anticipated this 10% blend in March 2018, *i.e.* it is currently in force.

This Brazilian experience in biofuels was largely assured, maintained and renewed over time through biofuel participation targets defined by law, a legacy of different governments recognising that biofuels were so important they needed to be managed via state policy. As a result of these private and public initiatives, there were three periods when the share of biofuels exceeded a quarter of all fuel traded in the country, namely, 1989 (25.1%), 2009 (25.5%) and 2015 (26.4%) (EPE, 201b). This high proportion is not found in any other country and is a result of the state's long-defined strategy regarding the use of sustainable fuels and its links to regional development. However, even though the share of biofuels in the mix is high compared to the rest of the world, it is relatively small in the Brazilian energy matrix, which comprises other important renewable energy sources.

Therefore, assuming the resumption of economic growth, maintaining the biofuel share will require major investment in both new ethanol and biodiesel plants and the commercial introduction of other biofuels, such as bio-kerosene and biogas/bio-methane.

Regarding climate commitments, *RenovaBio* is also in line with Brazil's commitment to the 21st Conference of the Parties (COP21) of the UNFCCC in Paris. The Conference adopted a new agreement with the central objective of strengthening the global response to the threat of climate change and strengthening the capacity of countries to deal with the impacts of climate change. In order to achieve the ultimate goal of the Agreement, governments made their commitments based on their so-called Nationally Determined Contributions (NDC). Through the NDCs, each country presented its contribution to reduce GHG emissions, following what each government considered suitable from its own socioeconomic scenario.

Brazil committed to reducing GHG emissions by 37% by 2025 and it has indicated a 43% reduction by 2030, with 2005 emissions as the baseline. Such measures encompass the energy, agriculture, forest, wastes and industry sectors (EPE, 2017b; Brasil, 2015). To this end, among other possible measures, the country undertakes to increase the share of sustainable bioenergy in its energy matrix to approximately 18% by 2030. This commitment assumed at COP21 offers the Brazilian society an opportunity to use biofuels as a development vector that contributes to emissions reduction, among other positive externalities.

2.2 The National Biofuel Policy Scheme

2.2.1 Biofuels Production Certification

The *RenovaBio* policy seeks to stimulate the improvement of biofuel environmental performance relative to fossil fuels, focusing on energy efficiency and reducing GHG emissions. This incentive translates into the concession of decarbonisation credits to fuel distributors, according to the energy and environmental efficiency scores associated with the biofuels in which they trade. The energy-environmental efficiency score of a biofuel is defined as the difference between its carbon intensity and the carbon intensity of its fossil fuel substitute, established by the certification process. Certification is the process that verifies the correctness of technical data regarding the biofuel and biomass production processes that feed *RenovaCal*, a support tool that calculates biofuel carbon intensity (in mass of CO_2 equivalent by unit of energy – gCO_{2e}/MJ). The intention of the certification process is to give credibility and transparency to the environmental performance evaluation of the *RenovaBio* program.

Certification takes place within the biofuel production unit (plant) and the biofuel importers and, in order to compare the national biofuel carbon intensity with that of imported biofuels, GHG emissions from the distribution phase are also taken into account. Foreign biofuel producers are now subject to the same verification procedures as domestic producers. The methodology used to calculate the GHG emissions of imported biofuels is the same as those used internationally, in that they include the GHG emissions caused by the transportation of that biofuel into Brazil. This means that biofuel importers can have confidence in the accuracy of the information they get about the products they are bringing into Brazil. Equally, Brazilian biofuel can be compared fairly with those imports.

Thus, focusing on determining the carbon intensity of biofuels, an environmental performance assessment protocol based on the Life Cycle Assessment (LCA) was developed internationally. The LCA evaluates the environmental impact of a product throughout its life cycle in terms of the materials and energy consumed by the production processes and released to the environment from natural resource extraction through manufacture, transportation, use and final disposal of the product. Although a full LCA covers several categories of environmental impact related to the protection of natural resources, ecological systems and human health, climate change is the only category that the *RenovaBio* LCA scheme analyses in its initial phase, using gCO_{2e} as the standard unit. However, neither the Federal Law n. 13,576 nor the Presidential Decree n. 9,308 mention indirect land-use change GHG emissions in their estimates. The *RenovaCal* is therefore unlikely to take into account ILUC GHG emissions when analysing and certifying biofuel plants through the LCA approach. The *RenovaBio* thus excludes a significant source of indirect effects that may offset GHG emission reductions achieved through the use of biofuels.

In the first phase of the *RenovaBio* program, the following biofuels will be considered: first- and second-generation sugarcane ethanol, corn ethanol, soybean biodiesel, animal fat biodiesel, hydro-processed ester fatty acids (HEFA) bio-kerosene, sugarcane synthesised iso-paraffin (SIP) bio-kerosene, bio-methane from sugarcane by-products, bio-methane from meat manufacturing and bio-methane from municipal solid waste.

A Committee for the Monitoring of Biofuels and Fuels (CMBC) will be constituted to monitor and evaluate the regularity of national biofuel and fuel supply, and it will propose to the CNPE (National Council for Energy Policy):

- annual compulsory targets to reduce carbon intensity in the total supply of fuel in the market
- guidelines, criteria and parameters for accreditation of regulating companies and certification of biofuels, and
- requirements for technical and economic regulation of decarbonisation credits.

The annual compulsory GHG emission reduction targets for the fuel market was expected to be defined by June 2018, for a minimum period of 10 years. Carbon intensity reduction targets will be individualised by the ANP for each distributor, based on their fossil fuel market share of the total market for these fuels in the period before the mandate came into effect, according to Presidential Decree n. 9,308 and until June 2019. The share of each fuel distributor in the fossil fuel market will determine its obligation for the following year.

2.2.2 Biofuel Decarbonisation Credits (CBIO)

The *CBIO* will be a financial instrument registered in book-entry form to record the objectives of the individual fuel distributors. The number of decarbonisation credits to be issued will take into consideration the volume of biofuel produced or imported by the primary issuer, and according to the relevant energy-environmental efficiency score contained in the primary issuer's certificate of efficient biofuel production. The energy-environmental efficiency score consists of a score attributed to each primary emitter, based on the difference between the carbon intensity established in the certification process and the carbon intensity of its fossil fuel substitute, having a tonne of CO_2 as the standard unit.

To determine the standard unit for regulation purposes, the first step will define the baseline of standard fossil fuel carbon intensity (gasoline, diesel, natural gas, etc.) and identify the standard biofuel substitutes. The second step would be to apply the *RenovaCal* LCA tool (the object of the certification process) to the specific biofuel production unit. The result will indicate the biofuel's carbon intensity, *i.e.* gCO_{2e}/MJ, for each specific plant. The certification score will then be given by the difference between the baseline of the fossil substitute and the *RenovaCal* result (**Figures 5** and **6**).

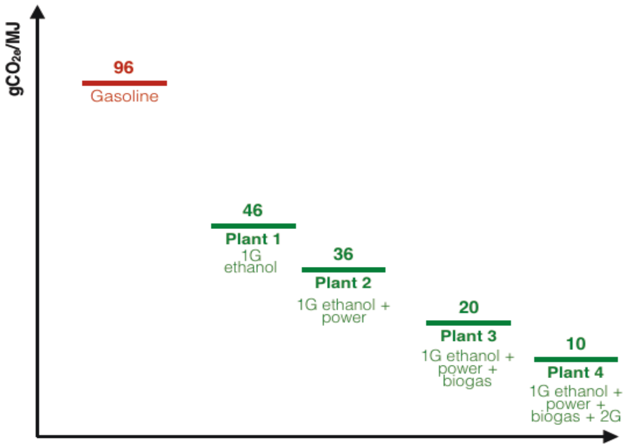
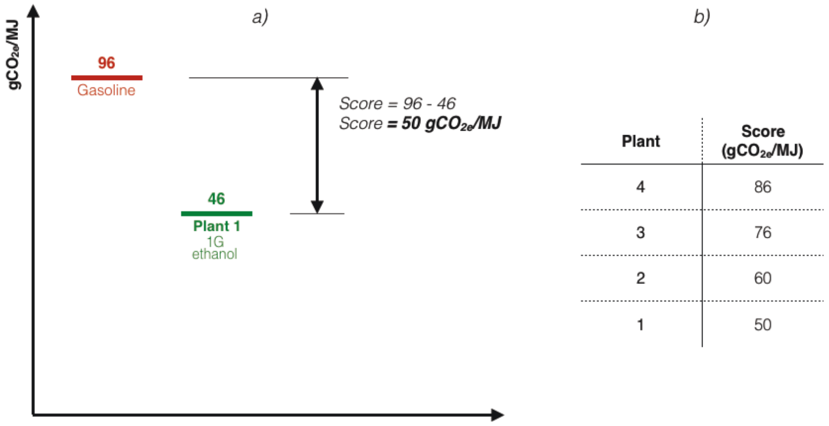


Figure 5. Calculation of the certification score.
Note: Score = Fossil baseline – RenovaCal results. Hypothetical values.
Source: Adapted from EPE (2017b).



Plant	Score (gCO_{2e}/MJ)
4	86
3	76
2	60
1	50

Figure 6. Hypothetical example of certification score calculation for *a)* plant 1 and *b)* other plants.
Source: EPE, 2017b.

Considering that in this hypothetical example, the hydrated ethanol energy content is equal to 21.35 MJ for each litre, it has been verified that hypothetical *plant 1* sold 640,500

MJ of energy by trading 30,000 litres. As its certification score is 50, multiplying 640,500 MJ by the certification score results in 32 million *CBIO*. What is intended to happen in reality, after trading a minimum quantity of certified biofuel (determined in specific regulations), the biofuel producer or importer will have the right to issue decarbonisation credits (*CBIO)* within 60 days. The biofuel producer or importer responsible for issuing book-entry decarbonisation credits will hire a bookkeeper, bank or financial institution to issue the *CBIO* on its behalf. Although this results in higher costs, the involvement of a financial institution brings more security to *CBIO* operations, which in turn attracts institutional investors (investment funds and banks) to the carbon credit market, discourages fraudulently (without invoice) commercialisation of biofuel trading and adds transparency to operations in the fuel market.

The organised market is therefore an environment with computerised systems and rules for trading in securities (stocks and other assets). The main role of the stock and over-the-counter markets is to organise, maintain, control and ensure favourable environments or systems for meeting offers and conducting business with efficient price formation, transparency and disclosure of information and security in clearing and settlement of business. Finally, the costs of the *CBIO* (in the financial market) will be individually negotiated with the bookkeeper and collectively with the organised market.

2.2.3 RenovaBio Impact Estimates

RenovaBio will promote the expansion of biofuel supplies in Brazil and seek efficiency and productivity. The favourable trading environment will allow the program to add 1.4 trillion R$ in investments by 2030[7]. This amount includes investment in new industrial facilities and the implementation of new agricultural areas (CAPEX), valued at 0.54 trillion R$, by 2030[8]. In turn, investments in OPEX will account for 0.86 trillion R$[9] (EPE, 2017b).

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[7] Around US$433 billion, assuming an average exchange rate of 3.23 R$/US$ for a year period (BCB, 2017). R$ = Brazilian Reais.

[8] Around US$167 billion, assuming an average exchange rate of 3.23 R$/US$ for a year period (BCB, 2017).

[9] Around, US$266 billion, assuming an average exchange rate of 3.23 R$/US$ for a year period (BCB, 2017).

These investments were estimated by EPE based on assumptions established by the MME and primary information provided by biofuel industry associations. Taking CAPEX (land price plus production unit cost, sugarcane cost, biodiesel raw material cost, soy crushing units) and OPEX (sugarcane fields renewal cost, replanting of soybean, operational cost) into account, EPE assumed a 3% GDP growth per year between 2017 to 2030, thereby cancelling out the national oil product imports (gasoline and diesel).

Based on these assumptions, *RenovaBio* will add 24 *1G* new ethanol production units and promote the expanded production of 31 existing plants, which will increase the national ethanol production by 25 hm^3. If we consider *2G* sugarcane ethanol alone, 29 new plants would be added to the system, producing 2.3 hm^3/year, giving a total of 84 new *1G* and *2G* production units in the sugar-energy sector. Biodiesel production will increase the production units' utilisation factor from 59% to 79% and lead to 27 new plants in the country. Investment in 10 soybean crushing units is also planned. *RenovaBio* is expected to add 7 hm^3/year to national biodiesel production by 2030.

Given these expectations, it is can be seen that with the implementation of *RenovaBio,* the biofuels sector will have added 22% to GDP in current values by 2030 (EPE, 2017b). In addition to bringing new investment into Brazil and generating income, *RenovaBio* will employ around 1.4 million workers in constructing and operating the new production capacity added to the agricultural phase of the process. In this preliminary analysis, jobs related to the production of raw material for biodiesel, ethanol and biogas production, as well as to the construction and operation of new manufacturing plants, were taken into account.

Therefore, the present proposal to create a national biofuel policy will have impact not only on the production sector, but also on the national economy. The enactment of this *RenovaBio* biofuel bill into law late in 2018 gives a positive signal to all the economic agents involved who are waiting for the implementation of an energy policy by the government regarding the role and importance of biofuels in the energy matrix. *RenovaBio* is characterised as a market solution, with no tax changes, with positive effects on tax collection and economic growth, without subsidies or any other form of burden on public accounts. Finally, other effects of *RenovaBio* implementation worth highlighting (EPE, 2017b) are as follows:

- import savings of around 13 hm³/year of gasoline, accounting for about R$18 billion per year in 2030[10], at today's prices, and
- under *RenovaBio*, increasing the share of biodiesel could generate savings by more than R$9 billion per year by 2030[11].

Since the Brazilian government has just implemented a national biofuel policy that will boost domestic ethanol production in the coming years, it is important to analyse the impact of biofuels expansion on water, land and energy uses, as well as on the GHG emissions related to the biofuel production process. The true impact of biofuel expansion on society, despite the obvious economic gains, can best be evaluated by integrating all the individual policy targets for water, energy, food and emissions, an approach that should be encouraged. In this context, we justify our choice of using a nexus approach by applying integrated tools that consider the socioeconomic, energy and environmental aspects of biofuels production to analyse the Brazilian sugarcane ethanol expansion through a case study.

2.3 Biofuels and the Brazilian Forest Code

The conflict between the need to increase agricultural production (including biofuels) and the conservation of Brazilian forests has generated political pressures to revise the Brazilian Forest Code, which provides, among others, environmental conservation in private properties. The proposal for a new code, more flexible or less demanding, has been debated for more than a decade in the Brazilian Congress and in society. Despite controversy, the 'New Brazilian Forest Code' (Federal Law n. 12,651) was enacted in October 2012, providing the main legislation for the protection of native vegetation and national biodiversity (Brasil, 2012).

The Forest Code establishes general rules for the protection of vegetation in Permanent Preservation Areas and areas of Legal Reserve, as well as for logging, supply of forest raw materials, control of the origin of forest products and control and prevention of forest

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[10] Around US$5.6 billion, assuming an average exchange rate of 3.23 R$/US$ for a year period (BCB, 2017).

[11] Around US$2.8 billion, assuming an average exchange rate of 3.23 R$/US$ for a year period (BCB, 2017).

fires. Overall, it provides economic and financial instruments to achieve the following goals (Brasil, 2012):

i) confirm Brazil's commitment to the preservation of its forests and other forms of native vegetation, as well as biodiversity, soil, water resources and the integrity of the climate system

ii) reaffirm the importance of the strategic function of agricultural activity and the role of forests and other forms of native vegetation in sustainability, economic growth, improvement of the Brazilian population's quality of life and the country's presence in the national and international markets for food and bioenergy, and

iii) provide governmental actions for the protection and sustainable use of forests, highlighting the country's commitment to the balance between the productive use of land and the preservation of water, soil and vegetation.

For the general understanding and enforcement of the Forest Code, Permanent Preservation Area (PPA) is defined as a protected area, covered or not by native vegetation, with the environmental function of preserving water resources, landscape, geological stability and biodiversity, which facilitates the genetic flow of fauna and flora, protecting the wellbeing of human populations. In short, PPAs can be understood as areas of significant environmental relevance, such as the margins of any natural and intermittent natural watercourse, areas around lakes and natural lagoons, areas surrounding artificial water reservoirs, areas around springs and perennial water springs, slopes or parts thereof with a slope greater than 45°, *restinga vegetations*[12], as dune fixers or mangrove stabilisers, mangroves in all their extent, the edges of plateaus, up to the relief line of hills, mountains and areas at an altitude greater than 1,800 metres, regardless of the vegetation. Therefore, according to the protection regime established, any vegetation located in PPAs shall be maintained by the owner of the area and, in the case

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[12] Restinga is a geographical space always formed by sandy deposits parallel to the shoreline, in a generally elongated form. The restinga vegetation is understood as a set of vegetation communities, physiognomically distinct, under marine and fluvio-marine influence. These communities occur in areas of great ecological diversity and are considered edaphic communities because they depend more on the nature of the soil rather than the weather.

of suppression of native vegetation in a PPA, the owner is obliged to promote native vegetation recovery.

For the purposes of the Forest Code, a Legal Reserve (LR) is an area located inside a rural property that ensures the sustainable economic use of a property's natural resources, assisting the conservation and rehabilitation of ecological processes and promoting biodiversity conservation, as well as providing shelter and protection for wildlife and native flora. The code states that all rural properties shall maintain an area with native vegetation cover as a LR, without prejudice to the application of the rules on PPAs, observing the minimum percentages with regards to the area of the property, *i.e.* 20% when the property is located outside the Legal Amazon[13]. However, if the property is located in the Legal Amazon, a minimum of 35% of the area shall be kept as native vegetation in the Cerrado biome and 80% of the area shall be preserved in the case of rural properties located in forest areas (Brasil, 2012).

In this context, LR areas must be preserved with native vegetation cover by the owner of the rural property (even if the economic exploitation of the LR is approved), provided that it occurs by the means of sustainable management. However, any activity on a LR shall be previously approved by the agency in charge and in the sustainable management of the LR forest vegetation, selective exploitation practices shall be adopted in the ways of sustainable management without commercial purpose for consumption in the property and sustainable management for commercial exploitation.

The aforementioned aspects of the Brazilian Forest Code constitute the main changes to the previous Forest Code in force before 2012 and, therefore, these aspects were and still are the most important controversial points of the 'Brazilian New Forest Code'. Overall, the Brazilian Forest Code has been criticised for eliminating or reducing several safeguards previously in force, such as the annulment of the need for vegetation recovery in consolidated areas[14] in small farms, and a reduction in the size of PPAs.

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[13] Legal Amazon consists of an area that covers the Brazilian states of Acre (AC), Pará (PA), Amazonas (AM), Roraima (RR), Rondônia (RO), Amapá (AP) e Mato Grosso (MT) and the regions located north of the 13º S parallel in the states of Tocantins (TO) and Goiás (GO) and West of the 44º W meridian in the state of Maranhão (MA).

[14] A consolidated rural area consists of an area of rural property with anthropic occupation pre-existing on the 22nd of July 2008, with buildings, improvements or agricultural activities (Brasil, 2012).

In this context, several studies indicate that there was a reduction in the need to recover native forests on rural properties. Soares-Filho *et al.* (2013) estimated that Brazilian forest liabilities[15] were reduced by 58% (*i.e.* from 500,000 to 210,000 km²), accounting for deforestation in LRs and PPAs. However, even with the reduction in reforestation obligations and other concessions introduced by the New Forest Code, Brazilian forest liabilities are still high (Soares-Filho *et al.*, 2013; Soares-Filho, 2015; Young *et al.*, 2016). Overall, environmental liabilities are concentrated on the edges of the Amazon, for almost the entire length of the Atlantic Forest and in the Southern Cerrado, where agricultural occupation is higher. Biomes with greater environmental liabilities are Amazon (*i.e.* 80,000 km²), Atlantic Forest (*i.e.* 60,000 km²) and Cerrado (*i.e.* 50,000 km², of which about 7,500 km² is in the state of Goiás) (Soares-Filho *et al.*, 2013; 2015; Young *et al.*, 2016) (**Figure 7**).

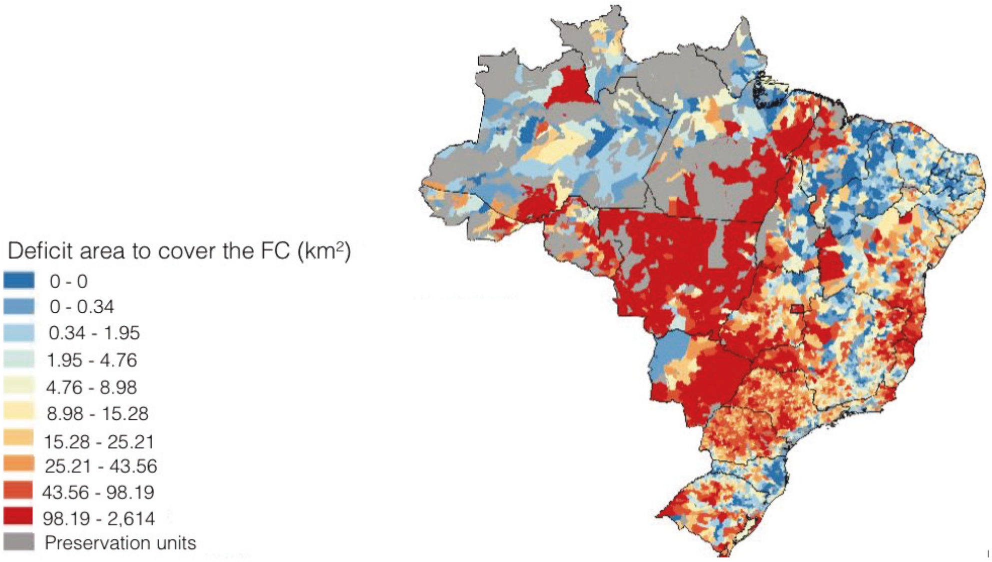

Figure 7: Environmental liabilities after the Brazilian Forest Code revision.
Source: Adapted from Young et al., 2016.

The revision of the Forest Code caused great loss in areas that needed to be revegetated. On the other hand, its improved mechanisms make revegetation more feasible. One of these mechanisms is the Environmental Reserve Quota (ERQ), which represents an area with native vegetation or in the process of recovery with recovery surplus to the Legal Reserve. The ERQ of one property can be used to offset the Legal Reserve deficit of

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[15] Forest liabilities refers to the area of native vegetation that a particular rural owner should add due to the native vegetation being below the minimum requirements required by the Forest Code.

another, provided that it has an area equivalence and is situated in the same biome and preferably in the same state. It is estimated that with the implementation of the ERQ, a monetary credit market for forested land can be consolidated, thereby adding value to native forests.

Soares-Filho *et al.* (2013) have confirmed the viability of this market by pointing out the sources of forest assets (surplus) and demonstrating that it is possible to reduce environmental liabilities in LRs by 55% (*i.e.* about 160,000 km²), offsetting the deficit by means of ERQs from the same biome and state. They state that the conflict between areas that need to be revegetated/reforested but are currently used for agricultural activities are relatively small in Brazil. Overall, Brazil has about 3 million km² occupied by agricultural activities, of which 680,000 km² are covered by crops and the rest by pasturelands in varying degrees of occupation, productivity or degradation. From the PPAs liabilities (*i.e.* 48,000 km²), it is estimated that only 6,000 km² may be occupied by crops, accounting for less than 1% of national agriculture (Soares-Filho *et al.*, 2013). Of the 2.3 million km² of pasture, 60% could be used for agriculture if climatic restrictions are not taken into account (**Figure 8**). Therefore, livestock production has to increase its productivity so that the same level of meat production is maintained at the same time as land is made available for the agricultural transition.

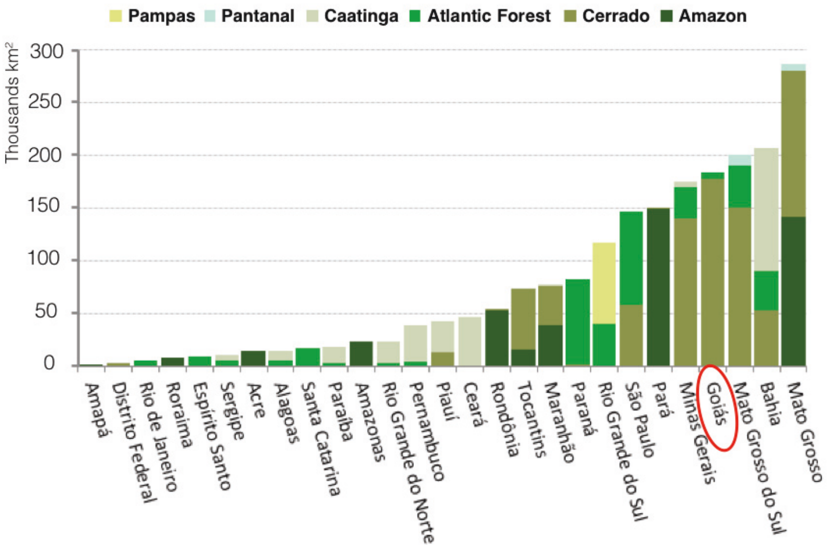

Figure 8: Available pasturelands suitable for agriculture production for each Brazilian state, without considering climate restrictions.
Note: the state of Goiás highlighted by the red circle.
Source: Adapted from Soares- Filho et al., 2013.

Although solutions exist, the costs of forest recovery are not negligible. If the opportunity costs of avoiding CO_2 emissions from deforestation are low, the costs of recovering PPA and LR can be prohibitive, especially for small and medium-sized rural producers (Soares-Filho *et al.*, 2013; Young *et al.*, 2016). There is also a need to enhance the recovery effort and forest preservation through payment for environmental services (PES). Environmental services are the benefits generated by ecosystems for society and can generally be grouped into four categories: *i)* carbon capture and storage, *ii)* biodiversity protection, *iii)* watershed protection, and *iv)* scenic beauty protection. The starting point of the PES is that conservationist behaviours revert to benefits for the whole society. However, the task of pricing is fraught with enormous technical complexity and political and economic sensitivity, as it impacts groups of paying and recipient agents. In general, it constitutes an intervention mechanism in the economic domain, deliberately constructed to change the relative opportunity cost of environmental services over other possible allocations of the assets involved.

Through estimating costs and benefits from a PES policy in Brazil, Young *et al.* (2016) have concluded that the cost of avoiding deforestation per unit of preserved area is significantly lower than the cost of recovering those areas with environmental deficits, mainly due to the high cost of revegetation and labour. For this reason, PES programs aimed at recovering deforested areas require payment values to owners and implementation costs that are much more expensive than those for forest conservation.

There is therefore a need to develop a national strategic plan to guide the responsible expansion of agriculture and biofuels. Also, there is need to invest in the conservation of the Brazilian environmental patrimony, thus transforming apparently divergent interests into complementary strategies. Solutions for agriculture encompass engagement in environmentally sustainable agricultural production by agents who promote deforestation. Improvements can also be achieved by creating international certification standards that include a ban on cultivation in newly deforested areas and areas of outstanding conservation interest, as well as compliance with local laws. As access to special markets or financial reward usually results from certification schemes, farmers, ranchers and loggers, among others, are joining together to create voluntary records, in which participants undertake to improve their socio-environmental performance. This is particularly important for the Cerrado biome due to its 400,000 km² forest asset, which may be legally deforested in the future, mostly due to increasing livestock production, as well as expansion of food and biofuel crops.

2.4 Biofuels and the Brazilian Climate Policy

Climate change is one of the greatest economic and political challenges faced by the world's economies today (IPCC, 2014). In recent decades, the increasing risks posed by climate change have motivated businesses, cities, states, national governments and the international community to commit to reduce their GHG emissions. Given the scale of the problem, the breadth of action must be effective and must set the foundation for increasing mitigation efforts over time (Aldy, 2016). Thus, meeting these commitments will require effective policies now to drive the deployment of low-carbon technologies and, in the future, the development of technological innovation that may help reduce exposure to climate change risks. Accordingly, required actions imply the need to reconcile the global nature of the problem with actions at regional, national and/or local levels (PMR, 2016; Aldy, 2016; Schütze, *et al.*, 2017).

With the current pressure to decarbonise the global economy rapidly, policymakers have turned to market solutions to reduce its carbon intensity (Da Mota, 2011; ICAP, 2018; Santos *et al.*, 2018). There is strong debate in international spheres about alternative policies and instruments that can be used to determine a price on carbon, hence signalling to economic agents a development strategy based on lower emission activities (CPLC, 2016; WB, 2017). In this context, policymakers have at their disposal command-and-control measures (*e.g.* emissions targets) and market-based instruments (including the commercialisation of GHG emissions permits through emissions trading schemes and the taxation of emissions through the imposition of a carbon tax) (GVCES, 2013).

2.4.1 Carbon Pricing Instruments

The monetary internalisation of external costs[16] should consider how to value these costs and which environmental policy instruments should be used to achieve the 'optimal level

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[16] External costs or externalities are unintended consequences to third parties from an economic activity. If real markets do not exist to evaluate the cost of an externality, the government needs to find a proxy market (such as the hedonic pricing approach, contingent valuation approach, dose-response relationship approach, travel-cost approach, among others) to determine the external costs of a given activity. That is, internalising

of pollution' (social optimum) (Pierce and Turner, 1989). In this sense, the main differences between the classical environmental policy instruments (mandatory command-and-control impositions or incentives through market instruments) are their cost-effectiveness, costs associated with monitoring, equity, distribution and flexibility and the level of information required (Pearce and Turner, 1989; Da Mota, 2011; WB, 2017). When compared to command-and-control instruments, market instruments are seen as more cost-effective since they reach the environmental goal at the lowest abatement cost, achieved by equalising the marginal abatement cost among the different firms (Narassimahn *et al.*, 2017; Santos *et al.*, 2018; ICAP, 2018). Compared to command-and-control mechanisms (such as technological, efficiency and emissions standards), economic instruments provide flexibility to polluters in order to choose the economically best alternative to achieve the objectives of improving environmental quality and their timing (Rathmann, 2012; Thomas and Callan, 2016).

Overall, carbon pricing instruments are based on the 'polluter pays' principle (PPP), which defines responsibility and establishes a cost for GHG emissions, thereby internalising negative externalities (Santos, *et al.*, 2018). This principle can be implemented through fiscal policies, for example a carbon tax, or by establishing a carbon market or a pollution trading system, known as emission trading schemes (ETS). By determining a price for GHG emissions, firms are encouraged to change their production processes to reduce their emissions per unit of output. These policies also affect consumer decisions, because rising prices of carbon-intensive goods encourage changes in consumption patterns towards less carbon-intensive goods.

Fiscal policies and trading schemes set the carbon price differently (PMR, 2016; Narassimahn, 2017). An ETS defines the amount of emissions allowed (as defined in the *RenovaBio* scheme), rather than the price. That is, the price of emissions is set indirectly; the regulatory authority determines the total allowed amount of emissions and then the price is established by the supply and demand of licences in the carbon market. With a

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externalities occurs when polluters compensate people who suffer from pollution caused by polluters. Therefore, by accepting that amount of money (the cost of externalities), it means that there is virtually no environmental problem anymore (because in economics, receiving money means that the welfare improves). Overall, in poor countries the cost of externalities is lower than that in developed countries; therefore, developed countries move their production to developing countries, thereby moving their pollution to the poorest.

carbon tax, the price of carbon emissions (usually $/$tCO_2$ or $/$tCO_{2e}$) is straightforward and defined by the regulatory authority (Thomas and Callan, 2010).

In the first year after the Paris Agreement came into effect, emissions trading worldwide took a significant step forward. Developments in 2017 brought the global ETS count to 21 systems in operation by early 2018, at different levels of government. With the launch of China's national ETS, the share of global emissions covered by a domestic ETS reached almost 15%. Now, economies with an ETS in place produce more than 50% of global GDP and are home to almost a third of the global population (ICAP, 2018). These figures reflect the steady expansion of ETS policy and the strengthening of implementation around the world.

Recently, the world has seen the emergence of new ETSs as well major reviews, reforms and new legislation in four of the world's pioneering systems, namely, the Western Climate Initiative (WCI) jurisdictions of California, Québec and Ontario, the Regional Greenhouse Gas Initiative (RGGI)[17], the European Union ETS (EU ETS) and the New Zealand ETS (NZ ETS). The reforms are coming at a crucial time, as policymakers are taking on board the lessons from past years of ETS operation, while sharpening their systems in preparation for the declared climate targets of the next decade and beyond. In this regard, the effect of the Paris Agreement has been to crystallise the international response into national and sub-national commitment to climate action, providing momentum to domestic policy at all levels of government (ICAP, 2018).

2.4.2 Carbon Pricing in the Brazilian Climate Policy

Brazil's National Policy on Climate Change (NPCC)[18], enacted in December 2009 (Federal Law n. 12,187/2009), is the regulatory framework that guides the government through the climate change institutional arrangements. It aims to reduce anthropogenic GHG emissions, foster measures promoting adaptation to climate change and promote the development of a Brazilian market for emissions reductions.

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[17] The RGGI was the first mandatory market-based program in the United States to reduce greenhouse gas emissions. RGGI is a cooperative effort among the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont to cap and reduce CO_2 emissions from the power sector. For more details please refer to: https://www.rggi.org.

[18] PNMC in Portuguese – Política Nacional sobre Mudança do Clima.

As part of its activities under the Partnership for Market Readiness (PMR), the Brazilian government is considering the implementation of market instruments to meet Brazil's voluntary GHG reduction commitment and reduce overall mitigation costs[19]. Brazil is currently assessing different carbon pricing instruments, including an ETS and a carbon tax. In this sense, the Ministry of Finance is developing design options and conducting comprehensive economic and regulatory impact assessments for both instruments and it has launched a strategy to strengthen the understanding of carbon pricing instruments among stakeholders through engagement, communication, and consultation (MF, 2014; ICAP, 2018). A proposal of a policy package analysing policy scenarios for carbon tax and ETS is under development with the support of the PMR (MF, 2014) and, depending on the impact assessment, the work stream is expected to culminate in a White Paper with design recommendations for a carbon pricing instrument for Brazil.

'The use of financial and economic mechanisms that are national in scope and referring to mitigation and adaptation to climate change' will be encouraged, as stated by article 5 (item VII) of the NPCC, emphasising that such mechanisms[20] are among those already existing within the framework of the UNFCCC, which must present environmental standards and quantifiable and verifiable targets (Brasil, 2009).

Currently, the Brazilian government is working on the regulatory impact assessment of a National GHG Reporting Program and a National GHG Emissions/Removals Registry, with support from the German development agency Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), thus developing the fundamentals of a central building block for carbon pricing (ICAP, 2018). Additionally, the country already has a legal framework, including the use of economic instruments as mechanisms for environmental protection, besides having experience in dedicating part of the taxes collected for social and environmental purposes – for example, the Ecological Tax on

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[19] Article 12 of the NPCC specifically states that the country has adopted GHG mitigation targets from 36.1% to 38.9% of its 2020 projected emissions as a voluntary commitment (Brasil, 2009). This goal should be achieved through sectoral plans for adaptation and mitigation of climate change that consider sectoral specificities. For instance, the 2014 Brazil's total GHG emission, *i.e.* 1,051 $MtCO_{2e}$, were divided into the following sectors: waste (6%), industry (9%), agricultural (41%) and energy (45%) and excluded LULUCF (land-use, land-use change and forestry) emissions (ICAP, 2018).

[20] Article 6 (item VI) of the NPCC states that *"fiscal and tax measures to encourage the reduction of emissions and removal of GHG, including differentiated rates, exemptions, compensations, and incentives, to be established in a specific law"* may be used as mechanisms of the NPCC.

Circulation of Goods and Services (*Ecological ICMS*) and the Contribution of Intervention in the Economic Domain – Fuel (*CIDE Fuels*) (Santos *et al.*, 2018).

Alternatively, the NPCC also refers to the possibility of adopting a market system for trading emission certificates, stating in its article 4, item VIII, that *'the development of the Brazilian Emission Reduction Market (MBRE) will be fostered'* (BRASIL, 2009). As described in the previous section, *RenovaBio*, the national policy for biofuels, was approved in 2017 (Federal Law n. 13,576 of 26 December 2017), establishing mandatory goals for the reduction of GHG emissions by avoiding fossil fuels. The policy provides for a trading mechanism for emissions reduction units generated by switching from fossil fuels to biofuels (ICAP, 2018).

Since 2013, a group of leading companies has been participating in a voluntary ETS simulation in the country. The initiative offers a platform whereby they can gain experience in and develop proposals for a wide-ranging and robust approach towards cap-and-trade in Brazil with the purpose of promoting the reduction of national GHG emissions at the lowest possible cost[21]. According to the International Carbon Action Partnership (ICAP 2018), 23 companies from diverse sectors of the Brazilian economy took part in this exercise in 2015, when the allocation process and trading were managed by the Rio de Janeiro Green Stock Exchange (*BVRio*) and the ETS design of the simulation was coordinated by the *Centro de Estudos em Sustentabilidade da Fundação Getúlio Vargas GVCes/FGV* (Centre for Sustainability Studies, Getúlio Vargas Foundation).

In addition, the Brazilian government presented its NDC at the 21st Conference of the Parties of the UNFCCC in 2015, the main result of which was the establishment of the Paris Agreement. Through this document, Brazil committed to reducing GHG emissions to 37% below 2005 levels by 2025, with a subsequent indicative contribution to reduce emissions by 43% below 2005 levels by 2030 (Brasil, 2015). Through a more detailed range of actions, Brazil intends to adopt further measures that are consistent with the 2°C temperature goal, in particular (Brasil, 2015):

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[21] The NPCC states in its article 9 that this market for emissions trade *"will be operationalized in commodities and futures exchanges, stock exchanges and organized over-the-counter entities authorized by the Securities and Exchange Commission (CVM), where securities will be negotiated representing certified greenhouse gas emissions avoided"* (Brasil, 2009).

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;

ii) In land-use change and forests:

- strengthening and enforcing the implementation of the Forest Code, at federal, state and municipal levels;

- strengthening policies and measures with a view to achieve, in the Brazilian Amazonia, zero illegal deforestation by 2030 and compensating for GHG emissions from legal suppression of vegetation by 2030;

- restoring and reforesting 12 million hectares of forests by 2030, for multiple purposes;

- enhancing sustainable native forest management systems, through georeferencing and tracking systems applicable to native forest management, with a view to curbing illegal and unsustainable practices;

iii) In the energy sector, achieving 45% of renewables in the energy mix by 2030, including:

- expanding the use of renewable energy sources other than hydropower in the total energy mix to between 28% and 33% by 2030;

- expanding the use of non-fossil-fuel energy sources domestically, increasing the share of renewables (other than hydropower) in the power supply to at least 23% by 2030, including by raising the share of wind, biomass and solar;

- achieving 10% efficiency gains in the electricity sector by 2030;

iv) In the agriculture sector, strengthen the Low Carbon Emission Agriculture Program (ABC) as the main strategy for sustainable agriculture development, including by restoring an additional 15 million hectares of degraded pasturelands by 2030 and enhancing 5 million hectares of integrated cropland-livestock-forestry systems (ICLFS) by 2030;

v) *In the industry sector, promote new standards of clean technology and further enhance energy efficiency measures and low-carbon infrastructure;*

vi) *In the transportation sector, further promote efficiency measures and improve infrastructure for transport and public transportation in urban areas.'*

However, although the NDC document considers the use of economic mechanisms, the configuration of the Brazilian climate policy is not clear in terms of economic instruments for carbon pricing. As stated in the NDC document (Brasil, 2015), '*Brazil reserves its position regarding the possibility of using any market mechanisms that may be established under the Paris Agreement*'.

Finally, Brazilian states are also actively engaging in climate policy. In 2012, both São Paulo and Rio de Janeiro states considered the implementation of a state-wide ETS (ICAP, 2018). However, from analysis of the official documents associated with the design of the country's climate policy, it is not clear how a national climate policy will be designed in terms of economic mechanisms and instruments for carbon pricing to reach the goals assumed by the country (Brasil, 2009; 2015; Santos *et al.*, 2018). Therefore, it is recommended conducting additional studies that focus on the energy, industry, agricultural and forestry sectors to design different carbon pricing instruments in order to help evaluate the potential impact of different policy options.

In this context, since the Brazilian government has just implemented a national biofuel policy and there are initiatives aimed at promoting carbon pricing in the country, it is important to analyse the impact of biofuels expansion on water, land and energy uses, as well as the carbon pricing impacts from GHG emissions in the biofuel production process. The intention of carbon pricing analyses is to assess the impact of price changes (changes in factor input prices, therefore, changes in the value added) due to a carbon pricing initiative (*e.g.* a carbon tax policy imposition), thereby providing opportunities to analyse overall impacts on the economy and local environment (discussed in *sections 4.3.2* and *4.4.3*). In this sense, the commitment made at COP21 offers the Brazilian society an opportunity to use biofuels as a development vector that will contribute to emissions reduction, among other positive externalities, provided that local specificities for producing biofuels are respected. Additionally, analyses to assess the impact of biofuel expansion in an integrated way by considering water, energy and emissions as targets in the nexus analysis previously mentioned should be encouraged. This is so that the full impact of biofuel production on society, taking its economic trade-offs into account due to an eventual carbon pricing initiative in the country, can be evaluated.

2.5 Summary and Conclusions

The main objective of this chapter was to provide an overview of the development of Brazilian policies for biofuel, forests and climate. It also aimed to develop a perspective on the Brazilian biofuel production and on carbon tax as a policy option to reduce Brazil's GHG emissions. The highlights of this chapter are summarised:

- Through the Brazilian Alcohol Program – PROALCOOL (developed in 1975), ethanol was first employed as an octane booster to gasoline and later as a complete substitute in properly adapted engines. The program has attracted significant investment in agricultural and industrial processes, stimulating sugarcane cultivation in the country. An important domestic ethanol market was consolidated. The PROALCOOL and its subsequent policies have been in place now for more than 40 years, setting up Brazil as an important ethanol producer.

- The national biofuel policy, *RenovaBio,* focuses on energy security as well as on mitigating GHG emissions from the fuel sector. It has been designed to introduce two basic market mechanisms to recognise the potential of each biofuel in reducing GHG emissions: *i)* establishment of national emission reduction targets for the fuel matrix; and *ii)* certification of biofuel production with different scores being attributed to each producer.

- The main motivations for the *RenovaBio* were: *i)* the fact that the country is likely to continue being a net importer of oil products; *ii)* Brazil's dependence on fuel imports has grown substantially since 2010; *iii)* Brazil became a net ethanol importer in 2017; *iv)* fossil fuel consumption has increased at high average rates but domestic production capacity has not developed at the same pace.

- The energy-environmental efficiency score of a biofuel under the *RenovaBio* scheme is defined as the difference between its carbon intensity and the carbon intensity of its fossil fuel substitute. Certification processes verify the data regarding the biofuel, taking place within the biofuel production plant.

- Biofuel decarbonization credits (*CBIO*) will be a financial instrument registered in book-entry form to record the objectives of the individual fuel distributors. The number of credits to be issued will take into consideration the volume of biofuel produced, and according to the relevant energy-environmental efficiency score. The costs of the *CBIO* (in the financial market) will be individually negotiated with the institution and collectively with the market.

- The proposal for a less demanding new Forest Code (FC) has been debated for more than a decade in Brazil. Despite controversy, the 'New Brazilian Forest Code' was enacted in 2012, providing the main legislation for the protection of native vegetation and national biodiversity. The FC establishes general rules for the protection of vegetation in Permanent Preservation Areas (PPA) and areas of Legal Reserve (LR), as well as for logging, supply of forest raw materials, control of the origin of forest products and control and prevention of forest fires.

- Overall, it provides economic and financial instruments to achieve the following goals: *i)* confirm Brazil's commitment to the preservation of its native vegetation; *ii)* reaffirm the importance of the strategic function of agricultural activity and the role of forests in sustainability, economic growth, and the country's presence in the international markets for food and bioenergy; and *iii)* provide governmental actions for the protection and sustainable use of forests.

- The FC states that all rural properties shall maintain an area with native vegetation cover as a LR, without prejudice to the application of the rules on PPA. Overall, the new FC caused great loss in areas that needed to be revegetated. On the other hand, its improved mechanisms make revegetation more feasible.

- Brazil's National Policy on Climate Change (enacted in 2009) is the regulatory framework that guides the government through the climate change institutional arrangements. The government is considering the implementation of market instruments to meet Brazil's voluntary GHG reduction commitment and reduce overall mitigation costs. Brazil is currently assessing different carbon pricing instruments, including an emission trading scheme (ETS) and a carbon tax. A proposal of a policy package analysing policy scenarios for carbon tax and ETS is under development.

- Currently, the Brazilian government is working on the regulatory impact assessment of a National GHG Reporting Program and a National GHG Emissions/Removals Registry. Additionally, the country already has a legal framework, including the use of economic instruments as mechanisms for environmental protection, besides having experience in dedicating part of the taxes collected for social and environmental purposes.
- The Brazilian government presented its NDC at COP21 of the UNFCCC in 2015. Brazil committed to reducing GHG emissions to 37% below 2005 levels by 2025, with a subsequent indicative contribution to reduce emissions by 43% below 2005 levels by 2030. Brazilian states are also actively engaging in climate policy. The commitment made at COP21 offers the Brazilian society an opportunity to use biofuels as a development vector that will contribute to emissions reduction, provided that local specificities for producing biofuels are respected.

Finally, analyses to assess the impact of biofuel expansion in an integrated way by considering water, energy and emissions as targets in the nexus analysis should be encouraged. In this context, *Chapter 3* presents some methods used to analyse these issues, highlighting the role of hybrid Input-Output models as useful tools in assessing the water-energy-food nexus of biofuel production in Brazil. In addition, the next chapter provides some insights on how changes in input price can affect the use of resources and the associated emissions. Finally, it also analyses the price impact of a carbon tax and CO_2 emissions abatement possibilities for Goiás' economic sectors.

3 Methodology

3.1 Scope of the Study

Assessing the use of a specific resource (*e.g.* water, land or energy, etc.) by any activity constitutes a complex task. There is often a lack of available data, as well as difficulties in analysing different issues together and their multiple interlinkages. As a result, there are few studies that focus on how to support decision-making at the nexus of water, energy and land (Bazilian, *et al.,* 2011). Additionally, as previously mentioned, there are very few studies that integrate water, energy and land concerns in relation to biofuel production in Brazil, specifically *1G* sugarcane ethanol.

In this regard, Maroun (2014) performed an integrated assessment of sugarcane expansion areas in the state of São Paulo, Brazil, based on the interface between the policies for each of the water, energy and land resource sectors. By integrating all three resources and their respective policies through the methodologies proposed by DOE (2012), IAEA (2009), Welsch *et al.* (2014) and Hermann *et al.* (2012), the results were different from those obtained when the polices for each resource were analysed in isolation, showing the importance of integrated analysis to the sustainable development of biofuels in the country. Therefore, biofuel-related policies should consider integrating the relevant individual policies.

This lack of policy integration linked to water, energy and land can create vicious cycles that negatively impact biofuel sustainability. Debates on sugarcane ethanol production in Brazil, for example, frequently focus on the impact caused by changes in land use, mainly through deforestation, which can also indirectly lead to the reduction of water availability. Water constraints in producing sugarcane would require more irrigation, energy consumption would increase and more land would be required for power generation, resulting in more competition for land between, for example, food, biofuels and power generation, leading to deforestation and so on.

Another indirect effect of biofuel cultivation is that it may induce the movement of cattle towards the Brazilian forests (*e.g.* mainly to the Amazon and Cerrado biomes), hence contributing to the most important cause of deforestation and GHG emissions in the country (Palermo, 2011; La Rovere *et al.*, 2011; Soares-Filho, 2013; Lapola *et al*., 2014; MAPBIOMAS, 2017; SEEG, 2017b). Competition for land may impact land prices, which may also lead to the use of poorer quality land for crops cultivation, requiring more irrigation and inputs, increasing energy demand. These changes will impact both biofuel energy balance and emissions, increasing production costs, pushing producers to seek even lower-quality, cheaper land, thus establishing a vicious cycle (**Figure 9**) (Maroun, 2014). If these individual policies are not treated through a nexus perspective, therefore, they can lead to misleading policy recommendations.

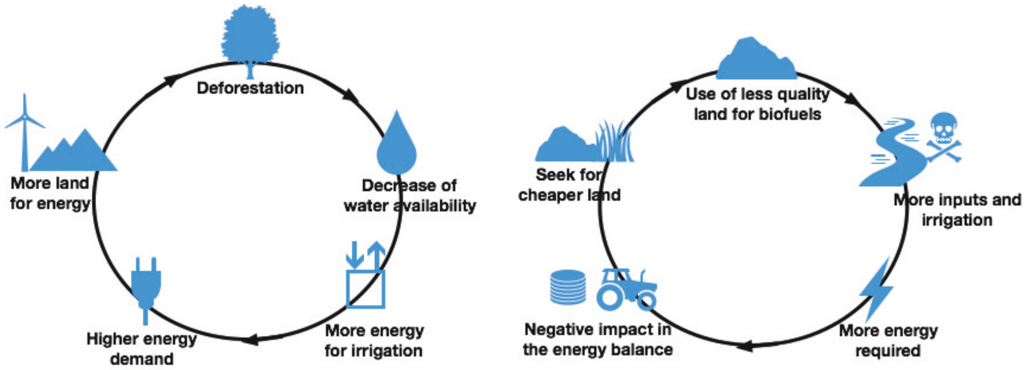

Figure 9. Justification for the nexus approach. Examples of vicious cycles due to isolated policies for biofuels.
Source: Author's adaptation based on Maroun (2014).

Assessments of land use, energy and water are often carried out in isolation by disconnected institutions. An institution focusing on water resources, for example, is likely to consider food and energy systems as end users (Hellegers, *et al.,* 2008). Similarly, agriculture assessments might see energy and water as resources (Khan and Hanjra, 2009; Mushtaq *et al.,* 2009), and the energy sector is likely to treat biomass and water as inputs. Thus, promoting biofuel expansion through the current sector-driven approach, disregarding indirect impacts on land and water resources and GHG emissions, could counteract one of the main objectives of biofuel policies (Howells, *et al.,* 2013).

Since there is no uniform way to analyse the interdependent resource issues of water, energy and land using an integrated framework in scientific analysis and policymaking, analyses will depend on the existing resource links in a certain region and the purpose of the analysis. The WEFN approach is conceptualised and measured using varying methods, such as macro-level assessments, life-cycle assessments (LCA), resource planning use modelling (CLEW) and multi-sectoral systems analysis (MSA), among others.

Additionally, general equilibrium models (*e.g.* computational general equilibrium (CGE), input-output analysis (IOA)) have been employed recently as decision-making tools for sustainable development and planning in models that incorporate the impact of environmental aspects and energy use on a national or regional level (Miller and Blair, 2009; Hristu-Varsakelis *et al.*, 2010; Zhang *et al*, 2016; Wang and Chen, 2016). Overall, IO models can evaluate indirect as well as direct flows to calculate the inputs required for producing goods and services based on sectoral interactions and exchanges in complex systems (Zhang *et al.,* 2016; Cazcarro, *et al.,* 2013). Unlike partial equilibrium models, general equilibrium models consider the interdependence between the different markets of a specific economy, making them more realistic than the partial equilibrium models (Ely, 2015).

The next sections (*sections 3.2* and *3.3*) explore the reasons why both the WEFN and the IO framework were chosen to perform the analysis required for this thesis. The general objective of this study is to analyse the impact of sugarcane expansion on the Brazilian Cerrado (Goiás State), aiming to understand how future demand for ethanol could impact water, energy and land availability and what the environmental constraints for ethanol production in the region of study would be. This study also focuses on the economic and environmental impacts of a national carbon pricing initiative on the Goiás economy. The state of Goiás was chosen due to its role in the Brazilian ethanol production and the historical trends of sugarcane expansion both in the state itself and into the state from other, neighbouring, states. *Section 4* presents the state of Goiás as the case study chosen for this thesis because of its major role in Brazilian sugarcane ethanol production.

3.2 The Water-Energy-Food Nexus

Through its focus on the inseparable links between the resources needed to provide basic rights to food, water and energy security, the 2011 World Economic Forum was the first global organisation to postulate ‘nexus thinking’. This approach has become an advanced tool on sector-specific governance of natural resource use (Biggs *et al.*, 2015) and it has been the basis for the development of alternative methodologies seeking to integrate the issues related to sustainability.

Through its focus on ensuring integrated water-energy-food security, the WEFN seeks greater policy coherence to overcome the unintended consequences of uncoordinated policy across different sectors. It also constitutes a way of framing cross-sector and cross-scale interactions in the context of growing concerns about the global economic crisis and WEF security (**Figure 10**) (Hoff, 2011; IISD, 2013; Allouche *et al.*, 2014; Weitz, *et al.*, 2017).

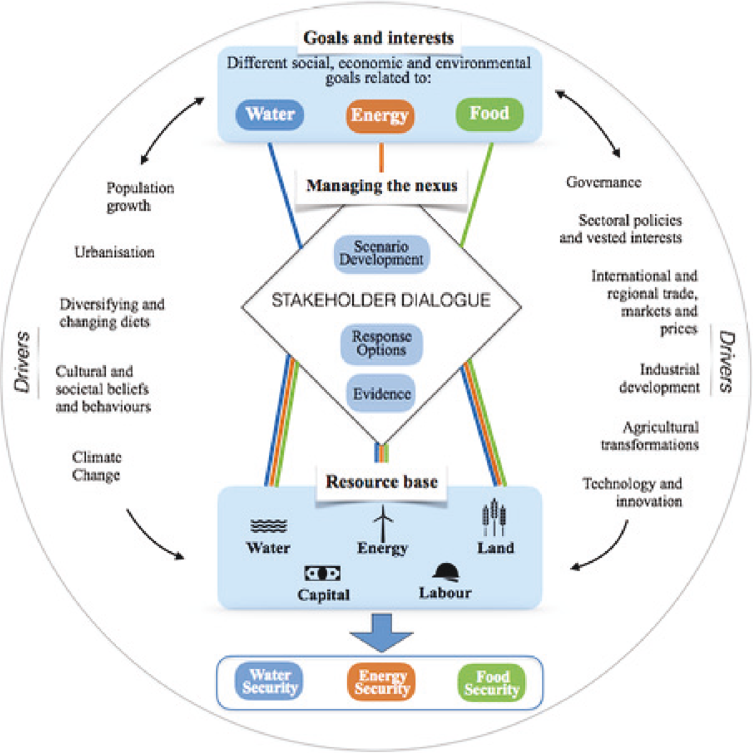

Figure 10. The water, energy and food nexus framework.
Source: Author's adaptation from FAO (2014).

Several studies have pointed out that the ultimate goal of nexus thinking focuses on promoting action by providing policy entry points that explore synergies, seek a reduction in trade-off and promote the transition to a more sustainable future (Hoff, 2011; Bazilian, 2011; IISD, 2013, Howells *et al.,* 2013; Welsch *et al.,* 2014; Al-Said and Elagib, 2017; Weitz, *et al.,* 2017). Most of the nexus studies follow the WEFN mainstream, focusing on the interlinkage between environmental resources through their physical connections (physical flows). However, anyone intending to design WEFN policies should add economic implications to the traditional nexus analyses, such as price analysis (changes in input prices from external changes) for water, energy, land or any other resource involved. This is important because physical relationships are not enough to produce high-quality outcomes for the policymaking process and physical relationships may be the main shortcoming of the traditional nexus analysis. In fact, policymaking demands economic arguments to justify the choice of a specific policy option; therefore, these physical interlinkages can be translated into policies when price change effects are included in the analysis. In this regard, biofuels are the focus of research because, first, they largely rely on water, land and energy to meet their growing demand and, second, they have a significant impact on the local and national economy where they are produced. Therefore, it is worth checking methodologies that have already been applied to integrate WEF resources.

There is no standard integrated framework for assessing WEFN issues in an interdisciplinary way and so various methodologies to integrate WEFN concerns have been applied to decision-making processes. The Climate, Land, Energy, and Water System (CLEWS), proposed by the International Atomic Energy Agency (IAEA (IAEA, 2009)), evolved from the original nexus concept, focusing on the expansion of a systems approach to support nexus analyses and it has its origins in LCA methodology (**Figure 11**).

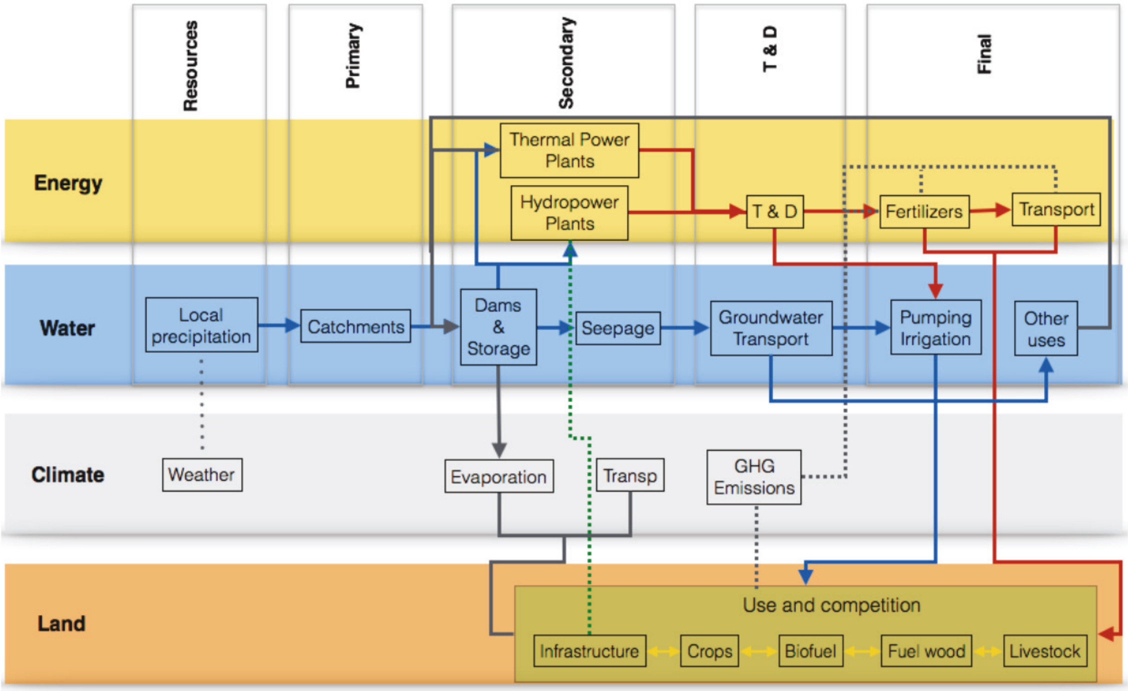

Figure 11. Example of the Climate, Land, Energy and Water System.
Source: Author's adaptation from IAEA (2009).

By applying CLEWS analysis, WELSCH *et al.* (2014) compared isolated conclusions derived from energy planning models with those of an integrated CLEWS approach. Aiming to evaluate CLEWS strategies applied to a study case conducted for the Republic of Mauritius, Howells *et al.* (2013) used well-stablished tools such as general circulation models (GCM) to estimate weather changes (IPCC, 1990; IIASA and FAO, 2012), the Long-range Energy Alternatives Planning (LEAP) model (HEAPS, 2008), the Water Evaluation and Planning System (WEAP) (SEI, 2015), and the Agro-Ecological Zones (AEZ) land production planning model (IIASA and FAO, 2012). By analysing different policy scenarios, a significant difference between the results of isolated energy planning models and the CLEWS approach was found. Howells *et al.* (2013) concluded that integrated assessment was imminently achievable, and a range of tools are available that could be adapted and used for CLEWS assessments. However, they also pointed out that *'although achievable, the process of integrating individual tools into a module-based framework requires considerable effort to ensure compatibility and efficient data transfer'* (Howells, *et al.,* 2013).

In a report of the University of Texas at Austin (UT Austin), King (2014) sought to inform actions for Hawaii's sustainable water use in agriculture by applying a systems approach. The report focused on the water and energy inputs and outputs for producing both biofuel feedstocks and food crops. This systems approach assumed water was available for multiple purposes to assess, using different policy scenarios, how Hawaii's water resources could be used to achieve multiple sustainability objectives. The overall conclusion was that there was a significant opportunity to meet multiple sustainability goals using the same or a lesser quantity of water for large-scale farming of biofuel crops in the country.

The WEFN of *1G* biofuels was explored by Marta *et al.,* (2011) from a net energy produced standpoint and the resulting implications for water and food security. A long-range climatic series of meteorological data was analysed through a crop model (*i.e.* CropSyst) to simulate water requirements, crop production and cultivation techniques in Tuscany, Italy. The results determined the real cost of producing energy crops in terms of net energy and water balances from an integrated point of view. However, this study estimated the real cost of producing energy crops from a physical point of view only, and did not consider input price change effects on the local economy and other assessed resources. Anyone intending to design biofuel policies should include economic arguments in order to translate physical analysis into policy more effectively and the mediation between the environmental and economic spheres will occur through price change analyses.

In 2013, an innovative accounting framework for the WEFN was proposed by the FAO (2013a), where a multi-scale integrated assessment of society and ecosystem metabolism (MuSIASEM) was applied to three case studies: (*i*) analysis of sugarcane biofuel production in the Republic of Mauritius, (*ii*) future grain exports in the Indian state of Punjab and (*iii*) assessment of two alternative energy sources to generate power in South Africa. The MuSIASEM model was originally developed to analyse the metabolic pattern of energy of modern society and it has been extended to consider the WEFN (FAO, 2013a).

Newell *et al.* (2011) have discussed practical ways in which policymakers can take up the systems challenge. They focused on resilience thinking and the use of influence diagrams, causal-loop diagrams and system archetypes. Taking a climate-energy-water nexus perspective, they used system concepts and tools to study the factors impacting the resilience of the Australian National Electricity Market (**Figure 12**). Their overall recommendation was that policymakers should work to reduce reliance on conventional market mechanisms, should institute continuing cross-sector dialogue and should promote basic education in system dynamics.

Since the seminal work by Leontief[22] (1936), several studies have used the traditional IO framework coupled with energy and environmental data for different purposes (see Isard *et al.,* 1972; Miller and Blair, 2009; Hristu-Varsakelis *et al.,* 2010; Cazcarro *et al.*, 2013; Zhang *et al.*, 2016; Wang and Chen, 2016). In fact, the IO framework can be extended to estimate environmental impacts from economic activities by determining a proportionality between sector outputs and their corresponding impact levels (**Table 1**).

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[22] Wassily W. Leontief first described the Input-Output methodology and its application to the economy in his article 'Quantitative Input-Output Relations in the Economic Systems of the United States' (1936), and later in the book *The Structure of the American Economy*, published in 1941. The basic input-output framework principle is how changes in one economic sector may affect other sectors. Input-output analysis has been traditionally used to study the interlinkages among different sectors in the economic system, describing the relationship between the inputs used and the outputs produced. Leontief won the Nobel Committee's Nobel Memorial Prize in Economic Sciences in 1973. For Leontief's biography, see https://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/1973/leontief-bio.html.

In this regard, White *et al.* (2017), have applied a transnational inter-regional IO approach in a tele-connected WEFN analysis of the East Asia global value-chain to assess competing demands for these resources and environmental outcomes. This analysis has shown the hidden virtual flows of water, energy and food embodied in intra-regional and transnational inter-regional trade. The results demonstrate a mismatch between the regional water, energy and land availability and the final resource consumption. The results also highlight the lack of attention given in national economic growth strategies to environmental impacts.

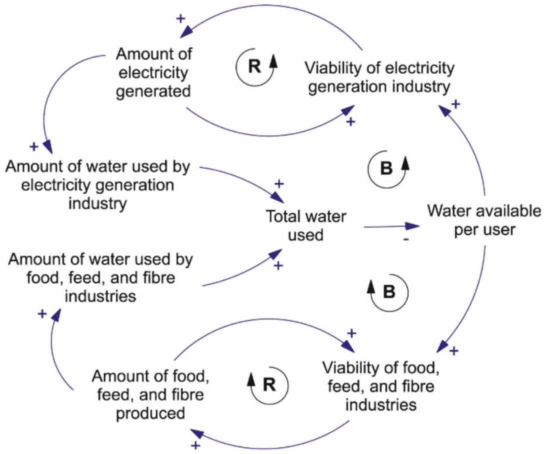

Figure 12. The electricity-water nexus in Australia.

According to the authors, this causal-loop diagram illustrates the Tragedy of the Commons system archetype as applied to the competition for water between the electricity sector and other sectors that use water. Overuse of this resource leaves all users vulnerable to the effects of climate change.

Note: The blocks of text represent system variables and the arrows represent causal links. Each arrow has been assigned a 'polarity' indicated by a plus (+) or minus (-) sign. The encircled R indicates that this is a reinforcing feedback loop that can cause runaway behaviour.

Source: Newell et al. (2011).

Table 1. Basic structure of economic-ecological IO models.

	Industries	*Ecologic process*
Industries	Flows between economic sectors	Flows from industry to the ecosystem
Ecologic process	Flows from the ecosystem to industry	Flows within the ecosystem

Source: Miller and Blair (2009).

Additionally, Carvalho *et al.* (2015, 2016, 2016a) used a hybrid IO framework that focused on assessing the trade-offs between economic, energy, environmental and social objectives in the Brazilian economic system. The traditional IO framework was reorganised to include the National Energy Balance, creating a hybrid IO framework that was extended to assess GHG emissions and employment levels. Although this work produced a comprehensive picture of the Brazilian ethanol production sector and its impact on the overall economy and environment, the authors did not include price change analysis in order to allow some level of substitution between factors of production, based on their new prices (prices may change for a number of reasons, such as political, social, technical and economic, among others). Price changes may lead to a certain level of substitution that impacts the technical coefficient ratios in the IO model, thereby changing the input requirements for the same level of output (this is discussed further in sub-*section 3.3.2* below).

For further examples on approaches to and methodologies for the nexus of water, energy, land, GHG emissions and climate change, please refer to Bazilian *et al.* (2011), Stillwell *et al.* (2011), Hussey and Pittock (2012), Ringler *et al.* (2013), Lawford *et al.* (2013), IISD (2013), SEI (2014), FAO (2014), Biggs *et al.* (2015), Feng *et al.* (2016), Wang and Chen (2016), Garcia and You (2016), White *et al.* (2017), Al-Said and Elagib (2017), Weitz *et al.* (2015, 2017), Endo *et al.* (2015, 2017), among others.

Regardless of the methodology applied, there are three main reasons for the need for the WEFN debate:

i) increasing resource interlinks due to growing scarcities. As an example, many dams worldwide are primarily built for energy purposes, although their benefits extend to other issues (*e.g.* flood control, irrigation and drought management) (Al-Said and Elagib, 2017).

ii) resource supply crises. This concern lies in recent water and food crises, as well as drought and heat waves across the globe. Since 2013, Brazil has experienced a severe water crisis that has impacted large sections of the country through water rationing for agriculture and human consumption, as well as hydropower supply, resulting in high energy prices and low reservoir levels, and

iii) failure of sector-driven management strategies. Increasing demand for food and energy, for example, is ultimately converted into increasing pressure on

> water resources, emphasising the natural interlinkages between resources (Al-Said and Elagib, 2017).

In fact, assessments of land use, energy and water are often carried out in isolation by institutions operating alone. The WEFN frameworks all focus on security challenges, taking into account the social, economic and environmental domains and changes in human behaviour to analyse different approaches to economic growth and promoting ecosystem services (IISD, 2013). Thus, promoting biofuel expansion through the current sector-driven approach, which disregards the indirect socioeconomic and environmental impacts on the resources used as inputs to bioenergy production could counteract one of the main objectives of biofuel policies, namely, GHG emissions reduction (Howells, *et al.,* 2013).

Since there is no uniform integrated framework to analyse the issues of water, energy and land, analyses will depend on the existing resource links and purpose of the analysis, reinforcing that the WEFN approach is conceived and measured using varying methods.

Among the usual methods to analyse the WEFN, the IO approach was chosen for our case study because of its wide potential to assess integrated impacts throughout the economy, besides being a reliable decision-making tool for planning purposes. Another reason was the data availability for the region under study. Moreover, environmental impacts have previously been considered through modified IO models using three basic modelling approaches: generalised IO models (Leontief, 1970), economic-ecological models (Isard *et al.,* 1972) and hybrid IO models (Miller and Blair, 2009). The economic-ecological model resulted from extending the inter-industry framework to include additional 'ecosystem' sectors, where flows between economic and ecosystem sectors are recorded along the lines of an inter-regional IO model (Miller and Blair, 2009). To analyse the WEFN through a case study, this thesis applies a hybrid economic-ecological IO approach in attributing water, energy, land use and emissions to the various sectors of the economy, and in calculating the interdependence of sectors regarding changes in final demand. Additionally, an IO price change analysis is carried out in order to include economic arguments in the traditional IO-WEFN approach and it aims to allow for substitution between factors of production when their original prices change. These price changes (for example, from the imposition of a carbon tax) impact the sectors' relationships in the traditional IO model and, therefore, they impact the final environmental requirements, because of changes in final demand for the biofuel sector (or any other target sector).

IO models with hybrid units have been developed to assess the Brazilian economic system and interactions between economic, energy and environmental systems (see Hilgemberg & Guilhoto, 2006; Imori and Guilhoto, 2010; Imori *et al.,* 2011; Carvalho *et al.,* 2015, 2016; Obermaier *et al.,* 2017). Thus, the IO approach has been used as a decision-making tool for sustainable development and planning in models that examine environmental and energy impacts by tracing the flow of resources from consumption activities, supported by outputs from production sectors (Hristu-Varsakelis *et al*., 2010; Wang and Chen, 2016; Carvalho *et al*., 2015, 2016).

Regardless of the methodology used to assess the WEFN, the nexus approach has tended towards technical assessments focusing on productivity, synergies and trade-offs across nexus sectors (Howells *et al*., 2013). As previously stated, they have traditionally put much emphasis on physical analysis, neglecting the economic sphere. This correlates to the origin of the nexus framework, based mostly on systems analysis and backed by scientific evidence, but only recently beginning to take hold in policymaking and planning (SEI, 2014). Therefore, when the term 'security' is used in WEFN analyses aimed at ensuring water, energy and food availability, it is noteworthy that this security is not driven solely by availability of resources but also by access to resources, the capacity to use those resources, the dynamics of social power relations and the strength of institutions (Pritchard *et al*., 2013; Biggs *et al.,* 2015). In this context, traditional environmental analyses of the nexus are useful but not sufficient to translate these physical aspects into policies because the policymaking process requires additional socioeconomic indicators; therefore, traditional environmental analysis of the nexus will become more satisfactory if price effects are considered in policymaking (*i.e.* the mediation between physical and economic aspects will occur though price analysis).

Similarly, Weitz *et al.* (2017) have identified three governance gaps in the nexus literature, which indicate that while governance matters to the nexus approach, it does not go into enough depth. According to the authors *'it falls short on providing insights on (i) conditions for cross-sector coordination and collaboration; (ii) dynamics that influence* *the nexus beyond cross-sector interactions; and (iii) political and cognitive factors as determinants of policy change'*, arguing that governance theory can help to fill these gaps. Although the nexus approach can explore interlinkages between water, energy and land and hence help to determine physical limits to the use of resources, governance issues have made it difficult to implement the WEFN and deliver real-world solutions (Wichelns, 2017; Leck *et al.,* 2015; White *et al.*, 2017). Although important to the nexus approach, governance issues are not the focus of this thesis and they will be discussed only briefly in the Conclusion section (*section 5*) of this thesis.

Integrated analyses use a WEFN approach and apply hybrid IO models to better understand the interlinkages between GHG emissions and water, energy and land uses from biofuels production. Although limited by governance issues, the WEFN approach can help shape bioenergy development and highlight the need for a specific biofuel policy through the integration of basic resources for bioenergy production.

3.3 The Input-Output Model

An IO model (also called the Leontief model) is a linear equations system and is understood as a direct technical coefficients matrix that denotes how much a given economic activity needs to consume from other activities so that it can produce an additional monetary unit (IBGE, 2008). In the model, the economy is made up of sectors that produce goods and services (outputs), but to do so, they also consume goods and services from other sectors (inputs). Thus, there are monetary flows of products from a given sector to another in a given period and site (Miller and Blair, 2009).

The IO approach is a simplified representation of the classical interdependence theory between economic sectors and it highlights their respective income distribution issues (Guilhoto, 2004). Thus, the IO model can be an interpretation of the circular flow of income between the markets for goods and services and the markets for factors of production (**Figure 13**).

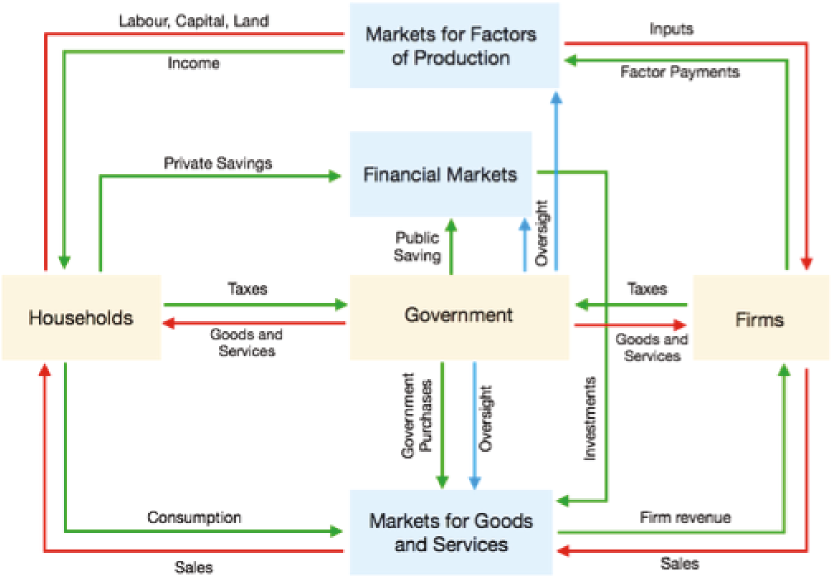

Figure 13. Circular flow of income diagram.
Source: Author's adaptation from Miller and Blair (2009) and Mankiw (2010).

The Leontief model is developed from IO tables, allowing the calculation of the production of each activity from an exogenous final demand (IBGE, 2008). Most national statistical institutions construct such databases, both for the public and as a base for estimating other databases for specific research goals (Ely, 2015). By providing economic and environmental data in a consistent Leontief-type framework, the hybrid IO model is well suited for analytical purposes (Leontief and Ford, 1971). The economic-ecological hybrid IO model, which considers environmental and energy data, is described more fully in *section 3.3.4*.

The basic IO table consists of a concise and systematic database that provides useful information on a complete set of production and consumption accounts in an economy, describing the flow of goods and services between all the individual sectors over a particular time period. The allocation of a sector's output throughout the economy is described by each row of this table, *i.e.*, the output of sectors from row *i* that are distributed to other production sectors in each column *j* are called intermediate goods. This product flow between industry sectors is called inter-industry flow, which is the main item of interest in IO analyses (**Figure 14**, *quadrant A*).

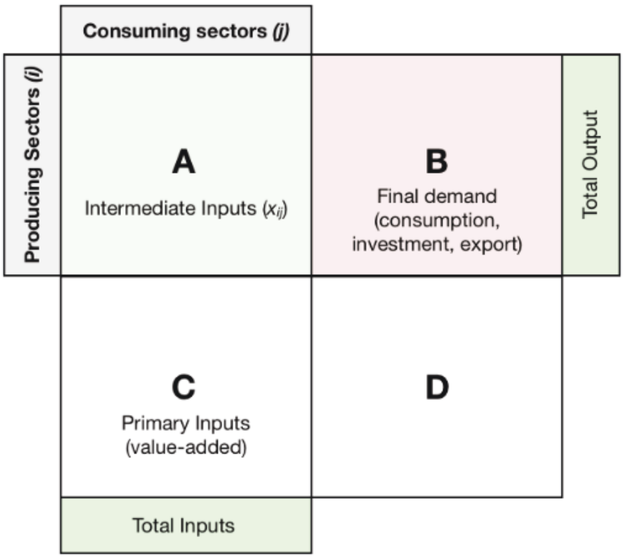

Figure 14. IO table main components.
Source: Author's adaptation from Miller and Blair (2009).

According to the basic Leontief IO structure (Miller and Blair, 2009), *quadrant B* is called the final demand category (represented by exports, household consumption, govern expenditures, investments, etc.) and it constitutes the national gross product of the economy. The primary production factors (such as labour and capital) and imported inputs are located in *quadrant C*. Overall, each column of the IO table describes the composition of inputs required by a particular industry and it can be understood as a production function (or cost function), since essentially, each column represents the total cost of producing the corresponding total output of that industry. Thus, inputs are supplied by other industries (in the form of intermediate inputs) from primary factors of production (in the form of value added) and from imports. Finally, payments by end users for value-added items are represented by the intersection of the value-added row and the final demand column (**Figure 14**, *quadrant D*). In short, each row represents a complete account of where the product is going (revenue received) and each column constitutes a complete account of where the product is coming from (cost of production).

These basic IO relationships show that sector sales can be used as inputs in the productive process by any sector of the economy or can be consumed by different components of final demand. Inputs are needed to produce goods and services, taxes must be paid, products are imported, jobs are created, and value is added to the economy (**Figure 15**) (Guilhoto, 2004).

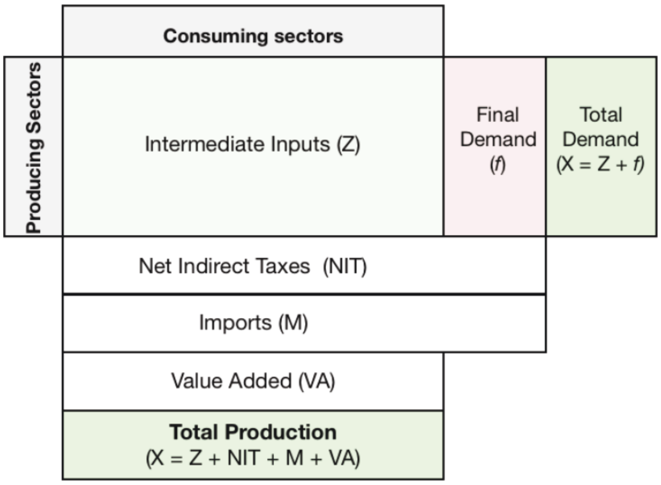

Figure 15. Basic IO model relationships.
Source: Author's adaptation from Guilhoto (2004).

Note that domestic inputs (obtained from domestic production), imported inputs and primary inputs (labour, capital, land) are used in the productive process to produce domestic products. Domestic products are then used by industries as intermediate inputs or consumed as final products. In addition, it should be noted that imports may be intermediate inputs, which are used in the productive process, or final goods, which are directly consumed by end users (**Figure 16**).

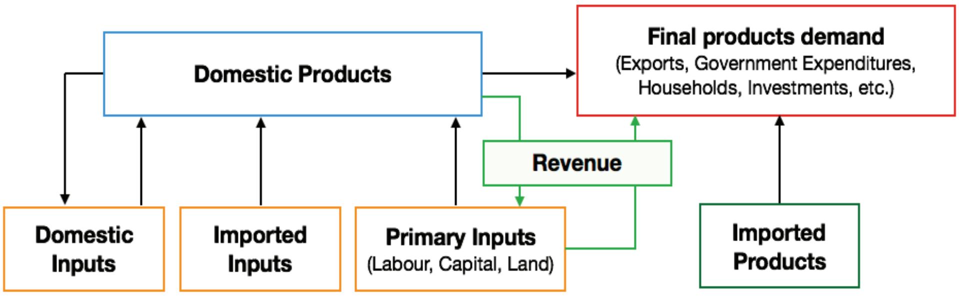

Figure 16. IO model flowchart.
Source: Author's adaptation from Guilhoto (2004).

Therefore, the revenue of the economy is generated from the remuneration of labour, capital and land, which is used in consuming final goods and services, whether they are destined for consumption or investment (Guilhoto, 2004). Government revenue is obtained through the payments of taxes by companies and individuals. Thus, the IO model assumes that there is equilibrium in all markets of the economy, thereby corroborating **Figures 13** and **15**.

There are two fundamental hypotheses regarding the economic system in the IO model (Miller and Blair, 2009):

i) *Homogeneity:* each product is supplied by a single activity (and only one technology is used to produce a product) and

ii) *Proportionality:* the inputs consumed by each activity are a function of the production level of the activity itself.

Therefore, constraints considered, the corresponding solutions are to be viewed as policy targets.

The system of equations of the IO model can be expressed in **Table 2**, as follows.

Table 2. IO table for a 2-sector economy

	Sector*1*	Sector*2*	Households	Government	Investment	Exports	Total
Sector *1*	Z_{11}	Z_{12}	C_1	G_1	I_1	E_1	X_1
Sector *2*	Z_{21}	Z_{22}	C_2	G_2	I_2	E_2	X_2
Imports	M_1	M_2	M_c	M_g	M_i		M
Taxes	T_1	T_2	T_c	T_g	T_i	T_e	T
Value added	W_1	W_2					W
Total	X_1	X_2	C	G	I	E	

Source: Author's adaptation from Guilhoto (2004), Miller and Blair (2009).

where:

Z_{ij} is the monetary flow between sectors *i* and *j*

C_i is households' consumption from sector *i*'s products

G_i is government's purchases from sector *i*

I_i is the demand for investments from sector *i*'s products

E_i is sector *i*'s total exports

X_i is sector *i*'s total output

T_i is sector *i*'s total net indirect taxes

M_i is sector *i*'s imports and

W_i is sector *i*'s value added.

Therefore, from the table above, we can establish the following equality:

$$X_1 + X_2 + C + G + I + E = X_1 + X_2 + M + T + W \qquad \textit{(Eq. 3.1)}$$

By eliminating X_1 and X_2 from both sides, we have:

$$C + G + I + E = M + T + W \qquad \textit{(Eq. 3.2)}$$

Arranged differently:

$$C + G + I + (E - M) = T + W \qquad \textit{(Eq. 3.3)}$$

In other words, the IO table preserves macroeconomic identities. From the above example with two economic sectors and generalising to *n* sectors, we have:

$$\sum_{j=1}^{n} z_{ij} + c_i + g_i + i_i + e_i \equiv x_i \qquad \textit{(Eq. 3.4)}$$

$i = 1, 2, \ldots, n$

where:

z_{ij} is the sector *j*'s demand for the products of sector *i*

c_i is sector *i*'s output consumed by households

g_i is sector *i*'s output consumed by the government

i_i is sector *i*'s output destined to investments

e_i is sector *i*'s exports and

x_i is sector *i*'s total domestic output.

Considering that the intermediate flows per unit of final product are fixed, *i.e.*, assuming a linear production function[23] (called Leontief production function), we can derive the Leontief open system[24], that is,

$$\sum_{j=1}^{n} a_{ij}.x_j + y_i = x_i \qquad \textit{(Eq. 3.5)}$$

$i = 1, 2, \ldots, n$

where:

a_{ij} is the technical coefficient which denotes the quantity of sector *i*'s product required as input to produce a unit of sector *j*'s final output

y_i is the sector *i*'s final demand, that is, $c_i + g_i + i_i + e_i$ and

x_i is the sum of final demand for that sector and its intermediate demand required by sector *j*.

The assumption of linear production function implies that there exists a fixed relationship between a sector's output and its inputs. In other words, it implies a fixed proportionality of inputs with outputs in each sector. As a result, the IO model ignores the economies of scale in production as well as the possibility of substitution between factors of production. Therefore:

$$a_{ij} = \frac{z_{ij}}{x_j} \qquad \textit{(Eq. 3.6)}$$

All other variables have been defined previously.

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[23] In basic microeconomics theory, a production function denotes the maximum output that could be produced from a given set of inputs with the help of the existing technology (Miller and Blair, 2009). A linear production function assumes that there is a fixed proportionality of inputs and outputs, *i.e.* the technology is fixed throughout time. Aiming to overcome this issue, it is necessary to introduce more flexible technologies in the system by including a flexible production function that allows for substitution between factors of production (the use of flexible production functions is discussed further, in *section 3.3.3*).

[24] The Leontief open system considers the final demand to be exogenous to the system, whereas in the closed system the final demand is considered as endogenous.

Note that *Eq. 3.5* illustrates the interdependence between all sectors in an economy in terms of inter-industry flows (Miller and Blair, 2009) and it can be written in a matrix form:

$$Ax + y = x \qquad \textit{(Eq. 3.7)}$$

where:

A is the direct technical coefficient matrix of size $(n \times n)$ and

x and y are column vectors of size $(n \times 1)$.

Solving the *Eq. 3.7*, we obtain the total output required to satisfy the final demand, that is,

$$x = (I - A)^{-1} \, . \, y \qquad \textit{(Eq. 3.8)}$$

where:

I is the identity matrix[25] and

$(I - A)^{-1}$ is the direct and indirect technical coefficient.

We have $L = (I - A)^{-1}$, where the element b_{ij} is the sector i's total output that is required to produce a unit of sector j's final demand.

The *Eq. 3.8* is the fundamental matrix representation of the IO model and this inverse matrix $(I - A)^{-1}$ is known as the famous 'Leontief inverse matrix'. The matrix, also called 'total requirements matrix' (because it indicates all of the direct and indirect requirements for production in the economy), is equivalent to ($I + A + A^2 + A^3 + \ldots + A^n$) by the power series approximation. Leontief inverse is a way of measuring the total effects caused by any y components variation (Δy) of the IO table (Miller and Blair, 2009).

Considering $x = (I - A)^{-1}. \, y$ as a system of linear equations representing an economic system (with x being the economic output and y the final demand), we can measure any variation of x, *(i.e.,* Δx*)*, resulting from any variation of y, *(i.e.,* Δy*)*, by $\Delta x = \Delta y + \Delta yA +$

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[25] The identity matrix of size n is the $(n \times n)$ square matrix with ones on the main diagonal and zeros elsewhere.

$\Delta yA^2 + \Delta yA^3 + \dots \Delta yA^n$), in which the first element of the right side of the equation is related to the initial output effect, *i.e.* totally computing the stimulus occurred by the y matrix variation (Δy). The second element, ΔyA, is the direct effects, *i.e.* the first order effects, directly related to the technical coefficients. Beyond the second order, we find the indirect effects ($\Delta yA^2 + \Delta yA^3 + \dots \Delta yA^n$), which measure the effects caused by the variation of inputs demanded by such technical coefficients. We can have the total effects by adding up all of them (Guilhoto, 2004; Miller and Blair, 2009; Ely, 2015). For a better understanding of IO theory, see Leontief (1970), Leontief and Ford (1971), Herendeen (1978) and Miller and Blair (2009).

The Brazilian Institute of Geography and Statistics (IBGE) began to formulate national IO tables in 1970. Its initial objectives were to create a structural framework for the national accounts system and an instrument with which to develop the economic statistics required to create macroeconomic frameworks (IBGE, 2011). To this end, the Brazilian IO matrix was formed by a set of tables detailing the production and consumption operations, by activity, which generated the technical coefficient matrices, which in turn resulted in tables with up to 67 economic activities and 127 products (IBGE, 2018). The IBGE recently released the latest version of the Brazilian IO matrix for the year 2015[26].

Guilhoto (2010) developed an inter-regional IO table for Goiás State and the Rest of Brazil, based on both the national and regional accounts for the year 2000, and considering 26 sectors of the economy (**Appendix I**). The methodology described in Guilhoto and Sesso Filho (2005, 2010) and Guilhoto *et al.* (2010) was applied to create it. However, all estimates provided by the Goiás hybrid IO model (presented below, in *section 3.3.4*) were based on original Goiás IO tables for the year 2008 (from Guilhoto, 2010). The use of 2008 data can be identified as a limitation of the current analysis and we strongly suggest further analyses using updated data from Brazil's national accounts

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[26] Unfortunately, the latest version of the Brazilian IO matrix was released after all the analyses for this research were done, that is, early 2018 (the 2015 Brazilian IO matrix is available through the link: https://biblioteca.ibge.gov.br/visualizacao/livros/liv101604.pdf). Therefore, this research suggests in *section 5.2*, future studies focusing on updating the analysis done herein through the use of data from the most recent Brazilian IO matrix available. Another reason justifying the use of a late version of the Brazilian IO matrix is because a full IO table for the state of Goiás (the case study of this research) was available only for the year 2008.

system, such as those for 2015 recently released by the IBGE (for more details please refer to *footnote #26* and *sections 4.5 – Work limitations* and *5.2 – Future studies*).

For the analysis proposed in this thesis, these 26 Goiás economy sectors were aggregated into 13 target sectors (**Table 3** and **Appendices II, III, IV** and **V**). Next, a nexus framework was developed by applying the Goiás hybrid inter-regional IO model to analyse its direct and indirect relationships while considering the water, energy, land use and GHG emissions that would be required due to any change in final demand.

Table 3. List of 26 sectors from the original Goiás IO table (Guilhoto, 2010) and the resulting 13 aggregated sectors.

Economy sectors			
	Original sectors		*Aggregated sectors*
1	Agriculture and forestry	*1*	*Agricultural*
2	Livestock and fishing		
3	Mining	*2*	*Mining*
4	Food, beverages and tobacco	*3*	*Food, beverages and tobacco*
5	Textile, clothes and shoes	*4*	*Textile, clothes and shoes*
6	Wood, paper and printing	*5*	*Wood, paper and printing*
7	Oil refining, coke and alcohol	*6*	*Biofuels*[1]
8	Chemical and pharmaceutical products	*7*	*Chemical and pharmaceutical products*
9	Plastic and rubber goods	*8*	*Other industries*[2]
10	Machinery and equipment		
11	Electrical and electronic materials		
12	Transport materials		
13	Miscellaneous industries		
14	Cement and other non-metallic mineral products	*9*	*Cement, construction and other non-metallic mineral products*
15	Construction		
16	Metallurgy	*10*	*Metallurgy*
17	Power, gas, sewage and public cleaning	*11*	*Power sector*[3,4]
18	Commerce	*12*	*Services*
19	Private services		
20	Financial and insurance		
21	Real estate services		
22	Accommodation and food services		
23	Public and private education		
24	Public and private healthcare		
25	Public administration and social security		
26	Transport, storage and mail	*13*	*Transport, storage and mail*

Note:[1] *Biofuels sector hereafter since the state of Goiás does not produce any oil or coke. The charcoal production (from the energy balance) was also allocated to the Biofuels sector in the following subsections*

[2] *Plastic and rubber goods, Machinery and equipment, Electrical and electronic materials, Transport materials, and Miscellaneous industries.*

[3] *It was assumed that 75% of the Power, gas, sewage and public cleaning sector (from the Goiás original IO table) was allocated to the Power sector, which represents electricity generation in*

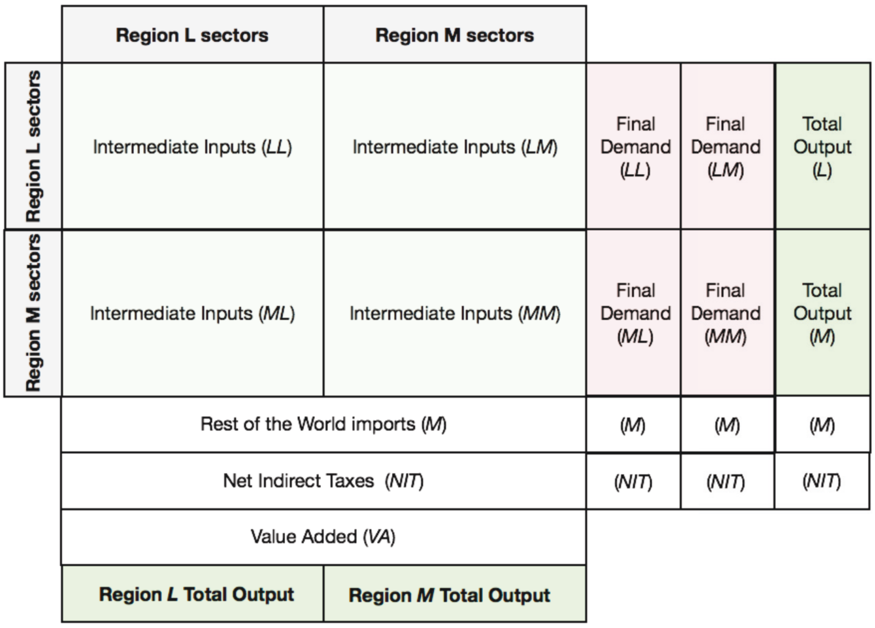
the state. The other 25% of the original sector was allocated to the Other industries sector, to represent sewage and public cleaning activities.

[4] *Of the total electricity generated in Goiás in 2015 (28,464 TWh), hydropower accounted for 81%, followed by thermal generation from sugarcane by-products (15%) and finally, by power from conventional oil products (4%) (MME, 2016). However, according to the Energy Balance for the Goiás State (Brasil, 2010), hydropower plants accounted for 97% of total power production in the state in 2008. Taking into account the low share of thermal energy sources in Goiás in 2008 (3% - conventional sources and sugarcane by-products together), we assumed hydropower plants as the only technology used by the Power sector in the IO analyses.*

3.3.1 Inter-Regional IO Matrix

The IO model concept that was previously shown in *section 1.3* refers basically to national matrices, even when working with models from a single region or models from several interconnected regions, that is, inter-regional models. In short, a regional matrix shows the same structure as a national matrix.

The inter-regional IO model, also known as the '*Isard model*' (1951), requires a huge amount of real or estimated data. In the inter-regional system, there are exchanges between regions through imports and exports, which are expressed by the flow of goods destined for both intermediate consumption and final demand (**Figure 17**).



	Region L sectors	**Region M sectors**			
Region L sectors	Intermediate Inputs (*LL*)	Intermediate Inputs (*LM*)	Final Demand (*LL*)	Final Demand (*LM*)	Total Output (*L*)
Region M sectors	Intermediate Inputs (*ML*)	Intermediate Inputs (*MM*)	Final Demand (*ML*)	Final Demand (*MM*)	Total Output (*M*)
	Rest of the World imports (*M*)		(*M*)	(*M*)	(*M*)
	Net Indirect Taxes (*NIT*)		(*NIT*)	(*NIT*)	(*NIT*)
	Value Added (*VA*)				
	Region *L* Total Output	**Region *M* Total Output**			

Figure 17. IO relationships in an inter-regional system.
Source: Author's adaptation from Guilhoto (2004), Miller and Blair (2009).

In summary, we can present the model from a hypothetical example of inter-sectoral and inter-regional flow of goods to regions *L* and *M*, as follows:

Z_{ij}^{LL} = monetary flow from sector *i* to sector *j* of region *L* and

Z_{ij}^{ML} = monetary flow from sector *i* of region *M* to sector *j* of region *L*.

We can set up the matrix:

$$Z = \begin{bmatrix} Z^{LL} & Z^{LM} \\ Z^{ML} & Z^{MM} \end{bmatrix} \qquad \textit{(Eq. 3.9)}$$

where:

Z^{LL} and Z^{MM} represent intra-regional monetary flow matrices and

Z^{LM} and Z^{ML} represent inter-regional monetary flow matrices.

Considering the Leontief equation,

$$X_i = z_{i1} + z_{i2} + \cdots + z_{ij} + \cdots + z_{in} + Y_i \qquad \textit{(Eq. 3.10)}$$

where

X_i indicates sector *i*'s total output

z_{in} the money flow from sector *i* to sector *n* and

Y_i the sector *i*'s final demand

then, in a regional context:

$$X_1^L = z_{11}^{LL} + z_{12}^{LL} + z_{11}^{LM} + z_{12}^{LM} + Y_1^L \qquad \textit{(Eq. 3.11)}$$

where X_1^L is the total product *1* produced in the *L* region.

Considering the regional input coefficients for *L* and *M* regions, we have the intra-regional coefficients:

$$a_{ij}^{LL} = \frac{z_{ij}^{LL}}{X_j^L} \quad \Rightarrow \quad z_{ij}^{LL} = a_{ij}^{LL} . X_j^L \qquad \textit{(Eq. 3.12)}$$

where a_{ij}^{LL} are the technical coefficients of production, and they represent how much the sector *j* of region *L* demands from sector *i* of region *L*.

$$a_{ij}^{MM} = \frac{z_{ij}^{MM}}{X_j^M} \quad \Longrightarrow \quad z_{ij}^{MM} = a_{ij}^{MM}.X_j^M \qquad \textit{(Eq. 3.13)}$$

where a_{ij}^{MM} are the technical coefficients of production, and they represent how much the sector *j* of region *M* demands from sector *i* of region *M*.

Finally, the inter-regional coefficients:

$$a_{ij}^{ML} = \frac{z_{ij}^{ML}}{X_j^L} \quad \Longrightarrow \quad z_{ij}^{ML} = a_{ij}^{ML}.X_j^L \qquad \textit{(Eq. 3.14)}$$

where a_{ij}^{ML} are the technical coefficients of production, and they represent how much the sector *j* of region *L* demands from sector *i* of region *M* and

$$a_{ij}^{LM} = \frac{z_{ij}^{LM}}{X_j^M} \quad \Longrightarrow \quad z_{ij}^{LM} = a_{ij}^{LM}.X_j^M \qquad \textit{(Eq.3.15)}$$

where a_{ij}^{LM} are the technical coefficients of production, and they represent how much the sector *j* of region *M* demands from sector *i* of region *L*.

These coefficients can be substitute in *Eq. 3.11*, obtaining:

$$X_1^L = a_{11}^{LL}X_1^L + a_{12}^{LL}X_2^L + a_{11}^{LM}X_1^M + a_{12}^{LM}X_2^M + Y_1^L \qquad \textit{(Eq. 3.16)}$$

The production for other sectors can be obtained in a similar way.

By isolating Y_1^L and evidencing X_1^L, we have:

$$(1 - a_{11}^{LL})X_1^L - a_{12}^{LL}X_2^L - a_{11}^{LM}X_1^M - a_{12}^{LM}X_2^M = Y_1^L \qquad \textit{(Eq. 3.17)}$$

The final demand for other sectors can be obtained in a similar way.

Therefore, according to:

$A^{LL} = Z^{LL}(\hat{X}^{L})^{-1}$, we can make the A^{LL} matrix for 2 sectors,

where A^{LL} represents the intra-regional technical coefficients of production matrix. Note that the same formulation can be used to A^{LM}, A^{MM} and A^{ML}.

Now, we can determine the following matrices:

$$A = \begin{bmatrix} A^{LL} & \vdots & A^{LM} \\ \cdots & \cdots & \cdots \\ A^{ML} & \vdots & A^{MM} \end{bmatrix}$$ *(Eq. 3.18)*

$$X = \begin{bmatrix} X^{L} \\ \cdots \\ X^{M} \end{bmatrix}$$ *(Eq. 3.19)*

$$Y = \begin{bmatrix} Y^{L} \\ \cdots \\ Y^{M} \end{bmatrix}$$ *(Eq.3.20)*

The complete inter-regional IO system can be expressed by:

$$(I - A)X = Y$$ *(Eq. 3.21)*

and the matrices can be set as follows:

$$\left\{ \begin{bmatrix} I & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & I \end{bmatrix} - \begin{bmatrix} A^{LL} & \vdots & A^{LM} \\ \cdots & \cdots & \cdots \\ A^{ML} & \vdots & A^{MM} \end{bmatrix} \right\} \begin{bmatrix} X^{L} \\ \cdots \\ X^{M} \end{bmatrix} = \begin{bmatrix} Y^{L} \\ \cdots \\ Y^{M} \end{bmatrix}$$ *(Eq. 3.22)*

By carrying out these operations, we obtain the basic models required for the inter-regional analysis proposed by Isard (1951), that is:

$$(I - A^{LL})X^{L} - A^{LM}X^{M} = Y^{L}$$

$$-A^{ML}X^{L} + (I - A^{MM})X^{M} = Y^{M}$$ *(Eq.3.23)*

resulting in the Leontief inter-regional model:

$$X = (I - A)^{-1} \qquad \textit{(Eq. 3.24)}$$

For a deeper understanding of IO theory and inter-regional IO models, please refer to Isard (1951), Leontief (1970), Herendeen (1978), Guilhoto (2004) and Miller and Blair (2009).

3.3.2 The IO Price Model

3.3.2.1 Supply Side IO Model (Gosh Model)

In 1958 Ghosh presented an alternative IO model based on the same set of base-year data that underpin the demand-driven model, as presented in *section 3.3*. In this case the Leontief inverse relates sectoral gross outputs to the amount of final product (final demand), *i.e.* to a unit of product leaving the inter-industry system at the end of the process. The alternative interpretation that Ghosh suggests relates sectoral gross production to the primary inputs, *i.e.* to a unit of value entering the inter-industry system at the beginning of the process (Miller and Blair, 2009).

This approach is made operational by essentially 'rotating' or transposing the vertical (column) view of the model to a horizontal (row) view. Instead of dividing each column of Z by the gross output of the sector associated with that column, the suggestion is to divide each row of Z by the gross output of the sector associated with that row. The direct-output coefficients matrix that results is usually denoted by 'B' (Miller and Blair, 2009). These bij coefficients represent the distribution of sector i's outputs across sector j that purchase inter-industry inputs from i; these are frequently called allocation coefficients, as opposed to technical coefficients, a_{ij}. Therefore:

$$x' = \sum Z' + v' \qquad (\textit{Eq. 3.25})$$

where $v' = [v_1, \ldots, v_n]$.

Thus, $Z = xB$:

$$x'_j = \sum b_{ij}\, x'_i + v'_j \qquad (\textit{Eq. 3.26})$$

and hence

$$x' = v'(I - B)^{-1} \qquad (Eq.\ 3.27)$$

defining the 'Gosh model':

$$G = (I - B)^{-1} \qquad (Eq.\ 3.28)$$

with elements g_{ij}. This has been called the output inverse, in contrast to the usual Leontief inverse, $L = [l_{ij}] = (I - A)^{-1}$ (the input inverse). In this view of the Ghosh model, row and column sums in the output inverse, $G = (I - B)^{-1} = [g_{ij}]$ were given interpretations that parallel those in the Leontief quantity model (Miller and Blair, 2009).

Aiming to provide an alternative interpretation of the Gosh model, Dietzenbacher (1997) suggested that the model be viewed not as a quantity model but as a 'price model'. In the demand-driven model (*i.e.* Leontief basic interpretation), all prices are assumed fixed and quantities change as a result of changes in final demand. Dietzenbacher assumes that all quantities are fixed and uses the Ghosh model to assess the repercussions throughout the economy of changes in primary input prices, *i.e.* labour, capital, land, etc. Changes in primary input costs are transmitted throughout the economy as they are passed on (completely) by producers in the price of the products purchased by other intermediate users, who in turn increase their prices accordingly (Miller and Blair, 2009). This is the reason this reinterpretation of the Gosh model is also called a 'cost-push IO model'.

Similar to the Gosh model, primary input price changes generate relative price changes in the Leontief price model as well, as presented below. Therefore, the next section (*section 1.3.2.2*) shows that the Ghosh price model and the Leontief price model generate exactly the same results. For a deeper understanding of the Gosh price model, the Leontief price model and the connections between them, see Miller and Blair (2009), *chapter 12*.

3.3.2.2 Leontief IO Price Model

In fact, the specification of the IO model allows duality – quantity and price – to be considered[27]. Therefore, the price identity can also be represented in the IO model as:

$$p_j = \sum a_{ij}\, p_i + v_j \qquad \text{(Eq. 3.29)}$$

where:

p_j: prices of sector *j* products

p_i: price of input *i* paid by sector *j* and

v_j: ratio of sector *j*'s value added to its total output, *i.e.* value added coefficients.

In short, the price of any particular sector *j* depends on the use of intermediate inputs and the use of primary inputs as a factor of production. Similar to the basic Leontief IO model, the Leontief price model is presented in its condensed matrix form, as follows:

$$P = AP + V \qquad \text{(Eq. 3.30)}$$

where:

P: vector of sectoral prices index and

V: matrix that represents the ratio of sectoral value added to total output.

Hence:

$$P = (I - A')^{-1}.V \qquad \text{(Eq. 3.31)}$$

Eq. 3.31 is Leontief's price model. This model can be used to '*assess the impact on prices throughout the economy of an increase in value-added costs in one or more sectors*'

---

[27] '*The quantity and price models – either Leontief or Ghosh – are often described as "dual" to each other, while the Leontief variant of the quantity model has been described as the "mirror image" of the Ghosh quantity model, and similarly for the Leontief and Ghosh price models'* (Miller and Blair, 2009).

(Miller and Blair, 2009). Therefore, in the Leontief price model, it is also the case that primary input price changes generate relative price changes[28]:

$$P = [I - (A^0)]^{-1} . v_c^1 \qquad \textit{(Eq. 3.32)}$$

$$P = (L^{0\prime}) v_c^1 \qquad (\textit{Eq. 3.33})$$

Similarly, in the Gosh model:

$$\pi = (L^{0\prime}) v_c^1 \qquad (\textit{Eq. 3.34})$$

Therefore, the Leontief price (cost-push) model and the Ghosh price model generate the same results; the former directly in terms of the vector of relative price changes, *P*, and the latter in terms of new outputs, from which π (instead of *P*) is found as the ratio of new-to-old output values. For a deeper understanding of IO price model theory, concepts and formulations, please refer to Leontief (1970), Kula (1998), Dixon and Rimmer (2000) and Miller and Blair (2009).

3.3.2.3 Price Impact of Carbon Tax

The Leontief price model (*Eq. 3.31*) can be used to analyse the impacts of an increase in value-added costs (in one or more sectors) on prices throughout the economy. Since a carbon tax will increase value-added costs, the model is useful for assessing its impact, and this (as well as any other policy initiative) can be estimated because the tax will increase product prices through increases in sectoral value-added costs. In order to perform the analysis, first the base-year price level needs to be calculated. When applying *Eq. 3.31* to base-year data (including base-year IO technical coefficients and sectoral value added), one obtains a vector of base-year prices for all sectors equal to one [1], which means there is no change in prices:

$$P^o = (L^{0\prime}) v_c^0 = [1] \qquad (\textit{Eq. 3.35})$$

---

[28] The superscript *0* denotes the base-year data (in this case, original technical coefficients and original *L* matrix) and the superscript *1* denotes new values for that variable (in this case, for the year t^{+1} or new value-added coefficients after changes in the previous value-added, *i.e.*, $(v^1) = (v^0) + (\Delta v)$.

where $v_c^0 = [v^0/x^0]$, *i.e.* base-year value added coefficients.

Next, the sectoral ad valorem carbon tax rate (which is obtained from the tax assumptions, explained below in *section 3.3.2.4*) is imposed on the sectoral value added, as follows:

$$P^n = (I - A^{0\prime})^{-1}.(V^0 + t^n) \qquad (Eq.\ 3.36)$$

where:

P^n = vector of new sectoral price level

A^0: matrix of IO technical coefficients for base year

V^o: matrix of sectoral base-year value added coefficients, and

t^n: vector of new sectoral ad valorem carbon tax rate (calculated as *Eq. 3.39*, below).

This results in an index of price changes for the chosen sector inputs, compared to the base year:

$$\frac{\dot{P}}{P} = \frac{(P^n - P^o)}{P^o} \qquad (Eq.\ 3.37)$$

where P^n and P^o represent new and old prices, respectively.

3.3.2.4 Carbon Tax Estimates

In order to calculate the vector of a new sectoral ad valorem carbon tax (t^n), an approach based on the PPP was assumed. According to the PPP definition, the allocation of CO_2 emissions is straightforward, and the emissions are based on the quantities and types of fossil fuels used directly at the point of combustion (SANDU, 2007). However, this research did not add a sub-matrix into the IO model to calculate the emissions from the energy used by the sectors of the economy; instead, it was developed using an estimation of CO_2 intensities based on given CO_2 emissions to each target sector (SEEG, 2017) and sectoral value added (Guilhoto, 2010). It is worth mentioning that the estimating system for GHG emissions (SEEG (2017)) consider all emissions from each sector, including the energy used directly by each economic activity. Accordingly, CO_2 intensities (*EI*) can be measured by the amount of CO_2 emitted (*E*) per unit of output (*X*):

$$EI = \frac{E}{X} \qquad (Eq.\ 3.38)$$

Therefore, it can be assumed that the carbon tax is fully transferred through factor input prices. As a result, a carbon tax (t^n) increases the price of factor inputs in proportion to their CO_2 emissions:

$$t^n = T\,.\,EI \qquad (Eq.\ 3.39)$$

where:

T: level of tax on CO_2 emissions (in US\$/tCO_{2e}), and

EI: CO_2 intensity (in tCO_2/US\$ of total sectoral output).

In this context, the term t^n can be considered as equivalent to a set of indirect taxes imposed on each sector *i*, which will be used to determine the impact of a carbon tax on price increases in target sectors. In this research, the level of tax considered for CO_2 emissions was US\$10/tCO_2, a value typically found in the literature and in carbon pricing international experiences put in place so far (Nordhaus, 2007; Aldy, 2016; Narassimahn *et al.*, 2017; ICAP, 2018; Santos *et al.*, 2018).

Therefore, the estimated sectoral ad valorem carbon tax rate (t^n) was finally imposed to sectoral value added through *Eq. 3.36,* in order to analyse the index of price changes caused by a carbon tax (for more details, please refer to **Appendix XIX**). After this, the price change index was applied to alternative production functions to update the IO original technical coefficients, in order then to analyse the outcomes of the hybrid economic-ecological IO model with a more realistic approach, as explained below.

3.3.3 Modification of IO Coefficients

Input prices are subject to change over time and, based on microeconomic theory, when these changes take place, producers seek to substitute these price-affected inputs with other factor inputs, such as labour and capital. The fundamental theory of IO analysis states that inputs are perfect complements[29] in an IO model, ignoring the possibility of substitution between different inputs due to price changes. Therefore, since IO models are not equipped with a mechanism that captures the impacts of changes in technology over time, substitution effects cannot be analysed using the traditional IO framework. In this context, the traditional IO model can be seen as a set of linear production functions. Therefore, since substitution is not allowed, when the availability of a given factor input decreases, it cannot be substituted with other input; rather, the producer has to decrease the level of production, hence impacting overall output in the model.

In fact, technology in the real world cannot be considered fixed over time. Changes in technology occur throughout time because it is constantly impacted through changes in consumer behaviour, producer preferences, technology development, policy implications, innovations, among others. Any of these changes may have an impact on input prices and hence changes in technology through changes in factor inputs. Therefore, an increase in the price of one production input will lead to some level of substitution between other inputs and hence, this substitution effect will impact the input mix of a technology or sector, depending on the substitution between various inputs.

A useful alternative to overcome the issue of fixed-input proportions in traditional IO models is to use neoclassical production functions to update the original IO technical coefficients. Since neoclassical production functions are more flexible than the Leontief production function, they allow the producer to substitute one input with another, reflecting economic rationalist behaviour.

The neoclassical production function, first developed by Cobb and Douglas (Cobb and Douglas, 1928), relates physical output to capital and labour inputs. The Cobb-Douglas production function has a constant elasticity of substitution, *i.e.* equal to 1 (*i.e.* inputs are perfectly substitutable):

---

[29] Inputs in a traditional IO model are considered perfect complements due to the assumption of fixed proportionality of technical coefficients. This assumption implies a linear (and fixed) relationship between a sector's output and its inputs; therefore, it represents a linear production function that reflects constant returns to scale. This type of production function is called a Leontief production function.

$$Y = F(K, L) = aK^{\alpha}L^{\alpha-1} \qquad (Eq.\ 3.40)$$

where:

Y: total production

K and *L:* factor inputs

a: relationship between industries in that country, *i.e.* structural coefficient ($a > 0$) and

α: cost share ($0 < \alpha < 1$)

and in its IO form:

$$x_i = a_{ij}\left(\frac{P_j}{P_i}\right) x_j \qquad (Eq.\ 3.41)$$

where:

P_i: price for input *I* and

P_j: price for input *j*.

The elasticity of substitution for the Cobb-Douglas production function is constant and is independent of other parameters of the production function (coefficient a, *i.e.* it is independent of the structure of the system). If the Cobb-Douglas function is constant, that means the percentage change in the relative factor mix is the same as the percentage change in relative factor prices, *i.e.* -1. Therefore, this characteristic represents the main weakness of the Cobb-Douglas production function, because it assumes the rate of substitution and factor shares of output are constant across all industries.

In order to overcome this issue, Arrow *et al*. (1961) developed a production function with a constant elasticity of substitution, but it was not restricted to unity. This type of production function is known as the constant elasticity of substitution (CES) production function:

$$Y = F(K, L) = (aK^{\rho} + bL^{\rho})^{\frac{1}{\rho}} \qquad (Eq.\ 3.42)$$

where:

a and b are structural parameters (scaling factors) and

ρ is the substitution parameter ($\rho < 1$, *i.e.*, there is no complete substitution).

In short, the elasticity of substitution (σ) can be defined as:

$$\sigma = \frac{1}{\rho - 1} \qquad (\textit{Eq. 3.43})$$

and if:

$\rho = 0 \quad \Rightarrow \quad$ Cobb-Douglas production function

$\rho = -\infty \quad \Rightarrow \quad$ Leontief production function and

$\rho = 1 \quad \Rightarrow \quad$ Linear production function.

By applying the CES production function to the IO model, we have:

$$x_i = \gamma^{\sigma-1} \, a \left(\frac{P_j}{P_i}\right)^{\sigma} x_j \qquad (\textit{Eq. 3.44})$$

where:

γ: scale parameter (constant returns to scale; CRS = 1) and

σ: substitution elasticity.

In order to update the original IO technical coefficients, the percentage changes in input prices are derived in this research into the price impact model from the imposition of a carbon tax, as discussed earlier in *subsections 3.3.2.2* and *3.3.2.3*. Therefore, it is straightforward that elasticities of substitution can be derived by assuming other types of production function, rather than the Leontief production function. Thus, the Leontief price model and the aforementioned production functions were applied to estimate the new technical coefficients. This was done after considering a more realistic analysis by allowing the substitution between factors of production, in this case, through a carbon pricing initiative in Brazil. Accordingly, the updated IO technical coefficients can be derived from the following equation:

$$a_{ij}^{n} = \frac{x_{ij}}{x_j} \cdot \left(\frac{P_i}{P_j}\right)^{\sigma} \cdot \frac{1}{\gamma^{\sigma-1}} \qquad (Eq.\ 3.45)$$

where:

a_{ij}^{n}: updated IO technical coefficient and all other variables already defined.

It is also worthwhile to mention here that the CES production function turns into the Cobb-Douglas form if substitution elasticities are restricted to unity. Therefore:

$\rho = 0\,;\ \sigma = -1 \quad \Rightarrow$ Cobb-Douglas production function

$\rho = 1\,;\ \sigma = \infty \quad \Rightarrow$ Linear production function

$\rho = \pm\infty\,;\ \sigma = 0 \quad \Rightarrow$ Leontief production function.

Also, although the price elasticities of demand derived from the Cobb-Douglas and CES production functions have limitations compared with those derived from more sophisticated production functions, such as the *Translog* production function[30], they are still better than assuming zero elasticities, as is the case with the Leontief production function (or traditional IO models). Finally, once the new sets of IO technical coefficients (updated IO coefficients) were derived, they were used to analyse the environmental and economy-wide impacts of price changes (through a carbon tax) in the Brazilian study case. Therefore:

$$X = (I - A_n)^{-1}.Y \qquad (Eq.\ 3.46)$$

where:

X: column vector of sectoral outputs

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[30] Developed by Christensen *et al.* (1971; 1973), the Transcendental Logarithmic (*Translog*) production (or cost) function is a second-order approximation in logarithms of an arbitrary cost function and it imposes no prior restrictions on the elasticities of substitution and the price elasticities of demand.

A_n: matrix of updated IO technical coefficients and

Y: column vector of sectoral final demands.

3.3.4 Goiás' Economic-Ecological IO Model

Since the late 1960s, the IO framework has been extended by many researchers to account for environmental pollution generation and abatement associated with inter-industry activity. This has been occurring because IO models are good analytical tools for measuring both direct and indirect impacts (Guilhoto, 2004; Miller and Blair, 2009). Leontief (1970) himself provided one of the key methodological extensions, which has since been applied widely and extended further.

The main goal of an environmental IO model is to analyse environmental (and energy) flows to determine the total inputs (*e.g.* water, land, energy) used in producing a given output for consumption in the final demand sectors (Miller and Blair, 2009).

Such an analysis requires the resetting of a hybrid IO table, in which the flows between sectors are represented in hybrid units. In other words, in a hybrid analysis, an environmental IO model shows its 'environmental flows' both in monetary and physical units (*e.g.* m³ of water, m² of land, J of energy consumed, etc.), whereas non-environmental flows are described only in monetary terms (**Table 4**). Through this hybrid IO model, we can estimate the environmental (and energy) requirements of producing sectors to produce goods and services in the economy. This will give us estimates of all resources used by each sector, driven by changes in final demand.

Table 4. General structure of an IO table with hybrid units*.

	Inter-industry Transactions				Environmental Commodity Outputs
	Consuming Sectors				
	Sector 1	Sector *n*	Final Demand	Total Output	Emissions
Producing Sectors					
Sector 1	*Z (US$)*		*Y(US$)*	*X (US$)*	gCO_{2e}
Sector *n*					
Environmental Commodity					
Land	m^2				
Water	m^3				
Energy	J				

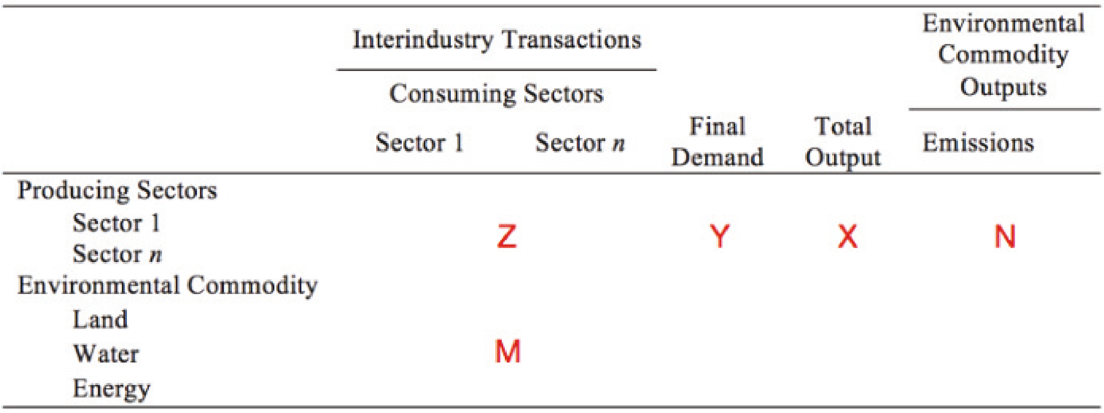
**Example of the Economic-Ecological IO model.*
Source: Author's adaptation from Miller and Blair (2009).

In environmental IO models, we seek an analogous set of matrices to *Z*, *A* and L, that is, respectively, an environmental transactions or flows matrix, a direct environmental requirements matrix and finally a total environmental requirements matrix (Miller and Blair, 2009).

To carry this out, we define a set of ecological commodity inputs, the magnitudes of which we will capture in a matrix $M = [m_{kj}]$, an element of which reflects the amount of ecological input of type *k* used in the production of economic sector *j*'s total output. Similarly, we define a set of ecological commodity outputs (*e.g.* gCO_{2e}). The corresponding matrix of ecological commodity output flows is $N = [n_{kj}]$, an element of which specifies the amount of ecological commodity output *k* associated with the output of sector *j*.

From **Table 4**, we can identify the matrices of ecological commodity inputs and outputs, respectively, *i.e.*, *M* and *N*, as well as the inter-industry transactions *(Z)*, the vector of total final demands *(Y)* and the vector of total industry outputs *(X)* (highlighted in **Table 5**).

Table 5. Economic-ecological commodity flows: Matrix definitions.



	Interindustry Transactions				Environmental Commodity Outputs
	Consuming Sectors				
	Sector 1	Sector *n*	Final Demand	Total Output	Emissions
Producing Sectors					
Sector 1	Z		Y	X	N
Sector *n*					
Environmental Commodity					
Land	M				
Water					
Energy					

Source: Author's adaptation from Miller and Blair (2009).

We can now define the ecological commodity input and output coefficients in much the same way as we defined the direct impact coefficients earlier, by first recalling that $A = Z\hat{x}^{-1}$, which defines the matrix of technical coefficients; hence, we define the matrices of ecological commodity input and output coefficients as:

$R = M\hat{x}^{-1}$, which defines the matrix of ecological commodity input coefficients, *i.e.,* the elements of $R = [r_{kj}]$ specify the amount of commodity k required per dollar's worth of output of industry j

$Q = N'\hat{x}^{-1}$, which defines the ecological commodity output coefficients, that is, $Q = [q_{kj}]$ specifies the amount of commodity k generated per dollar's worth of output of industry j (Miller and Blair, 2009).

Note that N' is the transpose of the matrix of ecological commodity output flows. Also, note that in matrix algebra notation, a 'hat' over a vector denotes a diagonal matrix with the elements of the vector along the main diagonal, so, for example:

$$\hat{\mathbf{x}} = \begin{bmatrix} x_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & x_n \end{bmatrix}$$

Thus, using R and Q as computed above, total impact coefficients – in this case, ecological commodity input and output coefficients as a function of final demands – can be respectively written as:

$$R^* = R(I - A)^{-1} \text{ and } Q^* = Q(I - A)^{-1} \qquad \textit{(Eq. 3.47)}$$

where

$R^* = [r^*_{ij}]$ reflects the amount of ecological input i required directly and indirectly to deliver a dollar's worth of industry j's output to final demand, and

$Q^* = [q^*_{ij}]$ reflects the amount of ecological output i associated with delivering a dollar's worth of industry j's output to final demand directly and indirectly.

Therefore, the use of hybrid economic-ecological IO models to analyse GHG emissions and water, energy and land use according to final demand is considered suitable both for verifying the direct consumption of resources by final demand, as well as for calculating the total environmental requirements to produce the outputs required by this final demand. To analyse future changes in the use of inputs (*i.e.* water, energy and land) from changes in final demand for ethanol in the state of Goiás, this thesis justifies the use of the environmental analysis tool provided by the hybrid economic-ecological IO model.

However, there are no market transactions of environmental requirements and therefore they are not represented in the standard national accounts (Hristu-Varsakelis *et al.*, 2010). In order to assess environmental requirements, Goiás' IO table was rearranged to include them in the analysis (see also Miller and Blair, 2009; Hristu-Varsakelis *et al.*, 2010; Carvalho *et al.*, 2015; Wang and Chen, 2016). In this regard, production and consumption of water, energy, land and emissions were incorporated into the original Goiás' IO table as an 'attached environmental account' to allocate the environmental flows between sectors (see **Appendix VI**).

This procedure generates an extended IO table with hybrid units, where environmental flows are considered in physical units (*i.e.,* hm^3, PJ, km^2, $TgCO_{2e}$) and all non-environmental sector flows are measured in monetary units (*US\$*) and an average exchange rate of R\$ 3.23/US\$ for the period of a year is assumed (BCB, 2017). This framework therefore allows the impacts associated with inter-industry production and generated in response to any new vector of final demands to be tracked. To carry out the analyses with extended IO tables, a linear programming problem is defined aiming at maximising the GDP (*Eq. 3.48*):

$$Max\ GDP = c^T\ X \qquad \text{(Eq. 3.48)}$$

where

$c^T = [1, 1, ..., 1]^T$ (so that c is the column-sum of the IO matrix).

The matrix of technological coefficients (from *Eq. 3.5,* $A = Zx^{-1}$) is obtained from the IO matrix and, through some algebraic manipulation, it results in the basic linear Leontief model *(Eq. 3.8)*. Thus, the maximisation of GDP was subject to the following (linear) constraints:

i) $c^T(I - A)X \le c^T(Y_{min} - M)$, where M represents imports and Y_{min} is a lower bound on the total sum of demand met across all sectors

ii) $X \ge X_{min}$, where X_{min} is the lower production level *iii)* $X \geq 0$, representing that gross value of production, must be non-negative in every sector

iv) $R^* \leq R_{min}$, where R_{min} is the current use of environmental resources, *i.e.* water, energy and land

v) $N'^* \leq N'_{min}$, where N'_{min} is the current GHG emissions and

vi) $J^* \leq J_{min}$, where J_{min} is the current employment level.

Additionally, ethanol scenarios were considered as the main changing variable in the IO model. After estimating these scenarios (in terms of % change from current (2015) levels), the new ethanol final demand requirement was incorporated into the extended IO model to estimate the impact on energy, environmental and economic systems and from there to obtain a better understanding of whether ethanol expansion in the region would threaten local environmental resources.

Thus, this work adopts a nexus approach through the application of the Goiás' hybrid economic-ecological IO model, taking into account the environmental aspects of (*i*) inputs: water withdrawal (hm^3), land-use (km^2) and energy use (*PJ*) and (*ii*) outputs: GHG emissions (as mass of $CO_{2e\ GWP\text{-}AR5} - in\ Tg$). Since the Goiás' IO model considers official employment data, the model can also be used to estimate the social impacts of future changes in final demand for ethanol. The impacts of a carbon tax can be assessed through IO price change analyses that identify the overall economic impacts of carbon pricing initiatives. As detailed in previous sections, these price change ratios were taken into account through the use of a more flexible production function that allows for factor inputs substitution between sectors of the economy, in order to update the original IO technical coefficients for the state of Goiás. An updated IO total requirements matrix (updated Leontief matrix) was therefore used to assess the overall socioeconomic and environmental impacts in the region studied, taking into consideration possible technological changes in the inter-industry sector from changes in factor input prices caused by a carbon tax policy. Finally, all the IO tables were processed through multiple spread-sheets (using *Microsoft Excel*) and the optimisations were performed through the *Opensolver*.

3.3.5 Sectoral Value-added Impacts and CO_2 Emissions Abatement

To internalise negative externalities, the PPP defines responsibility and establishes a cost for GHG emissions, *i.e.* carbon pricing. As previously explained in *sub-section 2.4.1*, carbon pricing initiatives can be implemented through different approaches: by establishing a carbon market, *i.e.* a pollution trading systems or emission trading schemes (ETS), or by implementing fiscal policies, such as a carbon tax. It is worth mentioning that a carbon tax policy affects not only the behaviours of producers, who have to pay for their externalities under this policy, but also consumer decisions, because higher prices due to carbon pricing may redirect consumer behaviour towards less carbon-intensive goods.

Taking into account the PPP and the emissions intensity concepts (already presented in *subsections 3.3.2.3* and *3.3.2.4*), the estimated impacts of the cost of carbon pricing on sectoral value added is expressed as the relative weight of the cost of carbon over production factors (Santos *et al.*, 2018). These impacts were reached by the ratio of the carbon cost to value added and they were estimated for different carbon prices, namely, 5, 10, 25 and US\$50/tCO_{2e}, reflecting a range typically found in the literature and in the international carbon pricing experiences put in place so far (Nordhaus, 2007; Sandu, 2007; Aldy, 2016; Narassimahn *et al.*, 2017; ICAP, 2018; Santos *et al.*, 2018). Analyses of the estimated impacts of carbon cost to value added consider full emissions for the year 2008 in the state of Goiás, Brazil. This estimate can be seen as a conservative indicator, assuming that the carbon cost is fully absorbed by the state's economic sectors, *i.e.*, without taking any mitigation measure into account.

Sectoral emissions intensity is therefore a useful indicator to analyse qualitatively the impact of a carbon tax on sectoral competitiveness by indicating the ratio of sectoral emissions over the sectoral value added (*i.e.* $EI = E/VA_s$). In fact, the sectoral emissions intensity indicator is pretty similar to the output emissions intensity, as described by *Eq. 3.38* (*i.e.* $EI = E/X$). In this regard, when including carbon prices to the emissions intensity indicator, results can be seen as a carbon cost share (CCS) of the total value added, *i.e.*, how much carbon pricing could impact the return on the production factors of these sectors:

$$CCS = \frac{CC}{VA_s} \qquad (Eq.\ 3.49)$$

where:

CCS: carbon cost share (as % of total value added)

CC: carbon cost = $TE_s \,.\, CP$

TE_s: total sectoral emissions

CP: carbon prices (for different carbon prices: 5, 10, 25 and US\$ 50/tCO_{2e}) and

VA_s: sectoral value added.

Another possibility for interpreting the impact of a carbon tax on the value added is to simulate a CCS according to different levels of reduction in absolute emissions, as performed by Santos *et al*. (2018) for the Brazilian industrial sector. This alternative analysis was also applied to the present research and it shows the effects (in terms of % of the value added) of internalising a carbon price for the year 2008, used to analyse the impact of different carbon prices and emissions abatement possibilities on Goiás' economic sectors. Therefore:

$$PE = TE_s - ER \qquad (Eq.\ 3.50)$$

where

PE: priced emissions (in % of total value added) and

ER: emissions reduction (varying from 0 to 45%).

This range of emissions reduction represents the abatement of emissions needed to reach Brazil's NDC targets as presented in *section 2* of this research, *i.e.* to reduce GHG emissions to 37% below 2005 levels by 2025, with a subsequent indicative reduction of emissions to 43% below 2005 levels by 2030. Another justification for the use of this range is the abatement potential found in a study led by the Brazilian Ministry of Science, Technology and Innovation (MCTI, 2016a), which was also mentioned by Santos *et al.* (2018).

3.3.6 Data Sources

Once Goiás' IO table for the year 2008 was estimated, all the other data required to formulate the hybrid IO model (*i.e.,* water, energy, land use and GHG emissions) were analysed for the same year to calibrate the model. The main purpose behind this initiative was to capture (through the Goiás' IO table) all the economic and environmental conjuncture (through analysing specific data sources, explained hereafter) for a specific year to understand the relationship between the inputs and outputs of that economy at that time. Analogously, it can be seen as a picture of the economy during the target year. Hence, it defined a pattern (ratio) between the sectors (coefficients) of the economy to be used as a tool to estimate the impact of future changes in final demand by following the structure (ratio) defined in the baseline year, *i.e.,* 2008. Despite the fixed relationship ratios between sectors, this method can be used to estimate economic and environmental impacts on the economy for any future year and, in our case study, the scenarios considered ethanol expansion in the year 2030. As already mentioned, the issues related to the fixed nature of technical coefficients was addressed in *section 3.3.3*, by suggesting the use of more flexible production functions in order to update the original technical IO coefficients, thereby bringing the analysis closer to reality.

3.3.6.1 Economic Data (Elasticity Estimates)

To overcome the issue of fixed technical coefficients in IO analysis, this research applies a flexible production function that allows for substitution between factors of production, *i.e.* the Cobb-Douglas production function and CES production function, in order to find out whether technological changes arising from substituting production factors among target sectors would significantly impact the results initially found through the application of the traditional IO model, *i.e.* with its fixed technical coefficients. The methodological steps used to estimate these technical coefficients were presented in previous sections. In this case, a range of elasticity of substitution values was applied, namely -0.905, -0.5, 0.5, 1.0 and 1.5. These are similar to values found by previous studies focusing on income and price elasticities of different products and services for Brazil (Hoffman, 2007; Payeras, 2009; Wills and Grotera, 2015). For instance, Payeras (2009) found an average price elasticity of -0.905 and an average income elasticity of 0.655 for a range of Brazilian products, while Hoffman (2007) estimated an average income elasticity of 0.795 (see **Appendix XVIII**).

Nordhaus (1977) applied the Cobb-Douglas production function to analyse international energy demand in seven countries (Belgium, France, Germany, Italy, the Netherlands, the United Kingdom and the United States), focusing on four sectors (energy, transport, industrial and residential sectors). The author estimated long-run price and income elasticities. Results were attained for all possible levels of aggregation and the average long-run price elasticity amounted to -0.85 and the average long-run income elasticity to 0.79. A more recent example from Joyeux and Ripple (2011) shows that between 1973 and 2008, the income elasticity of total energy demand in developing and industrialised countries was 0.85 and 1.08, respectively; however, the income elasticity of residential electricity demand in developing and industrialised countries was estimated to be substantially lower (0.56 and 0.42, respectively). These average elasticity values were therefore taken into consideration by the present research to determine the range of elasticities of substitution to be used in calculating and hence updating the original IO technical coefficients, in order to reach a more realistic outcome when analysing medium and long-term policies.

3.3.6.2 Land-use Data

Land-use data for the agriculture sector covers all the crop area used in Goiás State, *i.e.*, mainly soybean, corn and sugarcane crops, which together accounted for 71% of the total agriculture area in 2008 (**Figure 18**) (IBGE, 2009, MAPBIOMAS, 2017). The total area used by livestock production, 155,234 km², was estimated from IBGE (2009a, 2017) and MAPBIOMAS (2017).

Data on total industry area, whose footprint was lower than that of agriculture, was estimated from state government agencies such as the Goiás Secretariat of Planning and Development (SEPLAN, 2009, 2010) and the Institute for Statistics and Socioeconomic Studies (IMB, 2014). All the land-use estimates are presented in the **Table 6** and were applied as a land-use input vector in the Goiás' hybrid IO model (**Appendix VI**).

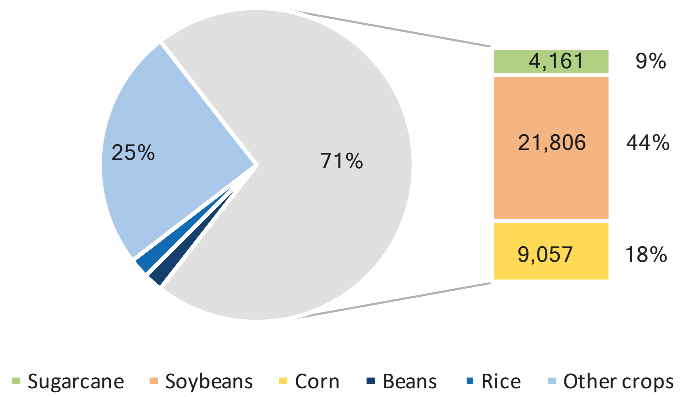


Figure 18. Goiás' agriculture land use, by crop, in km² (2008).
Source: Author's adaptation from IBGE (2009) and MAPBIOMAS (2017).

Table 6. Land-use in the state of Goiás (2008), by economy sectors.

Economy sectors	***Land use (km²)***	***%***
Agricultural	*204,517*	*98.64*
Livestock	155,234	74.87
Agriculture	49,283	23.77
Power sector[1]	*2,755*	*1.33*
Industry	*57*	*0.03*
Mining	30	0.02
Food, beverages and tobacco	7	0.00
Textile, clothes and shoes[2]	-	-
Wood, paper and printing	4	0.00
Biofuels[3]	0	0.00
Chemical and pharmaceutical products	4	0.00
Other industries	2	0.00
Cement, construction and other non-metallic minerals	4	0.00
Metallurgy	7	0.00
Transport[2]	-	-
Services[2]	-	-
Total (km²)	**207,330**	**-**

Note: [1] According to the Energy Balance for the Goiás State (Brasil, 2010), hydropower plants accounted for 97% of total power production in the state in 2008. Taking into account the low share of thermal energy sources in Goiás in 2008 (3% - conventional sources and sugarcane by-products together), we assumed hydropower plants as the only technology used by the Power sector in the IO analyses. The land use for the Power sector, therefore, was estimated only for hydro plants, from the area occupied by water reservoirs.

[2] The land use for the Services, Textiles, Clothes and Shoes sectors were not properly identified from the available references. There is no land use for the Transport sector.

[3] The Biofuels sector shows a land use of virtually nil (0.09 km²) when considered as part of the Industry sector, but its land use is accounted for in agricultural land use.

Finally, the land used by Goiás' *Power sector* (through the area occupied by water reservoirs) was estimated from the available hydropower stations and reservoirs data from the national electrical system operator (ONS, 2004, 2005, 2017) and by applying polynomial calculations to estimate the desired information.

To do this, each hydro station had at least two fourth-degree polynomial data sets with the following properties:

a) *Quota-Volume polynomial*: It is possible to calculate the reservoir surface in relation to the sea level from the water volume stock in the reservoir (in hm^3). Thus, for each hydro plant, the parameters a_{QVP}, b_{QVP}, c_{QVP}, d_{QVP} and e_{QVP} are available. The *equation 3.51* shows how the reservoir surface quota can be calculated from the reservoir volume (Vol).

$$Quota = a_{QVP} + b_{QVP}.Vol + c_{QVP}.Vol^2 + d_{QVP}.Vol^3 + e_{QVP.}Vol^4 \quad \textit{(Eq. 3.51)}$$

b) *Quota-Area polynomial*: From the reservoir quota (in metres), we can calculate the reservoir surface area (in km^2). So, from the reservoir surface area, which depends on the volume of water stored, we can also estimate the water lost to evaporation. Similarly, for each hydro plant, the parameters a_{QAP}, b_{QAP}, c_{QAP}, d_{QAP} and e_{QAP} are available. The *equation 3.52* shows how the area can be estimated from the reservoir surface quota relative to sea level:

$$Area = a_{QAP} + b_{QAP}.Quota + c_{QAP}.Quota^2 + d_{QAP}.Quota^3 + e_{QAP.}Quota^4 \quad \textit{(Eq. 3.52)}$$

The following hydropower reservoirs located in the study area were analysed (**Table 7**) and the maximum, minimum and useful water volume data for the year 2008 were obtained from the ONS's *Operation history: useful volume of the main reservoirs* (ONS, 2017).

Table 7. Maximum, minimum and useful water volume for the major hydro plants in the study area, in *hm³*.

Hydropower plant	Max Volume	Min Volume	Useful Volume
UHE Batalha	1,781	430	1,351
UHE Nova Ponte	12,792	2,412	10,380
UHE Corumbá I	1,500	470	1,030
UHE Barra dos Coqueiros	347	300	47
UHE Salto	826	826	0
UHE Emborcação	17,725	4,669	13,056
UHE Cachoeira Dourada	460	460	0
Queimado	557	95	461
Corumbá IV	3,708	2,936	771
Corumbá III	972	709	263
Serra do Facão	5,199	1,752	3,447
Itumbiara	17,027	4,573	12,454
Salto Verdinho	264	264	0
Cacu	231	197	34
Espora	209	71	138
Castelo Branco II	879	878	1
Castelo Branco I	241	228	12
Miranda	1,120	974	146
São Simão	12,540	7,000	5,540

Note: Useful volume = Max volume – Min volume; Min volume, also called 'dead volume'.
Source: Author's adaptation from the ONS (2017) data.

The *Power sector's* total land-use area obtained from the estimates listed above represent 2,755 km² of surface, as shown in **Table 6**. Additionally, the useful volume (monthly average), the real useful volume (monthly average), the relative quota and the average monthly area for all the 19 hydropower reservoirs located in the study area can be verified in **Appendices VII**, **VIII**, **X** and **XI**. Specifically, **Appendix IX** shows all the polynomials made available by the ONS (2017) that were used to estimate the volume of water and the area occupied by power plant reservoirs.

3.3.6.3 Water-Use Data

Since there is a lack of available data on water use by different activities in the country, estimating water use by economy sectors is not a trivial task. Most of the analyses performed herein were based on estimates on water use, from indicators such as water footprint (in the case of the *Agriculture* sector), specific water consumption (in the *Livestock* sector) and water-use technical coefficients (in the *Industry* sector).

Additionally, after calculating the area of hydropower reservoirs presented in the previous subsection, an estimation of evaporation from the reservoirs was carried out to determine the amount of water consumed by the *Power* sector.

The water used by the *agriculture* (blue water) and *livestock* sectors was based on IBGE (2009, 2009a), Mekonnen and Hoekstra (2011), EMBRAPA (2013) and FAO (2017). Regarding sugarcane production in Goiás State, the blue water coefficient applied was 0.075 m^3/kg of sugarcane, a coefficient established by Fachinelli and Pereira (2015) through their work on irrigated ethanol in the Paranaíba basin, Goiás.

Regarding water use by the *industry* sector, there was an issue around determining the sectoral technical coefficients, which ideally should be differentiated by product sector, by micro-region and by technological process (FUNARBE, 2011). Many studies (ANA, 2002; ONS, 2005; FUNARBE, 2011; CNI, 2013) have tried to find some water use coefficients related to water withdrawals. The industrial water-use coefficients applied to this study were related to water withdrawal (in m^3) per unit of production, based on the findings of FUNARBE (2011). In this context, the total national production for 2008 was obtained from Brazilian industrial research (IBGE, 2009b) and Guilhoto (2010), by sector. All the water-use coefficients, the bulk production and the estimates of total water use by sector can be checked in **Appendix XII**. Additionally, a short version of the water-use data in Goiás by economy sectors in 2008, is presented below (**Table 8**).

Finally, the water used by Goiás' *Power sector* was estimated from the national electrical system operator data (ONS, 2004, 2005, 2017). Evaporation causes the surface of the reservoir to drop, depending on the location of the reservoir and the month of the year. Thus, for each hydropower plant, 12 indexes of the average local evaporation (in mm) are available, corresponding to the months of the year. Evaporation is an important parameter in the Brazilian *Power sector*, since the rainy season varies widely from region to region.

Table 8. Total water use in Brazil and in the state of Goiás by sector, in 2008.

Economy sectors	*Brazil (hm^3)*	*Goiás (hm^3)*
Agricultural	-	*3,721.59*
Agriculture	-	3,394.86
Livestock	-	326.73
Industry	*3,850.02*	*200.49*
Mining	1,125.77	64.09
Food, beverages and tobacco	858.45	22.49
Textile, clothes and shoes	76.78	2.01
Wood, paper and printing	502.47	13.16
Biofuels*	436.12	1.67
Chemical and pharmaceutical products	802.55	21.03
Other industries	6.67	0.17
Cement, construction and other non-metallic minerals	41.21	1.36
Metallurgy	2,862.33	74.50
Power sector[1]	-	*699.26*
Transport sector	-	-
Services/Human supply	-	*38.47*

*Note: *According to Table 3, the production of charcoal was allocated to the Biofuels sector in the Goiás' aggregated IO table. Therefore, the water used by the Biofuels sector considers charcoal production and only the industrial phase of ethanol production.*

[1] *According to the Energy Balance for the Goiás State (Brasil, 2010), hydropower plants accounted for 97% of total power production in the state in 2008. Taking into account the low share of thermal energy sources in Goiás in 2008 (3% - conventional sources and sugarcane by-products together), we assumed hydropower plants as the only technology used by the Power sector in the IO analyses. The water use for the Power sector, therefore, was estimated only for hydro plants, from the water evaporated from water reservoirs. This water evaporation was used to estimate the water footprint of hydro plants in the Paranaíba basin (Appendix XV) from the average power generation in the basin during 2008 (data from ANEEL, 2017).*

Source: Author's adaptation from ONS (2004, 2017), IBGE (2009, 2009a, 2009b), FUNARBE (2011), Mekonnen and Hoekstra (2011), FAO (2017), EMBRAPA (2013, 2016), DNPM (2009), CETESB (2014), IPT (2013), GOIÁS (2010), ANA (2012, 2015), Fachinelli and Pereira (2015).

To estimate the volume of water lost by the evaporation from reservoirs (EVAV), the following equation can be applied:

$$EVAC = Area\,.\,10^2\,.\,EVAC_i\,.\,10^{-5} \qquad \text{(Eq. 3.53)}$$

where:

$EVAC_i$ is the evaporation coefficient of month *i*

the 10^2 constant consists in converting km^2 into hm^2, and the 10^{-5} constant consists in converting the evaporation coefficient given in mm into hm.

Thus, the volume of water lost by evaporation *(EVAV)* will be given in hm³, the most common unit used to determine water stocks in reservoirs. In short, the *Eq. 3.53* can be rewritten as follows:

$$EVAC = 10^{-3} \,.\, Area \,.\, EVAC_i \qquad (Eq.\ 3.54)$$

The monthly average evaporation coefficient ($EVAC$) was obtained from the ONS (2004) and can be verified in **Appendix XIII**. By applying the *Eq. 3.54*, the total net evaporation of the reservoirs in the region of study in 2008 accounted for 1,219 hm³ of water, as shown in **Appendix XIV**. This value was used to estimate the water footprint of hydro plants in the Paranaíba basin (**Appendix XV**) from the average power generation in the basin during 2008 (data from ANEEL, 2017). Thus, the water footprint of the hydro plants in the Paranaíba basin was equivalent to 28.742 m³/MWh. From this indicator of water used by unit of energy, we calculated the total amount of water consumed by power plants (*i.e.,* 699.26 hm³) (**Table 8**) from the total amount of power generated in the state of Goiás in 2008 (BRAZIL, 2010). All the water-use estimates presented in **Table 8** were applied as a water-use input vector in the Goiás' hybrid IO model (**Appendix VI**).

3.3.6.4 Energy Data

Data on both Brazil's and Goiás' energy balances were obtained from the Goiás State government (GOIÁS, 2010) and the Ministry of Energy and Mines (MME, 2016, 2017) (**Tables 9** and **10**). Ethanol and gasoline demand and supply forecasts were obtained from the Brazilian Energy Research Centre (EPE (EPE, 2017)) and are explained in greater detail in *sub-section 4.2*.

Table 9. Summarised 2008 Goiás' energy balance (in *10^3 toe*).

Energy source	*Economy sectors[1]*												
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*
Natural gas	0	0	0	0	0	0	0	0	0	0	0	0	957
Hydropower	0	0	0	0	0	0	0	0	0	0	2,092	0	0
Firewood[2]	29	0	27	0	12	545	2	9	22	0	3	2	0
Sugarcane products[2]	0	0	533	0	0	3,011	0	0	0	0	137	0	0
Other primary	0	0	0	0	0	0	0	0	15	0	0	0	0
Diesel oil	205	32	20	0	0	5	39	28	9	0	15	36	1,282
Fuel oil	0	93	54	0	0	3	2	5	192	0	8	4	0
Gasoline	0	0	0	0	0	0	0	0	0	0	0	0	713
LPG	2	0	5	0	0	0	0	1	18	0	0	5	0
Kerosene	0	0	0	0	0	0	0	0	0	0	0	0	40
Electricity	87	43	98	3	6	0	14	28	63	3	110	133	0
Charcoal	0	0	0	0	0	8	0	0	0	0	0	0	0
Ethanol	0	0	0	0	0	0	0	0	0	0	0	0	435
Other sec oil	0	0	0	0	0	0	0	0	45	0	0	0	0
Total	**323**	**168**	**737**	**3**	**18**	**3,572**	**57**	**71**	**364**	**3**	**2,365**	**180**	**3,427**
Total (PJ)	**13.5**	**7.0**	**30.8**	**0.1**	**0.8**	**149.5**	**2.4**	**3.0**	**15.2**	**0.1**	**99.0**	**7.5**	**143.5**

Note: [1]Economy sectors from Table 3. [2]Since there is no manufacture of coke in the state of Goiás, firewood production was allocated into the Biofuels sector. Similarly, since there is no oil refining in the state, sugarcane products were also allocated into the Oil refining, coke end ethanol sector. That is the reason why this sector has been called only by Biofuels sector.
Conversion factors: 1 toe = 41.87 x 10^9 J; 1 PJ = 1 x 10^{15}J.
Source: Brasil (2010) and MME (2016, 2017).

Table 10. Goiás' energy-use structure in 2008, in *PJ*.

Economy sectors	*Energy use (PJ)*
Agricultural	*13.5*
Industrial processes	*208.9*
Mining	7.0
Food, beverages and tobacco	30.8
Textile, clothes and shoes	0.1
Wood, paper and printing	0.8
Biofuels	149.5
Chemical and pharmaceutical products	2.4
Other industries	3.0
Cement, construction and other non-metallic minerals	15.2
Metallurgy	0.1
Power sector	*99.0*
Transport sector	*143.5*
Services / Commercial	*7.5*

Source: Brasil (2010) and MME (2016, 2017).

All the energy use presented in the table above was applied as an energy-use input vector in the Goiás' hybrid IO model (**Appendix VI**). Ethanol and gasoline forecasts demand for the state of Goiás were used to create future ethanol supply scenarios, aiming to analyse future environmental impacts from changes in ethanol demand (*sub-section 4.2*).

3.3.6.5 GHG Emissions Data

GHG emissions for Brazil and Goiás State were obtained from the Brazilian national GHG inventory (Brasil, 2016), the national emissions record system, SIRENE (SIRENE, 2017) and the emission estimating system for GHG, SEEG (SEEG, 2017) (**Appendices XVI** and **XVII**). After analysing the available data sources, data from SEEG (2017) was considered the most suitable source for this study because it made available the GHG emissions from the state of Goiás for all the economy sectors covered here. All direct land-use (DLUC) GHG emissions were included in the *Agricultural* sector due to the origin of the emissions (*i.e*. land-use change, liming and forestry residues). Indirect land-use change (ILUC) GHG emissions[31] were not included in the modelling exercise due to data constraints regarding the state of Goiás for the year 2008. However, ILUC GHG emissions were estimated for the additional land required in each scenario (analysed in the results of this paper, *section 4.3.1.2*) to identify ILUC GHG emissions when replacing pasturelands for sugarcane crops and considering that cattle may be forced to move towards Brazilian forests. Additionally, due to their importance in a country such as Brazil, LUC issues were considered in this thesis's discussions and conclusion.

A summary of the GHG emissions identified for the state of Goiás in 2008 is presented in **Table 11**. All the estimated GHG emissions were used as a GHG emissions output vector in the Goiás' hybrid IO model (**Appendix VI**).

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[31] According to *Chapter 11: Agriculture, Forestry and Other Land Use (AFOLU)* of the IPCC 5th Assessment Report (2014), indirect land-use change is difficult to ascertain because the magnitude of these effects must be modelled, raising important questions about model validity and uncertainty and policy implications. Available model-based studies have consistently found positive and, in some cases, high emissions from LUC and ILUC, mostly of first-generation biofuels, albeit with high variability and uncertainty in results (Hertel *et al.*, 2010; Taheripour *et al.*, 2011; Dumortier *et al.*, 2011; Havlík *et al.*, 2011; Timilsina *et al.*, 2012; Warner *et al.*, 2014). However, as ILUC GHG emissions represent a significant source of emissions in Brazil, these issues will be better addressed in the results of this paper, taking into account the case study for the state of Goiás.

Table 11. Goiás' GHG emissions, in 2008 (in $TgCO_{2e\ GWP\text{-}AR5}$).

Economy sectors	*GHG Emissions*
Agricultural[1]	*89.4023*
Industrial processes[2]	*4.6892*
Mining	0.1894
Food, beverages and tobacco	0.5908
Textile, clothes and shoes	0.0005
Wood, paper and printing	0.0256
Biofuels	0.1540
Chemical and pharmaceutical products	0.0665
Other industries	2.4583
Cement, construction and other non-metallic minerals	0.4392
Metallurgy	0.7649
Power sector	*0.0736*
Transport sector	*5.9243*
Services / Commercial	*0.0679*
Total	**100.1573**

Note: [1]*Emissions from the agricultural sector (41.6740* $TgCO_{2e}$*) were added to all the emissions from land-use change in the state (47.7283* $TgCO_{2e}$*).*
[2]*The main emission sources are releases from industrial processes that chemically or physically transform materials (for example, the blast furnace in the iron and steel industry, ammonia and other chemical products manufactured from fossil fuels used as chemical feedstock and the cement industry are notable examples of industrial processes that release a significant amount of* CO_2*). During these processes, many different greenhouse gases, including carbon dioxide (*CO_2*), methane (*CH_4*), nitrous oxide (*N_2O*), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), can be produced. In addition, GHG often are used in products such as refrigerators, foams or aerosol cans (IPCC, 2006).*

Source: SEEG (2017), from MCTI (2016).

By using the 2008 Goiás' value added from the Goiás' original IO table, it was assumed a carbon price of US$10 per tonne of CO_{2e} would be imposed on the emissions intensity for each producing sector[32]. As previously described in *subsections 3.3.2.3, 3.3.2.4* and *3.3.5*, this procedure was used to analyse the impact of the application of the IO price model on the sectoral value added and the overall impact of price changes on the economy. This value of US$ 10/tCO_{2e} reflects a value typically found in the literature and

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[32] The US$10 carbon price was used in this research to estimate new value-added coefficients from a carbon tax imposition in order to update the original IO technical coefficients and, hence, analyse the impacts on local environment and economy from changes in input prices; in this case, caused by a carbon tax policy. Conversely, sectoral value-added impacts regarding a carbon tax imposition were analysed for a different range of carbon prices, namely US$5, US$10, US$25 and US$50, to assess the carbon cost share in each sector of the economy, according to different carbon prices and emissions abatement possibilities (from 0 to 45%).

in international carbon pricing experience so far (Nordhaus, 2007; Sandu, 2007; Aldy, 2016; Narassimahn *et al.*, 2017; ICAP, 2018; Santos *et al.*, 2018).

With such information and by applying IO concepts, it is possible to estimate future changes related to GHG emissions, water, energy and land use, value added and job creation, when the final demand in any sector of the economy increases by a monetary unit (in this case, US$1 million). The impact of carbon pricing can also be analysed through the IO price model, which provides information to update the original IO technical coefficients by applying a flexible production function. The updated total requirement matrix can be used to analyse medium and long-term policies, providing a more realistic outcome when compared to the traditional Leontief analysis (see *section 3.3.3*). Therefore, the hybrid economic-ecological IO model coupled with the IO price model helps in analysing future scenarios regarding changes in ethanol demand in the state of Goiás and how these could impact the use of inputs and the outputs production throughout the economy, by applying an integrated analysis that considers water, energy, land and emissions in a given policy goal.

3.4 Summary and Conclusions

This chapter has reviewed various methodologies that have been employed to develop the WEF nexus framework. The purpose of this review was to analyse their strengths and weaknesses and to use these insights to select an appropriate method for this research. The main findings of this chapter include:

- There are few studies that focus on how to support decision-making at the nexus of water, energy and land (WEFN). Even fewer studies are available integrating water, energy and land concerns in relation to biofuel production in Brazil, specifically 1G sugarcane ethanol. This lack of policy integration linked to water, energy and land can create vicious cycles that negatively impact biofuel sustainability.

- Through its focus on ensuring integrated WEF security, the WEFN seeks greater policy coherence to overcome the unintended consequences of uncoordinated policy across different sectors. Most of the nexus studies follow the WEFN mainstream, focusing on the interlinkage between environmental resources through their physical connections. However, anyone intending to design WEFN policies should add economic implications to the traditional nexus analyses, such as price analysis. This is important because physical relationships are not enough to produce high-quality outcomes for the policymaking process.

- The WEFN approach is conceptualised and measured using varying methods, such as macro-level assessments, life-cycle assessments, resource planning use modelling, multi-sectoral systems analysis, multi-scale integrated assessment, system dynamics and net energy production approaches, Input-Output framework, among others.
- Input-Output analyses have been employed recently as decision-making tools for sustainable development and planning in models that incorporate the impact of environmental aspects and energy use on a national or regional level. Overall, IO models can evaluate indirect as well as direct flows to calculate the inputs required for producing goods and services based on sectoral interactions in complex systems.
- In fact, the IO framework can be extended to estimate environmental impacts from economic activities by determining a proportionality between sector outputs and their corresponding impact levels. This process creates the so-called economic-ecological IO framework with hybrid units. This model resulted from extending the inter-industry framework to include additional ‘ecosystem’ sectors, where flows between economic and ecosystem sectors are recorded along the lines of an inter-regional IO model.
- Integrated analyses use a WEFN approach and apply hybrid IO models to better understand the interlinkages between GHG emissions and water, energy and land uses from biofuels production. Although limited by governance issues, the WEFN approach coupled with IO models can help shape bioenergy development and highlight the need for a specific biofuel policy through the integration of basic resources for bioenergy production.
- The traditional Leontief’s IO method is appropriate for the analysis of disaggregated economic sectors, by making use of IO tables which are publicly

available. The "dynamic" version of IO method also allows for capital adjustments in response to price changes induced by carbon tax. However, in order to capture other aspects of economic reality (e.g., producer/consumer behaviour in relation to prices), the underlying Leontief production function must be replaced with other flexible forms of production functions. Such replacement of production functions could allow IO analysis to be used for analysing the impacts of a price-driven policy like carbon tax.

- Based on the review in this chapter, the hybrid economic-ecological IO method with a flexible form of production function is selected as the methodological framework for this research.

The specific objectives of this chapter were *i)* to develop a methodological framework based on a hybrid WEFN-IO approach by including water, energy and land uses and GHG emissions as ecosystem sectors in the original IO model, for the analysis of the environmental impact from sugarcane ethanol expansion in Goiás, *ii)* to develop a methodological framework based on a hybrid WEFN-IO approach with a modified production function – for the analysis of the impact of carbon tax on the wider economy, and *iii)* describe the sources of data as well as the methodology used in this research. The major conclusions from this chapter are summarised as follows:

- The methodological framework developed in this research comprises six interlinked functional modules
    a) In the first module, the original IO model was reset to a hybrid economic-ecological IO model, in which the flows between sectors are represented in hybrid units. In other words, an environmental IO model shows its 'environmental flows' both in monetary and physical units (e.g. m^3 of water), whereas non-environmental flows are described only in monetary terms. Production and consumption of water, energy, land and emissions were incorporated into the original Goiás' IO table as an "attached environmental account" to allocate the environmental flows between sectors. We can now define the ecological commodity input and output coefficients in much the same way as we defined the direct impact coefficients in the original Leontief

model. This will give us estimates of all resources used by each sector, driven by changes in final demand (i.e., sugarcane ethanol scenarios).

b) In the second module, the sectoral CO_2 emissions and intensities are calculated, based on the Polluter Pays Principle (PPP). The CO_2 emissions and intensities for the PPP are simply calculated, based on direct energy consumption represented in the traditional energy balance.

c) In the third module, a carbon tax is introduced based on sectoral CO_2 intensities. This tax is introduced on the top of the existing value added tax. Different carbon prices reflecting a range typically found in the literature were applied. Emissions abatement possibilities were also estimated, according to Brazilian NDCs.

d) In the fourth module, the impact of carbon tax, in terms of changes in sectoral prices, is estimated. This is estimated using the standard Leontief's IO price model, which is appropriate for analysing changes in value added tax.

e) In the fifth module, economic sectors are allowed to substitute their factor inputs in response to changes in sectoral prices brought about by the application of a carbon tax. This is achieved by assuming a nested input structure for the sector and replacement of the Leontief's production function with both the Cobb-Douglas and the "Constant Elasticity of Substitution" production functions.

f) In the final module, based on the new IO coefficients, the economy-wide impacts of carbon tax are assessed for the Goiás state. These impacts are classified into energy, environmental, economic, and social impacts. The result of these impacts is discussed in the next chapter.

4 Case Study

4.1 Sugarcane Industry and Environmental Concerns in Brazil

Brazil has great potential for further agricultural expansion in the 21st century (FAO, 2012). Understanding recent LUC patterns and visualising a sustainable land-use pathway in Brazil have become highly strategic, given that regional and global climate change, food and energy provision and biodiversity conservation are all at stake (Lapola *et al.*, 2014).

In a national context, the expansion of sugarcane crop verified since the 1970s has apparently had low impact on deforestation and biodiversity loss (La Rovere *et al.,* 2011). According to the Brazilian Sugarcane Industry Association UNICA (UNICA, 2017), Brazil's 2014/2015 sugarcane planted area amounted to 103,000 km². This represents about 14% of total cultivated area in the country, 5% of pasturelands, 3% of all agricultural properties and only 1% of Brazil's total area (IBGE, 2017, 2017a). Since the 1990s, sugarcane crop expansion was concentrated in the Centre-South of Brazil and distant from the Amazon, the Pantanal and the Atlantic forest biomes, which, along with the Cerrado, are the main Brazilian ecosystems (La Rovere *et al.,* 2011). However, agricultural activities have expanded mostly in the Cerrado biome in the last 40 years, resulting in extensive land-cover transformation and significant changes to the water cycle (Hunke *et al.,* 2015; Spera *et al.,* 2016).

Over 80% of the cropland expansion in Brazil from 1990 to 2011 occurred in the Amazon and Cerrado regions (IBGE, 2012) and currently, agriculture covers about half of the Cerrado's original extent (IBGE, 2012; Lapola *et al.*, 2014). Cattle ranching is by far the dominant land use, but a fraction of these pastures has been replaced recently by advanced large-scale mechanised cropping of soybean and sugarcane (IBGE, 2012, Martinelli and Filoso, 2008; Walter *et al.*, 2011). The Cerrado is Brazil's most important beef producing region, hosting the greatest extent of pastureland and about 50% of the national herd (**Figure 19a**). The radical conversion of the Cerrado into soybean monoculture over the past two decades was one of the main contributors to the expansion in total cropland area in Brazil (**Figure 19b**).

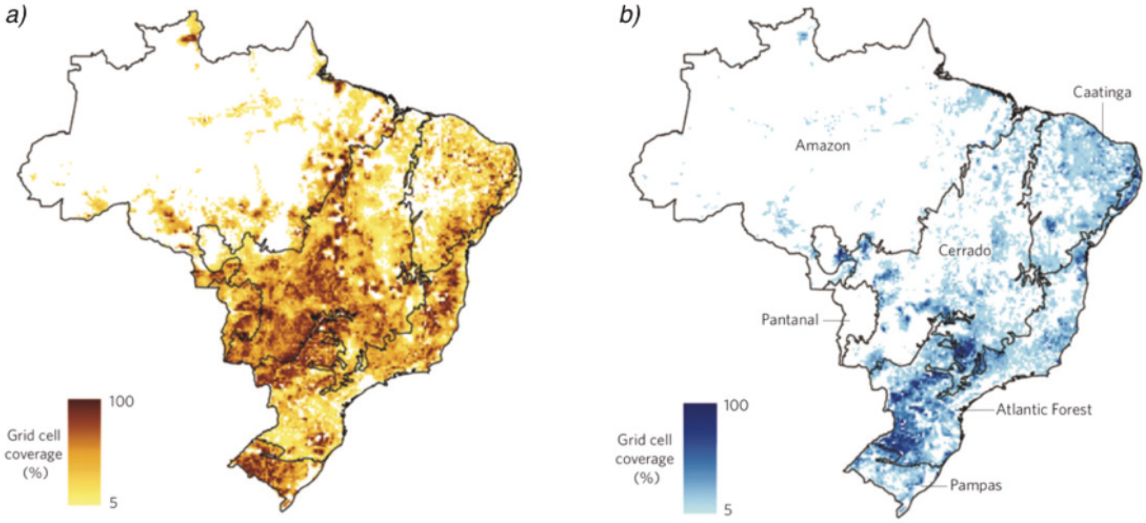

Figure 19: Spatial distribution of agricultural activities in Brazilian biomes in 2000. *a)* Livestock production, *b)* Croplands.
Source: Lapola et al., 2014.

Thus, the high suitability of the Cerrado topography and soil for mechanised agriculture, the reduced number and total extent of protected areas (Sparovek *et al.*, 2010), the lack of a well-established and regulated deforestation surveillance program, and potential leakage pressure resulting from declining deforestation in the Amazon all indicate that the Cerrado will continue to be a principal region of LUC in Brazil (Nepstad, *et al.*, 2009; Lapola *et al.*, 2011, 2014; Noojipady *et al.*, 2017).

With regard to sugarcane crops, the Brazilian Sugarcane Agro-ecological Zoning[33] (ZAE Cana) policy indicates the Centre-West region as the one with the largest total suitable area for sugarcane expansion (Manzatto *et al.,* 2009). The Brazilian Cerrado represents about 10% of the total area of tropical savannahs in the world and is one of the world's biodiversity hotspots (Spera *et al.,* 2016), despite the small number and total extent of protected areas (**Figure 20a**) (Lapola, *et al.*, 2014). Besides its large biodiversity, the Cerrado shows the worst deforestation record of the last 15 years in Brazil (*i.e.* 236,000 km²), even more than the Amazonian forests (*i.e.* 208,000 km²) (**Figure 20b**) (Reis *et al.*, 2017; MMA, 2018[34]). In 2015 alone, the Cerrado lost about 9,400 km² of native forests,

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[33] Presidential decree n. 6,961, enacted on the 17th of September 2009, "Approves the sugarcane agro-ecological zoning and it determines to the National Monetary Council the establishment of financing operation norms for the sugarcane industry, under the terms of the zoning". Presidential decree available at: http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/decreto/d6961.htm.

[34] Brazilian Ministry of Environment, Deforestation Prevention and Control. Federal Deforestation Prevention and Control Plan, available at: http://combateaodesmatamento.mma.gov.br.

52% more than the Amazon for the same year, obviously raising concerns about conservation efforts in the biome (MMA, 2018). Therefore, land use in the region (including but not only for sugarcane) should be based on sustainable practices regarding biodiversity, water resources and soil preservation, while maximising economic and social gains.

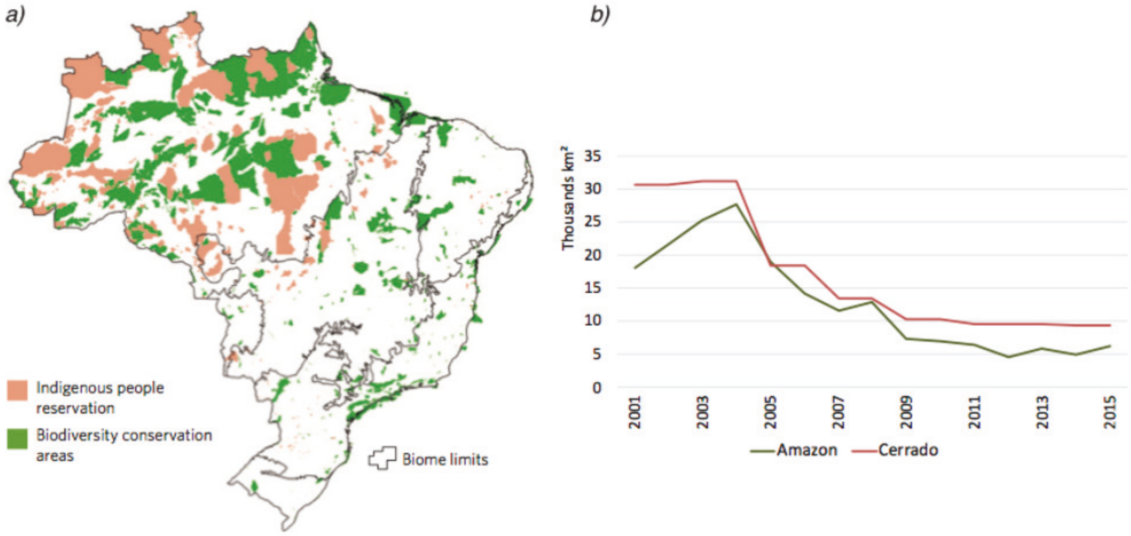

Figure 20: Protected areas and deforestation in Brazil. *a)* Protected areas in Brazilian biomes. *b)* Deforestation in Cerrado and Amazon between 2001 and 2015, in km².
Source: a) Lapola et al., 2014, b) MMA (2018).

As a measure to control unsustainable ways of producing sugarcane, the Brazilian government created the ZAE Cana to protect environmentally sensitive areas and the native vegetation while guiding sugarcane expansion in the country. Overall, the zoning promotes sustainable sugarcane development while constraining the expansion of sugarcane crops and the licensing of ethanol mills towards biomes such as the Amazon and the Pantanal.

The ZAE Cana consists of a comprehensive product from renowned Brazilian institutes and researchers and its main goal is to determine suitable areas for large-scale sugarcane cultivation in the country. It is also an incipient initiative towards formulating Brazil's biofuel policies by providing technical support for sustainable sugarcane production and expansion. In this regard, the ZAE Cana focuses on sugarcane production under rain-fed conditions by analysing the chemical, physical and mineralogical characteristics of soils and relating them to the sugarcane crop's requirements. The ZAE Cana considered such indicators as land vulnerability, climate risk, the potential for sustainable agricultural production and environmental regulations, to determine suitable areas (Manzatto *et al.*, 2009). These areas were classified according to their potential for sugarcane growing (*i.e.*, low, medium and high) and to their current land use (*i.e.*, *Ap:* Pasture; *Ac:* Agriculture; *Ag:* Agriculture and pasture) (**Table 12**).

Table 12. Suitable areas for sugarcane expansion in Brazil, by agricultural potential and land use, in 2008.

Site	*Potential*	*Suitable areas by land use (in km^2)*			
		Pastureland (Ap)	*Agriculture (Ac)*	*Agricultural (Ag)*	*Ap+Ac+Ag*
Goiás	*High (H)*	7,832	2,208	0	10,040
	Medium (M)	69,985	45,980	0	115,965
	H + M	77,817	48,188	0	**126,005**
Centre-West	*H*	62,093	10,368	0	72,461
	M	104,021	104,713	0	208,734
	H + M	166,114	115,081	0	**281,195**
Brazil	*H*	113,023	73,603	6,008	192,634
	M	228,639	164,967	21,264	414,870
	H + M	341,662	238,570	27,272	**607,504**

Note: Low-potential areas were excluded because we consider that the use of low-quality land may induce vicious cycles, as already mentioned (Figure 9). In short, the total low-quality land represented 21,649 km^2 and 42,555 km^2, in the Centre-West region and in Brazil, respectively. There was no data for low-quality land for the state of Goiás.

Source: Adapted from Manzatto et al., (2009).

According to the ZAE Cana, only 82% of Goiás' suitable areas would be able to support the 2015 total sugarcane planted area, *i.e.*, 103,000 km^2. Also, both the high and medium potential suitable areas in the state of Goiás represent 45% of the Centre-West's region high and medium potential suitable areas and 21% of Brazil's. Additionally, the Centre-West region accounts for 46% of the whole country's area that is suitable for growing sugarcane. However, this data must be carefully analysed, since the ZAE Cana also covers the area already occupied by sugarcane crops in 2008, which makes it difficult to analyse the real extent of suitable and available land and whether sugarcane expansion would impact food crops. At the same time, about half of the suitable area (either medium or high potential) is currently used as pastureland, indicating opportunities to greater cattle densification and to grow sugarcane in old or fallow pastureland. For instance, the Brazilian state of Rondônia shows higher densification rates (*i.e.* between 1.23 to 3 head of cattle/ha) compared to the Brazilian average (*i.e.* about 1 head of cattle/ha[35]) (Soares-Filho *et al.*, 2009; CSR, 2018); the intensification of livestock production with the objective of freeing up space for both regular and flex-crops is therefore the most likely outcome in the coming years.

However, this is not that simple, since the potential for cattle densification to replace pastureland with sugarcane crops may also cause ILUC negative impacts. As previously mentioned in the section about the 'Brazilian New Forest Code' and its implications for the reduction of protected areas in Brazilian biomes (*section 2.3*), despite having about 150,000 km² of pasturelands, the state of Goiás shows a deficit of Legal Reserves that amounts to about 7,500 km² of forest to be recovered, especially in its South-Western section (Soares-Filho *et al.*, 2013) and another 16,300 km² are projected to be deforested in the coming years (Young *et al.*, 2016). Overall, there is a significant shortage of Legal Reserve surplus in certain parts of the country, especially in regions where there is a significant expansion of agricultural activities, such as the state of Goiás. Therefore, we cannot ensure that there will not be deforestation and competition between sugarcane and food crops in the state, for example, just from analysing ZAE Cana maps and estimates. According to the ZAE Cana, the total suitable area in Goiás in 2008 amounted to 126,000 km², of which 62% was used by livestock production and the remaining 38% by other agricultural activities (**Figure 21**).

The *Agribusiness Outlook in Brazil, 2015/16 to 2025/26*, formulated by the Ministry of Agriculture, MAPA (2016), estimates an expansion of 19,000 km² in sugarcane crops in the country by 2026, 8,000 km² of which will be in the Centre-West region. The states of Mato Grosso do Sul (45.6%) and Goiás (34.3%) are projected to show the highest growth rates in sugarcane planted area, which confirms the sector's tendency to expanding near traditional producing areas (see **Figures 1** and **22**). However, the Brazilian Cerrado is typified by periods of water shortages and river basin with economic, social and environmental conflicts related to multiple water uses. Thus, the expansion of sugarcane crops towards the Centre-West region may trigger a water constraint on ethanol production.

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[35] The area unit km² is used throughout this paper. However, to facilitate understanding, the indicator cattle heads/km² was replaced by cattle heads/ha because the latter is easier to imagine and measure. That is, 0.01 km² = 1 hectare (ha), therefore, 0.03 cattle heads/km² is equal to 3 cattle heads/ha.

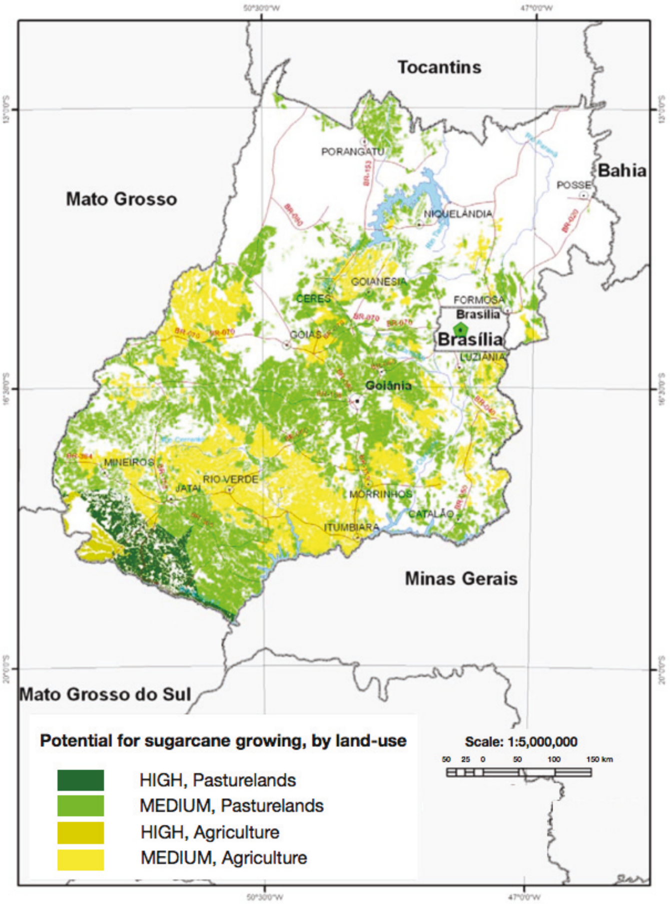

Figure 21. Goiás' Sugarcane Agro-ecological Zoning. Suitable areas for sugarcane expansion, by land use, in 2008.
Source: Adapted from Manzatto et al. (2009).

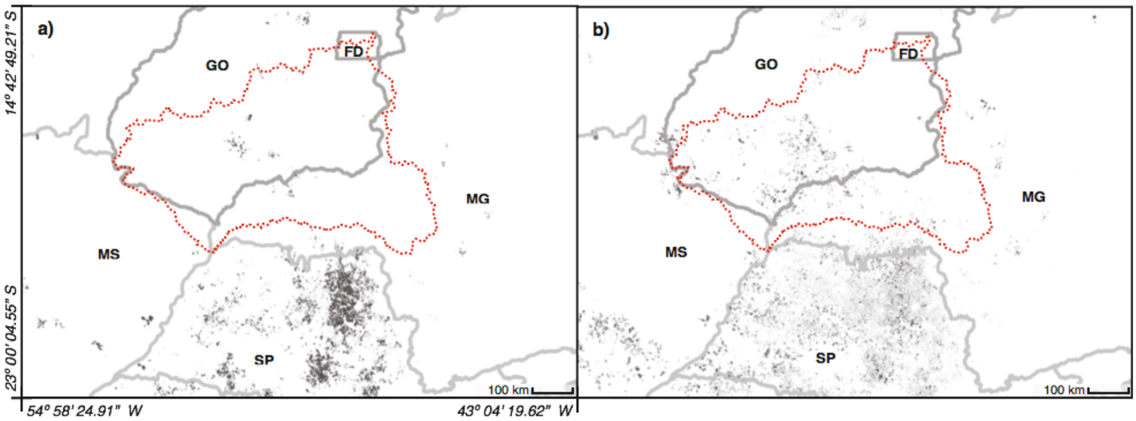

Figure 22. Crop area in Centre-South region of Brazil, highlighting the Paranaíba basin (dotted) and the states of São Paulo (SP) and Goiás (GO) in *a)* 2003 and *b)* 2011.
Note: Different grey scales represent different crop growth stages, unimportant to the current analysis.
Source: Author's adaptation from INPE (2013).

While São Paulo State has less area available for expansion, the sugarcane area in Goiás State soared 18%, twice the Centre-West region's growth rate (**Table 13** and **Figure 22**). Goiás' sugarcane accounts for about half the entire Centre-West's sugarcane area and production.

Table 13. Sugarcane crop area and outputs in Brazil.

Site	*Crop area (km^2)*			*Output (million t)*		
	2013	*2014*	*(%)*	*2013*	*2014*	*(%)*
Brazil	102,230	106,457	4.1	588.48	651.29	10.7
São Paulo State	54,150	54,174	0.0	329.92	367.45	11.4
Centre-West region	17,864	19,479	9.0	106.38	120.50	13.3
Goiás State	8,605	10,183	18.3	52.73	62.02	17.6

Source: Author's adaptation from UNICA (2017) and IBGE (2017).

Currently, sugarcane crops in the state of Goiás cover about 9,600 km^2, with an output of 67.6 million tonnes of sugarcane, resulting in 2.1 million tonnes of sugar and about 4.4 hm^3 of ethanol (UNICA, 2017; CONAB, 2017). The sugarcane planted area in the state grew by 416% from 2000 to 2010 and by 170% from 2010 to 2015; the most rapid sugarcane growth recorded in Brazil for the period (**Figure 23**).

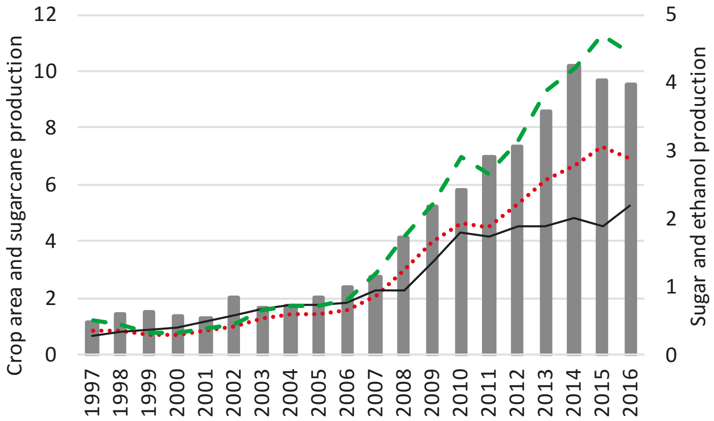

Figure 23. Crop area (columns)[a] and sugarcane (dotted line)[b], sugar (black line)[c] and ethanol (dashed line)[d] production in Goiás State.

Note: [a] in 10^3 km^2; [b] in 10 million t; [c] in million t; and [d] in hm^3.

Source: Author's adaptation from UNICA (2017) and CONAB (2017).

Therefore, this work focuses on Goiás State (**Figures 1** and **22**), situated in Brazil's Centre-West region, because it is one of the most rapidly expanding states in terms of sugarcane cultivation. The state encompasses an important river basin, the Paranaíba basin, from both an energy and agricultural point of view, and it was used here as a proxy to determine the environmental impact on land and water resources in the state. The Paranaíba basin covers about 220,000 km² (**Figures 24** and **25**), of which 141,000 km² are in the state of Goiás (63%), and the remaining 80,000 km² are divided between the states of Minas Gerais (32%), the Mato Grosso do Sul (3.5%) and the Federal District (1.5%) (ANA, 2015).

Current land use in the basin shows the predominance of livestock (35%) and agriculture (34%), with emphasis on soybeans, corn and sugarcane. The basin still has about 25% of native vegetation coverage, mainly located in the Northeast section of the basin, according to estimates from the National Water Agency ANA (ANA, 2015).

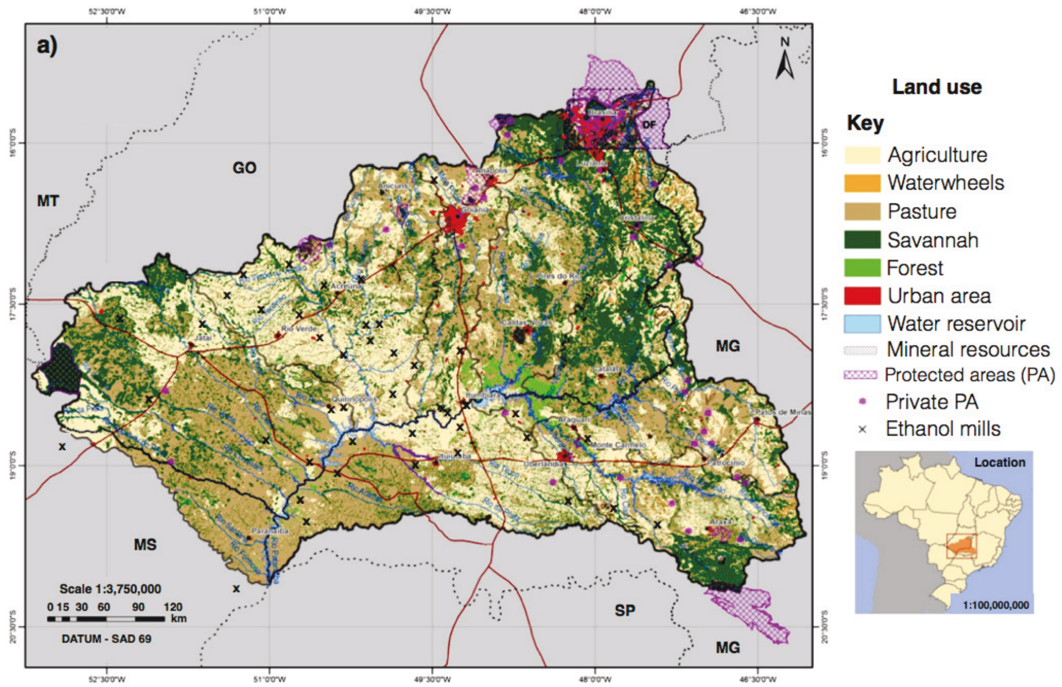

Figure 24. Geographical limits of the Paranaíba basin and its land use.
Source: Adapted from ANA (2015).

The activities developed in the Paranaíba basin have led to growing water demand, 89.5% of it for irrigation. Moreover, most industrial water demand (3.5%) comes from agribusiness, specifically the sugarcane industry (ANA, 2015). The basin has been undergoing rapid agricultural expansion, with sugarcane replacing pasturelands, corn and soybean crops. Irrigated sugarcane has expanded by 2,300 km² since 2010; overall, the irrigated area in the basin rose from 2,100 km² in 1995 to 6,100 km² in 2010, virtually tripling in 15 years (ANA, 2015). However, as previously mentioned, most of the irrigated sugarcane in the region is the so-called salvage irrigation which corresponds to the application of vinasse in the soil. Conversely, although about 3,800 km² of irrigated sugarcane crops were identified in Goiás in 2016 through recent geospatial images, the National Water Agency, ANA, states that the use of water to irrigate sugarcane is relatively unknown (ANA, 2017).

It is worth mentioning here that the National Water Resource Plan (NWRP), a Federal law enacted in 1997 (BRASIL, 1997), requires that water resources management should be decentralised and include the participation of government, users and local communities. The NWRP determines the river basin plans (RBP) that must be implemented by the ANA and approved by the river basin committees. These committees, composed of representatives from government, civil society and water users and considered the basis for participatory and integrated water management, have a deliberative role. The RBPs contain data regarding water quality, priority uses, water availability and demand, etc. According to the Paranaíba's RBP (ANA, 2015), the basin is divided into 10 water management units (WMUs) (**Figure 25**).

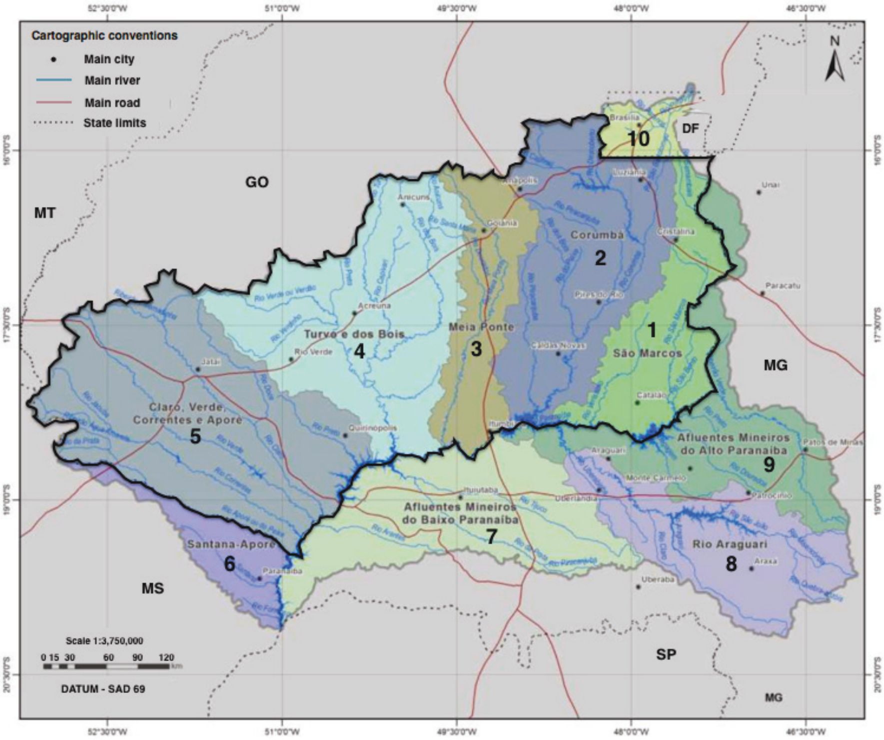

Figure 25. Paranaíba Basin Water Management Units.

Note: Highlighted, the WMUs located in the state of Goiás (1 - São Marcos; 2 - Corumbá; 3 - Meia Ponte; 4 – Turvo-Bois; 5 - Claro, Verde, Correntes and Aporé).

Source: Adapted from ANA (2015).

By overlaying the data from the ZAE Cana (**Figure 21**), the land use in the Paranaíba basin (**Figure 24**) and the location of the Goiás WMUs (**Figure 25**), we can observe that the areas recommended for sugarcane production and expansion are exactly those where sugarcane has already been cultivated (**Figure 26**). They are also the same areas indicated by the CANASAT monitoring project (INPE, 2013) (**Figure 22**).

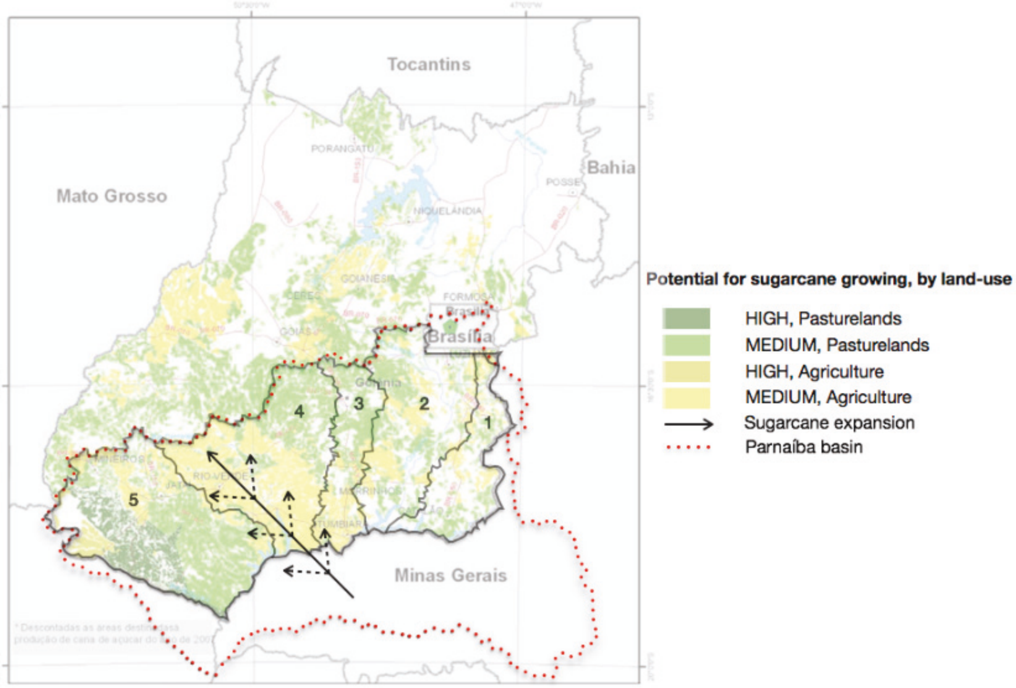

Figure 26. Paranaíba's basin WMU location *versus* sugarcane agro-ecological zoning.
Note: The Paranaíba's River Basin Plan has also pointed out that the region indicated by the arrows has shown intensification of irrigation practices.
Source: Author's adaptation from Manzatto et al. (2009) and ANA (2015).

Therefore, besides the water-use analysis for the whole Paranaíba basin, it is important to verify the water availability in each WMU. In the context of water resources management, this research considered the water availability and demand from WMUs where the more extensive sugarcane expansion had taken place, namely, *Meia Ponte* WMU (*3*), *Turvo-Bois* WMU (*4*), *Claro, Verde, Correntes and Aporé* WMU (*5*) and *Lower Paranaíba Minas Tributaries* WMU (*7*). Despite the last WMU being located outside Goiás' state boundary (WMU #7 in **Figure 25**), it was included in the analysis of water availability as a sugarcane expansion constraint. According to ANA (2015), water availability at the mouth of the Paranaíba River is 1,252 m³/s for the reference flow $Q_{95\%}$ and 626 m³/s for the flow used to grant rights to use water resources as adopted by the state of Goiás, *i.e., 50%* $Q_{95\%}$. It should be noted that there is higher water availability in *Claro, Verde,* *Correntes and Aporé* WMU and lower water availability in *Meia Ponte* and *São Marcos* WMUs (**Table 14**).

Table 14. Surface water availability, water withdrawals and water balance in the Paranaíba basin, by WMU.

Water Management Units (WMU)	*SWA*[a] $Q_{95\%}$	*SWA*[b] 50% $Q_{95\%}$	*WW*[c] +*WWS*[d]	*Water Balance*[f] *WW+WWS* $Q_{95\%}$	*WW+WWS* 50% $Q_{95\%}$
	m^3/s	m^3/s	m^3/s	%	%
Paranaíba basin	1,251.7	625.85	364.95	29	58
São Marcos[e]	75.30	37.65	30.70	41	82
Meia Ponte	62.79	31.39	33.68	54	107
Turvo-Bois	162.19	81.09	60.22	37	74
Claro, Verde, Correntes and Aporé	377.03	188.52	25.32	7	13
Lower Paranaíba Minas Tributaries	104.52	52.26	30.44	29	58

Note: [a]Surface water availability, reference flow $Q_{95\%}$: the flow with 95% probability of occurrence.

[b]Surface water availability, reference flow 50% $Q_{95\%}$: the flow used for granting of rights to the use of water resources adopted by the state of Goiás.

[c]WW: Water withdrawals minus water withdrawals for sugarcane irrigation, presented in ANA (2015).

[d]WWS: Water withdrawals for sugarcane destined for ethanol production, calculated by Fachinelli and Pereira (2015).

[e]There is no data on irrigated sugarcane in the São Marcos WMU. Thus, it was used in the analysis of the total water withdrawal in the WMU, estimated by ANA (2015).

[f]Quantitative impairment indicators (I)

I < 50% *(Normal)*	*50% < I < 80%* *(Alert)*	*80% < I < 100%* *(Moderately critical)*	*>100%* *(Highly critical)*

Source: Author's adaptation from SEMARH (2012), ANA (2015) and Fachinelli and Pereira (2015).

Again, by merging the data from the location of current sugarcane production and the forecasted expansion, we can verify that sugarcane crops have been occupying mainly the *Turvo-Bois (4)* and *Meia Ponte (3)* WMUs and a smaller section of the *Claro, Verde, Correntes and Aporé (5)* WMU. Since the *Meia Ponte* WMU shows the lowest water availability, it would be important to consider it as the lowest limit regarding water availability for irrigated sugarcane expansion in the region. Additionally, according to quantitative impairment indicators, the *Meia Ponte* WMU showed an 'alert' situation in the reference flow $Q_{95\%}$ and a 'highly critical' condition when considering the flow used for granting rights to water use, *i.e., 50%* $Q_{95\%}$. Similarly, the *Turvo-Bois* and *Lower Paranaiba Minas Tributaries* WMUs were identified as in 'alert' condition when considering the reference flow *50%* $Q_{95\%}$, as well as the Paranaíba basin as a whole.

Accordingly, the water availability in each WMU mentioned above should be further analysed when considering the water requirements in the Goiás' hybrid IO model in order to estimate future ethanol demand and supply in the region. There is however a limitation here in regards to spatial data distribution in the IO model, since we do not know exactly where the IO table data are geographically located. Then, although we indicated that the *Meia Ponte* WMU was the lowest limit regarding water availability in the region, we could not perform an analysis on this specific WMU because we could not indicate the share of this WMU from the Goiás' IO economic and environmental data. When analysing all WMUs of the Paranaíba basin we can determine the water availability in the region (and its limits), considering the flow used for granting rights to water use, *i.e., 50%* $Q_{95\%}$ (**Table 15**). Converting the water flow rate (given in m³/s) to an annual basis allows for comparisons between the water available in the basin and the water requirements determined by the Goiás' hybrid IO model, which helps to determine water-use limits in the region.

Table 15. Surface water availability for granting rights to water use, water withdrawal and annual surface water availability in the Paranaíba basin, by WMU.

Water Management Units (WMU)	*SWA[a] 50% $Q_{95\%}$*	*WW[b] +WWS[c]*	*SWA – (WW+WWS)*	*Annual SWA*
	m³/s	*m³/s*	*m³/s*	*hm³*
Paranaíba basin[d]	625.85	364.95	164.37	5,183
São Marcos[e]	37.65	30.70	6.95	219
Meia Ponte	31.39	33.68	(2.29)	(72)
Turvo-Bois	81.09	60.22	20.87	658
Claro, Verde, Correntes and Aporé	188.52	25.32	163.20	5,146
Lower Paranaíba Minas Tributaries	52.26	30.44	21.82	688

Note: [a]Surface water availability, reference flow 50% $Q_{95\%}$*: the flow used for granting of rights to the use of water resources adopted by the state of Goiás.*

[b]WW: Water withdrawals minus water withdrawals for sugarcane irrigation, presented in ANA (2015).

[c]WWS: Water withdrawals for sugarcane destined for ethanol production, calculated by Fachinelli and Pereira (2015).

[d]The subtraction result was multiplied by 63% since this is the share of Paranaíba basin in the state of Goiás.

[e]There is no data on irrigated sugarcane in the São Marcos WMU. Thus, it was used in the analysis of the total water withdrawals in the WMU, estimated by ANA (2015).

Source: Author's adaptation from SEMARH (2012), ANA (2015) and Fachinelli and Pereira (2015).

It can be observed from the table above that *Claro Verde, Correntes and Aporé* WMU alone accounts for 30% of total surface water availability in the section of the Paranaíba basin located in Goiás' territory, before deducting water withdrawals. After subtracting water withdrawals from each WMU, the *Claro Verde, Correntes and Aporé* WMU shows 5,146 hm³ of water availability (annually), against 5,183 hm³ for the whole Paranaíba basin (again, considering only the section of the basin in the Goiás State, *i.e.*, 63%). This can be explained by both high water availability and low water withdrawals in this WMU, which correlates to high livestock production and low agriculture footprint. On the other hand, the remaining WMUs that make up the Paranaíba basin indicators show lower water availability and higher water withdrawals. In other words, 99% of the water availability (after discounting the total water withdrawals) in the section of the basin located in the state of Goiás comes from the *Claro Verde, Correntes and Aporé* WMU. These water availability indicators will be used as the water-use limits considered when analysing water requirements according to the Goiás' hybrid IO model to estimate future ethanol demand and supply in the region.

Despite this issue being discussed further, it is worth mentioning here that sugarcane production is putting pressure on the water availability in specific WMUs and hence, sugarcane expansion would be better addressed by focusing on the preservation of local water resources.

Additionally, from the energy standpoint, there are 20 hydropower stations in Goiás with a 4.8 GW total capacity plus 309 MW from small hydroelectric plants (SHP) (ANEEL, 2017) that were omitted from this study (**Figure 27**) and 163 hydropower plants with a combined capacity of 3.2 GW in the planning stage[36] (ANA, 2015) (**Figure 28**).

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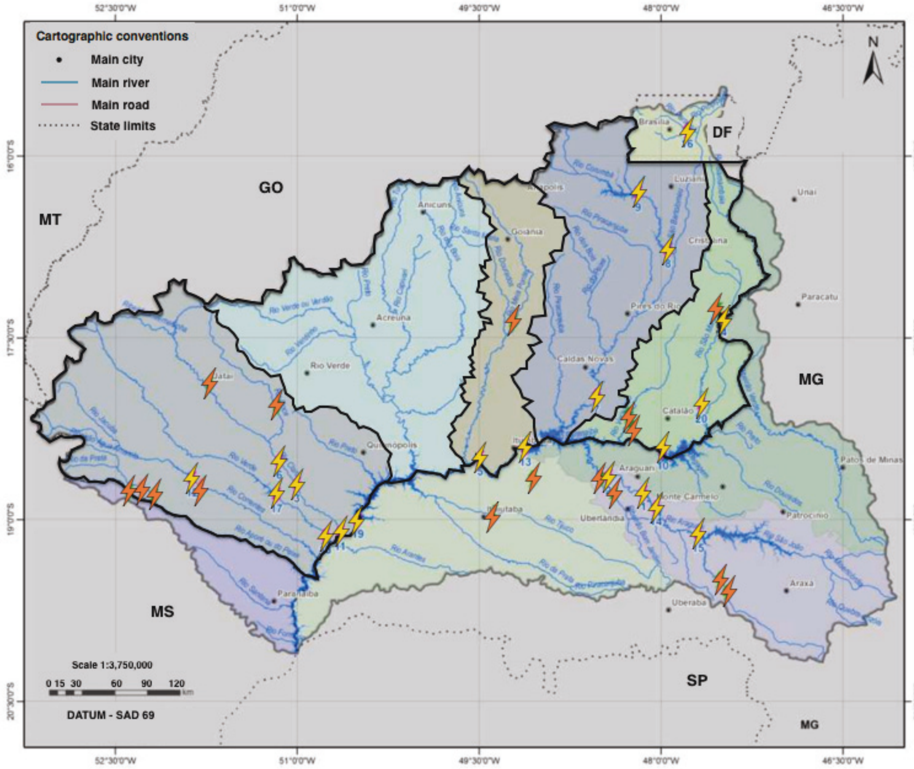
[36] All hydropower plants in the planning stage were omitted from the analyses.

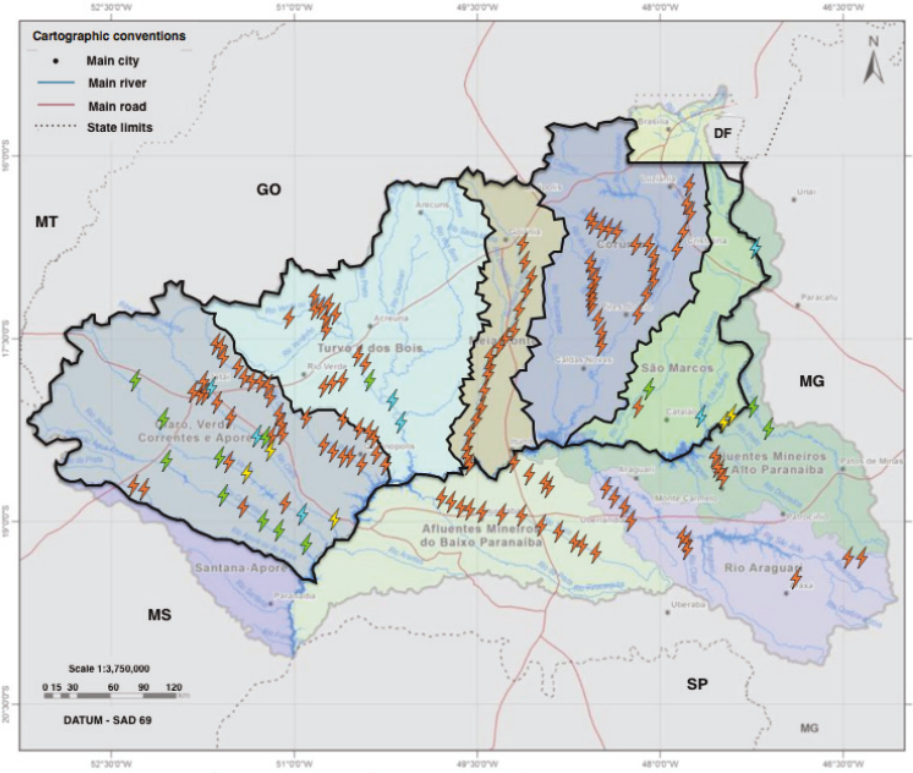


Key: ⚡ Hydropower station; ⚡ Small hydroelectric plant (SHP)

Figure 27. Operating hydropower plants and SHP.

Note: Highlighted, the Paranaíba basin section located in the state of Goiás.

Source: Adapted from ANA (2015).



Key: ⚡ up to 30 MW; ⚡ 30 to 50 MW; ⚡ 50 to 99 MW; ⚡ 99 to 157 MW

Figure 28. Hydropower plants and SHP in planning stage.

Source: Adapted from ANA (2015).

In Brazil, sugarcane bagasse, a by-product, is used to co-generate electricity in ethanol mills. As stated by the Ministry of Energy and Mines (MME, 2016), hydropower generation accounted for 81%, *i.e.* 28,468 GWh, of the total electricity supply in Goiás in 2015, while sugarcane by-products represented 15%. Additionally, Goiás is the nation's second largest ethanol producer with 37 mills (**Figure 29**), which produced 4.72 hm^3 of fuel in 2015 (an 11% increase over 2014) (UNICA, 2017; ANP, 2017).

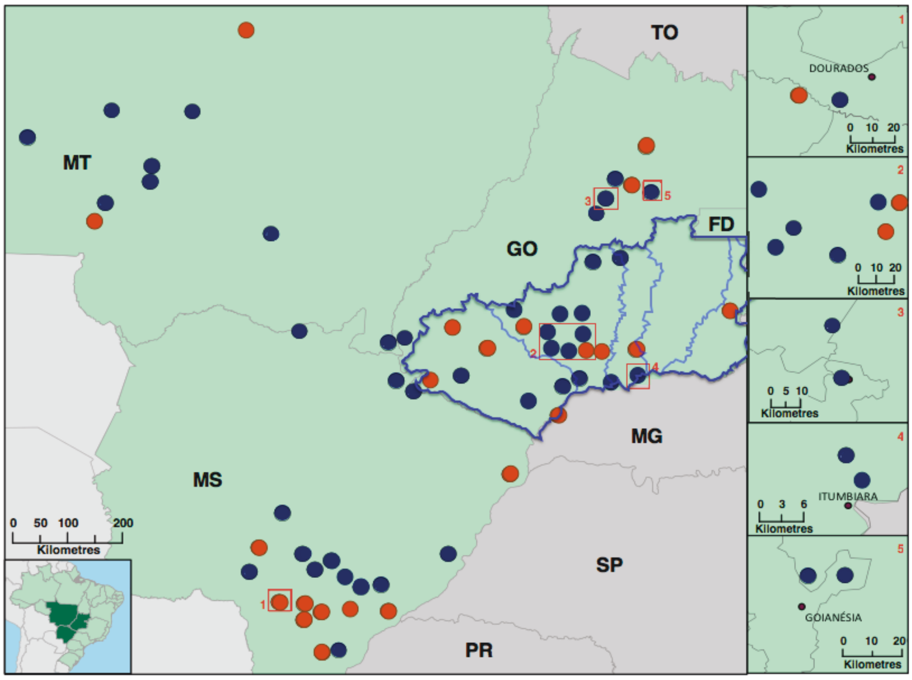


Figure 29. Location of Centre-West ethanol producers.

Note: Orange circles: hydrous ethanol plants. Blue circles: Hydrous and anhydrous ethanol plants. Total: 70 plants. GO: 37 (53%). MS: 23 (33%) and MT: 10 (14%). Highlighted in blue, the Paranaíba's basin WMUs located in Goiás State.

Source: Adapted from ANP (2017).

When LUC GHG emissions are excluded from the analysis, Goiás' main economic activities contribute little to GHG emissions, as renewable sources are predominant in the power grid. In 2016, the highest emissions occurred in the *agricultural* sector, accounting for 71.97 $TgCO_{2e}$, (*i.e.* 83%), followed by *transport* (8.39 $TgCO_{2e}$ (*i.e.* 9.6%)), and *industry* (6.02 $TgCO_{2e}$ (*i.e.* 7%)), with little contribution from the s*ervices* (0.7 $TgCO_{2e}$ (*i.e.* >1%)) and *Power sectors* combined (**Figure 30**) (SEEG, 2017). It is worth observing that the *Agricultural* sector in Goiás' GHG total emissions accounts for about eight times more emissions than the *Transport* sector.

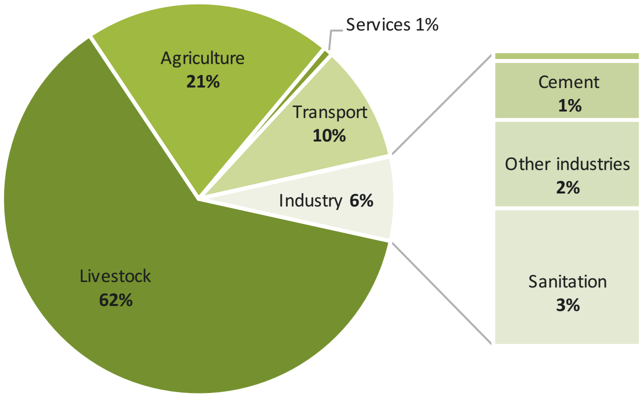


Figure 30. GHG emissions in the state of Goiás, by sector, in 2016.
Note: Emissions from the Power sector and the metallurgy industry were insignificant, i.e. 0.06 $TgCO_{2e}$ *and 0.2* $TgCO_{2e}$*, respectively. In this graph, sanitation (2.8* $TgCO_{2e}$*) was included in the industry sector, as per the Goiás' aggregated IO table.*
Source: Author's adaptation from SEEG (2017).

When ranking Brazil's gross national GHG emissions (a total of 2,278 $TgCO_{2e}$) by state, in 2016 Goiás accounted for 3.82% (*i.e.* 87.1 $TgCO_{2e}$) and had the 11th highest state emissions in the country. The leading GHG emitter was the state of Pará (280.4 $TgCO_{2e}$), with 12.3% of gross national emissions, most due to land-use change and deforestation practices (SEEG, 2017).

However, when ranking GHG emissions in Goiás according to the major categories, such as *agriculture, land use, energy, waste* and *industrial processes*, the share of emissions may differ. Eighty-five per cent (85%, *i.e.* 24.45 $TgCO_{2e}$) of the GHG emissions from land use in Goiás come from LUC (**Figure 31**). In the *agricultural* category (47.09 $TgCO_{2e}$ (*i.e.* 54%)), the highest emitter is *enteric fermentation* at 69% (*i.e.* 32.2 $TgCO_{2e}$) (SEEG, 2017).

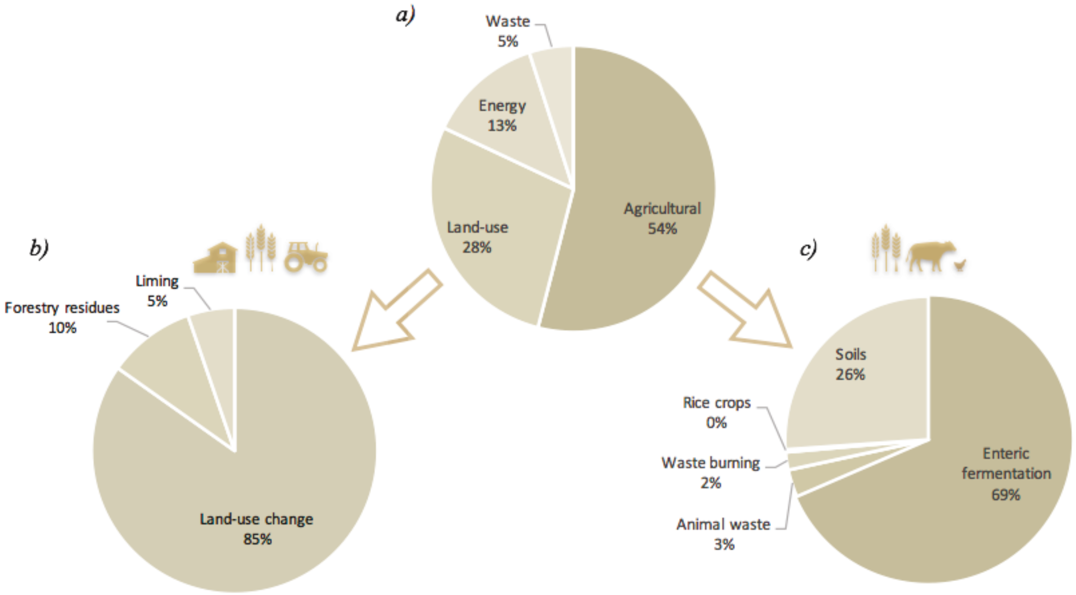


Figure 31. Share of GHG emissions in Goiás State in 2016, by *a)* major categories, *b)* land use and *c)* agricultural activities.
Source: SEEG (2017).

4.2 Ethanol Policy Scenarios

Scenarios can be useful to explore strategic questions, to review policies and investment decisions, and to create common ground and improved understanding of the interrelations between water, energy and food resources. They present plausible evolutions from a current situation, depending on how major driving forces develop and interact, and they help to assess the implications of specific decisions (FAO, 2014).

Our analysis uses the 2008 IO table for the Goiás economy as a baseline for making comparisons with a set of policy scenarios described briefly next. As stated, the aim of this thesis is to analyse the environmental impact of sugarcane expansion on the Paranaíba basin and its subsequent impact on the Goiás economy. In addition, it will estimate the environmental constraints on sugarcane expansion in the region and the possible economic and environmental impacts of implementing a carbon tax.

As previously mentioned, sugarcane crops have grown steadily in recent times, mainly because of ethanol demand by flex-fuel vehicles, but also because of growing worldwide sugar demand. The Brazilian Energy Research Centre (EPE, 2017) has developed three different scenarios for ethanol supply in Brazil to 2030: expansion by 12.4 hm^3 in the low supply scenario, expansion by 18.2 hm^3 in the intermediate scenario and expansion by

23.5 hm³ in the high supply scenario. Overall, the forecasts for each scenario by 2030 are 43 hm³, 49 hm³ and 54 hm³ of ethanol, respectively in the low, intermediate and high supply scenarios. Since the current study focuses on the environmental impact from changes in ethanol production, we selected the EPE high supply scenario, *i.e.* 54 hm³ of ethanol, as the reference for our ethanol scenarios.

As mentioned, Brazil has about 334,000 m³/day of ethanol installed capacity, of which Goiás accounts for 14%. This share of overall domestic installed capacity was used as a proxy to determine ethanol that could be supplied by the state in the future. Brazil produces both anhydrous (gasoline additive) and hydrous (employed mainly in flex-fuel engines, up to E100) ethanol. Anhydrous ethanol must have less than 0.4% water content, while hydrated ethanol has between 4 to 4.9% water content; therefore, their lower heating values (LHV) differ. According to the Ministry of Energy and Mines (MME, 2017), Brazilian anhydrous ethanol has a LHV = 22.36 GJ/m³, whereas hydrated ethanol has a LHV = 21.35 GJ/m³.

Historically, the domestic ethanol-to-gasoline price ratio has varied according to the vagaries of politics. Therefore, we will assume that, for the period up to 2030, the proportion between anhydrous and hydrated ethanol production in Brazil and in Goiás State is the national average observed between 2008 and 2015, namely 36.7% anhydrous and 63.3% hydrated (ANP, 2016). Thus, an average ethanol LHV = 21.72 GJ/m³ has been used in the following calculations. Since most government scenarios are expressed in energy terms, a weighted LHV value is necessary to derive the projected ethanol volume.

Goiás produced 4.72 hm³ (102.5 PJ) of *1G* ethanol in 2015. Of this, it exported 2.97 hm³ (64.48 PJ) to other states and consumed 1.75 hm³ (38.01 PJ), thus showing an exporter profile (MME, 2016). The following scenarios were created to analyse the impact of different ethanol policies promoting sugarcane expansion towards the Brazilian Cerrado. We also applied the EPE higher ethanol supply scenario to determine a worst-case scenario in terms of environmental impacts on the region. Since Goiás produces no gasoline, we also used the four different scenarios to measure the impacts of different levels of gasoline substitution for ethanol, *i.e.* 0%; 25%; 50% and 100% of estimated future gasoline demand in the state.

Scenario 1 - Meeting ethanol demand by 2030

Assuming the higher supply scenario of 54 hm³ of ethanol (EPE, 2017), Goiás should produce 7.56 hm³ of ethanol to meet 2030 demand, assuming the state keeps its 14% share of Brazil's installed capacity throughout the period. Since Goiás produced 4.72 hm³ (102.5 PJ) of ethanol in 2015 (UNICA, 2017; MME, 2016), sugarcane crops should provide an additional 2.84 hm³ (61.68 PJ) to meet the required 7.56 hm³ by 2030. This future demand could be met in two different ways:

> *a)* by cutting ethanol exports to other states, and
>
> *b)* by maintaining current (and future) exports to other states, while adding 2.84 hm³ to achieve a total of 7.56 hm³ (164.2 PJ).

Scenario 2 – Substituting Goiás State's gasoline consumption

According to the Ministry of Energy and Mines (MME, 2016) and the National Agency of Petroleum, Natural Gas and Biofuels (ANP, 2017a), in 2015 gasoline accounted for 45% (1.47 hm³ or 47.39 PJ[37]) of oil product demand in Goiás' *Transport* sector. As stated by EPE (2017), Brazil's domestic gasoline demand in the period 2015 – 2030 will increase at a constant annual rate of 0.8%. If Goiás' gasoline demand grows at the same rate, this will result in 53.41 PJ (or about 1.65 hm³) of gasoline demand by 2030.

By converting this gasoline demand of 53.41 PJ into an ethanol energy equivalent, the state of Goiás should produce 2.46 hm³ of ethanol to replace all its projected 2030 gasoline demand[38]. This *Scenario 2* analyses the impact of substituting gasoline with ethanol in four different ways:

> *a)* by substituting all future Goiás' gasoline demand but meeting neither ethanol export demand from other states nor future ethanol demand in Goiás
>
> *b)* by meeting the export demand from other states and substituting 50% of gasoline for ethanol, but not meeting future ethanol demand in Goiás

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[37] Assuming the average coefficient of equivalence to gasoline: 1m³ of gasoline = 32.24 GJ (MME, 2017).

[38] Converting gasoline future demand to an ethanol energy equivalent through the estimated ethanol LHV of 53.41 / 21.72 = 2.46 hm³.

c) by meeting the export demand from other states and the projected 2030 ethanol demand in Goiás and replacing only 25% of gasoline with ethanol, and

d) by meeting the export demand from other states, meeting the projected 2030 ethanol demand in Goiás and replacing all gasoline demand with ethanol.

A summary of the scenarios is shown in **Table 16**. Of course, additional scenarios can easily be examined using the same methodology. Additionally, estimates were based only on *1G* sugarcane ethanol production due its technological maturity and the fact that *2G* ethanol is not commercially competitive in Brazil due to high production costs and technological constraints. EPE estimates that only a few *2G* ethanol plants are possible in Brazil by 2030 without the full implementation of *RenovaBio* (EPE, 2017; MME, 2017). Conversely, the water and land footprints of *1G* ethanol production are much higher than those of *2G* ethanol, justifying the more pessimistic scenarios regarding the use of natural resources by *1G* ethanol production and the environmental impact of sugarcane expansion in Goiás.

Table 16. Ethanol production scenarios based on Goiás' internal demand, exports to other states, meeting 2030 demand and different levels of gasoline substitution for ethanol.

Scenarios	*Current ethanol demand (hm^3)^a*	*Ethanol exports (hm^3)^a*	*Meeting future demand (hm^3)^b*	*Gasoline substitution (hm^3)^c*	*Total ethanol production (hm^3)*	*Total ethanol production (PJ)*	*% of current production*
1a	1.75	0	2.84	0	4.59	99.69	97%
1b	1.75	2.97	2.84	0	7.56	164.20	+60%
2a	1.75	0	0	2.46 (100%)	4.21	91.44	89%
2b	1.75	2.97	0	1.23 (50%)	5.95	129.22	+26%
2c	1.75	2.97	2.84	0.62 (25%)	8.18	177.66	+73%
2d	1.75	2.97	2.84	2.46 (100%)	10.02	217.63	+112%

Source: ^{a}MME (2016); Estimated from ^{b}EPE (2017) and ^{c}MME (2017b).

Since the assumptions made for *scenarios 1a* and *2a* do not require any sugarcane expansion beyond current (*i.e.* 2015) production, additional ethanol production was estimated for the remaining policy scenarios as follows (**Figure 32**):

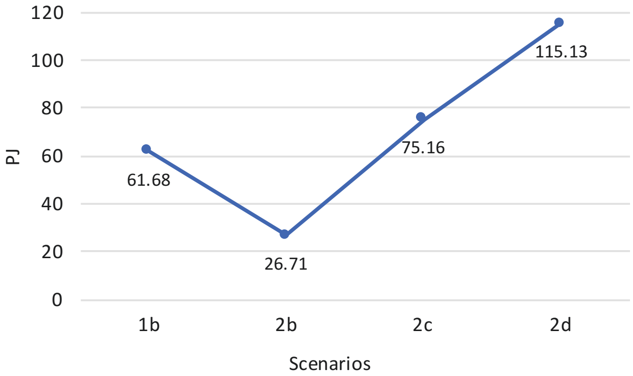

Figure 32. Additional ethanol production required, according to each policy scenario.
Source: Author

After analysing both the Goiás' hybrid IO model structure and its water and land availability, we can estimate land and water use limits in the region, apply these limits to create other sugarcane expansion scenarios and determine the environmental constraints. In this research, we assume that the water withdrawals required for sugarcane expansion in Goiás must not exceed the water availability of 5,183 hm³ (**Table 15**).

When it comes to land use, even though we may determine the geographical limits or the amount of land as a limit for sugarcane expansion in the basin, the existence of 155,000 km² of pasturelands in the region makes such an exercise unnecessary[39]. Pasturelands cover three times more area than all crops cultivated throughout the state and, since cattle are raised mostly free range (and inefficiently so from a land-use standpoint), there is considerable potential for densification in those areas. In addition, since sugarcane crops have historically occupied old pasturelands in that region and Brazilian livestock production has a low-density profile in terms of head of cattle per km², we have assumed that will be no major constraints for sugarcane expansion in terms of area required. Further, soybean cultivation currently covers about 32,000 km² (about three times the sugarcane area) throughout the state and it should attract more attention from policymakers regarding its land and water use in the region, as well as its direct or indirect impact on native forests.

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[39] Alternatives to the current extensive livestock production, such as pasture rotation aiming to improve cattle productivity and the optimal use of photosynthesis in growing grasses, are discussed further in *sub-section 4.3.1.2*.

Finally, it is easier to cultivate sugarcane on marginal land than soybeans, even marginal pastureland. Several researchers have confirmed that the expansion of biofuels production in Brazil is most likely to occur in areas currently used for livestock (Nassar *et al.,* 2010; Soares-Filho and Hissa, 2010). Land-use modelling for the period 2011-2020 shows that sugarcane expansion will occur in areas currently covered by pasture, especially degraded pasturelands (Nassar, *et al.*, 2011). However, despite the potential for livestock densification, some of the cattle raised on pasturelands since replaced by sugarcane crops may be forced to move to other areas and this may have ILUC impact. This ILUC issue is discussed further in the results (*sub-section 4.3.1.2*) and discussion of this paper (*sub-section 4.4.2*).

Since replacing gasoline with ethanol helps reduce GHG emissions, it is not necessary to determine limits for GHG emissions. Studies show that replacing one litre of gasoline with one litre of ethanol reduces GHG emissions by between 19% and 47% per kilometre (well-to-wheels analysis) in the case of corn ethanol, from 35% to 56% in the case of sugar beet and by 92% in the case of sugarcane ethanol (La Rovere *et al.,* 2011 *apud* Macedo, 1998). Including Goiás' land-use GHG emissions in the *agricultural* sector emissions brings some uncertainty to the estimates of this study, since GHG emissions in the state decreased in previous years (*i.e.* prior to 2015), mostly due to LUC (**Figure 33**).

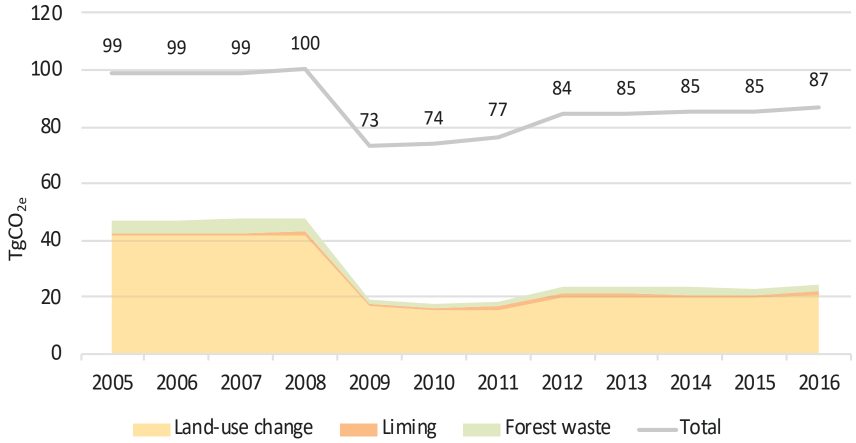

Figure 33. Evolution of GHG emissions in Goiás, highlighting the role of land-use change in GHG emissions, 2005-2016.
Source: SEEG (2017).

In this context, Goiás' gross 2008 GHG emissions amounted to 100 $TgCO_{2e}$, while its gross 2016 GHG emissions were about 85% of that, *i.e.* 87 $TgCO_{2e}$. However, since we are also adding land-use GHG emissions to the 2008 emissions from the *agricultural* sector, the GHG estimates provided by the Goiás hybrid IO model will be much higher than the emissions observed, for example, in 2016. This explains why it is not necessary to determine limits for direct GHG emissions in the IO model; *i.e.*, all policy scenarios will emit more GHG than any year after the baseline year (2008) because of the major reduction in LUC GHG emissions after 2008. Again, despite not being included in the modelling exercise, the ILUC was estimated for the additional land required in each scenario by taking into account that cattle may be forced to move towards Brazilian forests. This would enable the ILUC GHG emissions from replacing pasturelands by sugarcane crops in Goiás to be identified (analysed further in *section 4.3.1.2*).

Similarly, as energy supply and demand is the main variable in the Goiás hybrid IO model (through changes in ethanol final demand in the *Biofuels* sector according to each policy scenario), it is not essential to determine limits for energy demand in the state. The ethanol demand will be guided by the policy scenarios described in **Table 16** and limited by resource, especially water constraints in the region. The next section presents the results from running the Goiás economic-ecological hybrid IO model, including the scenario that determines limits for water use in the region of study and what the economic impact of the various policy choices would be. Finally, the section presents the impact of a carbon tax as a carbon pricing instrument, as well as the impact on the sectoral value added in the state of different carbon price scenarios and emissions abatement possibilities.

4.3 Results

The traditional Leontief IO analysis performed in this research is very useful to determine the impact from changes in future demand for ethanol on both the overall economy and the local environment. In this case, environmental (physical) indicators, such as energy, land and water use and GHG emissions, can be assessed in order to identify the environmental impact of changes in future ethanol demand. Accordingly, the Leontief model also helps to assess the socioeconomic impacts (mainly in terms of employment and GDP changes) of changes in ethanol consumption in the various ethanol scenarios.

However, this physical approach is more useful for policymaking when it includes more economic parameters that bring these physical estimates closer to reality, such as by including price change mechanisms that allow for some level of substitution between factors of production. In fact, the use of physical inputs and the production of undesirable externalities as outputs impact the local environment as a whole. However, the physical impact from changes in final demand for ethanol are also affected in reality by changes in factor input prices, which in turn change because of a carbon tax or any other reason (environmental, political, social, economic) that may affect factor prices. The logic here states that when the price of an input changes, it not only has a monetary impact, it also affects the system as a whole, including changing the level of environmental impact on the same level of production (*i.e.* impacts due only to price change implications). Therefore, to carry out medium- to long-term energy policy analyses (in this case, biofuel policies), one should also analyse the overall socioeconomic and environmental impacts through a price change model that allows for substitution between factors of production.

The results of this paper are, therefore, divided into two main sections; one with a focus on identifying the physical impacts from changes in future demand for ethanol (*section 4.3.1 – Environmental Implications*) and the other showing how these environmental impacts would differ when considering price change possibilities due to a carbon tax (*section 4.3.2 – Economic Implications*). The latter includes an additional analysis on the sectoral value added in Goiás, based on different carbon prices and emissions abatement possibilities.

4.3.1 Environmental Implications

Based on Brazilian government data, soybean crops occupied 21,800 km² (44%) of the total *agricultural* area (*i.e.* 49,280 km²) in Goiás in 2008, followed by corn (9,060 km²) and sugarcane (4,160 km²) (**Figure 34a**). *Livestock* represented the main land-use activity in the region, accounting for 155,230 km² (76% of the total *land-use* area). The *Industry* (600 km²) and *Power* sector (2,800 km²) footprints were the smallest of those measured (**Figure 34b**). Overall, we estimated that the *Agricultural* sector accounted for 80% (3,720 hm³) of water use in 2008, , followed by the *Power* sector (700 hm³, *i.e.* 15%), *Industry* (200 hm³, *i.e.* 4%) and *Human supply* (38 hm³, *i.e.* 1%) (**Figure 34c**).

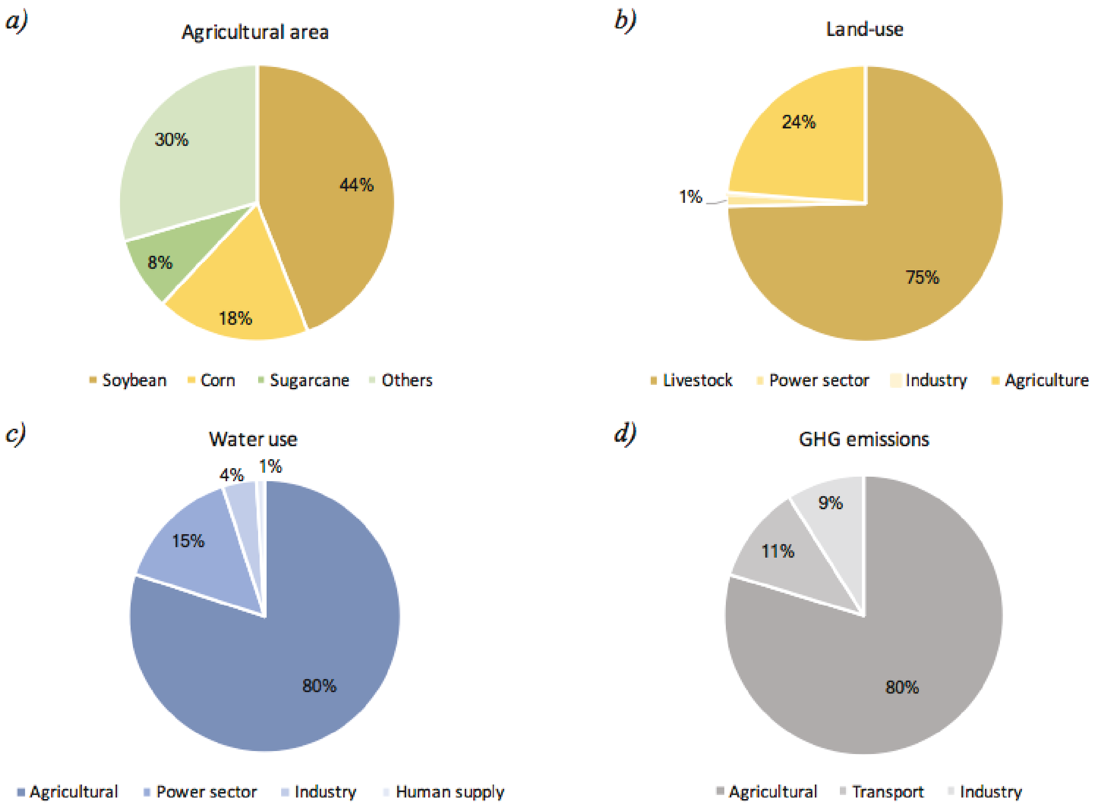

Figure 34. 2008 Goiás *a)* agricultural area, *b)* land use, *c)* water use and *d)* GHG emissions.

Regarding GHG as mass of CO_{2e}, the *Agricultural* sector dominated emissions in the state for 2008, accounting for 80% (41.67 Tg), followed by the *Transport* sector with 11% (5.92 Tg). *Industrial processes* accounted for the remaining 9% (4.69 Tg) (**Figure 34d**). Thermoelectric power plant emissions were insignificant, and they represented all the emissions from the *Power sector.* This was because, for lack of a universal accounting methodology, hydropower reservoir emissions were not considered. This is important when considering the fact that hydropower generates 81% of all the power in the state[40]. When taking into account the major GHG emission categories, such as *Agricultural, Land-use change, Energy, Industrial processes* and *Waste*, the relative share of GHG emissions may differ (**Figure 35**). *Land-use change* has led GHG emissions in Goiás with 47.73 $TgCO_{2e}$, followed by *Agricultural* (40.23 $TgCO_{2e}$) and *Energy* (9.38 $TgCO_{2e}$). The percentage of GHG emissions from *Waste* (2.74 $TgCO_{2e}$) and *Industrial processes* (0.38 $TgCO_{2e}$) was much smaller.

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[40] Of the total electricity generated in Goiás in 2015 (28,464 TWh), hydropower accounted for 81% (22,944TWh), followed by thermal generation from sugarcane by-products (15%, *i.e.* 4,309 TWh) and finally, by power from conventional oil products (4%, *i.e.* 1,184 TWh) (MME, 2016).

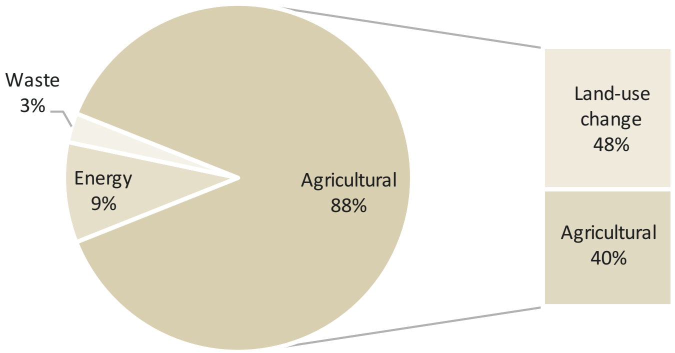

Figure 35. 2008 Goiás' GHG emissions, by major categories.

Note that the Energy category comprises the energy used in industrial processes, all the fuel used in all transport modals and the energy used by the energy sector itself. All emissions from land-use change were allocated to the Agricultural sector, i.e. 41.7 $TgCO_{2e}$ *from land-use change, 1.28* $TgCO_{2e}$ *from liming and 4.77* $TgCO_{2e}$ *from forestry residues, because of the origin of the emissions.*

Source: SEEG (2017), from MCTI (2016).

Therefore, by adding GHG emissions from *land use*, *i.e.* land-use change, liming and forestry residues, into the *Agricultural* sector we get 89.4 $TgCO_{2e}$ from the *Agricultural* sector, 5.92 $TgCO_{2e}$ from the *Transport* sector and 4.59 $TgCO_{2e}$ from *Industrial processes* (**Figure 36**).

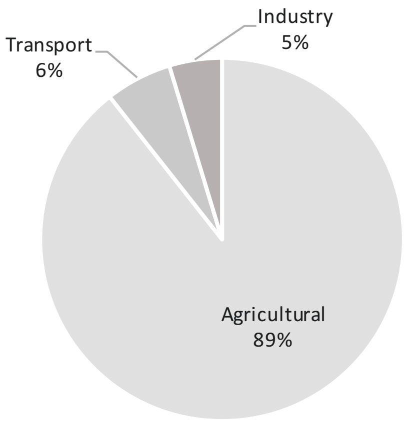

Figure 36. 2008 Goiás' GHG emissions, by sector.

Note that the Services and Power sectors were much smaller in 2008, i.e. 0.068 $TgCO_{2e}$ *and 0.074* $TgCO_{2e}$*, respectively.*

Source: SEEG (2017), from MCTI (2016).

By simulating the Goiás' economic-ecological hybrid IO table, we estimated the use of energy, water and land, as well as GHG emissions, job creation and GDP changing according to changes in future ethanol demand (**Table 17**), following the scenarios described in *section 4.2,* (**Table 16**).

Table 17. Summary of estimates for water, energy and land use, as well as GHG emissions, employment and GDP changes for each ethanol scenario.

			*Environmental**								*Social**		*Economic**	
Scenarios	*Additional Ethanol (PJ)*	*Change over 2015 (%)*	*Water (hm^3)*	*Change (%)*	*Land (km^2)*	*Change (%)*	*Energy (PJ)*	*Change (%)*	*GHG (in TgCO$_{2e}$)*	*Change (%)*	*Jobs (Thousands)*	*Change (%)*	*GDP (M US$)*	*Change (%)*
1a	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1b	61.68	60	54.5	1.2	2,815	1.3	80.1	14.5	1.345	1.3	23.7	0.8	177	0.87
2a	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2b	26.71	26	23.6	0.5	1,220	0.6	34.72	6.8	0.583	0.57	10.3	0.35	76.5	0.38
2c	75.16	73	66.3	1.4	3,425	1.6	97.5	17	1.637	1.6	28.8	0.96	214.7	1.05
2d	115.13	112	101.7	2.1	5,250	2.5	149.5	24	2.512	2.4	44.2	1.5	329.4	1.62

*Note: *additional requirements regarding the 2008 Goiás IO structure.*

To meet the estimated 2030 ethanol demand, Goiás would have to produce an additional 61.68 PJ of ethanol. According to *scenario 1a*, it could do this simply by cutting ethanol exports to other states, thereby causing no additional environmental impact to the Paranaíba basin. However, other states would have to increase their production to provide about 95% of the 64.48 PJ currently exported by Goiás. Since most of the remaining suitable areas for ethanol expansion are in the Cerrado, this demand would most likely be met by Mato Grosso do Sul State. Therefore, the environmental impact of expanding sugarcane cultivation would simply be transferred from one state to another, but still in the same water-stressed region.

In *scenario 2a*, all the 2030 gasoline demand in Goiás, equivalent to 53.41 PJ, is substituted. In this scenario, there is no need for additional ethanol production since, again, exports to other states could be cut back. By reducing its current ethanol exports by 83%, Goiás State could replace all its 2030 gasoline consumption. Since there are no refineries in Goiás, it imports all its gasoline, mainly from nearby states. The gradual replacement of gasoline with ethanol might therefore be politically interesting for Goiás' economic and environmental agendas.

Some highlights from the four remaining scenarios are presented below (**Table 17**):

- *Scenario 1b: 60% increase (additional 61.68 PJ) over 2015 production, to satisfy both current (102.5 PJ) and future (164.20 PJ) ethanol demand.*

About 54.5 hm^3 of water and 2,815 km^2 of land would be necessary in this scenario. According to Beuchle *et al.* (2015), the land required to meet future ethanol demand accounts for 2.4% of natural vegetation cover loss in the Cerrado biome from 2000 to 2010. All energy sources and industrial processes would require an additional 14.5% (80.1 PJ) of energy, emitting an additional 1.3% (1.345 $TgCO_{2e}$). About 23,700 new jobs (0.8% increase over current levels) would be created, of which 11,500 would be in the *Agricultural* sector, 8,800 in the *Biofuels* and 2,300 in the *Services* sector. Regarding GDP changes, estimates show an 0.87% (US$177 million) increase in response to changes in ethanol demand, impacting mostly the *Biofuels* (53%), *Agricultural* (1.4%), *Transport* (0.55%) and *Chemical products* (0.33%) sectors.

It is worth remembering that *scenario 1b* may be the most realistic scenario in terms of ethanol policies because it does not propose to replace any gasoline in the state and it aims to meet future ethanol demand projected to 2030. In this regard, the economic and environmental impacts calculated here can be seen as the closest estimates to the reality.

- *Scenario 2b: 26%* (*26.71 PJ*) *increase over 2015 production to substitute 50% of 2030 estimated gasoline consumption but not meeting future internal ethanol demand*

This scenario shows the lower additional ethanol requirement and, therefore, lower impact on the state's energy, environmental and socioeconomic systems. It would demand less than 50% of *scenario 1b* requirements in terms of water (*i.e.* 23.6 hm^3), land (*i.e.* 1,220 km^2), energy (*i.e.* 34.72 PJ), GHG emissions (*i.e.* 0.583 $TgCO_{2e}$), jobs (*i.e.* 10,300) and GDP (*i.e. US$*76.5 million). The direct and indirect impacts of changes in final demand would increase the value added, mainly in the *Biofuels* (23%), *Agricultural* (0.6%), *Transport* (0.24%) and *Power* (0.14%) sectors.

- *Scenario 2c: 73% increase over 2015 production, i.e. additional 75.16 PJ, to meet future ethanol demand and substitute 25% of 2030 estimated gasoline consumption in Goiás*

The only difference between *scenarios 1b* and *2c* is the 25% of gasoline substitution with ethanol instead of no gasoline substitution in *scenario 1b*. This difference between the estimates of both scenarios would show the various impacts this level of gasoline substitution in the state, namely, an additional 11.8 hm³ of water, 610 km² of land, 17.4 PJ of energy, 0.292 $TgCO_{2e}$, 5,100 additional jobs and, finally, a US$37.7 million increase in GDP in *scenario 1b*. The total requirements for *scenario 2c* can be verified in **Table 17**. As one might expect, the *Biofuels* sector would have its value added increased by 64%, while the *Agricultural* (1.7%), *Transport* (0.67%), *Chemical products* (0.4%) and *Power* (0.39%) sectors would show much lower indirect impacts. Most of the 28,800 new jobs in *scenario 2c* would be created in in the *Agricultural* sector (14,000), followed by the *Biofuels* (10,700) and *Services* (2,800) sectors.

Again, *scenario 2c* constitutes a realistic scenario in terms of ethanol policies because it aims to meet future ethanol demand and replace 25% of the gasoline projected to be consumed in Goiás in 2030. Even if the Goiás' government does not support any policy to replace gasoline with ethanol, this scenario may help us understanding the likely economic and environmental impacts in the event of a gradual gasoline replacement in the state.

- Sc*enario 2d: 112% increase (i.e. an additional 115.16 PJ) over 2015 production, to meet future ethanol demand and substitute 100% of the estimated 2030 gasoline consumption in Goiás.*

With this major change in the state's ethanol supply chain, GDP would increase 1.62%, (to US$20,720 million), an additional US$329.4 million due to changes in final demand in the ethanol sector alone. To reach the new final demand requirement, an additional 101.7 hm³ of water and 5,250 km² of land would be necessary, an increase of 2.1% and 2.5% respectively. Overall energy supply would increase 24% to 622.15 PJ, while GHG emissions would go up 2.5% to about 102.67 $TgCO_{2e}$ (**Figures 37** and **38**). Employment would increase by 1.5%, accounting for 44,200 new jobs, 49% of them in the *Agricultural* sector, due to increased demand for ethanol. In terms of value added, the *Biofuels* sector would obviously enjoy the greatest impact (98%), followed by the *Agricultural* (2.56%), *Transport* (1.03%), *Chemical products* (0.61%), *Power* (0.59%) and *Metallurgy* (0.28%) sectors. In terms of land and water use, however, the *Agricultural* sector would experience the greatest impact, a 99% change in land use and an 80% change in water use. The land-use change estimated from future ethanol demand in *scenario 2d* would account for 4.6% of natural vegetation loss in the Cerrado (equivalent to twice the area of Luxembourg) from 2000 to 2010 (Beuchle *et al.*, 2015).

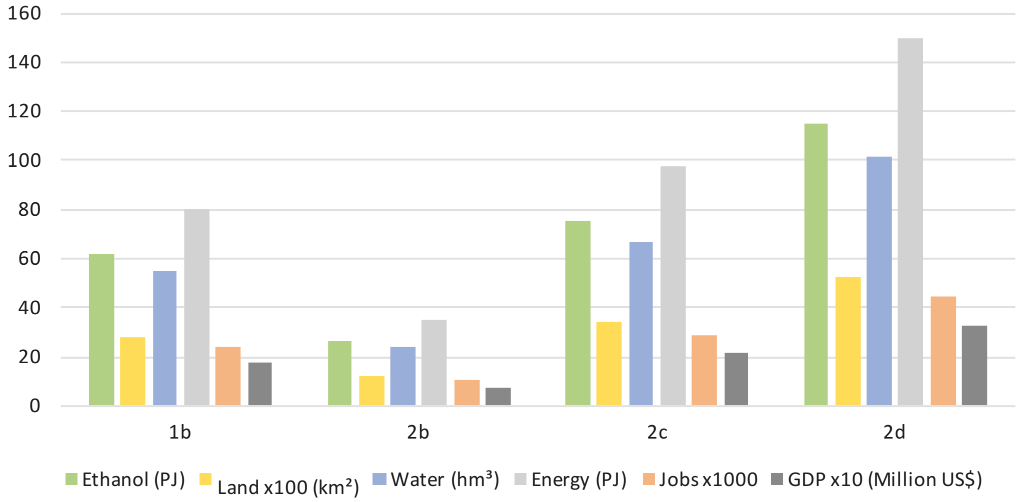

Figure 37. Additional water, energy and land-use requirements, ethanol production, job creation and GDP for all scenarios by 2030.

Note: Scenarios 1a and 2a are not compared in this figure. According to scenario 1a, Goiás would have to produce an additional 61.68 PJ of ethanol. It could do this simply by cutting ethanol exports to other states, thereby causing no additional environmental impact to the Paranaíba basin. In scenario 2a (replacement of all future Goiás' gasoline demand but meeting neither ethanol export demand from other states nor future ethanol demand in Goiás), there is no need for additional ethanol production since, again, exports to other states could be cut back.

Source: Author.

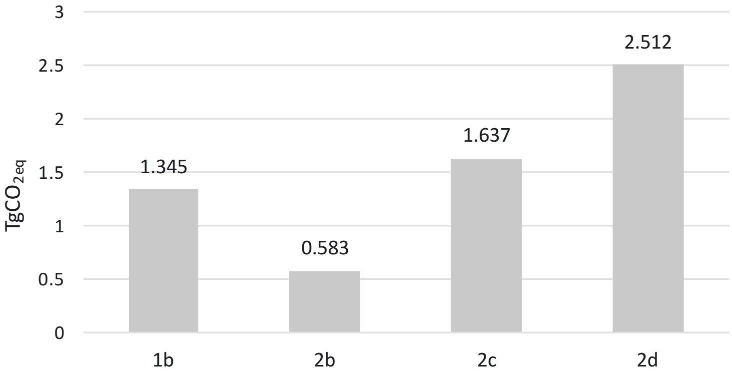

Figure 38. Additional GHG emissions for all scenarios by 2030.

Source: Author.

Some general remarks can be made based on the results above:

- For every 1% increase in final demand for ethanol, water demand will increase by 0.019%, land use by 0.023%, GHG emissions by 0.022%, job creation by 0.013% and GDP will change by 0.014% (**Figure 39**).

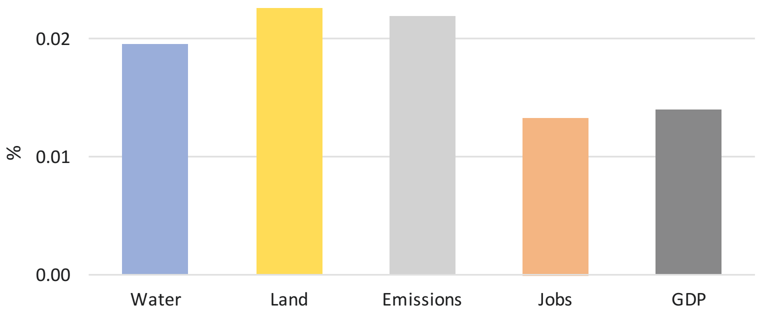

Figure 39. Changes in water and land requirements, GHG emissions, job creation and GDP, from 1% change in final demand for ethanol in the state of Goiás. *Source: Author.*

- The assumptions made in *scenarios 1b* and *2c* seem to be the most realistic when taking into account policy goals, since these scenarios target meeting both current and future ethanol demand, as well as ethanol exports to other states. However, the potential ethanol supply does not necessarily mean that this production level is feasible or desirable. This production level will also depend on such variables land prices, production costs, externality costs, required investment in production capacity and infrastructure.

- Respectively, *scenarios 1b, 2c* and *2d* represent 15%, 18% and 28% of MAPA's forecasts for the whole country, *i.e.* an expansion of 19,000 km² of sugarcane crops in the country by 2026 (MAPA, 2016). Considering only MAPA's projections for the Centre-West region by 2026, *i.e.* 8,000 km², *scenarios 1b, 2c* and *2d* would account for 35%, 43% and 66% respectively of the total area projected for expanded ethanol production for the entire region but produced only in Goiás State (**Figure 40**).

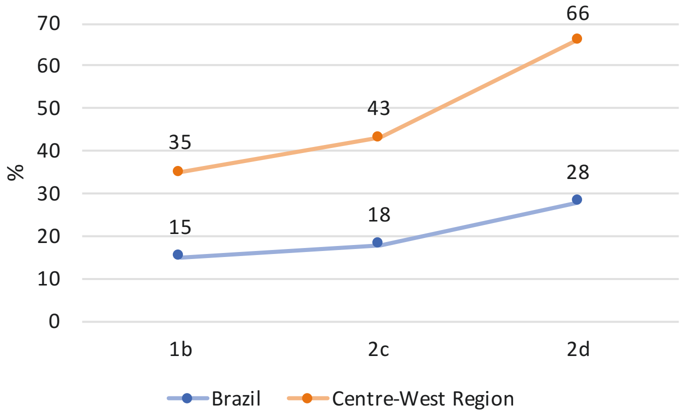

Figure 40. Share of ethanol policy scenarios regarding Brazilian government ethanol expansion forecasts.
Source: Author.

- By comparing *scenarios 1b* and *2c*, we can observe that replacing 25% of gasoline with ethanol in the state would take up an additional 3% of land use according to MAPA's forecast for Brazil and about 8% when considering the projections for the Centre-West region alone. If a 25% ethanol substitution can be achieved with only a 3% increase in land use in the Centre-West, the potential for a local gradual gasoline substitution of ethanol is significant.

- The land use estimated in *scenarios 1b* and *2c* accounts respectively for 30% and 35% of the 2015 sugarcane crop area in Goiás, and for 2.6% and 3.2% of the 2015 sugarcane crop area in the whole of Brazil (MAPA, 2016) (**Figure 41**). Since sugarcane crops have historically replaced old pasture lands, there are still plenty of areas available for sugarcane expansion in the state. This is particularly so because Brazilian livestock production still has a low-density profile, although great strides are being taken to intensify land use by concentrating more head of cattle per unit of land.

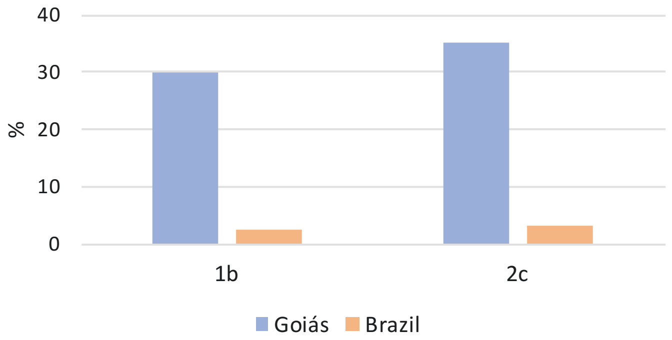

Figure 41. Additional land-use estimates for Goiás' sugarcane crop area for *Scenarios 1b* and *2c*, based on 2015 figures.
Source: Author.

- *Scenarios 2c* and *2d* would have a total energy demand of 570 PJ and 622 PJ, respectively, an additional 28% and 40% of Goiás' 2015 internal energy supply (MME, 2016) (**Figure 42**). Note that changes in ethanol demand would change the overall energy demand in Goiás' economy, which is directly and indirectly used by inter-industry sectors to produce the inputs required to meeting that new ethanol demand.

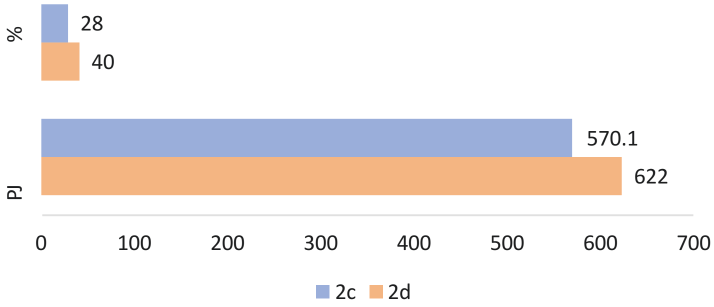

Figure 42. Total energy demand and share of 2015 Goiás' internal energy supply for *Scenarios 2c* and *2d*.
Source: Author adaptation based on MME (2016).

4.3.1.1 Concerns about Local Water Resources

Despite the Paranaíba basin showing high overall water availability, the National Water Agency (ANA, 2015) pointed out some conflict areas regarding multiple water uses, especially those caused by agricultural demands. In this regard, even in the worst-case scenario (*2d*), the additional water requirements due to changes in ethanol demand (*i.e.* 3.2 m^3/s or 102 hm^3 on an annual basis, equivalent to 1.5% of 2010 total water consumption in the basin (ANA, 2015)) would have little impact on local availability. However, it is crucial to note where in the basin the sugarcane expansion would occur to minimise potential conflicts over this resource.

To that end, we have developed an alternative ethanol production scenario focusing on limiting ethanol expansion according to water-use limits in the basin. As previously mentioned, the estimated water availability in the section of the Paranaíba basin located in Goiás in 2015 was 5,183 hm^3/year, a water-use volume which must not be exceeded. Keeping this in mind and by manipulating the Goiás' economic-ecological hybrid IO model, we have estimated the limits for ethanol expansion in the basin to a 576% increase over 2015 production level, *i.e. scenario 2e*. This alternative scenario would make available an additional 24.86 hm^3 (82%) of total 2015 national ethanol production (UNICA, 2017) for export to other states, after meeting the state's own demand of 1.75 hm^3, meeting the 2030 demand of 2.84 hm^3, and replacing Goiás' total 2030 estimated gasoline consumption of 2.46 hm^3.

Thus, *scenario 2e* would require an additional 523 hm^3 of water to meet that massive ethanol demand, an increase of 10.1% on water use. It should be noted that this scenario calculates the remaining available surface water according to the water flow used for granting rights to water use in the basin (**Table 15**), which means a half the reference flow $Q_{95\%}$ (*i.e.*, a more restrictive measure). Regardless of the amount of sugarcane that could be produced by using this volume of water, no policy would recommend expanding sugarcane production up to the limits of surface water availability. This policy scenario is purely an exercise to understand whether an ethanol expansion of 576% would have enough room to expand towards the Paranaíba basin without significantly impacting water resources and what the economic impacts of such a measure would be.

Since we have observed a 3-fold increase in the basin's irrigated area in 15 years (between 1995 and 2010), an approximate 400% increase in the area planted under sugarcane between 2000 and 2010 and another, more recent, expansion of 170% in the five years between 2010 and 2015, it is not extreme to hypothesise what could happen to the Paranaíba basin's resources with another 500% sugarcane expansion over the next 15-year period.

Under this major change in Goiás' ethanol supply chain, GDP would increase 8.31% to US$22,085 million, of which an additional US$1,694 million would due to changes in final demand for ethanol (**Figure 43**). *Scenario 2e* would see 111,000 new jobs created in the *Agricultural* sector (a 13.2% increase), followed by 84,800 new jobs in the *Biofuels* sector, 22,600 in *Services*, 5,900 in *Transport* and 1,100 in the *Food and beverages* sector. Overall, *scenario 2e* would create 227,500 new jobs, bringing the total to 3.19 million jobs in the state, a 7.13% increase. Overall energy supply would increase by 62% (770 PJ) to 1,242 PJ, while GHG emissions would go up 11.42% (12.92 $TgCO_{2e}$) to about 113.07 $TgCO_{2e}$.

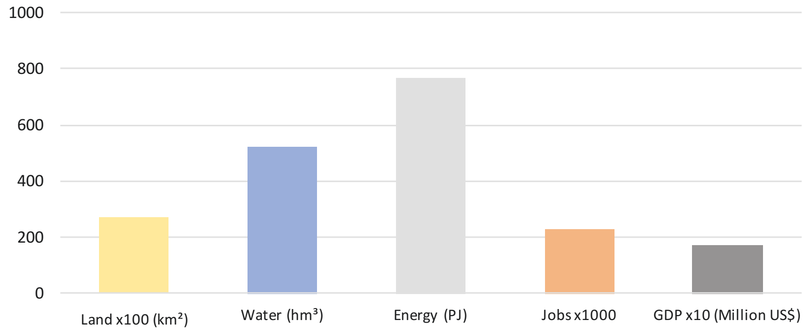

Figure 43. Additional water, energy and land-use requirements, job creation and GDP over 2015 levels, for *Scenario 2e*.
Source: Author

To meet this new final demand, it would be necessary an additional 27,022 km² of land, an increase of 11.53%, an area that is 5,000 km² bigger than the smallest Brazilian state, Sergipe, which itself accounts for about 0.3% of Brazil's total land. To give a better idea of the scale, this 27,000 km² expansion area accounts for 90% of Belgium. In terms of the area used for agricultural production in Goiás, the land required for this sugarcane expansion would account for only 18% of total current pasturelands and for 47% of the total agriculture area currently (*i.e.* 2016) used in the state (MAPBIOMAS, 2017).

When one examines each WMU, the data in **Tables 14** and **15** distinguish between water resource use, management and planning. The *Meia Ponte, Turvo-Bois* and *Lower Paranaíba Minas Tributaries* WMUs are concerning regarding the status of their water impairment indicators, *i.e.*, 'highly critical' and 'alert', respectively. This can be explained due to high sugarcane production in the *Turvo-Bois* WMU (about 15% of total sugarcane production in the basin), and low surface water availability in the *Meia Ponte* and *Lower Paranaíba Minas Tributaries.* Although the *Claro, Verde, Correntes and Aporé* WMU produces more sugarcane (17% of the total) than the *Meia Ponte* WMU (5%) and the *Lower Paranaíba Minas Tributaries* WMU (5%), its water resources were considered normal due to its higher water availability and lower withdrawals.

The *Turvo-Bois* is the WMU that uses more water for irrigation than the other WMUs analysed here (**Figure 44**). It also ranks second in its use of water for livestock production, which makes it the most demanding (18.3% of total water demand) WMU in the whole Paranaíba basin. Since this WMU also has the largest number of ethanol mills in the basin and historically has experienced the greatest sugarcane expansion in the region, it is important to take local environmental and political action, based on the specificity of each WMU to understand the real impacts of growing sugarcane in that region.

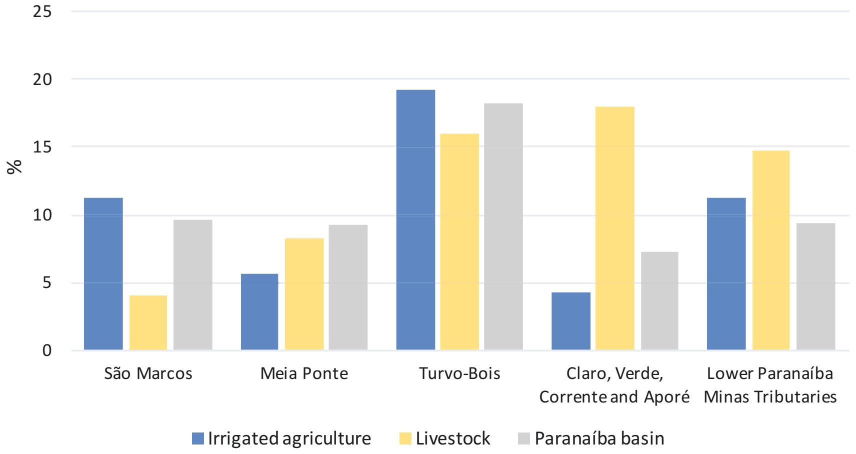

Figure 44. Share of irrigated crops, livestock production and in relation to the whole Paranaíba basin, by WMU.
Source: Author's adaptation from ANA (2015).

4.3.1.2 Indirect Land-use Change Impacts

The replacement of agricultural land with biofuel production may lead to indirect land-use changes, which occur as unintended consequences of land-use decisions elsewhere. The main reason for ILUC analysis is to understand the risk that biofuels production may shift other agricultural activities to land with high natural carbon stocks, resulting in significant GHG emissions from land conversion processes. These effects are also known as *leak*, *i.e.* the result of an action occurring in a system that induces indirect effects outside the limits of this system, but which can be attributed to the actions occurring within the system.

Each of the scenarios previously analysed shows different additional land requirements according to changes in future demand for ethanol in Goiás. Given pastureland availability with medium and high potential for growing sugarcane crops, future sugarcane expansion in the area could replace old or idle pasturelands. However, the question that arises from this substitution is: what would be the indirect impacts from these changes in terms of GHG emissions, considering that cattle may have to move towards Brazilian forests? To understand the magnitude of this indirect impact, estimates for ILUC GHG emissions from replacing pasturelands with sugarcane crops are presented below (**Table 18**).

Table 18: Estimates of GHG emissions from expanding Goiás sugarcane crops.

Scenarios	*Area (km^2)*	*Area (ha)*	*Herd*	*Forest area*	*Emissions Cerrado ($TgCO_2$)*	*Emissions Amazon ($TgCO_2$)*
2b	1,220	122,000	122,000	122,000	24.60	53.68
1b	2,815	281,500	281,500	281,500	56.77	123.86
2c	3,425	342,500	342,500	342,500	69.07	150.70
2d	5,250	525,000	525,000	525,000	105.88	231.00

Note: Scenarios ranked according to the forest area required.
Forest area required = Area (ha) x Herd; assuming 1 head of cattle/ha.
Emissions = Forest area x Carbon stock in biome x δMM.
Carbon stock in Cerrado forests = 55 t/ha
Carbon stock in Amazon forests = 120 t/ha
δMM (molecular mass ratio) = MM CO_2 / MM C
MM CO_2 = 44 u; MM C = 12 u
1 km^2 = 100 ha
1 tonne = 10^{-6} Tg

In fact, if replacing pasturelands with sugarcane cultivation pushes the livestock towards the Amazon, indirect GHG emissions would be about 50% higher than if the cattle was moved to the Cerrado forests. This is because the Amazon has a higher carbon density (120 t/ha) than the Cerrado (55 t/ha) (Young *et al.*, 2016). However, the opportunity cost of land in the Cerrado biome is higher than in the Amazon, causing livestock producers to seek cheaper land for their production, which in turn pushing deforestation in the Amazon. When considering the indirect GHG emissions caused by indirect deforestation in the Cerrado, the most realistic scenarios (*i.e. Scenarios 1b* and *2c*) would account for an additional 56% and 69% respectively in GHG emissions compared to the 2008 GHG emissions baseline. If the same deforestation happened in the Amazon biome, the numbers would be worse, about 120% and 150% of additional indirect GHG emissions, respectively. In any of these cases, the possibility of deforestation in native forests caused indirectly by sugarcane expansion in the state of Goiás would make this level of expansion prohibitive.

It is important to emphasise that while sugarcane expansion in Southern Cerrado (*i.e.* where part of Goiás State is located) has occurred predominantly over pasturelands or croplands that have been used inefficiently, in the northern frontier region of MATOPIBA[41] the increase has taken place mostly in areas of native vegetation, despite the availability of suitable lands already cleared and inefficiently used (Carneiro Filho and Costa, 2016). Overall, there are about 300,000 km² of Cerrado land available, with high- or medium-quality soil and a climate suitable for cultivation that are currently being inefficiently used (Reis *et al.*, 2017).

Additionally, and as mentioned previously, cattle can be reared in a more intensive way than is current practice in Brazil. Overall, this low productivity lies in poor livestock management such as producer inefficiency, food inefficiency, low pregnancy rate, high incidence of invasive plants, soil fertility reduction and erosion. However, there are alternatives to improve productivity and reduce both the costs and GHG emissions of livestock production.

In this context, rotation systems use solar energy as a basic input, focusing on pastures' photosynthetic potential. A basic premise of these systems is the division of pastures into plots whereby, while one of them is in use, others remain at rest, encouraging photosynthesis and the accumulation of both energy and protein reserves in plant roots. Pasture at its optimum resting point has a more balanced composition, in addition to producing a greater amount of dry matter per area with better fibre content (Villela, 2014). Following agro-ecological concepts, the rotation system is the most efficient and economical technology for cattle production (Castagna e*t al.*, 2008). Additionally, according to Barreto and Silva (2013), simply dividing pastures into plots and rotating cattle correctly could increase productivity in Brazil from 75 to about 260 kg/ha/year.

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[41] Portuguese acronym for the initials of the names of each state that makes up the MATOPIBA region, *i.e.* Maranhão (MA), Tocantins (TO), Piauí (PI) and Bahia (BA).

From a GHG emissions standpoint, the rotation system offers even more benefits. This is because the plough is not used in a rotation system and therefore almost all CO_2 is transformed into H_2CO_3, minimising CO_2 release into the atmosphere. This is an improvement on the use of plough, which buries organic matter and produces an anaerobic environment; decomposition occurs by anaerobic bacteria, which releases methane into the atmosphere. A well-managed rotated pasture consumed at optimum resting point thus releases less CO_2 and CH_4 into the atmosphere than a pasture produced with ploughing. As an alternative, Young *et al.* (2016) have estimated CH_4 emissions from cattle's anaerobic digestion, taking into account that through its planned environmental services policy, which has yet to be passed into law, the Brazilian government would encourage ranchers to avoid CH_4 emissions by switching from extensive to intensive livestock production and would compensate them accordingly. Their results for the CH_4 that could be avoided by intensifying livestock production by 30% showed a reduction of up to 6.3 $GgCH_4$ (176.5 $GgCO_{2e}$[42]), making clear that there is great potential for the intensification of livestock production in the Cerrado and Amazon biomes.

This methane reduction by the means of intensification of livestock production could offset some of the indirect CO_2 emissions from sugarcane expansion over old pasturelands. Also, if intensification raises the Brazilian average by at least two head of cattle/ha, the total indirect CO_2 emissions showed in **Table 18** could be halved. It needs to be reiterated that these indirect GHG emission scenarios from native forest deforestation assume that the whole area required for sugarcane expansion would be met by local existing pastureland and that 100% of the cattle produced in the area required for sugarcane crops would therefore move to native forests. Of course, this is the upper limit of indirect impact estimated by this paper, in terms of deforestation of native forests and its related GHG emissions.

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[42] Methane (CH_4) is estimated to have a global warming potential (GWP) of 28 over 100 years, according to the IPCC Fifth Assessment Report (AR5) (IPCC, 2014). CH_4 emitted today lasts about a decade on average, which is much less time than CO_2. But CH_4 also absorbs much more energy than CO_2. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. The CH_4 GWP also accounts for some indirect effects, such as the fact that CH_4 is a precursor to ozone, and ozone is itself a GHG. See more details at https://www.ipcc.ch/report/ar5/.

4.3.2 Economic Implications

In order to convert the results of the physical IO approach presented above into something more useful for the policymaking process, this research has applied the Leontief IO price model to analyse the impacts of changes in input prices over the local economy and environment by considering the implementation of a hypothetical carbon tax. The logic here states that when the price of an input changes, it not only causes monetary impacts but also affects the system as a whole, including changing the level of environmental impacts to the same level of output in the economy. The following sections therefore explore the economic and environmental impacts of a carbon pricing initiative (*subsections 4.3.2.1* and *4.3.2.2*), assuming different carbon prices and emissions abatement possibilities for the state of Goiás (*sub-section 4.3.2.3*), as explored below.

4.3.2.1 Price Change Impacts from a Carbon Tax

Carbon tax estimates were based on the emissions intensity indicator, the carbon price considered and the value added coefficient from the original IO table for Goiás (see **Appendix XIX**). By taking a carbon tax into account, the price of factor inputs in an economy changes (*i.e.* it increases the sectoral value added costs), showing the economic (price) impacts of imposing a carbon tax. These price changes can be regarded as equivalent to indirect taxes (Cornwell and Creedy, 1995). In this research, the price change impacts for each sector were therefore estimated through the Leontief IO price model by calculating the difference between the old and new input prices (*i.e.* the value added costs), assuming a carbon price of US\$10/tCO$_{2e}$. Price change estimates for this research are presented in **Table 19** through the index of price changes (*i.e.* percentage changes relative to the original prices in the Goiás IO table). For more detail on the results of the Leontief IO price model and other price change estimates (for 5, 10, 25 and 50 US\$/tCO$_{2e}$), please refer to **Appendix XIX**.

After a US\$10 carbon price was attributed to the total GHG emissions of each sector of the Goiás economy, the *Agricultural* sector was found to be the most impacted in terms of price changes, showing an approximate 25% of increase over its original prices. This was followed by the *Food and beverages* (7.5%), *Biofuels* (5.5%) and *Transport* (5%) sectors. Sectors that could be considered less affected by changes in factor input prices due to a carbon tax were *Services, Power, Cement, Chemical* and *Textile*, all of which changed by less than 1% compared to their original price (*i.e.* prior to the US$10 carbon tax).

This trend can be roughly explained by the emissions profile of each sector (*e.g.* the *Agricultural* sector has led the emissions in the state with 89% of the total (SEEG, 2017)), since the carbon tax is applied to the total GHG emissions in each sector, and assumes the original value added for each sector. In addition to the emission intensity of each sector, price change analyses take the sectoral value added coefficient from the original IO table into account. Thus, once the *Agricultural* sector showed the highest emission intensity indicator among Goiás' economic sectors, its sectoral value added costs were impacted most, indicating the price impacts of imposing a carbon tax to the sector. Since percentage changes (*i.e.* 25% change after the imposition of a carbon tax) relative to the original prices in the Goiás IO were higher for the *Agricultural* sector, it was found to be the most impacted in terms of price change (**Table 19**).

Table 19. Leontief price model estimates for a 10 US$/tCO$_{2e}$ carbon price scenario.

	Economy sectors												
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
GDP	2,973	296	1,984	252	121	318	646	870	1,548	378	888	12,161	990
VP	5,405	641	8,186	572	299	967	1,601	2,183	2,799	922	1,368	16,926	1,789
VA Ccoeff.	0.5501	0.4616	0.2424	0.4402	0.4039	0.3285	0.4031	0.3987	0.5531	0.4101	0.6495	0.7185	0.5532
EI (TgCO$_{2e}$)	0.0165	0.0003	0.0001	0.000	0.0001	0.0002	0.000	0.0011	0.0002	0.0008	0.0001	0.000	0.0033
Carbon tax	0.1654	0.0030	0.0007	0.000	0.0009	0.0016	0.0004	0.0113	0.0016	0.0083	0.0005	0.000	0.0331
New VA	0.7155	0.4646	0.2431	0.4403	0.4048	0.3301	0.4035	0.4099	0.5547	0.4184	0.6500	0.7185	0.5697
New Price	0.8795	0.6499	0.6005	0.6512	0.7543	0.5124	0.6644	0.6224	0.7127	0.6224	0.8473	0.8906	0.7615
Old Price	0.7017	0.6438	0.5583	0.6474	0.7414	0.4854	0.6605	0.6086	0.7099	0.6111	0.8453	0.8887	0.7251
Price Change	**25.34**	**0.95**	**7.55**	**0.58**	**1.74**	**5.56**	**0.59**	**2.26**	**0.39**	**1.84**	**0.24**	**0.22**	**5.01**

Note: Economy sectors: (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Biofuels; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail.

GDP = GDP + Imports
VP = Value of Production
VA Coeff. = Original value-added coefficient (v_c^0) *= GDP / VP*
EI = Emissions intensity = E / Output
Carbon tax = EI . Carbon price (10 US$)
New VA = v_c^0 *+ Carbon tax* (v_c^{10})
New Price = $L^{0\,\prime} \;.\; v_c^{10}$
Old Price = $L^{0\,\prime} \;.\; v_c^{0}$
Price change = index of changes in prices (%) = $(P^{New} - P^{Old})/P^{Old}$

This makes clear the role of the *Agricultural* sector in Goiás' economy, highlighting the importance of planning the growth of this sector by considering integrated strategies that include water, energy, land use and GHG emission policies in order to promote the sustainable development of this sector in the state and in Brazil. Since the *Agricultural* sector is the highest emitter in Goiás, it is to be expected that a carbon pricing initiative would impact this sector most in terms of input price changes, stimulating fundamental questions about the sustainability of local agriculture and livestock production in the event that a carbon tax is implemented in Brazil. Whether the carbon price was US\$25/CO_{2e} or US\$50/CO_{2e}, the *Agricultural* sector would be significantly impacted in terms of changes in input prices (by 63% and 126%, respectively, for the two carbon prices given above) and these new prices would be included in that sector's new production costs. In turn, these would be passed on directly to consumers, negatively impacting food and biofuel prices. Other sectors such as *Food and beverages* (19% and 38%), *Biofuels* (14% and 28%) and *Transport* (12% and 25%) would also be significantly affected by such high carbon prices. On the other hand, if the carbon price was US\$5/CO_{2e}, the most significant price increase would be 12% in the *Agricultural* sector, followed by the *Food* (4%) and *Biofuels* (3%) sectors (see **Appendix XIX**).

The IO price model highlights the sectors that would be most affected by price changes brought about by a carbon pricing initiative in Brazil (analysed here through its effects on the Goiás economy). When factor input prices increase, based on microeconomic theory, producers will seek to substitute these inputs with another, such as capital and labour. However, this substitution effect cannot be captured in the traditional Leontief IO model, which does not provide a mechanism for evaluating the impact of changes in technology (*i.e.* through its technical coefficients). Therefore, as described in *section 3.3.3*, estimated price change indices were applied to the Cobb-Douglas and the CES production functions to determine new (*i.e.* updated) technical coefficients by adding a carbon tax to selected sectors of the Goiás economy[43]. Accordingly, these economy sectors were, therefore, 'allowed' to substitute their inputs composition (*i.e.* to change

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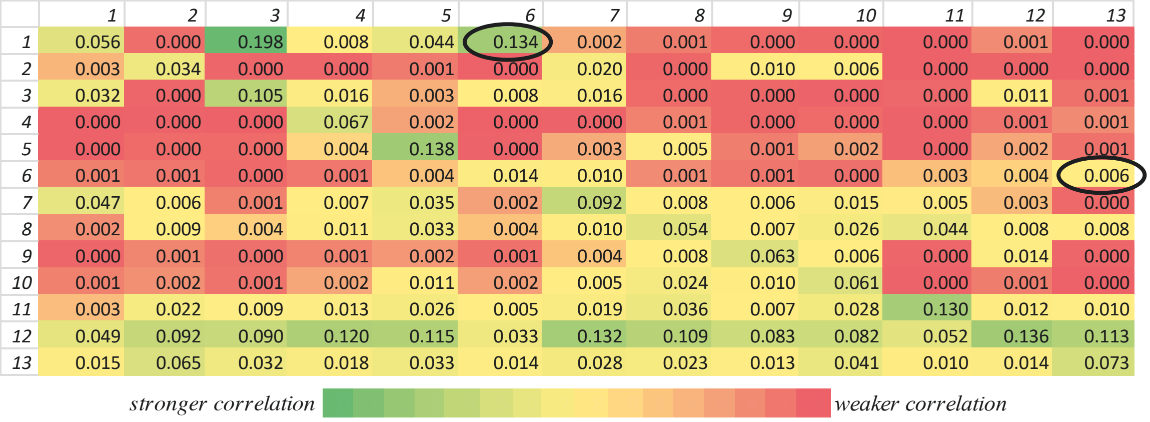
[43] This research assumes that the substitution between factor inputs is limited only to two pairs of sectors in Goiás' economy, namely, *Agricultural and Biofuels* and *Biofuels and Transport* sectors. The substitution effect will be analysed for each and both pairs of sectors, for varying values of elasticity of substitution. Finally, the most extreme elasticity of substitution values (positive and negative) will be used to determine the environmental impacts in Goiás of factor input price changes, in the case of a carbon tax implementation.

their technical coefficients) according to changes in price brought about by a US$10 carbon tax, in order to compare the economic and environmental effects of input price changes throughout the economy. The inclusion of economic arguments such as price change analyses into the traditional (*i.e.* physical) IO approach brings the model's results closer to reality and, in doing so, the information derived from applying these models can be seen as a more reliable instrument for policymaking.

The price change impacts due to implementation of a carbon tax were estimated based on the price change index (*i.e.* percentage change related to original prices) and its application to alternative production functions, as described in *section 3.3.3.* (*Eq. 3.45* and *Eq. 3.46*), and by using varying elasticity of substitution values (from $\sigma = -0.905$ to $\sigma = 1.5$; see *section 3.3.6.1*). These calculations translate into possibilities to update the Goiás' original IO technical coefficients and therefore, by updating them from changes in factor input prices, the results show opportunities to (i) include any initiative that will have an impact on input prices (*e.g.* implementation of other fiscal policies or changing the technology for a given sector) and (ii) analyse the economy-wide impacts of a carbon tax, again bringing the analysis closer to reality.

Overall, analyses of substitution possibilities between economy sectors are made in pairs (i.e. by analysing the changes in the use of resources between two specific sectors), according to the objectives of each study; therefore, since this research focuses mainly on agricultural and biofuel activities, comparisons were made between these two sectors. It is important to note that in the original Goiás IO table, the technical coefficient for the *Agricultural/Biofuels* sectors (0.134) is the second largest among all technical coefficients, after only the *Agricultural/Food* sectors coefficient (0.198), confirming the strong correlation between these sectors. The Goiás original technical coefficients are shown in **Table 20**, with the aim of clarifying the significance of their relationship to the current analysis.

Table 20. Goiás original technical coefficients, classified by their level of relationship



	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0.056	0.000	0.198	0.008	0.044	0.134	0.002	0.001	0.000	0.000	0.000	0.001	0.000
2	0.003	0.034	0.000	0.000	0.001	0.000	0.020	0.000	0.010	0.006	0.000	0.000	0.000
3	0.032	0.000	0.105	0.016	0.003	0.008	0.016	0.000	0.000	0.000	0.000	0.011	0.001
4	0.000	0.000	0.000	0.067	0.002	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.001
5	0.000	0.000	0.000	0.004	0.138	0.000	0.003	0.005	0.001	0.002	0.000	0.002	0.001
6	0.001	0.001	0.000	0.001	0.004	0.014	0.010	0.001	0.001	0.000	0.003	0.004	0.006
7	0.047	0.006	0.001	0.007	0.035	0.002	0.092	0.008	0.006	0.015	0.005	0.003	0.000
8	0.002	0.009	0.004	0.011	0.033	0.004	0.010	0.054	0.007	0.026	0.044	0.008	0.008
9	0.000	0.001	0.000	0.001	0.002	0.001	0.004	0.008	0.063	0.006	0.000	0.014	0.000
10	0.001	0.002	0.001	0.002	0.011	0.002	0.005	0.024	0.010	0.061	0.000	0.001	0.000
11	0.003	0.022	0.009	0.013	0.026	0.005	0.019	0.036	0.007	0.028	0.130	0.012	0.010
12	0.049	0.092	0.090	0.120	0.115	0.033	0.132	0.109	0.083	0.082	0.052	0.136	0.113
13	0.015	0.065	0.032	0.018	0.033	0.014	0.028	0.023	0.013	0.041	0.010	0.014	0.073

Note: Economy sectors: (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Oil refining, coke and ethanol; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail.

Sectors chosen for analysing substitution effects are represented by intersections between columns 6 (Biofuels) and 13 (Transport), with rows 1 (Agriculture) and 6 (Biofuels), respectively.

Source: Author's adaptation from Guilhoto (2010).

Based on the original values presented above, the updated technical coefficients for Goiás for different values of elasticity of substitution (σ), assuming substitutions between the *Agricultural/Biofuels* sectors and between the *Biofuels/Transport* sectors, are presented in **Table 21**.

Table 21. Updated technical coefficients for different levels of substitution for a US$10 carbon price scenario, for two pairs of sectors in the economy.

Technical coefficients	*Economy sectors*	
	Agricultural/Biofuels ($a_{1;6}$)	*Biofuels/Transport* ($a_{6;13}$)
a_{ij} *Original*	0.13442	0.00603
	$\sigma = -0.905$	
a_{ij} **New**	**0.04263***	**0.04487**
	$\sigma = -0.5$	
a_{ij} **New**	**0.07127***	**0.01828**
	$\sigma = 0.5$	
a_{ij} **New**	**0.25353**	**0.00199***
	$\sigma = 1$	
a_{ij} **New**	**0.47818**	**0.00066***
	$\sigma = 1.5$	
a_{ij} **New**	**0.90191**	**0.00022***

Note: σ: Elasticity of substitution parameter;

$a_{ij\ Original}$: *Goiás' original IO technical coefficients;*

$a_{ij\ New}$: *Updated Goiás' IO technical coefficients;*

**Technical coefficients lower than original technical coefficients.*

Source: Author

Since the calculation for updating the technical coefficients rely mostly on the index of changes in price in target sectors (*e.g. Agricultural/Biofuels* and *Biofuels/Transport*), as well as the original technical coefficient for those sectors, the sectors impacted most by changes in input prices would be those with updated technical coefficients (*i.e.* coefficients $a_{1;6}$ and $a_{6;13}$). However, because of the interconnected nature of IO tables, any change in the technical coefficients of any one sector will affect both the overall structure of the economy (*i.e.* it will have indirect impacts) and the environmental impacts of future changes in final demand for ethanol in the state of Goiás.

In this context, the updated technical coefficients obtained in **Table 21** above were applied to the base-year IO model to generate an updated $(I - A)$ matrix and hence an updated total requirements matrix (*i.e.* the Leontief matrix – L) with which to analyse different types of economy-wide impacts. These impacts, which include economic (*e.g.* changes in sectoral output and GDP), energy, environmental and social aspects, were assessed after imposing a carbon tax. Although these updated tables change the results of the whole economy, they are similar to the original except for changes in the technical coefficients of target sectors, that is, the coefficients for the intersection between the *Agricultural/Biofuels* sectors (*i.e.* $a_{1;6}$) and the *Biofuels/Transport* sectors (*i.e.* $a_{6;13}$). Estimates of monetary differences in terms of final output in the Goiás economy (when comparing the original values to the updated ones), based on changes in input prices due to the imposition of a US$10 carbon tax, are presented below. Additionally, estimates on environmental impacts from inputs price changes due to a US$10 carbon tax policy are presented next, in *sub-section 4.3.2.2*.

Substitutions between Agricultural and Biofuels sectors (coefficient $a_{1;6}$)

i) Higher level of substitution

As one may expect, the most extreme elasticity values applied to this research have produced the most extreme results in terms of changes in an economy's final output. Thus, with a negative elasticity of substitution close to unity (*i.e.* σ = -0.9) between the *Agricultural* and *Biofuels* sectors (coefficient $a_{1;6}$), the overall economic impacts in terms of old to new output changes would be negative; that is, activity throughout the economy (including the *Rest of Brazil* region) would be reduced. In this case, the *Agricultural* sector was the most impacted, with a reduction of US$95 million (-1.76%), followed by the *Chemical* (-0.31%) and *Transport* (-0.11%) sectors compared to Goiás' original output (**Table 22**).

Table 22. Changes in output, by sector, from changes in input prices for the *Agricultural* and *Biofuel* sectors due to a US$10 carbon tax, for a varying level of substitution.

		Level of substitution									
		σ = -0.905		*σ = -0.5*		*σ = 0.5*		*σ = 1*		*σ = 1.5*	
*	*Original Output***	*M $*	*%*	*M $*	*%*	*M $*	*%*	*M $*	*%*	*M $*	*%*
1	*5,405*	-94.94	*-1.76*	-65.32	*-1.21*	123.26	*2.28*	355.94	*6.59*	795.53	*14.72*
2	*641*	-0.43	*-0.07*	-0.29	*-0.05*	0.55	*0.09*	1.59	*0.25*	3.56	*0.56*
3	*8,186*	-3.73	*-0.05*	-2.57	*-0.03*	4.85	*0.06*	14.00	*0.17*	31.28	*0.38*
4	*572*	-0.01	*0.00*	-0.01	*0.00*	0.02	*0.00*	0.05	*0.01*	0.12	*0.02*
5	*299*	-0.05	*-0.02*	-0.03	*-0.01*	0.06	*0.02*	0.18	*0.06*	0.41	*0.14*
6	*967*	-0.22	*-0.02*	-0.15	*-0.02*	0.29	*0.03*	0.84	*0.09*	1.88	*0.19*
7	*1,601*	-4.99	*-0.31*	-3.43	*-0.21*	6.48	*0.40*	18.71	*1.17*	41.83	*2.61*
8	*2,183*	-0.35	*-0.02*	-0.24	*-0.01*	0.45	*0.02*	1.31	*0.06*	2.94	*0.13*
9	*2,799*	-0.15	*-0.01*	-0.10	*0.00*	0.19	*0.01*	0.55	*0.02*	1.23	*0.04*
10	*922*	-0.18	*-0.02*	-0.12	*-0.01*	0.23	*0.02*	0.66	*0.07*	1.47	*0.16*
11	*1,368*	-0.67	*-0.05*	-0.46	*-0.03*	0.87	*0.06*	2.50	*0.18*	5.59	*0.41*
12	*16,926*	-6.95	*-0.04*	-4.78	*-0.03*	9.02	*0.05*	26.06	*0.15*	58.24	*0.34*
13	*1,789*	-2.03	*-0.11*	-1.40	*-0.08*	2.64	*0.15*	7.61	*0.43*	17.01	*0.95*
T[a]	***43,659***	***-115***	***-0.26***	***-79***	***-0.18***	***149***	***0.34***	***430***	***0.98***	***961***	***2.20***
T[b]	***1,643,465***	***-168***	***-0.01***	***-115***	***-0.007***	***218***	***0.013***	***631***	***0.038***	***1,412***	***0.086***

*Note: *Economy sectors: (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Biofuels; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail.*

*** In US$ million;*

[a] *Goiás total original output and differences from old to new output, according to each level of substitution. Output differences in US$ million.*

[b] *Total original output (Goiás + Rest of Brazil) and differences from old to new output, according to each level of substitution. Output differences in US$ million.*

Source: Author

On the other hand, when the possibility of substitution between the *Agricultural* and *Biofuels* sectors is the highest positive value analysed (*i.e.* σ =1.5), for instance, by simulating higher fractions of sugarcane being diverted to the *Biofuels* sector instead of for producing sugar, the general picture of the economy changes a lot. The *Agricultural* sector would show an increase of 15% (US$795 million) in final output, amounting to US$6,201 million (**Table 22**). Overall, all economy sectors (including those located in the *Rest of Brazil* region) would see a moderate increase (about 0.1% of increase in total final output and 2.2% in Goiás alone) in terms of output, generated by higher positive levels of substitution between the *Agricultural* and *Biofuels* sectors. The *Chemical* (2.6%) and *Transport* (1%) sectors would show the next highest increases in output, after

Agricultural. For comparisons between the old (*i.e.* original) and new outputs (*i.e.* after a US$10 carbon tax imposition) in Goiás and the *Rest of Brazil* region, by sector and for varying levels of substitution, please see **Appendix XX**.

ii) Lower level of substitution

Overall, negative substitution values have negatively impacted local and national economy in our estimates for the *Agricultural/Biofuels* sector pair, reducing their overall output. In this context, technical coefficients updated by an elasticity value of σ = -0.5 have generated outputs 30% lower than those estimated by a higher negative level of substitution (*i.e.* σ = -0.905) between these two sectors. The maximum total loss to the economy from negative levels of substitution between these sectors would represent about US$170 million (-0.01%), while a lower negative level of substitution (σ =-0.5) would amount to –US$115 million (-0.007%).

When positive levels of substitution between the *Agricultural* and *Biofuels* sectors are analysed, changes in input prices positively affect output throughout the economy. The smallest positive level of substitution estimated (σ = 0.5) would generate an increase of US$220 million in overall output, 85% lower than the highest positive value of substitution analysed (σ = +1.5), which is US$1,410 million (about 0.1% of increase relative to the original output) (**Table 22**). The application of the Cobb-Douglas production function (*i.e.* σ = 1) has resulted in a 6.5% increase (about US$355 million) in the output of the *Agricultural* sector, with overall positive impacts throughout the economy (*i.e.* an increase of US$631 million or 0.04% relative to the original output values).

Substitutions between the Biofuels and Transport sectors (coefficient $a_{6;13}$)

Because the price change index for these sectors differs from that of the *Agricultural/Biofuels* sector pair, the positive and negative elasticity of substitution values behave differently from the *Agricultural/Biofuels* sector pair when output changes for varying levels of substitution between the *Biofuels* and *Transport* sectors are analysed. Thus, the highest negative value of substitution analysed (*i.e.* σ = -0.9) generated the highest positive change in output terms for this pair of sectors. Overall, the economy would be positively impacted by an increase of US$155 million (0.01%) when compared to the original output, 45% of which (US$70 million) coming from the *Biofuels* sector. A lower negative level of substitution ($\sigma = -0.5$) would show even lower positive impacts (US$49 million in total), most of them (about US$22 million or a 2.3% increase) in the *Biofuels* sector (**Table 23**).

Table 23. Changes in output, by sector, from changes in input prices for the *Biofuels* and *Transport* sectors due to a US$10 carbon tax, for varying levels of substitution.

		Level of substitution									
	Original	$\sigma = -0.905$		$\sigma = -0.5$		$\sigma = 0.5$		$\sigma = 1$		$\sigma = 1.5$	
*	*Output***	*M $*	*%*	*M $*	*%*	*M $*	*%*	*M $*	*%*	*M $*	*%*
1	*5,405*	10.34	*0.19*	3.26	*0.06*	-1.08	*-0.02*	-1.43	*-0.03*	-1.55	*-0.03*
2	*641*	0.07	*0.01*	0.02	*0.00*	-0.01	*0.00*	-0.01	*0.00*	-0.01	*0.00*
3	*8,186*	1.10	*0.01*	0.35	*0.00*	-0.11	*0.00*	-0.15	*0.00*	-0.16	*0.00*
4	*572*	0.01	*0.00*	0.00	*0.00*	0.00	*0.00*	0.00	*0.00*	0.00	*0.00*
5	*299*	0.03	*0.01*	0.01	*0.00*	0.00	*0.00*	0.00	*0.00*	0.00	*0.00*
6	*967*	70.61	*7.30*	22.25	*2.30*	-7.34	*-0.76*	-9.76	*-1.01*	-10.56	*-1.09*
7	*1,601*	0.76	*0.05*	0.24	*0.02*	-0.08	*0.00*	-0.11	*-0.01*	-0.11	*-0.01*
8	*2,183*	0.39	*0.02*	0.12	*0.01*	-0.04	*0.00*	-0.05	*0.00*	-0.06	*0.00*
9	*2,799*	0.11	*0.00*	0.04	*0.00*	-0.01	*0.00*	-0.02	*0.00*	-0.02	*0.00*
10	*922*	0.21	*0.02*	0.07	*0.01*	-0.02	*0.00*	-0.03	*0.00*	-0.03	*0.00*
11	*1,368*	0.61	*0.04*	0.19	*0.01*	-0.06	*0.00*	-0.08	*-0.01*	-0.09	*-0.01*
12	*16,926*	3.88	*0.02*	1.22	*0.01*	-0.40	*0.00*	-0.54	*0.00*	-0.58	*0.00*
13	*1,789*	1.38	*0.08*	0.43	*0.02*	-0.14	*-0.01*	-0.19	*-0.01*	-0.21	*-0.01*
T^a	***43,659***	***90***	***0.21***	***28***	***0.06***	***-9***	***-0.02***	***-12***	***-0.03***	***-13***	***-0.03***
T^b	***1,643,465***	***155***	***0.009***	***49***	***0.003***	***-16***	***-0.001***	***-22***	***-0.001***	***-24***	***-0.001***

*Note: *Economy sectors: (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Oil refining, coke and ethanol; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail.*

*** In US$ million;*

[a]*Goiás total original output and differences from old to new output, according to each level of substitution. Output differences in US$ million.*

[b]*Total original output (Goiás + Rest of Brazil) and differences from old to new output, according to each level of substitution. Output differences in US$ million.*

Source: Author

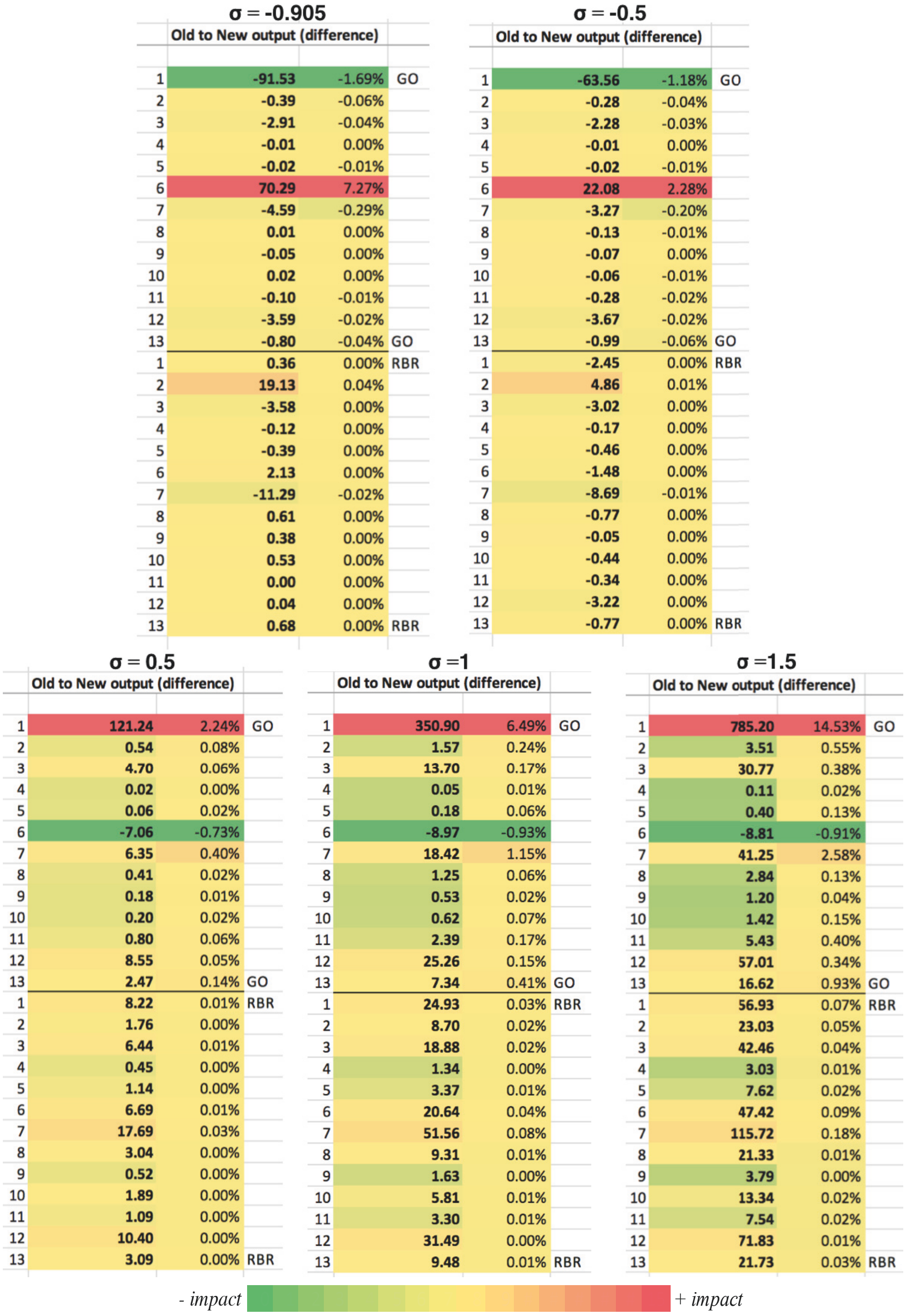
On the other hand, positive substitution values between the *Biofuels* and *Transport* sectors (coefficient $a_{6;13}$) can be understood, for example, as a higher penetration rate of biofuels into the fuels market, giving consumers greater choice. In this context, the extreme substitution value analysed ($\sigma = 1.5$) indicates the highest negative impacts throughout the economy (namely, a reduction of US$13 million or -0.03% in the state of Goiás only and US$24 million or -0.001% compared to the original output), with output values decreasing according to the increase in the level of substitution. An example is if the overall output of the economy rises by 5% (US$1 million) when the substitution falls from $\sigma = 1.5$ to $\sigma = 1$ and the output increases by 27% (US$7 million) when the substitution level falls from $\sigma = 1$ to $\sigma = 0.5$. Overall, price changes due to a US$10 carbon price would have little impact on the *Biofuels* and *Transport* sectors relationship, or on their impacts throughout the economy (*i.e.* the total highest impact for Goias and Goias + Brazil, as shown in Table 23) would be less than 1%).

Substitutions between both Agricultural/Biofuels and Biofuels/Transport sector pairs

In a scenario that assumes the same level of substitutions between both the *Agricultural/Biofuels* sectors (*i.e.* coefficient $a_{1;6}$) and *Biofuels/Transport* sectors (*i.e.* coefficient $a_{6;13}$), an elasticity value of $\sigma = -0.9$ would result in negative impacts (*i.e.* total reduction of -0.02% or US$25 million) throughout the economy. In this case, the *Agricultural* sector would be the most impacted in Goiás, showing a reduction of US$92 million (-1.7%) relative to its original output values. The *Biofuels* sector, however, would increase its final output by US$70 million, a 7.3% of increase compared to factor input prices without a US$10 carbon tax (**Figure 45**). When looking only at the Goiás economy, the total reduction due to a carbon tax would amount to a US$34 million or 0.08% reduction compared to a non-substitution scenario.

Estimates that assume $\sigma = -0.5$ in both pairs of sectors show a reduction of US$69 million in total output, 91% of that coming from losses in the *Agricultural* sector. Goiás State would show a reduction of US$52 million (0.12%), amounting to a 75% total change. However, the *Biofuels* sector in Goiás, would increase its output by US$22 million (2.3%) to US$989 million, thereby helping to reduce the negative impacts affecting other sectors.

The total output of the economy would increase by US$200 million (0.012%), US$138 million (0.31%) of that in Goiás alone, when estimates assume an elasticity of substitution of $\sigma = 0.5$ for these target sectors. In this substitution scenario, the *Agricultural* sector would show the most significant changes, increasing its output by 2.24% (US$121 million), followed by the *Chemical* (0.4%, *i.e.* US$6.4 million) and *Transport* (0.14%, *i.e.* US$2.4 million) sectors. Again, as the level of substitution increases, the total output of the economy also increases. For a $\sigma = 1$, results show an increase of about US$410 million (0.94%) in Goiás and about US$600 million (0.04%) in Brazil's national economy, with the *Agricultural* sector in Goiás accounting for 58% of that. At the same time, the *Biofuels* sector would reduce its production to about US$958 million, a drop of 0.93% or about US$9 million.



σ = -0.905

	Old to New output (difference)		
1	-91.53	-1.69%	GO
2	-0.39	-0.06%	
3	-2.91	-0.04%	
4	-0.01	0.00%	
5	-0.02	-0.01%	
6	70.29	7.27%	
7	-4.59	-0.29%	
8	0.01	0.00%	
9	-0.05	0.00%	
10	0.02	0.00%	
11	-0.10	-0.01%	
12	-3.59	-0.02%	
13	-0.80	-0.04%	GO
1	0.36	0.00%	RBR
2	19.13	0.04%	
3	-3.58	0.00%	
4	-0.12	0.00%	
5	-0.39	0.00%	
6	2.13	0.00%	
7	-11.29	-0.02%	
8	0.61	0.00%	
9	0.38	0.00%	
10	0.53	0.00%	
11	0.00	0.00%	
12	0.04	0.00%	
13	0.68	0.00%	RBR

σ = -0.5

	Old to New output (difference)		
1	-63.56	-1.18%	GO
2	-0.28	-0.04%	
3	-2.28	-0.03%	
4	-0.01	0.00%	
5	-0.02	-0.01%	
6	22.08	2.28%	
7	-3.27	-0.20%	
8	-0.13	-0.01%	
9	-0.07	0.00%	
10	-0.06	-0.01%	
11	-0.28	-0.02%	
12	-3.67	-0.02%	
13	-0.99	-0.06%	GO
1	-2.45	0.00%	RBR
2	4.86	0.01%	
3	-3.02	0.00%	
4	-0.17	0.00%	
5	-0.46	0.00%	
6	-1.48	0.00%	
7	-8.69	-0.01%	
8	-0.77	0.00%	
9	-0.05	0.00%	
10	-0.44	0.00%	
11	-0.34	0.00%	
12	-3.22	0.00%	
13	-0.77	0.00%	RBR

σ = 0.5

	Old to New output (difference)		
1	121.24	2.24%	GO
2	0.54	0.08%	
3	4.70	0.06%	
4	0.02	0.00%	
5	0.06	0.02%	
6	-7.06	-0.73%	
7	6.35	0.40%	
8	0.41	0.02%	
9	0.18	0.01%	
10	0.20	0.02%	
11	0.80	0.06%	
12	8.55	0.05%	
13	2.47	0.14%	GO
1	8.22	0.01%	RBR
2	1.76	0.00%	
3	6.44	0.01%	
4	0.45	0.00%	
5	1.14	0.00%	
6	6.69	0.01%	
7	17.69	0.03%	
8	3.04	0.00%	
9	0.52	0.00%	
10	1.89	0.00%	
11	1.09	0.00%	
12	10.40	0.00%	
13	3.09	0.00%	RBR

σ =1

	Old to New output (difference)		
1	350.90	6.49%	GO
2	1.57	0.24%	
3	13.70	0.17%	
4	0.05	0.01%	
5	0.18	0.06%	
6	-8.97	-0.93%	
7	18.42	1.15%	
8	1.25	0.06%	
9	0.53	0.02%	
10	0.62	0.07%	
11	2.39	0.17%	
12	25.26	0.15%	
13	7.34	0.41%	GO
1	24.93	0.03%	RBR
2	8.70	0.02%	
3	18.88	0.02%	
4	1.34	0.00%	
5	3.37	0.01%	
6	20.64	0.04%	
7	51.56	0.08%	
8	9.31	0.01%	
9	1.63	0.00%	
10	5.81	0.01%	
11	3.30	0.01%	
12	31.49	0.00%	
13	9.48	0.01%	RBR

σ =1.5

	Old to New output (difference)		
1	785.20	14.53%	GO
2	3.51	0.55%	
3	30.77	0.38%	
4	0.11	0.02%	
5	0.40	0.13%	
6	-8.81	-0.91%	
7	41.25	2.58%	
8	2.84	0.13%	
9	1.20	0.04%	
10	1.42	0.15%	
11	5.43	0.40%	
12	57.01	0.34%	
13	16.62	0.93%	GO
1	56.93	0.07%	RBR
2	23.03	0.05%	
3	42.46	0.04%	
4	3.03	0.01%	
5	7.62	0.02%	
6	47.42	0.09%	
7	115.72	0.18%	
8	21.33	0.01%	
9	3.79	0.00%	
10	13.34	0.02%	
11	7.54	0.02%	
12	71.83	0.01%	
13	21.73	0.03%	RBR

Figure 45. Comparison between old (original) and new output in Goiás and the Rest of Brazil, by sector, for different levels of substitution, assuming a carbon tax of US\$10/CO_{2e}.

Note: Economy sectors: (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Biofuels; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail. GO: Goiás State; RBR: Rest of Brazil

Source: Author's adaptation based on Guilhoto (2010).

Finally, the *Agricultural* sector in Goiás would be positively impacted by an increase of US$785 million (14.5%) in its output when the elasticity of substitution considered is $\sigma = 1.5$. This would be followed by the *Services* sector with an increase of US$57 million (0.34%) and the *Chemical* sector with an increase of US$41 million (2.6%). The *Biofuels* sector would reduce its production by 0.91%, a very similar result to that produced by a lower elasticity of substitution (**Figure 45**). Overall, the country's output would increase by US$1,373 million (0.084%) to about US$1,645 billion, 2.8% less than the results for the *Agricultural/Biofuels* sector pair on its own, assuming the same rate of substitution ($\sigma = 1.5$). When analysing the Goiás economy on its own, the increase in overall output amounts to 2.15%, an additional US$937 million in the scenario where $\sigma = 1.5$.

In the next section, we apply the output values found above for the Goiás economy to the most extreme substitution scenarios (*i.e.* $\sigma = -0.9$ and $+1.5$). Therefore, any estimate of the Goiás GDP should add 2.15% of Goiás' total output due to input price changes in the scenario with $\sigma = 1.5$, and subtract 0.08% of Goiás' total output when analysing the scenario where $\sigma = -0.9$.

4.3.2.2 Environmental Impacts from Price Changes due to a Carbon Tax

To assess the level of environmental impacts from changes in factor input prices due to a US$10 carbon tax, this section analyses the highest negative and positive rates of substitution ($\sigma = -0.9$ and $+1.5$). It does this by assuming the results of updating the technical coefficients for both pairs of sectors evaluated, namely, *Agricultural/Biofuels* and *Biofuels/Transport*. The environmental impacts estimated here are caused by the most changed economic conditions (previously identified) due to the application of a carbon price instrument to the sectors' emissions intensity indicator. Accordingly, the estimates assumed the highest level of substitution between the target sectors, and assumed both the highest positive and negative levels of economic impact, namely, the scenarios where $\sigma = +1.5$ and -0.9, as shown in **Figure 45**.

Additionally, the ethanol scenarios analysed in this section are *scenarios 1b* and *2c*, namely, those considered the most realistic scenarios in terms of ethanol expansion in Goiás, and *scenario 2d*, the most demanding scenario. The aim here was to assess additional environmental impacts following the imposition of a US$10 carbon price, specifically the direct and indirect environmental impacts resulting from price changes.

By simulating the updated Goiás' economic-ecological hybrid IO table, we estimated the use of energy, water and land, as well as changes in GHG emissions, job creation and GDP according to changes in future ethanol demand (**Table 24**) and following the scenarios described in *section 4.2,* (**Table 16**).

Table 24. Summary of estimates for water, energy and land use, as well as GHG emissions, employment and GDP changes for each ethanol scenario, assuming a US$10 carbon tax.

Scenarios	*Change over 2015 (%)*	*Environmental**								*Social**		*Economic***	
		Water (hm^3)	*Change (%)*	*Land (km^2)*	*Change (%)*	*Energy (PJ)*	*Change (%)*	*GHG (in $TgCO_{2e}$)*	*Change (%)*	*Jobs (Thousands)*	*Change (%)*	*GDP (M US$)*	*Change (%)*
		No substitution (σ = 0.0)											
1b	60	54.5	1.2	2,815	1.3	80.1	14.5	1.35	1.3	23.7	0.8	177	0.87
2c	73	66.3	1.4	3,425	1.6	97.5	17	1.64	1.6	28.8	0.96	214.7	1.05
2d	112	101.7	2.1	5,250	2.5	149.5	24	2.51	2.4	44.2	1.5	329.4	1.62
		Negative elasticity of substitution (σ = -0.9)											
1b	60	20.0	0.43	940	0.45	74.6	13.6	0.52	0.51	15.0	0.5	141.8	0.70
2c	73	24.4	0.52	1,144	0.55	90.7	16.1	0.63	0.62	18.2	0.61	172.6	0.85
2d	112	37.4	0.80	1,755	0.84	139.1	22.8	0.97	0.95	27.9	0.93	264.7	1.30
		Positive elasticity of substitution (σ = +1.5)											
1b	60	301	6.08	16,280	7.3	82.9	14.9	7.27	6.77	82.8	2.7	378	1.85
2c	73	367	7.30	19,810	8.7	100.9	17.6	8.84	8.11	100.8	3.29	460	2.26
2d	112	563	10.8	30,400	12.8	154.7	24.7	13.57	11.9	154.7	4.96	705.6	3.46

*Note: *additional requirements relating to 2008 Goiás IO structure; **additional requirements regarding new output values estimated from σ = -0.9 and σ = +1.5 in the previous section.*

General remarks can be made based on the results presented in **Table 24**, for each ethanol scenario and substitution possibilities:

- *Scenario 1b: 60% (61.68 PJ) increase over 2015 production to satisfy both current and future ethanol demand*
    - *assuming σ = -0.9*

Assuming a negative substitution value for the estimates of additional requirements for land, water and energy and additional GHG emissions, GDP and employment in Goiás, the results are lower than the estimates for scenarios with no substitution possibilities (*i.e.* the original hybrid IO table with fixed technical coefficients). The energy (-7%), GDP (-20%) and employment (-37%) indicators show additional requirements closer to those found in ethanol scenarios with no substitution possibilities (**Table 24**). The GHG emissions (-61%), water (-63%) and land use (-67%) indicators show greater differences than the original ethanol scenarios (*i.e.* all of those with no substitution possibilities), and even lower environmental impacts than those with negative substitution possibilities. Overall, about 15,000 new jobs (a 0.5% increase over current levels) would be created in this scenario, of which 8,200 would be in the *Biofuels* sector, 3,800 in the *Agricultural* and 2,050 in the *Services* sector. Regarding GDP changes, estimates show an increase of 0.7% (US$142 million) in response to the 60% increase in ethanol demand, impacting mostly the *Biofuels* (49%), *Transport* (0.5%), *Agricultural* (0.46%) and *Power* (0.3%) sectors.

- *assuming $\sigma = +1.5$*

In the highest positive substitution scenario (*i.e.* that with the greatest positive economic changes, as shown in **Figure 45**), an additional 300 hm^3 of water and 16,280 km^2 of land would be necessary, an increase of 6% and 7.3% respectively compared to current levels. According to Beuchle *et al.* (2015), the land required to meet future ethanol demand is equal to 14% (16,280 km^2) of the natural vegetation cover loss that occurred in the Cerrado biome (117,290 km^2) from 2000 to 2010. All energy sources and industrial processes would require an additional 83 PJ (15% increase) of energy, emitting an additional 7.27 $TgCO_{2e}$ (6.8%). About 82,800 new jobs (a 2.7% increase over current levels) would be created, of which 66,800 would be in the *Agricultural* sector, 8,900 in the *Biofuels* and 4,900 in the *Services* sector. Regarding GDP changes, estimates show a 1.85% (US$378 million) increase in response to changes in ethanol demand, impacting mostly the *Biofuels* (53%), *Agricultural* (8%), *Chemical products* (1.7%) and *Transport* (1%) sectors. Overall, water, land and emissions indicators would rise by five times the impact levels found in those ethanol scenarios that have no change in input prices, while the increases in employment (3.5-fold), GDP (2-fold) and energy (+3.5%) would be lower. Accordingly, since the IO table is based on ratios between inputs and outputs, all the trends found here (*i.e.* the percentage differences between scenarios with and without substitution possibilities) are constant for any ethanol scenario, with only the absolute values changing.

- *Scenario 2c: 73% (75.16 PJ) increase over 2015 production, to meet future ethanol demand and substitute 25% of the 2030 estimated gasoline consumption in Goiás*

  - *assuming* $\sigma = -0.9$

Similar to *scenario 1b* with an elasticity of $\sigma = -0.9$, *scenarios 2c* and *2d* would show the same rate of reduction in ethanol scenarios with no substitution possibilities (*i.e.* with fixed original technical coefficients), namely, a 7% reduction in energy, 20% reduction in GDP, 37% reduction in employment, 61% reduction in GHG emissions, 63% reduction in water and a 67% reduction in land-use indicators. The total requirements for *scenario 2c* compared to other substitution scenarios can be verified in **Table 24**. As one might expect, the *Biofuels* sector would have its value added increased by 59.8% in this scenario, while the *Transport* (0.6%), *Agricultural* (0.55%) and *Power* (0.35%) sectors would show lower indirect impacts. Of the new jobs (a total of 18,200), most (10,000) would be created in the *Biofuels* sector, followed by the *Agricultural* (4,600) and *Services* (2,500) sectors

  - *assuming* $\sigma = +1.5$

The only difference between *scenarios 1b* and *2c* is the 25% of gasoline substitution for ethanol. The difference therefore between the estimates in both scenarios would represent the impacts this level of gasoline substitution would have in the state, namely, an additional 66 hm^3 of water, 3,530 km^2 of land, 17 PJ of energy, 1.57 $TgCO_{2e}$, 18,000 additional jobs and, finally, a US$82 million increase in GDP in *scenario 1b*. The total requirements for *scenario 2c* can be verified in **Table 24**. As one might expect, the *Biofuels* sector would have its value added increased by 64%, while the *Agricultural* (9.7%), *Chemical products* (2%), *Transport* (1.3%) and *Power* (0.64%) sectors would show lower indirect impacts. Regarding the total of

100,800 new jobs, most (81,000) would be created in in the *Agricultural* sector, followed by 10,800 in the *Biofuels* and 6,000 in the *Services* sectors.

- Sc*enario 2d: 112% (additional 115.16 PJ) increase over 2015 production, to meet future ethanol demand and substitute 100% of 2030 estimated gasoline consumption in Goiás*
    - *assuming σ = -0.9*

Again, the total environmental impacts caused by a US$10 carbon tax (*i.e.* from changes in input prices) would be limited to the ratios presented above. Assuming even the most demanding scenario in terms of ethanol production, the total environmental impacts would be lower than those found for scenarios with fixed technical coefficients, in other words, that did not allow for substitutions due to changes in input prices. In *scenario 2d*, which assumes a negative substitution value and a significant increase in future ethanol production, GDP would grow by US$264.7 million (1.3%) to US$20,656 million and employment would rise by 0.93%, accounting for 28,000 new jobs. Of these, 55% would be in the *Biofuels* sector, due to increased demand for ethanol. Total environmental requirements would be as follows: an additional 37 hm^3 of water and 1,750 km^2 of land (respective increases of 0.8% and 0.84%), an additional 23% (611.8 PJ) of energy and a 0.95% of increase (0.97 $TgCO_{2e}$) in GHG emissions

- *assuming σ = +1.5*

Regarding this major change in the state's ethanol supply chain, GDP would increase by 3.46% to US$21,097 million, accounting for an additional US$705.6 million due to changes in final demand for ethanol and the high possibility of positive substitution. To meet the new final demand requirement, an additional 562 hm^3 of water and a massive 30,400 km^2 of land would be necessary, an increase of 10.8% and 12.8% respectively over original levels. Overall energy supply would increase by 24.6% to 627.4 PJ, while GHG emissions would go up 12% to about 113.7 $TgCO_{2e}$. Due to the increased demand for ethanol, employment would increase by 5%, accounting for 144,700 new jobs, 81% of them in the *Agricultural*

> sector. Besides the *Biofuels* sector (99% of changes in the value added), the sectors most impacted in terms of value added would be *Agricultural* (14.86%) and *Chemical products* (3.07%), followed by the less impacted sectors, such as *Transport* (1.93%), *Power* (1%) and *Services* (0.64%). The estimated land use resulting from future ethanol demand in *scenario 2d* would account for 26% of natural vegetation cover loss in the Cerrado (30,000 km², an area equivalent to that of Belgium) in the 2000–2010 period (Beuchle *et al.*, 2015).
>
> As previously mentioned, the environmental impacts of this level of substitution are much higher compared to the ethanol scenarios with no substitution possibilities (*i.e.* those with results derived only from a physical IO approach). Therefore, these significant changes in environmental impacts can be interpreted as resulting from changes in input prices, such as a carbon tax. In other words, they show the environmental changes caused by economic changes. By including price change effects in the analysis, results may differ significantly from ethanol scenarios that do not consider price change impacts; therefore, price change analysis can help in designing biofuel expansion scenarios closer to reality, thereby being more useful for policymaking.

The Leontief IO price model is important for including changes in factor input prices in the analysis. This is because the price model can capture the environmental impacts resulting from any economic changes included in the analysis, such as changes in original prices (e.g. a carbon tax) and ethanol scenarios estimates. In this context, we can assess the differences in environmental impacts, comparing those from scenarios that include the effects of price change mechanisms in the analysis.

Therefore, changes in input prices in any sector of the Goiás economy would impact all the other sectors of the economy (in both economic and environmental terms), as well as the country's overall economy. The most relevant arguments from the economic and environmental estimates found herein are presented in *section4.4 4.4.3* (Discussion) and *section 5* (Conclusions). *Section 4.3.2.3* below presents the results from analysing the various carbon price scenarios and emissions abatement possibilities, in order to verify the range of impacts that a carbon price instrument (and abatement initiatives) may cause to sectoral value added in the state of Goiás, based on the state's economy in 2008. This additional analysis will help to evaluate the impacts of imposing a carbon tax in Brazil.

4.3.2.3 Impacts of Carbon Pricing on Sectoral Value Added

As previously discussed, Brazil's climate policy is uncertain in terms of the mechanisms and economic instruments for carbon pricing; therefore, any analyses of economic and sectoral impacts of a carbon tax policy undertaken here should be seen as a theoretical exercise, based on a qualitative assessment and quantitative modelling (*i.e.* through the application of IO models). By using official Goiás emissions data (SEEG, 2017), this section focuses on the impacts of carbon pricing in terms of value added. Based on the ratio of carbon cost to value added (*Equations 3.49* and *3.50*, *section 3.3.5*) and calculated for different carbon prices, the estimated impacts of carbon pricing on the value added express the relative cost of carbon on the economic rents of the production factors. Since carbon tax values vary considerably in the literature[44], we have applied different carbon price scenarios, from US\$5 to US\$50/CO_{2e}[45] (for more details, please refer to **Appendix XXI**). The results therefore represent the cost of carbon in relation to the value added, that is, how much the carbon pricing could impact the return on the production factors of Goiás' economy sectors (**Figures 46** and **47**).

For all sectors except the *Agricultural*), the impact of a carbon price of US\$5/tCO_{2e} would be less than 3% of the sectoral value added and would be less than 6% for a US\$10/tCO_{2e} carbon price (see **Appendix XXI**). Most of the sectors would show impacts lower than 5% of the sectoral value added when considering a US\$25/tCO_{2e}, except for *Other industries* (7%) and *Transport* sectors (15%). Even under a US\$50/tCO_{2e} carbon price, sectors such as *Textiles* (0.01%), *Services* (0.03%), *Power* (0.41%), *Chemical products* (0.52%), *Wood and paper* (1.06%), *Cement and construction* (1.42%), *Food and beverages* (1.49%), *Biofuels* (2.42%) and *Mining* (3.2%) would not suffer high impacts under such a high carbon price. The highest emitting sectors would be significantly

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[44] For instance, Nordhaus (2007) suggested a value of US\$ 30/tCO_{2e}, while the Stern report (2007) recommended a much higher tax of over US\$ 300/tCO_{2e} globally.

[45] Carbon price scenarios of US\$5, US\$10, US\$25 and US\$50/CO_{2e}. Additional scenarios also considered different possibilities in the reduction in absolute emissions, varying from 5% to 45% of the total.

impacted under a hypothetical US$50 carbon tax, reaching 10.1% in the *Metallurgy* sector, 14.1% in *Other industries* and an impressive 30% in the *Transport* sector.

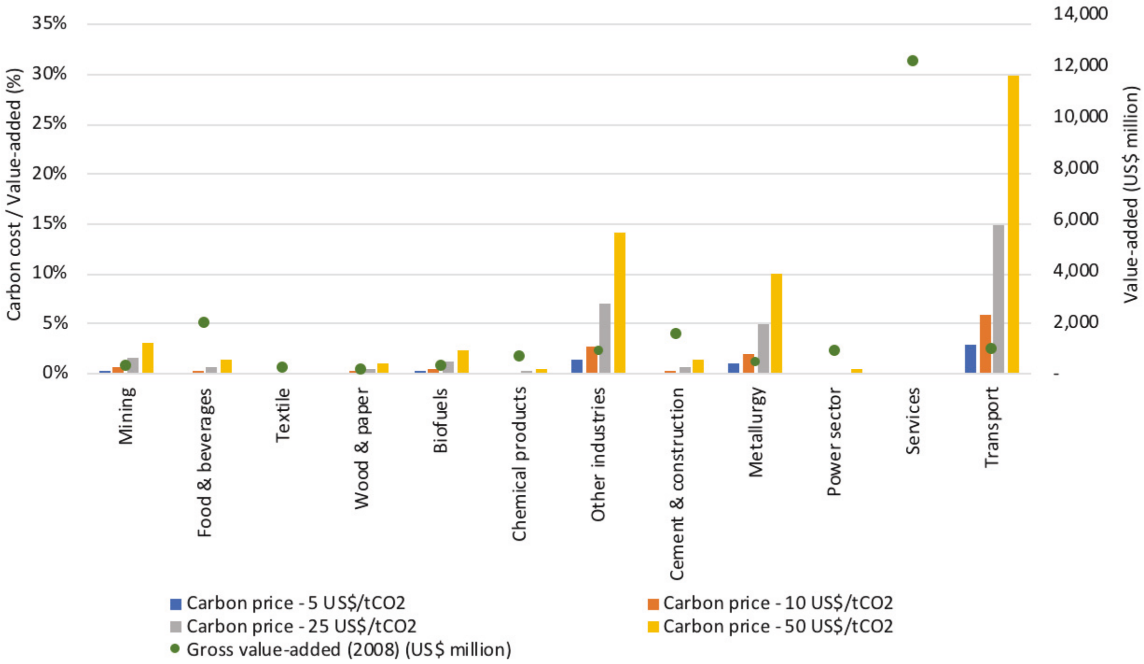

Figure 46. Carbon costs regarding the sectoral value added according to carbon prices (%) and sectoral value added (US$ million), for 2008.
Note: Excludes the Agricultural sector.
Source: Author's adaptation, based on Guilhoto (2010) and SEEG (2017).

As previously highlighted, the *Agricultural* sector is the largest emitter in Goiás and hence is the sector that one would expect to experience the greatest impacts in terms of value added, with those impacts increasing as the carbon price also increases. In such a circumstance, even in a low-carbon price scenario (US$5/tCO$_{2e}$), the *Agricultural* value added would be impacted by 15%, a number that would double under a US$10 carbon tax, and would reach a massive 75% in a US$ 25/tCO$_{2e}$ scenario (**Figure 47**). In the case of a US$50 carbon tax policy, the *Agricultural* sector in Goiás would face extreme challenges.

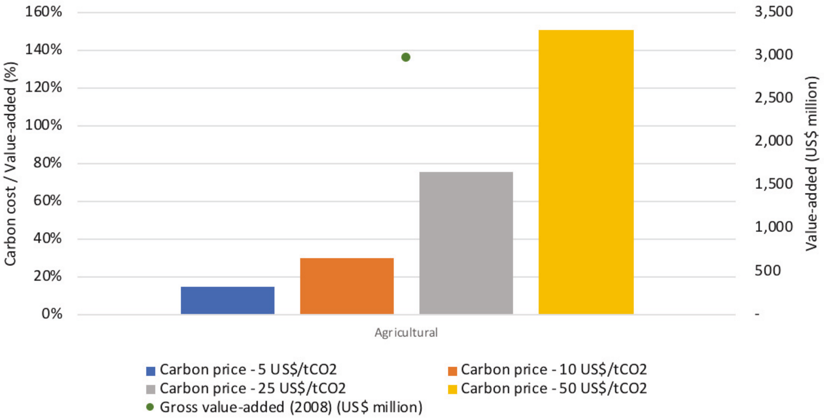

Figure 47. Carbon costs regarding the sectoral value added according to carbon prices (%) and sectoral value added (US$ million), for the *Agricultural* sector, in 2008. *Source: Author's adaptation, based on Guilhoto (2010) and SEEG (2017).*

Another possibility for interpreting the impacts on the value added is to simulate a carbon price according to different levels of reduction in absolute emissions. This alternative analysis shows the effects (in terms of % of the value added) of internalising a carbon price for the year 2008. The emissions priced are the total emissions minus the reduction of emissions varying from 0% to 45%. Again, the values were calculated for different carbon prices, ranging from US$5/tCO$_{2e}$ to US$50/tCO$_{2e}$ (**Table 25**).

Under an emissions reduction scheme, the impacts in terms of value added can be classified into three different groups, namely, low, intermediate and high. In the low impact group, results show impacts ranging from 0% to 1.4% for the *Food and beverages, Textile, Wood and paper, Chemical products, Cement and construction, Power* and *Services* economic sectors in Goiás (*Food and beverages* in a 5% emissions reduction scenario) for all carbon prices analysed. The *Biofuels, Mining* and *Metallurgy* sectors constitute the so-called intermediate impact group, with impacts ranging from 0.13% (*Biofuels* in a 45% emissions reduction scenario with a US$5/tCO$_{2e}$ carbon price) to 9.61% (*Metallurgy* in a 5% emissions reduction scenario with a US$ 50/CO$_{2e}$ carbon tax).

Table 25. Impacts on sectoral value added (%) according to different carbon prices (in US$/t$CO_{2e}$) and emissions reduction (% of total), in Goiás 2008.

Economy sectors		*Emissions reduction (% over total)*					
	US$/CO $_{2e}$	**0%**	**5%**	**15%**	**25%**	**35%**	**45%**
Agricultural	**5**	15.04%	14.28%	12.78%	11.28%	9.77%	8.27%
	10	30.07%	28.57%	25.56%	22.55%	19.55%	16.54%
	25	75.18%	71.42%	63.90%	56.38%	48.86%	41.35%
	50	150.35%	142.83%	127.80%	112.76%	97.73%	82.69%
Mining	**5**	0.32%	0.30%	0.27%	0.24%	0.21%	0.18%
	10	0.64%	0.61%	0.54%	0.48%	0.42%	0.35%
	25	1.60%	1.52%	1.36%	1.20%	1.04%	0.88%
	50	3.20%	3.04%	2.72%	2.40%	2.08%	1.76%
Food & beverages	**5**	0.15%	0.14%	0.13%	0.11%	0.10%	0.08%
	10	0.30%	0.28%	0.25%	0.22%	0.19%	0.16%
	25	0.74%	0.71%	0.63%	0.56%	0.48%	0.41%
	50	1.49%	1.41%	1.27%	1.12%	0.97%	0.82%
Textile	**5**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	10	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	25	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	50	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
Wood & paper	**5**	0.11%	0.10%	0.09%	0.08%	0.07%	0.06%
	10	0.21%	0.20%	0.18%	0.16%	0.14%	0.12%
	25	0.53%	0.50%	0.45%	0.40%	0.34%	0.29%
	50	1.06%	1.01%	0.90%	0.80%	0.69%	0.58%
Biofuels	**5**	0.24%	0.23%	0.21%	0.18%	0.16%	0.13%
	10	0.48%	0.46%	0.41%	0.36%	0.31%	0.27%
	25	1.21%	1.15%	1.03%	0.91%	0.79%	0.67%
	50	2.42%	2.30%	2.06%	1.82%	1.57%	1.33%
Chemical products	**5**	0.05%	0.05%	0.04%	0.04%	0.03%	0.03%
	10	0.10%	0.10%	0.09%	0.08%	0.07%	0.06%
	25	0.26%	0.24%	0.22%	0.19%	0.17%	0.14%
	50	0.52%	0.49%	0.44%	0.39%	0.33%	0.28%
Other industries	**5**	1.41%	1.34%	1.20%	1.06%	0.92%	0.78%
	10	2.82%	2.68%	2.40%	2.12%	1.84%	1.55%
	25	7.06%	6.71%	6.00%	5.30%	4.59%	3.88%
	50	14.12%	13.42%	12.00%	10.59%	9.18%	7.77%
Cement & construction	**5**	0.14%	0.13%	0.12%	0.11%	0.09%	0.08%
	10	0.28%	0.27%	0.24%	0.21%	0.18%	0.16%
	25	0.71%	0.67%	0.60%	0.53%	0.46%	0.39%
	50	1.42%	1.35%	1.21%	1.06%	0.92%	0.78%
Metallurgy	**5**	1.01%	0.96%	0.86%	0.76%	0.66%	0.56%
	10	2.02%	1.92%	1.72%	1.52%	1.31%	1.11%
	25	5.06%	4.80%	4.30%	3.79%	3.29%	2.78%
	50	10.11%	9.61%	8.60%	7.59%	6.57%	5.56%
Power sector	**5**	0.04%	0.04%	0.04%	0.03%	0.03%	0.02%
	10	0.08%	0.08%	0.07%	0.06%	0.05%	0.05%
	25	0.21%	0.20%	0.18%	0.16%	0.13%	0.11%
	50	0.41%	0.39%	0.35%	0.31%	0.27%	0.23%
Services	**5**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	10	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%
	25	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
	50	0.03%	0.03%	0.02%	0.02%	0.02%	0.02%
Transport	**5**	2.99%	2.84%	2.54%	2.24%	1.95%	1.65%
	10	5.99%	5.69%	5.09%	4.49%	3.89%	3.29%
	25	14.96%	14.22%	12.72%	11.22%	9.73%	8.23%
	50	29.93%	28.43%	25.44%	22.45%	19.45%	16.46%

- impact 🟩🟨🟧🟥 *+ impact*

The high-impact group covers the *Other industries*, *Transport* and *Agricultural* sectors; the last with values much higher than the others. For instance, for a carbon price of US$10/$CO_{2e}$, the *Agricultural* sector would show an impact ranging from 16.5% in a 45% emissions reductions scenario to 19.5% in a 35% emissions reductions scenario. For the same carbon price, the *Other industries* and *Transport* sectors show impacts from 1.5%

to 1.8% and from 3.3% to 3.9%, respectively, for the 45% and 35% emissions abatement scenarios.

The range of reduction by 35% to 45% covers the same range as the Brazilian NDC target for the years 2025 and 2030 and could express the upper limits for the mitigation costs in a scenario where the NDC target is divided equally between all the sectors in the economy (LULUCF, power, industry, etc.). Again, assuming a carbon tax of US\$10/tCO_{2e}, the mitigation cost of reducing emissions by 35% to 45% could represent an impact of 0.05% to 3.89% on sectoral value added, depending on the sector assessed (excluding the *Agricultural* sector) (**Table 26**).

Table 26. Impacts on sectoral value added (%) according to a US\$10/tCO_{2e} and emissions reductions of 35% and 45% in Goiás, based on the 2008 Goias economy.

	CO_2 abatement	
Sectors	**35%**	**45%**
Agricultural	19.55%	16.54%
Mining	0.42%	0.35%
Food & beverages	0.19%	0.16%
Wood & paper	0.14%	0.12%
Biofuels	0.31%	0.27%
Chemical products	0.07%	0.06%
Other industries	1.84%	1.55%
Cement & construction	0.18%	0.16%
Metallurgy	1.31%	1.11%
Power sector	0.05%	0.05%
Transport	3.89%	3.29%

- impact 🟩🟨🟧🟥 *+ impact*

Note: The Agricultural sector was excluded from the classification of impacts based on colour gradients because of its high percentage values.

4.4 Discussion

Although the more realistic scenarios for sugarcane expansion in Goiás require an increase of up to 35% in crop area compared to 2015 levels (when changes in input prices were not considered), there is a possibility that these estimated expansions will not impact land use in the region significantly, given the availability of suitable pasturelands for sugarcane crop expansion. This is a very relevant point in relation to GHG emissions since sugarcane crops store much more biomass than natural grasses. On the other hand, when considering that sugarcane expansion over pasturelands may cause indirect impacts through ILUC in native forests, this sugarcane expansion raises controversial issues, mainly in relation to indirect deforestation in already threatened Brazilian biomes, which cause massive indirect GHG emissions. In this case, the ILUC impacts of sugarcane would make local expansion questionable.

Pastures comprise roughly a quarter of Brazil´s territory, three times the land used in agriculture. However, Brazil's federal agricultural research agency, EMBRAPA, points out that 60% of pasture in the Cerrado biome is degraded due to inefficient management (Andrade *et al.,* 2016). While cattle are raised mostly free range, this is inefficient from a land-use standpoint; there is, therefore, considerable potential for densification, freeing up land for food and fuel crops demanded throughout the world. Additionally, a 30% intensification in livestock in Brazil could reduce methane emissions from enteric fermentation by 35% (Young *et al.*, 2016).

According to the FAO (2009), in order to feed a larger, more urban and richer population, world food production must increase by 70% by 2050. The UNEP (2014), however, stated that worldwide, yield increases of cereals and primary crops in general have been slowing down since the 1960s. Yield growth for cereals is expected to drop from an average of 1.96% per annum for the period 1980-2000 to 1.01% in the period 2000-2050, with even slower growth rates for developed countries.

Fischer and Shah (2010) calculated the potentially available good land in current grassland/woodland ecosystems for several food crops and concluded that Brazil had more land available for rain-fed maize, soybean, sugarcane and cassava than any other country in the world. Thus, Brazil´s importance in meeting future global food and biofuel demand cannot be overstated. However, most of these crops are cultivated in the Cerrado biome (*i.e.* 60% of Brazil's annual crops output), which is an important carbon reservoir, stocking around 32,000 $TgCO_2$ (MCTI, 2016). Unfortunately, despite its rich biodiversity, the current rate of deforestation in the Cerrado (the highest in the country in the last 15 years and about 43% higher than that of the Amazon over the same period) is not sustainable, releasing as it does an unprecedented volume of CO_2 (Reis, *et al.*, 2017; Noojipady *et al.*, 2017). Overall, there are about 300,000 km^2 of Cerrado land available, with high- or medium-quality soil and climate suitability for croplands, currently being inefficiently used (Reis *et al.*, 2017).

The issue of food crop displacement due to biofuel competition has been raised by the United Nations Environment Programme (UNEP, 2012), the conclusion being that LUC is the main cause of biofuel GHG emissions general. LUC is a complex process caused by the interaction of natural and social systems on different temporal and spatial scales. It can induce GHG emissions due to oxidation of soil organic carbon and to burning or decomposition of above-ground biomass. Unfortunately, we could not estimate the land-use GHG emissions from sugarcane production alone since all the available data for these emissions did not identify their source. As a result, and as explained in previous sections, all the land-use GHG emissions were allocated together into the *Agricultural* sector. It is known, however, that 70% of GHG emissions from the *Agricultural* sector in Goiás, excluding land-use emissions, comes from livestock production.

Biofuel crops account for about 4% of global agricultural production area (UNEP, 2009). The magnitude of GHG emissions due to LUC from global biofuel production is therefore small compared to total LUC-related emissions, including agricultural land expansion for food, feed, fibre, cattle ranching, fuel wood and timber logging. The expansion of infrastructure generates the greatest part of LUC emissions.

However, competition between food crops means the most suitable areas must be identified and analysed through further studies that also take into consideration variations in both land and agricultural commodity prices. The sugar market, oil prices, land prices, GHG abatement opportunity costs and public subsidies are some of the key variables to be considered in such analyses. Regarding investments in land, a high-level panel of experts (HLPE, 2013) recommended that governments ensure that the principles of responsible investment in agriculture are effectively implemented and monitored, especially in the case of investment in biofuel production. According to Rathmann *et al.* (2010), the emergence of agro-energy on a large scale has changed the land-use dynamics in the Brazilian state of Paraná, where traditional food-producing areas have shifted to biofuels production, thereby contributing to short-term increases in food prices. Another negative impact on local food production is the higher monetary returns that farmers get from converting their land to the production of agro-energy (Rathmann *et al.*, 2010).

While the Brazilian Cerrado has been under increasing anthropic pressure for many years, land-cover and land-use change in the biome have been largely overlooked. Cropland expansion in the biome has partially offset recent declines in Amazon deforestation emissions, highlighting the critical need to account for successful climate mitigation on a national scale through REDD+[46] (Noojipady *et al.*, 2017). Although it is an important agricultural producing state, Goiás must comply with the Brazilian Forest Code, which requires 20% of each rural property to be Legal Reserve; currently, the state has a reserve deficit of 7,500 km² and another 16,300 km² of land are projected to be deforested in coming years (Soares-Filho *et al.*, 2013; Young *et al.*, 2016). Thus, besides the need to comply with environmental legislation, understanding recent land-use change patterns (and how they affect the regional water balance) and visualising a sustainable land-use pathway in the state might become even more important strategically in developing local and national policies that ensure sustainable agricultural (and biofuel) development.

The additional water demanded by increases in sugarcane production is unlikely to impact the region significantly (provided changes in input prices are not taken into account), given the high water availability in most of the Paranaíba basin, especially in the western section. However, the National Water Agency (ANA, 2015) has pointed out some conflict areas regarding multiple water use, especially those caused by agricultural demand. Overall, water availability in the basin are not considered unthreatened (Fachinelli and Pereira, 2015; Tayt-Sohn, 2014), but as cropland continues to expand at the expense of Cerrado vegetation, this could affect the rainfall regime that supports both natural vegetation and agricultural production (Spera *et al.,* 2016; Hunke *et al.,* 2015). From a broader standpoint, the Cerrado biome feeds eight of the 12 hydrographic regions of Brazil and because 70% of the country's electricity comes from hydropower plants, conservation of the biome is also critical for Brazil's energy security (Oliveira *et al.,* 2015).

Although most of the basin is suitable for growing sugarcane, any expansion in the crop would rely greatly on supplementary irrigation, according to climate scenarios that take into consideration local changes in temperature, evapotranspiration and humidity (Tayt-Sohn, 2014). It is also worth mentioning the relatively low water impact from irrigated sugarcane in the region due to so-called salvage irrigation, which corresponds to vinasse.

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[46] REDD+ stands for national efforts to reduce emissions resulting from deforestation and forest degradation, and foster conservation, sustainable management of forests, and enhancement of forest carbon stocks.

However, the ANA (2017) states that the water used to irrigate sugarcane in Brazil is relatively unknown, raising concerns over the use of this resource.

Thus, both ethanol production limits and environmental constraints, as well as food crops (*e.g.* soybean) and livestock production expansion, should be taken into account to avoid impacts on water and land resources in Goiás State. Additionally, analyses must consider the water and land availability in each WMUs of the Paranaíba basin since these resources widely vary depending on local activities and development.

In the scenarios that assumed prices were not affected by external changes (such as a carbon tax imposition), Goiás' economy was only slightly impacted in terms of economic growth and societal wellbeing in response to changes in final ethanol demand[47]. Still, a positive correlation between GDP growth and the employment level was observed. As expected and in all scenarios, the *Biofuels* sector showed major changes in terms of value added, followed by the *Agricultural* sector. Although in the worst-case scenario (*scenario 2e*) water constraints were purposely limited by fixed factor input prices, sugarcane crops could still expand by about 5-fold the current level of production in the region, causing significant positive impacts (an 8.3% increase in local GDP and a 7.1% increase in employment). However, if biofuel production relies on high mechanisation and displacement of traditional agriculture, it could lead to employment losses (Ravindranath *et al.*, 2011; La Rovere *et al.*, 2011).

In fact, the *Agricultural sector* is one of the sectors with the highest increase in unemployment rates in recent years in Brazil. While the sector's contribution to GDP increased from US$32.44 million in 2000 to US$47.16 million in 2015 (an increase of 45.4%), labour demand decreased from 7.88 million jobs in 2000 to 6.42 million jobs in 2015, a reduction of 1.46 million jobs (-18.6%) (IBGE, 2017b). Overall, the occupation/GDP ratio declined by 56%, from 0.243 jobs for every US$ added by the sector in 2000 to 0.136 jobs/US$ in 2015. Therefore, there is a strong falling trend in the technical coefficient of labour demand per unit of agricultural output, possibly reflecting the effects of improved agricultural productivity and increased mechanisation in farming.

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[47] Economic and environmental impacts from scenarios considering changes in factor inputs prices due to a carbon tax policy in the country will be discussed later in this section (*sub-section 4.4.3*).

This trend requires further analysis to address the potential socioeconomic impacts of promoting biofuel expansion in the country.

Without considering land and food price changes from changing traditional food crops to biofuel crops, it is difficult to estimate the socioeconomic impacts on low-income classes regarding their access to food resources. Increasing local GDP from future sugarcane expansion may impact the local socioeconomic indicator for income positively (*i.e.* employment may be positively impacted only if sugarcane expansion is based on traditional agricultural practices). On the other hand, expanding sugarcane production may also impact socioeconomic development and equity negatively, by causing higher food prices and lower accessibility to food and land. However, by modelling the macroeconomic and environmental impacts of biofuels production in Brazil, Obermaier *et al*. (2017) have shown reduced macroeconomic impacts, even when there was a lot of pressure on land resources. Their results show that neither climate change nor the implementation of sustainable measures for land use, as suggested by Brazilian NDCs, would have negative significant impacts on national GDP.

As pointed out by some authors (Hristu-Varsakelis *et al.,* 2010; White *et al.,* 2017; Carvalho *et al.,* 2015; Wang and Chen, 2016), our findings may also be useful to theoretical and empirical research in specifying the economic and environmental effects of policies with the use of hybrid IO tables. However, it must be noted that the deterministic nature of the technical coefficients, which are constant and reflect the economic structure in the base year, does not capture the fact that livestock and sugarcane production expand towards less and less appropriate areas in terms of soil quality, water availability, land slope, etc. In other words, the first unit of final demand has the same impact as the n^{th} unit in IO models, underestimating the real impacts. Additionally, some estimates may be biased due to interrelationships among sectors being different in 2030 compared to the baseline year of 2008. Nevertheless, it is important to recognise any initiative focused on introducing environmental and energy aspects into conventional national accounts, whatever the limitations of that initiative.

To overcome the criticism of the underlying assumption about the fixed proportionality of IO technical coefficients, this research has made the IO coefficients responsive to price changes, as discussed in previous sections. This was necessary because the substitution effect cannot be captured within the traditional Leontief IO model, because that model does not provide a mechanism (through its technical coefficients) for evaluating the impact of changes in technology. In reality, these coefficients are likely to undergo continual changes, for example, due to new innovations, changes in consumer/producer preferences, and policy-induced changes (Sandu, 2007). Therefore, these changes would have an impact on input prices and hence changes in technology through changes in factor inputs. The effects of changes in factor inputs prices resulting from a US\$10/tCO$_{2e}$ carbon tax on the Goiás economy is discussed further in *sub-section 4.4.3*.

Several studies have pointed out that the ultimate goal of nexus thinking is to encourage action by providing policy entry points, exploring synergies, seeking trade-off reduction and facilitating the transition to a more sustainable future. Therefore, biofuel-related policies should consider the integration of individual policies and different modelling initiatives. In fact, assessments of land use, energy and water are often carried out in isolation by unrelated institutions. The resulting lack of policy integration linked to water, energy and land can create vicious cycles that impact biofuels sustainability and, when interlinkages between policies are not treated holistically, these vicious cycles can threaten the sustainability of biofuels. Accordingly, a WEFN approach that considers both the physical and economic implications of different policy strategies could be a major opportunity for integrated solutions that respond to the inter-dependencies of the water, energy, food and economic systems.

Although the nexus literature identifies policy barriers and the options for overcoming them, it is based on a technical-administrative view that is a little distant from the reality of decision-making processes. Further, because ideology, norms and values shape policymaking, the search for policy coherence is not an objective process free of interests (Weitz *et al.,* 2017). Conflicting objectives may arise from negotiation between varying interests, represented by stakeholders with unequal power and, therefore, nexus analysis must look beyond policy objectives and analyse the principles they are built on (Weitz *et al.,* 2017). Thus, connecting the nexus to decision-making processes also requires rethinking the boundaries of the nexus analysis, sharing principles that can guide decision-making towards policy coherence and viewing policy coherence as a continuous process of changing values and perception rather than as an outcome (Weitz *et al.,* 2017).

4.4.1 Managing Local Water Resources

Despite showing low water demand for agricultural uses and hence low sugarcane production, the *Meia Ponte* WMU showed the worst, *i.e.* highly critical, water impairment indicator, when considering the water flow used to grant rights to water use in the region. Therefore, this WMU must not be the focus of sugarcane expansion in the basin since it has already faced real threats regarding surface water availability.

Additionally, since the *Turvo-Bois* and *Lower Paranaíba Minas Tributaries* WMUs have shown low surface water availability and historically high sugarcane expansion rates, they should be the focus of specific studies regarding water use and availability, irrigated sugarcane crops expansion, available water for irrigating food crops, water requirements for hydroelectric plants and so on to determine the real water resource availability in these specific regions and then, maybe further limiting sugarcane expansion in these areas.

As an alternative, the *Claro, Verde, Correntes and Aporé* WMU shows high potential for growing sugarcane, according to the ZAE Cana, besides having higher surface water availability, high available pasturelands with low-density heads of cattle per unit of area, high availability of suitable agriculture areas and relatively low current sugarcane production. Thus, sugarcane producers could be encouraged to expand sugarcane crops towards this WMU instead of into traditional areas where they may have been harming water availability. However, although this WMU is dominated by livestock production, soybean and corn crops are cultivated in its northwest section and producing more sugarcane in the WMU may lead to some level of competition for water and land resources. Biofuel policies should therefore show a good understanding of these distinctions among the different WMUs before promoting sugarcane expansion in a river basin, region or state.

Another water issue not addressed by the current study is related to water quality indicators. Water quality indicators, if properly managed, provide an early warning system for potential water pollution. Key water quality indicators are: Dissolved Oxygen (measures the amount of oxygen dissolved in the water – in mg/L); Water temperature (aquatic organisms are dependent on certain temperature ranges for optimal health – in C°); pH (pollution from accidental spills, agricultural runoff and sewer overflows can also change the pH); Escherichia coli (E. coli is a fecal coliform bacteria that comes from human and animal waste – in number of colony forming units per 100 mL); Specific Conductance (measures the ability of water to pass an electrical current – in µS/cm); Nitrates (excessive amounts of nitrates increase algae growth. Algae can rob the water of dissolved oxygen and eventually kill fish and other aquatic life – in mg/L); and Transparency (measures how far light can penetrate a body of water – in cm). Therefore, the resulting water quality data provide baseline information, helps identify trends or changes in water quality, and aids investigations into problems such as nonpoint-source pollution and nutrient enrichment.

Sugarcane production requires the use of nitrogenous fertilisers, pesticides and even herbicides, all of which lead to the pollution of soil and downstream bodies of water (Ravindranath *et al.,* 2011). The run-off of nutrients, particularly nitrogen and phosphorus, leads to eutrophication of these water bodies, thereby affecting aquatic biodiversity. In addition, the fertigation of sugarcane crops with vinasse, a potassium-rich sugarcane by-product, is widely practised in the Paranaíba basin and this may be an important source of water pollution in the region. As for the issue of water availability in each WMU, further studies should focus on the water quality in these target WMUs before sugarcane expansion towards these regions is encouraged, bearing in mind that, if properly managed, fertigation can reduce both fertiliser applications and water withdrawals for sugarcane irrigation.

This work has focused on the worst-case sugarcane expansion scenario in order to understand the limits to which sugarcane crops could be cultivated in the Paranaíba basin. In this regard, we have applied to our estimates the higher ethanol supply scenarios (*i.e.* Brazilian official data, from EPE, and our calculations) and the most restrictive data regarding water use, *i.e.* 50% of reference flow $Q_{95\%}$. Also, the analyses here have used both surface water availability and water withdrawals, instead of water consumption[48], because water consumption is less restrictive. Therefore, when considering the water consumption, *i.e.* different water rates of return, depending on the activity, water availability and the impairment indicators of water could be higher (therefore, better) than

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[48] The water consumption indicator was used to estimate the water use by economic sectors in the Goiás hybrid IO table, to show the volume of water that could not be used for other uses. However, when analysing both the water balance and the water availability in the Paranaiba basin, the water withdrawals indicator was used instead because it was more restrictive. The water consumption indicator assumes different rates of water return, depending on the activity.

those presented in this study. Again, we are focusing on the worst-case scenario to limit sugarcane expansion up to the point where under that limit would cause fewer impacts than those described here.

As mentioned above, groundwater availability was not considered for the Paranaíba basin and its WMUs. Therefore, for every WMU identified here as having water constraints, there is additional water from groundwater reserves (**Table 27**). In addition, sugarcane crops can pollute groundwater resources through fertigation processes, besides impacting groundwater availability through water withdrawals.

Regardless of the fact that neither availability nor groundwater quality were included in our estimates, we can verify patterns similar to the surface water availability in the basin; specifically, the *Meia Ponte* WMU showed the lowest groundwater availability and the *Claro, Verde, Correntes and Aporé* WMU showed the highest groundwater availability of all the WMUs throughout the basin.

Table 27. Groundwater resources in the Paranaíba basin. Active reserves and water availability, by WMU.

Water Management Units (WMU)	*Active reserve*	*GA*[a]	*Annual GA*
	m^3/s	*m^3/s*	*hm^3*
Paranaíba basin[b]	857.43	428.87	13,525
São Marcos	80.78	40.39	1.273
Meia Ponte	61.59	30.79	971
Turvo-Bois	165.34	82.67	2.607
Claro, Verde, Corrente and Aporé	439.35	219.68	6,928
Lower Paranaíba Minas Tributaries	104.67	52.33	1,650

Note: [a]GA: Groundwater Availability. [b]Data from the Paranaíba basin was multiplied by 63% since this is the share of Paranaíba basin in the state of Goiás.
Values for the whole Paranaíba basin (100%): Active reserve (1,361 m^3/s); GA (680.75 m^3/s); Annual GA (21,468 hm^3).
Source: ANA (2015).

4.4.2 Indirect Land-use Change Impacts

The possibility of expanding future sugarcane cultivation into old pasturelands raises important concerns related to ILUC impacts. If sugarcane expansion in Goiás pushed most of the livestock production towards native forests, the outcome would be quite impactful in terms of deforestation and its associated GHG emissions. However, the use of unproductive lands, better management practices, intensification of livestock production, as well as the implementation of a payment for environmental services could reduce the need for new production areas and promote better outcomes in the sector, using the same or lesser amount of land. These measures to free up space for sugarcane production on old pasturelands could reducing the ILUC impacts of expanding sugarcane. However, cattle ranchers tend to reduce the number of cattle on their lands deliberately in order to ensure that the Brazilian Institute for Agrarian Reform (INCRA) does not expropriate their land for agrarian reform purposes; therefore, the intensification of livestock production constitutes a challenge for the Brazilian government.

Agricultural activities in the southern section of the Cerrado account for a significant share of total national production. They are expanding, mostly in pasturelands and croplands located in the southern section of the Cerrado biome. Thus, identifying unproductive land in this section of the biome could help address important gaps in crops expansion in the region, adjust activities through agro-ecological zoning and the Low Carbon Emission Agriculture Program[49] and explore better socioeconomic and environmental conditions for each type of production. In this context, if sugarcane crops expand towards the recommended WMU according to water and pastureland availability (*i.e. Claro, Verde, Correntes* and *Aporé* WMU), the livestock could move to native forests, causing unintended indirect impacts from biofuel expansion in the basin. Agricultural expansion in the northern section of the biome, especially in the MATOPIBA region, has been directly threatening native forests and offsetting most of the avoided emissions in the Amazon biome in recent years, jeopardising Brazilian NDCs targets. Overall, GHG emission reductions in the Amazon are being compensated by emissions in the neighbouring biome due to recent increases in legal, monitoring and control efforts in the Amazon, highlighting the importance of monitoring and controlling Cerrado's native forests.

This increase in deforestation may be occurring because of the reduced number of areas under protection in Cerrado, which are insufficient for controlling unregulated agricultural expansion and for dismantling land-grabbing and speculation. Additionally,

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[49] Low Carbon Emission Agriculture Program, Plan ABC in Portuguese (*Plano Agricultura de Baixa Emissão de Carbono*), is one of the sectoral plans developed in accordance with article 3 of Decree No. 7,390/2010 and its purpose is to organise and plan the actions needed to adopt sustainable production technologies, with the objective of meeting GHG emission reduction commitments in the agricultural sector. Available at: http://www.agricultura.gov.br/assuntos/sustentabilidade/plano-abc/arquivo-publicacoes-plano-abc/download.pdf.

the Forest Code states that only 20% of a farm must be kept as a protected area (Legal Reserve), but this can also be used as productive land, as long as sustainable production practices are implemented. This percentage of Legal Reserve is considered low compared to the 80% required in the Amazon biome. Lack of knowledge and information gaps also contribute to deforestation in the biome, as Cerrado's full potential as a carbon sink and storage is still uncertain. The role of Cerrado's vegetation in water balance, both in terms of supporting the recharge of aquifers and the relationship with rainfall, is not fully understood and recent changes in precipitation patterns are already affecting agricultural productivity in the biome (Spera *et al.*, 2016).

Another significant indirect driver for deforestation in the Cerrado is international demand from agricultural commodities markets. The estimated GHG emissions from deforestation in the biome for soybean production alone amount to 1,830 $TgCO_2$, which was about 80% of Brazil's gross GHG emissions in 2016 (SEEG, 2017). Although soy and other mechanised crop production is not the major driver of deforestation in the Amazon or Cerrado, cropland expansion has larger gross and net carbon emissions per unit area than pasture expansion, based on the need for complete removal of above- and below-ground biomass (Noojipady *et al.*, 2017).

To avoid further deforestation caused by increasing agricultural production in the country, Brazil must prevent further clearing of native forests through the following measures, among others: *i)* promote and immediately implement the economic mechanisms provided by the Forest Code, which are still lacking regulation and implementation, *ii)* strengthen the enforcement against illegal deforestation, especially in the Cerrado biome, *iii)* implement in the shortest time possible a payment for environmental services policy[50] and *iv)* regulate ILUC patterns from agricultural activities to reduce indirect impacts on native forests.

Solutions to prevent deforestation and reduce GHG emissions from agricultural activities encompass persuading agents of deforestation to engage in environmentally sustainable

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[50] However, through estimating costs and benefits from a Payment for Environmental Services policy (PES) in Brazil, Young *et al.* (2016) have concluded that the cost of avoiding deforestation per unit of preserved area is significantly lower than the cost of recovering those areas with environmental deficits, mainly due to the high costs of revegetation and labour. For this reason, PES programs aimed at recovering deforested areas require payment values to owners and implementation costs that are much more expensive than those for forest conservation.

agricultural production. This would be achieved by creating international certification standards that include a ban on cultivation in newly deforested areas and areas of outstanding conservation interest, as well as compliance with local laws and, in the case of biofuels, by including indirect (ILUC emissions) GHG emissions in their production process. As access to special markets or financial rewards usually results from certification schemes, farmers, ranchers and loggers, among others, are joining together to create voluntary records in which participants undertake to improve their socio-environmental performance.

In order to mitigate the externalities of intensifying livestock production and agricultural expansion, the government and the agricultural sector must focus on large-scale environmental conservation and restoration to maintain the climate stability and environmental services provided by forest ecosystems.

4.4.3 Impacts of a Carbon Tax

The imposition of a carbon tax in Brazil would affect many sectors of the economy and the impacts in each would vary depending on the carbon price determined and their emissions abatement possibilities. Factor input prices would change by about 25% in the *Agricultural* sector in Goiás due to a US\$10/tCO_{2e} carbon tax, by 7.5% in the *Food* sector, by 5.5% in *Biofuels* and by 5% in *Transport*. The IO price model was useful therefore in highlighting the most affected sectors in terms of price changes when considering the implementation of a carbon pricing initiative in the country. As one may expect, these factor input price impacts are directly related to the emissions profile of each economy sector, highlighting the importance of planning a sustainable way to develop agricultural activities in the state (and elsewhere), by promoting the expansion of flex-crops for producing biofuels.

Again, when factor input prices increase, based on microeconomic theory, producers seek to substitute these inputs with other factor inputs, such as capital and labour. In such a circumstance, the possibility of substitution by the use of alternative production functions to update original technical coefficients can be seen as a useful tool to overcome the main criticism of the fixed nature of traditional IO coefficients (Sandu, 2007; Miller and Blair, 2009; Santos and Filho, 2017). Accordingly, it is worth mentioning that small changes in factor input prices (*e.g.* from an alternative tax policy or from technological changes in relevant sectors) may cause significant changes in an economy's overall output. Overall, estimates of price change indexes to every economy sector in Goiás, achieved by applying different production functions to the base-year IO table, have shown a positive correlation between the overall output of the economy and the positive values of elasticity for the *Agricultural and Biofuels* pair of sectors. Conversely, the *Biofuels and Transport* pair of sectors has shown an inverse correlation when analysing substitution values and economy output; *i.e.* with increasing levels of output, the elasticity of substitution becomes more negative.

When both sectors pairs (*i.e. Agricultural/Biofuels* and *Biofuels/Transport*) were analysed simultaneously for the same level of substitution, the economic impacts of each pair offset the impacts of the other. In short, the difference between a combined scenario with both pairs of sectors varying according to the same level of substitution is basically the output for the first pair of sectors minus the output for the second pair of sectors. When considering changes in both pairs of sectors, the differences between the worst- and the best-case scenario in terms of overall output (*i.e.* $\sigma = -0.9$ and $\sigma = 1.5$, respectively) would amount to US$805 million. The index of change in Goiás' total output ranged from -0.08% to +2.15% in a non-substitution scenario, showing the range of possible change in total (and sectoral) output due to changes in factor input prices alone. Regardless of the substitution scenario, the most impacted sector in Goiás would be the *Agricultural*, ranging from -1.7% (-US$92 million) to +14.5% (US$785 million) compared to its original output. Overall, due to the inverse correlation presented, the *Biofuels* sector was the main sector offsetting the output changes in the *Agricultural* sector in Goiás. Therefore, using negative substitution values for one pair of sectors (*e.g. Biofuels and Transport*) and a positive rate of substitution for the other (*e.g. Agricultural and Biofuels*), the overall impacts throughout the economy would be even higher, showing the importance of estimating and analysing economic impacts from different input prices changes, as well as from varying substitution possibilities, according to the objective of the research.

As a result, changes in factor input prices also affect the level of environmental impacts to produce the same level of output in the economy, for different substitution scenarios and carbon prices. In this regard, after considering the price change impacts of a US$10/t$CO_{2e}$ carbon tax, all estimated impacts in the scenarios under a negative substitution possibility would be lower than those impacts found in the scenarios where no substitutions are 'allowed' (*i.e.* those with fixed IO technical coefficients; original physical IO analysis, *section 4.3.1*). Therefore, one may conclude that negative substitution possibilities simultaneously affecting these specific pairs of sectors would negatively impact the Goiás economy and hence the environmental impacts would also be lower than the estimates that considered only the physical impacts of changes in future ethanol demand. For instance, the most realistic scenarios in this case (*i.e. 1b* and *2c*) would show a reduction of about 20% in Goiás' GDP compared to traditional Leontief estimates, highlighting the importance of including price change effects into the overall analysis.

However, positive substitution possibilities would also affect the Goiás' economy, and with significant environmental impacts. These major changes in environmental impacts would come basically from taking into account the input price change possibilities that could arise from a US$10 carbon pricing initiative. In the most realistic scenarios analysed (*i.e. scenarios 1b* and *2c*), the negative environmental impacts offset the economic gains, highlighting the importance of including price change mechanisms in analyses that focus on designing, implementing and assessing biofuel policies. For instance, *scenario 1b* would require about five times more water, land and GHG emissions than it initially required in a non-substitution scenario, and it would generate three times more jobs and GDP would double. According to Beuchle *et al.* (2015), the land required to meet future ethanol demand amounts to for 14% of natural vegetation cover loss in the Cerrado biome in the period 2000-2010 and the local ethanol expansion in *scenario 2c* (an additional 30,000 km^2 of land) would be prohibitive when taking input price changes into account.

Therefore, by considering a mere US$10 carbon tax though a price change module, the overall environmental impacts would differ significantly from the traditional physical IO analysis, showing the additional environmental impacts caused by price change effects (*i.e.* when economic implications are translated into environmental impacts). Accordingly, by updating the original technical coefficients from changes in factor input prices, the results show opportunities to include any initiative impacting input prices (*e.g.* implementation of other fiscal policies or changing the technology for a given sector). Updated technical coefficients can help to assess the economy-wide impacts of a carbon tax policy, bringing medium- to long-term biofuels policy analysis closer to reality. Accordingly, a WEFN approach that considers physical and economic implications of different policy strategies could be a major opportunity for integrated solutions that respond to the interdependencies of water, energy, food and economic systems.

Finally, sectoral value-added impacts should also be taken into account for the different carbon price scenarios and various emissions abatement possibilities when analysing the impacts of any carbon pricing initiative in Brazil. Such an analysis is important analysis because it may show a range of economic impacts in an economy, indicating the most affected sectors in the case of carbon tax policy imposition (Santos *et al.*, 2018), (and in the case of this research, specifically in the state of Goiás). Apart from the *Agricultural*, no other Goiás economic sector would be significantly impacted by a carbon tax of between US\$5 and US\$10/tCO$_{2e}$. The *Transport* sector would show higher impacts (*i.e.* 15% and 30% of total value added) if the carbon price was US\$25 or US\$50/tCO$_{2e}$, respectively, showing that the sector may face huge challenges in a future world focused on pricing GHG emissions. The *Other industries* and *Metallurgy* sectors should also be aware of significant increasing impacts on their value added in the event of even higher carbon prices (*i.e.* above US\$25/tCO$_{2e}$).

Without considering any emissions abatement possibilities, the *Agricultural* sector would be the most impacted sector in terms of carbon costs in relation to the value added, that is, the carbon pricing impacts on the return of the sector's production factors. This can be explained by the sector's emissions profile; since it is the largest emitting sector in Goiás, one would expect it to show greater impacts in terms of value added, with these impacts increasing as the carbon price also increases. Additionally, the original value added for all the sectors should be considered when analysing carbon pricing impacts, since sectors showing high value added would naturally show lower value-added impacts, *i.e.* a lower percentage of total value added (*e.g.* the *Services* sector, in **Figure 46**). Finally, the *Agricultural* sector would face extreme challenges in the case of a carbon pricing initiative above US\$15/tCO$_{2e}$.

However, when considering a possible range of reduction in absolute emissions from 35% to 45% (*i.e.* the same range as Brazil's NDC target reduction for the years 2025 and 2030), impacts in terms of value added change a lot and most of the Goiás economy sectors would show no significant impacts, even with a carbon tax of US\$50/tCO_{2e}. This suggests that these sectors should not be concerned about high carbon prices in the future, provided they can simultaneously reduce their GHG emissions. The *Agricultural* sector would show impacts of 17% to 20% in value added terms under a 45% and 35% emissions reduction scenario, respectively, with a US\$10/CO_{2e} carbon price, suggesting that even low carbon prices may affect the *Agricultural* sector drastically. Therefore, policymakers should be aware of these trends when designing and implementing biofuel policies in Brazil, since the main objective of a biofuel policy may be negatively offset by the increase in local and regional environmental impacts, as well as by increasing carbon prices to avoid higher GHG emissions in the future. Finally, the use of price models can help in assessing economic and environmental impacts of any price change policy in the economy (Miller and Blair, 2009; Santos and Filho, 2017), by identifying the impacts of changes in input prices and those from changes in final demand.

4.4.4 Integrated Biofuel Policy

The main Brazilian energy policy, PDE (MME, 2017b), was useful in determining future ethanol demand and supply scenarios, as was the publication by EPE/MME regarding ethanol demand and supply scenarios to 2030 (EPE, 2017). The *2050 energy demand* technical report (EPE, 2016) was helpful for understanding Brazil's long-term targets for its energy policies. Although macroeconomic and socioeconomic data forecasts were considered when these energy policies were formulated, the policies themselves have none of the additional integrative aspects that are included in the current study. For example, if one examines just the social impacts of future changes in ethanol demand and production practices, it is clear that their analysis was the result of an isolated approach to the analyses and therefore lacks the holistic picture that a nexus approach would give.

Another omission, related to GHG emissions reduction by reducing sugarcane burning during the harvesting process, is that such GHG reduction is not quantitatively linked to the NPCC and its emissions targets. Neither the PDE nor the ZAE Cana consider GHG emissions from land-use change on any geographic scale. That is a major issue when estimating GHG emissions from land use at a national level, since DLUC and ILUC show many methodological inconsistences to date. Another issue related to national emissions regulations is that, as mentioned in *section 2,* there is still uncertainty about the configuration of the Brazilian climate policy in terms of the mechanisms and economic instruments for carbon pricing. Brazil's NDC is among the countries that considered the use of market mechanisms, although it shows no clear indication of how these instruments would be used, reserving its position to adopt the international mechanisms established under the Paris Agreement. Additionally, the National Inventory for GHG Emissions is not currently linked to other land, water or energy policies, having been developed from estimates of energy use, agricultural and industrial processes. However, the *RenovaBio* biofuel policy is intended to overcome part of the issues related to GHG emissions, since its aim is to determine the emission targets to be met by fuel distributors in the country. The *RenovaBio* trading scheme is based on national emission reduction targets which are translated to individual targets and the issuing of biofuel decarbonisation credits (CBIO) to certified biofuel producers/importers. The *RenovaBio* estimates are therefore unlikely to take ILUC GHG emissions into account when analysing and certifying biofuel plants according to the LCA approach, which means that the policy excludes a significant source of indirect effects that may offset biofuel GHG emission reductions.

The PDE also considers in its forecasts the water required for sugarcane production. However, this water requirement is applied as a national water-use coefficient (*i.e.* average) for ethanol production, which includes both the agricultural and industrial production phases. This is a preliminary initiative to include water requirements from sugarcane production in the country. However, in a country the size of a continent, such as Brazil, it is necessary to evaluate local water use and local water availability according to each river basin where sugarcane is cultivated.

Our results show that when considering a specific river basin, the use of indicators for availability and total water demand may be inadequate for analysing the water available for expanding irrigated sugarcane crops. The land use, sugarcane production and water availability of each water management unit differs, indicating that water use and availability for sugarcane must be analysed from a WMU standpoint. Nor does the PDE take into account the competition for water between different crops and between other consumption uses such as public supply, livestock production, hydroelectric generation, etc. Therefore, one of the most important reports on energy planning in Brazil lacks multiple water-use forecasts and does not consider climate change scenarios when assessing the expansion of biofuels in the country.

The ZAE Cana is another very useful tool for mapping the land available in Brazil for sugarcane cultivation, by indicating specific current and potential land use. However, it does not consider the PDE's forecasts regarding future ethanol production. The ZAE Cana was created using land-use data before 2008, clearly requiring an urgent update, as does the last Agricultural Census, which is dated 2006 and whose agricultural, energy, economic and social data also needs updating. Despite being useful, the ZAE Cana is not enough to evaluate the potentially suitable areas in Brazil or in the Cerrado biome, because it cannot take updated land-use patterns, energy policy forecasts (both biofuels, biomass and hydropower generation) or water availability for each strategic region of sugarcane production into consideration.

Nor can the ZAE Cana, published in 2009, cover Brazil's Forest Code new requirements on planning the sugarcane expansion in the country, because the Forest Code came into effect in 2012. However, the ZAE Cana is still useful in analysing sugarcane expansion in Brazil and determining suitable land. This is because the ZAE Cana excludes areas with native vegetation cover, the Amazon and Pantanal biomes, environmental protection areas, indigenous lands, forest remnants and dunes and mangroves, and the Forest Code imposes use restrictions on these types of land cover, even though they have not been updated. Conversely, the ZAE Cana does not consider the forest recovery liability required by the Forest Code, *i.e.* 20% of Legal Reserves in all farms outside the Amazon biome and 80% in the Amazon.

The Paranaíba River Basin Plan (PRBP) has a very comprehensive explanation of water use, water availability and water balance based on the total average surface water flow in the basin. It also includes socioeconomic data and land and water-use patterns for each WMU in the basin. The Paranaíba river basin is very complex; it covers four different Brazilian states (*i.e.*, it is transboundary) and its main river, the Paraná, is nationally strategic. Despite this complexity, we can affirm that the PRBP constitutes a very well implemented water management structure, especially when compared to most of the Brazilian states. However, in the context of future projections for water use and land use, the PRBP does not mention the ZAE Cana in relation to the potential expansion of sugarcane areas in the basin, nor does the PRBP consider the PDE's ethanol forecasts for sugarcane cultivation in Brazil or in the Centre-West region.

In this regard, a projected increase in biomass production will demand more water and land in the region, a demand that is not currently properly addressed through the PRBP or the ZAE Cana. As an example, the PRBP shows absolute values for water availability for each WMU but these data are not merged with data from the PDE and the ZAE Cana to better address sugarcane expansion towards WMUs with higher water availability and potentially more suitable areas for growing sugarcane. This is the case with the *Meia Ponte*, the *Turvo-Bois* and the *Claro, Verde, Correntes e Aporé* WMUs. The first shows low water availability, high water demand, low potential for sugarcane production and low sugarcane production; the second shows medium-low water availability, high water demand, high potential for sugarcane production and high sugarcane production; and the last shows high water availability, low water demand, high potential for sugarcane production and relatively low sugarcane production. Historically, sugarcane has been produced mainly in the *Turvo-Bois* WMU, but we can observe from our analysis that the best WMU for sugarcane expansion would be the *Claro, Verde, Correntes and Aporé*. However, neither the PDE, the ZAE Cana nor the PRBP mention this pattern or indicate the best region for expanding sugarcane in the basin, after analysing land, water and energy. This confirms the lack of an integrated approach to promoting sugarcane expansion in Brazil. This clearly shows a lack of communication between the various Brazilian agencies in charge of managing fundamental production inputs (not only for sugarcane and ethanol production).

Neither the PRBP nor the ZAE Cana show any specific strategy for expanding sugarcane cultivation in the region, nor do these policies consider any level of competition for land and water resources in the region of study between different users, both present and future, such as sugarcane, soybean and corn production, hydropower generation, livestock production, deforestation or the recovery of riparian forests and sensitive areas. Finally, neither the PDE nor the PRBP mention the Forest Code’s legal requirements in planning their energy and water management. The assessment of available land hardly considers uses other than crop production, which is often crucial to the food security of local populations (HLPE, 2016); therefore, competition for land and water must be assessed and managed at local level. Again, these competing or replacing issues are not taken into account, either by the PDE or by the Brazilian Policy on Climate Change.

Taking this lack of policy integration into account, this work aimed to apply an integrated approach that analysed related impacts of sugarcane expansion in the state of Goiás as a preliminary initiative towards understanding the integrated social, economic and environmental impacts of future ethanol demand in the region. In this context, and considering the worst-case scenarios (*2d* and *2e*), our results show that there would probably be no major direct impacts on water and land resources in the region, provided that sugarcane expansion occurred over old pasturelands located mainly in the *Claro, Verde, Correntes and Aporé* WMU (*i.e.* high water availability, high pasturelands with low-density head of cattle per area and low current sugarcane production). However, the overall results differ a lot when a hypothetical carbon tax is considered and the consequent price change effects on local biofuel expansion are analysed. These show that political and economic decisions may have more environmental implications for biofuels expansion than physical and technical decisions. Additionally, ILUC effects must be taken into account if production of any commodity is encouraged, especially in the case of flex-crops, due to their potential to replace traditional agricultural activities and create an indirect need for new agricultural land, pushing the previous production to areas even closer to native forests. In fact, indirect GHG emissions from biofuels production can offset the main objective of an emissions reduction policy, justifying the conception of a biofuel policy through an integrated standpoint considering all inputs and outputs related to the biofuel production process.

It is possible that the results found here are not the most important part of this study. Results from model simulations are only numbers that can be managed in any way, depending on the basic assumptions. In a broader context, there is little significant evidence of the economic and social consequences of biofuel development, mainly because these impacts take longer to manifest (HLPE, 2016). But the effective result obtained here is related to the possibility of integrating water, land, energy and GHG emissions to economic and social data through a framework that can model and detect the integrated impacts on a region, state or river basin. By applying the economic-ecological hybrid IO model coupled with the Leontief IO price model, we can suggest better options to design biofuel policies than those policies developed in a traditional and isolated way, and that do not encompass the range of impacts on the economy that can derive from a single change in future final demand for goods and services. Therefore, a WEFN approach that considers the physical and economic implications of different policy strategies could be a major opportunity for integrated solutions that respond to the inter-dependencies of water, energy, food and economic systems.

Even if one rejects the set of hybrid IO models as the best tools for evaluating integrated impacts on biofuel policies, we can state that regardless of the tool or methodology used, the most important change in biofuel policy approach resides in integrating different policies with distinct objectives into a single more embracing and local-specific biofuel policy. Greater coherence between policies related to water, energy, food and GHG emissions is needed at both the basin and nation levels to improve the sustainability of water, energy and food (Lawford, *et al.,* 2013). In this context, Maroun (2014) applied an integrated approach to assess biofuel sustainability in Brazil through a case study of ethanol production in the state of São Paulo. Her conclusions were similar to those found here, namely that biofuel analyses undertaken in isolation, in that they do not integrate energy, water and land-use policies, may lead to misleading conclusions. She suggests that specific biofuel policies should be designed to ensure the sustainable development of biofuels in Brazil (**Figure 48**).

Finally, as presented in *section 2*, the Brazilian government is expected to implement a national biofuel policy to better address biofuel development in the country for the coming years. Although this is a relevant measure to boost biofuel production and use in the country, and it will be based on decarbonisation credits issued by producers and verified by certification process before being traded through market mechanisms, this biofuel policy does not mention any policy integration between biofuels, land and water.

Based on GHG emission targets, the *RenovaBio* constitutes a step forward regarding national initiatives to encourage the development of renewable energy in Brazil and link the energy sector (through biofuels) to climate commitments. However, at this time, the *RenovaBio* fails to consider ILUC GHG emissions from biofuel crops, and it ignores the fact that biofuel expansion may push other crops (and mainly cattle) to new land, especially in the Cerrado and the Amazon biomes, emitting a significant amount of GHG due to deforestation. It also fails to treat water and land as fundamental resources for planning national biofuel production, which raises concerns about this measure. Despite the current Legal Reserve deficit that must be reforested as required by the Forest Code, Brazil has plenty of land available to expand its agricultural activities. Recently, however, both water quality and availability have been ignored by government initiatives, causing supply shortages and socioeconomic losses. In this context, even though the *RenovaBio* exists to boost Brazil's biofuel sector and socioeconomic indicators, society will still demand structural changes regarding the way we plan our future, planning that embraces all externalities related to an energy policy option, whether fossil or renewable.

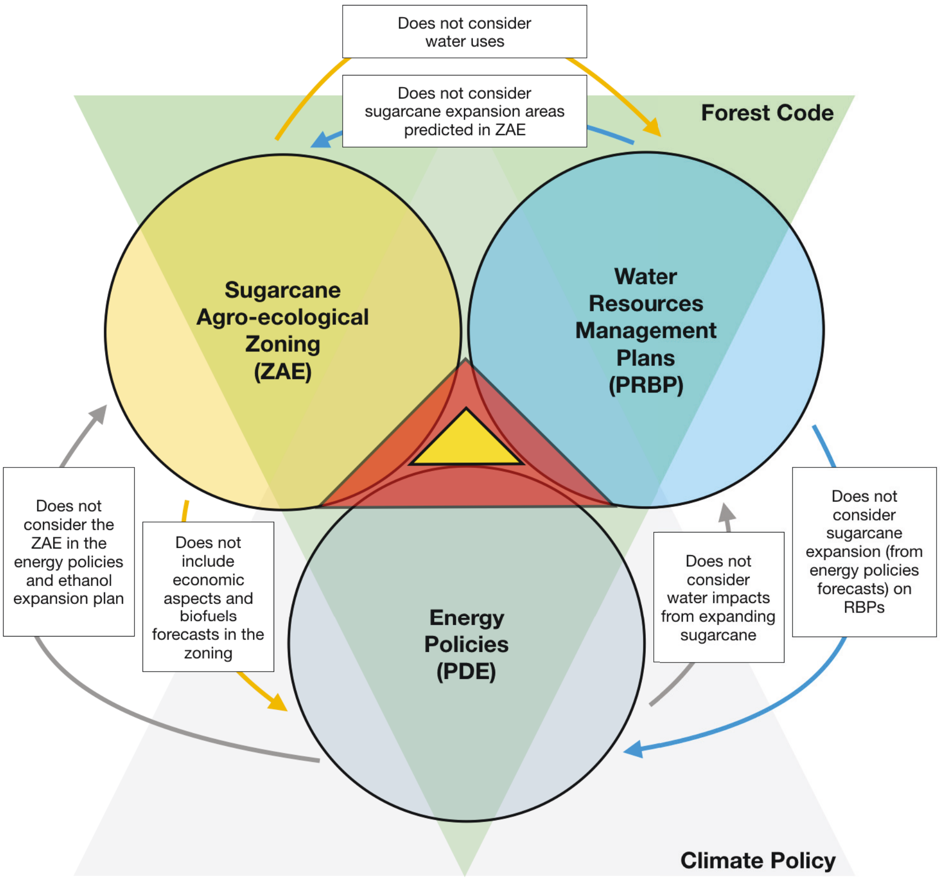

Figure 48. Lack of integration between energy, water, land and climate policies.
Note that the yellow triangle represents the gaps between current isolated policies for water, energy and land use. The red triangle represents the desired policy integration taking into account the goals of all the three policies combined, targeting sustainable ethanol sugarcane expansion. The Forest Code and the Climate Policy, i.e. green and grey triangles, respectively, must also be considered for every policy, isolated or not.
Source: Adapted from Maroum (2014).

Therefore, biofuel-related policies should consider the integration of individual policies. Assessments of land use, energy and water are often carried out in isolation by unrelated institutions. The resulting lack of policy integration linked to water, energy and land can create vicious cycles that impact biofuel sustainability.

4.5 Work Limitations

Because the Brazilian government does not produce a statistical information system that combines conventional national accounts and environmental accounts, part of the data required to carry out the analyses herein had to be estimated from different sources and based on a set of assumptions. Some uncertainty must be assumed by anyone intending to use the results found here to perform further analysis. However, all the assumptions applied to cover the lack of data availability were performed through scientific fundamentals focusing on justifying and limiting that uncertainty. At the same time, it is important to recognise the issues and limitations of introducing environmental and energy aspects into conventional national accounts.

The estimates of water use in this research were arrived at by applying water-use coefficients to bulk production in Brazil for the 2008 base year (**Appendix XII**). Thus, some units of industrial production in the national accounts system were incompatible with some water-use coefficients, preventing the most accurate estimates in these cases. However, the *Industry* sector was less important than other sectors in terms of water use in the Goiás economy. There were also difficulties in estimating water use by the *Power sector*, and this was done mainly by estimating reservoir evaporation (**Appendices XIII**, **XIV** and **XV**), even though the country's best available data was employed (ONS, 2004, 2005, 2017).

Regarding livestock production, there are no official data for the sector's land use in terms of area; the most recent available data is the 2006 Agricultural Census. Most government data relates to the quantities and types of animals and this data does not relate well to the area required to raise them. However, there are several smaller and frequently non-governmental and research initiatives that map livestock land use in Brazil and thus better address the issue of livestock land use (see MAPBIOMAS, 2017). Finally, the agriculture and livestock footprint and production applied to this study are data for the state of Goiás, not for the agricultural production located only in the Paranaíba basin. The land use by these activities was therefore overestimated.

The GHG emissions estimated by the Goiás hybrid IO model was conducted according to the sector emissions published in the emission estimating system for GHG (SEEG). However, when our policy scenarios assumed substituting gasoline with ethanol, the difference in emissions resulting from the replacement were not calculated by the model. Therefore, all GHG emissions for scenarios where gasoline was replaced by ethanol (*scenarios 2b*, *2c*, *2d* and *2e*) were overestimated due to this GHG emissions gap between fuels. Researchers have mentioned that the production and use of ethanol in Brazil has a direct and very positive impact on GHG emissions mitigation (Szklo *et al.,* 2005, Coelho *et al.,* 2006, Macedo *et al.*, 1998, 2008, Goldemberg, 2008, Goldemberg and Guardabassi, 2009, Pacca and Moreira, 2009, Hira and Oliveira, 2009, La Rovere *et al.*, 2011; Moreira *et al.*, 2014).

Additionally, the GHG emissions for all the scenarios may have been overestimated due to differences in accounting the land-use GHG emissions for the baseline year, when considering years subsequent to 2008 (as explained in *section 3.3.6.5*). However, the data provider, SEEG, does not mention any inconsistency regarding this major difference between emissions before and after 2008. Despite the high-quality GHG emissions data from the *Agricultural* sector (SEEG, 2017b), land-use emissions in the Cerrado do not show the same quality. Most of the data regarding land-use change is classified as medium quality, requiring some additional data (*i.e.* the data is incomplete or restricted) or needing to improve the method of quantification and the emissions allocation. The liming process is considered to have high-quality data, while forestry residues show medium-quality data due to the same restrictions as land-use data.

Finally, climate change effects (such as temperature increase, rainfall and evaporation changes) on sugarcane crops and other crops, on water availability and on future hydropower generation in Goiás were not examined in this study, nor for the PDE or the PRBP. This shows an opportunity to develop further analyses of future scenarios for sugarcane and food crop production in the region, and of the additional impacts of reduced water and land availability to develop the local economy, taking climate change scenarios into account.

4.6 Summary and Conclusions

In this chapter, sugarcane industry and environmental concerns in Brazil were discussed, highlighting the role of the state of Goiás as a key ethanol producer in the country. The historical demands for water, land and energy in sugarcane production were presented, helping to justify the choice of the case study. Ethanol policy scenarios were developed to analyse the environmental impact of sugarcane expansion on the Paranaíba basin and its subsequent impact on the Goiás economy. A carbon tax policy based on the Polluter-Pays Principle is analysed, and its impact on energy, environment, economy, and society are assessed. Finally, the chapter has analysed how biofuel policies connect to water, energy, land and climate policies. A final section is dedicated to exploring some limitations of this research. The major conclusions of this chapter are summarised as follows:

- The most realistic ethanol expansion scenarios in Goiás (*scenarios 1b* and *2c*) would not cause significant local environmental impacts, if only physical approaches are analysed (*i.e.* if price change effects are not considered).
- With no price change effects (*i.e.* no carbon tax policy), replacing 25% of gasoline consumption with ethanol would be a feasible strategy for the state, considering the economic gains of this option and the relatively low additional environmental impacts compared to a non-gasoline substitution scenario.
- Even in the worst-case expansion scenario (*2e*), environmental impacts could be moderate in terms of additional water and land-use requirements, provided that sugarcane crops expand over old pasturelands in water management units that are not under water stress.
- When a US\$10/tCO_{2e} carbon price is included in the traditional IO analysis, through the application of the Leontief IO price model, the *Agricultural* sector experiences the greatest impacts in terms of input price changes (+25%), when compared to other Goiás' economic sectors. Because of both its high emission intensity and value added costs, the *Agricultural* sector was the most impacted by a hypothetical carbon tax policy.
- A negative substitution scenario ($\sigma = -0.9$) for the *Agricultural/Biofuels* and the *Biofuels/Transport* sectors showed lower environmental impacts in all the ethanol scenarios when compared to the initial analysis that did not consider the price effects of a carbon tax policy on the Goiás economy (*i.e.* the physical IO

approach). The price change analyses in this research include therefore the environmental impacts of economic changes or forces.

- When positive substitution scenarios were taken into account (*i.e.* $\sigma = 1.5$), all the environmental impact estimates were much higher than the initial impact levels, showing the importance of including price change effects and substitution possibilities in traditional (*i.e.* physical) IO analyses.

- Any ethanol expansion scenario subject to price change effects would turn into a highly-impacting development option for Goiás if a US$10 carbon tax is imposed, increasing the level of environmental impacts by five times as compared with the non-carbon pricing scenarios.

- The environmental and economic impacts of a carbon tax in *scenario 1b* would be similar to the impacts in *scenario 2e* (the scenario with the greatest impact) with no carbon pricing initiative, which was developed based on the upper limit of water availability in the state.

- Impacts on the return of a sector's value added show that no Goiás economic sector apart from the *Agricultural* sector would be significantly impacted by a carbon price of up to US$10/t$CO_{2e}$. However, the *Other industries* and *Transport* sectors in Goiás would be significantly impacted if GHG emissions were priced at US$25/t$CO_{2e}$.

- The *Agricultural* sector would face huge challenges in the case of a US$10 carbon tax imposition, even under a 45% and 35% emissions reduction scenario, with impacts of 17% to 20% in value added terms, respectively.

- Overall, the cost of reducing emissions from 35% to 45% with a US$10 carbon tax could create an impact of between 0.05% and 3.89% on sectoral value added, depending on the sector (but excluding the *Agricultural* sector).

- Sugarcane ethanol expansion into old pasturelands in Goiás in all scenarios (including those with no carbon pricing initiative) becomes prohibitive if it leads to ILUC GHG emissions due to impacts on native forests.

- Finally, the existing biofuels-related policies settings are typified by a narrow sectoral, issue-specific and fragmented viewpoint. These isolated policies are therefore incapable of addressing long-term energy challenges facing the country, especially future biofuel expansion.

- To overcome these shortcomings and to provide meaningful insights into policy issues, this research developed an analytical framework that integrates the technical, economic and social dimensions of biofuels policy in the Brazilian context. The key elements of this framework are a scenario-based approach (*i.e.* ethanol scenarios based on official Brazilian data) and environmental and economic analysis (*i.e.* an economic-ecological hybrid IO model and an IO price model).

5 Conclusions and Recommendations

5.1 Summary and Conclusions

5.1.1 Overall objective and motivation for the research

The main objective of this research was to analyse the impacts of the ongoing expansion of sugarcane ethanol production is the Brazilian Cerrado (specifically in the Paranaíba basin, Goiás State) in order to understand (i) how the interlinkages between the local economic sectors may influence the availability of resources in the region, (ii) how future demand for ethanol could impact local resource availability, based on current Brazilian ethanol policies and targets and (iii) what is the impact of input price changes by imposing a carbon tax on the local economy and environment.

The main motivation to carry out this research resides in:

(i) The role of the state of Goiás (GO) in producing sugarcane ethanol in Brazil

Since GO is one of the leading Brazilian states in sugarcane expansion, it was selected as the case study for analysis in this thesis. The existence of a water resource plan for the important Paranaíba river basin in the state was taken into account when choosing the study area. Finally, there are some conflicts between water, energy and food demands in the region, which raises important questions about promoting the local sugarcane expansion.

(ii) The lack of previous studies using hybrid IO models taking into account water, energy, land use and GHG emissions as elements of an ethanol nexus analysis

Since most of the studies on hybrid IO have focused on the economic aspects of the ethanol sector, they unfortunately could not properly address environmental issues regarding the sector itself and the Brazilian economy. However, despite some recent relevant studies that use hybrid IO models and focus on analysing the environmental impacts of the Brazilian ethanol system, these studies exclude water and land resources (see *section 1.3* for more details). Indeed, studies with hybrid IO models that take GHG emissions and water, energy and land uses into account as variables in the same nexus analysis as explored in this thesis are rare.

(iii) The lack of previous studies on WEFN including price change analysis, specially applied to the Brazilian ethanol sector

In fact, policymaking demands economic arguments to justify the choice of a specific policy option. Another motivation of this research was to include economic analysis into a physical IO model. Understanding about the physical interdependences, obtained from traditional IO analyses, can be translated into policies only when price change effects are included into the analysis.

5.1.2 The Methodology Adopted

This research presents an economic-ecological hybrid IO framework, used to develop a WEFN analysis of the Goiás State economic system. The Goiás IO table was extended to assess water, energy, land use and GHG emissions. This enabled both environmental and economic aspects to be evaluated, using 13 activity sectors and seven ethanol supply scenarios, taking into account direct and indirect effects on the whole economic system, from changes in final demand for ethanol. The main objective of the analysis was to identify the economic and environmental impacts of *1G* sugarcane ethanol expansion in the state of Goiás, through an integrated approach that took all resources involved into account.

The environmental impacts involved assessing possible ethanol scenarios to 2030 in terms of the additional water and land required to meet local ethanol demand, as well as meeting Goiás' future exports to nearby states and, in some cases, replacing gasoline consumption for fuel ethanol. GHG emissions were also assessed, including estimates of ILUC emissions, since the expansion of biofuel cultivation may cause indirect deforestation.

Economic impacts were analysed through GDP and employment indicators. The input price change effects of imposing a hypothetical national carbon tax were also analysed, thereby showing the impacts on sectoral value added to different carbon price and emissions abatement possibilities. Finally, the impacts on the local environment of expanding sugarcane ethanol in Goiás were compared to the additional environmental impacts of including price change (*i.e.* through a carbon tax) in the traditional IO approach. Including price change effects in a physical (*i.e.* traditional IO) analysis produces results that reflect the economic implications of environmental policies.

As a backdrop for setting the above targets, this research reviewed the country's existing biofuel and climate policies, Goiás' water and land-use policies and their analytical and philosophical underpinnings, as well as the theoretical background to WEFN and IO approaches. The review suggested that the existing biofuels-related policies settings are typified by a narrow sectoral, issue-specific and fragmented viewpoint. These isolated policies are therefore incapable of addressing long-term energy challenges facing the country, especially future biofuel expansion. To overcome these shortcomings and to provide meaningful insights into policy issues (and the implications of supporting sugarcane ethanol expansion in the study area), this research developed an analytical framework that integrates the technical, economic and social dimensions of biofuels policy in the Brazilian context. The key elements of this framework are a scenario-based approach (*i.e.* ethanol scenarios based on official Brazilian data) and environmental and economic analysis (*i.e.* an economic-ecological hybrid IO model and an IO price model).

5.1.3 Key Findings

To recapitulate, the main findings of this research are:

- The most realistic ethanol expansion scenarios in Goiás (*scenarios 1b* and *2c*) would not cause significant local environmental impacts, if only physical approaches are analysed (*i.e.* if price change effects are not considered).
- With no price change effects (*i.e.* no carbon tax policy), replacing 25% of gasoline consumption with ethanol would be a feasible strategy for the state, considering the economic gains of this option and the relatively low additional environmental impacts compared to a non-gasoline substitution scenario (and taking into account that there are no refineries in Goiás).
- Even in the worst-case expansion scenario (*2e*), environmental impacts could be moderate in terms of additional water and land-use requirements, provided

that sugarcane crops expand over old pasturelands in the *Claro, Verde, Correntes and Aporé* WMU in the Paranaíba basin.

- When a US\$10/tCO_{2e} carbon price is included in the traditional IO analysis, through the application of the Leontief IO price model, the *Agricultural* sector experiences the greatest impacts in terms of input price changes (+25%), when compared to other Goiás' economic sectors. Because of both its high emission intensity and value added costs, the *Agricultural* sector was the most impacted by a hypothetical carbon tax policy.

- A negative substitution scenario (σ = -0.9) for the *Agricultural/Biofuels* and the *Biofuels/Transport* sectors showed lower environmental impacts in all the ethanol scenarios when compared to the initial analysis that did not consider the price effects of a carbon tax policy on the Goiás economy (*i.e.* the physical IO approach). The price change analyses in this research include therefore the environmental impacts of economic changes or forces.

- When positive substitution scenarios were taken into account (*i.e.* σ = 1.5), all the environmental impact estimates were much higher than the initial impact levels, showing the importance of including price change effects and substitution possibilities in traditional (*i.e.* physical) IO analyses.

- Any ethanol expansion scenario subject to price change effects would turn into a highly-impacting development option for Goiás if a US\$10 carbon tax is imposed, increasing the level of environmental impacts by five times as compared with the non-carbon pricing scenarios.

- The environmental and economic impacts of a carbon tax in *scenario 1b* would be similar to the impacts in *scenario 2e* (the scenario with the greatest impact) with no carbon pricing initiative, which was developed based on the upper limit of water availability in the state.

- Impacts on the return of a sector's value added show that no Goiás economic sector apart from the *Agricultural* sector would be significantly impacted by a carbon price of up to US\$10/tCO_{2e}. However, the *Other industries*[51] and *Transport* sectors in Goiás would be significantly impacted if GHG emissions were priced at US\$25/tCO_{2e}.

- The *Agricultural* sector would face huge challenges in the case of a US\$10 carbon tax imposition, even under a 45% and 35% emissions reduction scenario, with impacts of 17% to 20% in value added terms, respectively.

- Overall, the cost of reducing emissions from 35% to 45% with a US\$10 carbon tax could create an impact of between 0.05% and 3.89% on sectoral value added, depending on the sector (but excluding the *Agricultural* sector).

- Finally, sugarcane ethanol expansion into old pasturelands in Goiás in all scenarios (including those with no carbon pricing initiative) becomes prohibitive if it leads to ILUC GHG emissions due to impacts on native forests.

5.1.4 Conclusion and contributions of this research

Based on the main results presented above, the major conclusions from this research are summarised as follows:

- Overall, the IO framework is useful for developing WEFN analyses, since they can be extended to assess GHG emissions, water, energy and land use, employment levels and GDP as policy targets. Therefore, coupling hybrid IO models with a WEFN approach is useful for assessing the integrated impacts of biofuel policies and these models can be applied to other energy commodities, economic sectors and regions in order to provide better solutions towards a greener economy.

- The results obtained using the WEFN approach provided useful insights into the trade-offs involved in biofuel expansion and both the results and the WEFN approach itself may be used as tools for decision makers and planners to collectively address economic, social, environmental and energy goals.

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[51] Plastic and rubber goods, Machinery and equipment, Electrical and electronic materials, Transport materials, and Miscellaneous industries. For more details please refer to Table 3.

Coupling the economic-ecological hybrid IO model with the Leontief IO price model means that together they can determine both the environmental and the economic impacts of ethanol scenarios and carbon pricing initiatives.

- If decision makers look only at the results of a traditional, physical IO analysis, they may keep pushing for *1G* ethanol expansion in Goiás (after considering some important environmental concerns and restrictions), since it apparently has no major negative direct impacts on the local environment. However, negative environmental impacts (such as land, water and energy uses and GHG emissions) from expanding sugarcane cultivation in Goiás would be five times higher if one takes price change effects, such as a national US$10 carbon tax policy, into account. The big picture of biofuel expansion in the state thus changes significantly when physical and economic models are applied jointly. This difference in the results of the physical and price models are an important way of assessing environmental impacts from economic implications, bringing results and policy recommendations closer to reality.

- Unintended impacts, such as the possibility of indirect deforestation and its related GHG emissions, must always be taken into account before promoting sugarcane expansion in the Paranaíba basin. Inasmuch as this study did not address the use of agrochemicals and pesticides in sugarcane production, we cannot confirm that biofuels expansion would not significantly impact local environmental quality in terms of contaminants in the soil, water and groundwater. As the expansion of sugarcane crops may have significant impact on the region of study, this thesis recommends greater investment in R&D to find more productive agricultural and industrial ways of producing sugarcane ethanol in Brazil, as an alternative to increasing ethanol production using the same amount of environmental inputs. It is also important to determine and restrict sugarcane expansion in areas with water constraints, especially in the water management units located in the central section of the Paranaíba basin, namely *Meia Ponte* and *Turvo-Bois* WMUs (Fachinelli and Pereira, 2015; ANA, 2015).

- The competition between food crops and sugarcane ethanol is a relevant socioeconomic and environmental concern. Suitable areas in Brazil must be identified and analysed by further studies that take into consideration variations in both land and agricultural commodity prices. Brazil’s Cerrado has been under increasing anthropic pressure for many years, but land-use change in the biome has been largely overlooked and in Brazil, land-use change requires specific policies. Thus, greater understanding of recent land-use change patterns and the ability to visualise a sustainable land-use pathway in Goiás means local and national political agendas can become much more strategic in obtaining the necessary changes/benefits.

- Considering the share of Goiás in national ethanol production, expanding *1G* ethanol in the region could help Brazil achieve a 45% share of renewable energy in the national energy matrix, and a 43% reduction in GHG emissions by 2030, in accordance with the NDCs to which it committed at the UNFCCC. However, the *Agricultural* sector could be significantly affected by a US$10 carbon price, even under a 45% emissions reduction scheme, showing that decision makers should encourage a more integrated and sustainable pathway for the development of the *Agricultural* and *Biofuels* sectors in Brazil, since most of their emissions come from LUC activities. It is also important to consider the indirect GHG emissions from unintended deforestation that may be caused by sugarcane expansion, which could offset or even surpass the GHG emissions avoided by using more ethanol fuel.

- Under a carbon pricing initiative, any ethanol scenario could produce much greater environmental impact than non-carbon pricing scenarios, because long-term environmental impacts would offset economic gains. This highlights, for researchers, decision makers and planners, the importance of including economic effects in any environmental analysis, in order to estimate the environmental impact of economic and political changes, so that they can focus on designing and implementing good long-term biofuel policies.

- Overall, Goiás’ economic sectors would not be significantly affected by a carbon tax policy even with no emissions abatement possibilities, showing a low emitting profile and hence, low impacts on the return of the sector’s value added. However, the *Agricultural* sector would be significantly affected by any carbon pricing initiative starting at US\$5/tCO$_{2e}$, highlighting both its high GHG emissions profile and the challenges that decision makers and planners could face if a national carbon tax is implemented. Thus, carbon pricing initiatives could jeopardise years of national development in biofuels, unless traditional agriculture shifts to more sustainable practices.

- From the social standpoint, mechanised cropping in agriculture shows a trend of reduction in terms of labour demand per unit of agricultural output and, therefore, if sugarcane expansion is based on this type of production, socioeconomic indicators could be negatively impacted. In this regard, government should promote better agricultural practices such as agro-ecological production concepts to develop a more sustainable agricultural sector and include concepts of smallholder agriculture in producing food and fuels in the country. Such measures could promote better environmental quality, higher agricultural productivity, increase employment and income in rural populations and help compliance with environmental legislation and with national goals and international agreements.

- Brazilian public agencies project a significant increase in ethanol production in coming years, stating that the implementation of the *RenovaBio* policy would help to overcome the biofuel sector’s financial problems and add 24 new *1G* ethanol production units and 29 new *2G* sugarcane ethanol plants to the system. However, it should be noted that if a policy that contributes to the reversal of this negative financial cycle is not implemented, stagnation or declining sugarcane productivity may affect fuel prices, with negative impacts on consumers. Considering that climate change will amplify the challenges in balancing elements of the WEFN, the expected increase in ethanol production in Brazil will put more pressure on the government, since the environmental impacts estimated from integrated policies scenarios (and taking carbon pricing into consideration) may be higher than those presented in conventional sector-driven approaches.

- Brazil suffers from a general lack of integrated federal land and water management, and its environmental policy is similarly fragmented (Hochstetler, 2007). The sustainable management of resources implies action at various levels; national management requires resource-use planning policies that consider biomass use and its social, environmental and economic impacts from an integrated standpoint. Given the central role of the national government in the governance of both the biofuels market and the impacts of their production, Brazilian public agencies such as MAPA, MME, EPE, ANP, etc., should develop policies to manage the nexus of energy, water, food and GHG emissions, according to local conditions and by using integrated tools to assist the decision-making process. Discussions on biofuel sustainability should consider contextual factors instead of concentrating on limited sectoral assessments and it is worth remembering that Brazilian NDCs depend heavily on land-use strategies that include biofuels, agricultural development and reductions in deforestation (Obermaier *et al.*, 2017).

- Brazil's high reliance on renewable energy, water and land resources calls for careful ex-ante analysis of policies and projects, taking into account all potential direct and indirect effects. The big question therefore is how to integrate these issues into a comprehensive framework. From a broad review of WEFN projects worldwide, Endo *et al.* (2017) have pointed that developing methods to integrate interdisciplinary, multi-sectoral and multi-dimensional research results is essential to analyse and understand interrelationships and trade-offs among these three resources. In this sense, this work presents an approach that may be used to support and overcome some issues identified in the traditional policymaking process, often carried out in isolation, by unrelated institutions.

5.2 Recommendations for Future Research

This research contributes to the understanding and use of hybrid IO models coupled with price change models to estimate economic and environmental impacts, performed here in the case of sugarcane ethanol expansion in Brazil. Another contribution is related to WEFN analyses applied to biofuel production, when water, energy, land use, GHG emission, GDP and job creation were taken into account. This integrated WEFN analysis can help to identify environmental and economic trade-offs and synergies involved in promoting the expansion of a given commodity in any economy (*e.g.,* when assessing the trade-offs of biofuel expansion, accounting for reductions in GHG emissions, but also for direct and indirect impacts of increasing demands for water and land).

These contributions can be useful for researchers and planners intending to either apply these models to different economic sectors or develop integrated models to analyse any socioeconomic and environmental aspect of the WEFN, to provide better solutions for a greener economy. Such an integrated analysis could provide good strategies for sustainable management of natural resources, regardless of the different political interests. Policymakers can also take advantage of the key findings of this research to design biofuel and energy policies in Brazil or elsewhere. They should be aware of the trade-offs involved in designing and implementing biofuel policies, since the main objective of a biofuel policy (*i.e.*, GHG emissions reduction) may be negatively offset by the increase in local and regional environmental impacts (*e.g.* deforestation), as well as by increasing carbon prices to avoid higher GHG emissions in the future. Thus, this work may be a useful tool for decision makers to address collectively economic, social, environmental and energy goals.

However, further improvements to the extended IO models applied to the Brazilian ethanol case can include more accurate data and coefficients related to water use, land use and job creation in economic sectors, including detailed DLUC and ILUC GHG emissions data from the *Agricultural* sector. We strongly suggest analyses consider applying general equilibrium models to the ethanol analysis system used in this thesis. Regarding both the limitations and the main findings of this thesis, we suggest further studies to overcome and better investigate the issues described here, as follows:

- Since all estimates provided by the Goiás hybrid IO model were based on original Goiás IO tables for the year 2008 and national data for the year 2000, we strongly suggest further analyses using updated data from Brazil's national accounts system, such as those for 2015 recently released by the IBGE.

Additionally, we suggest including analyses of changes in final demand for goods and services, other than those in the *Biofuels* sector.

- Overall, our analyses focused on first-generation sugarcane ethanol production in the state of Goiás (specifically in the Paranaíba basin) but these analyses can be applied to any other Brazilian sugarcane-producing state. The results suggest that conflicts may occur between food and fuel crops over water and land resources, in the short and long term, depending on the crop's location. However, we could not identify and address these issues properly. Conflicts between food and fuel crops for land resources are the consequence of a quasi-open access frontier that exists in Brazil, *i.e.* since the agricultural land is continuously 'produced' by deforestation, land-use conflicts are hidden; therefore, in a zero-deforestation situation, these results are very likely to be quite different. Further studies that focus on local competition between food and fuel crops are therefore recommended, including analyses of soybean biodiesel and second-generation ethanol expansion from a variety of locally-available feedstocks.

- We also recommend the use of specific tools to model land-use patterns in any region and to analyse current land use and identify conflicts between food and fuel crops. This would help in estimating the impacts of local biofuel production on both direct and indirect land-use change. We strongly recommend that these analyses are carried out in each WMU of the Paranaíba basin and others in the Centre-West region. Land-price change analyses are also recommended to gain understanding of how price changes could impact land availability, food prices and social equity in the region.

- Despite the data provided by the PRBP, water resource modelling is required to obtain better estimates of water use and availability. Water modelling tools applied to each WMU could also include future water demand for power generation, to enable better understanding of the role of hydropower stations in meeting a region's water demand. Modelling the water required to irrigate food and fuel crops in a region and the surface and groundwater availability in each WMU is also recommended. Additionally, we suggest that simulations of climate change scenarios consider both crop yield reduction and water availability in relation to future changes in the local environment aspects and how climate change could impact the socioeconomic and environmental indicators for the region.

- Regarding GHG emission estimates, we recommend computing GHG emission reductions by replacing gasoline with ethanol. Overall, there is a need to developing better GHG emission inventories, especially regarding emission from DLUC and ILUC in biofuel production. Again, climate change scenarios are required to estimate the impact of those scenarios on future sugarcane expansion and local GDP. Additionally, different carbon tax (or ETS) scenarios would help us to better understand the role of Goiás' (and that of the Centre-West region) sugarcane ethanol production in a broader context. We strongly recommend that analysis uses the GHG emissions reduction scheme proposed by the *RenovaBio* targets.

- Considering both the lack of a national biofuel policy[52] and the intrinsic complexity of integrated approaches, we strongly recommend the creation of a working group of experts from several strategic fields related to water, energy, land use, climate change, economy and social issues to help design integrated biofuel policies through a comprehensive and more participative framework (including the panel of experts who developed the *RenovaBio*). We also recommend updating the data from ZAE Cana by including the water-energy-food-emissions-climate nexus issues in this relevant report. Similarly, we encourage applying the same policy and technical structure to evaluate all the major commodities produced in Brazil, including mineral resources. The same nexus approach should also be used to grant rights to water resources when local, regional and national water resource policies and plans are being developed.

- Finally, we strongly recommend that further studies focus on governance issues related to the water-energy-food-climate nexus of biofuel production, since

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[52] The *RenovaBio* policy is currently in force, however, it is under its initial implementation phase. Therefore, there are no emissions reduction targets defined at the moment to be negotiated by fuel distributors. The emissions reduction targets definition is expected to occur in June 2019.

none of the technical findings translate into action in real life without proper communication and engagement of policymakers and stakeholders. In short, information alone does not necessarily lead to policy change and administrative processes are not necessarily objective; the WEFN approach will arguably have the difficult task of reconciling distinct institutions and interests. Thus, institutional reforms expected from the nexus integration idea can be seen as a key element within a broader nexus governance framework.

6 Appendices

Appendix I: Goiás Original Input-Output Table

Goiás original inter-regional IO table (Guilhoto, 2010).

		Goiás State																									
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)
Goiás State	*Agriculture and forestry (1)*	361	286	1	2,486	13	41	411	10	4	2	1	0	0	0	2	0	1	1	0	9	0	0	28	6	1	3
	Livestock and fishing (2)	43	285	0	2,754	3	1	9	3	0	0	0	0	0	0	1	0	0	0	0	7	0	0	15	3	1	3
	Mining (3)	10	43	70	5	0	1	0	102	0	32	19	1	0	0	0	0	59	1	0	1	0	0	0	0	0	1
	Food, beverages and tobacco (4)	90	475	0	2,768	30	3	24	82	0	0	0	0	0	0	1	1	2	22	3	63	1	1	421	45	20	50
	Textile, clothes and shoes (5)	0	0	0	0	124	2	0	1	2	0	1	2	0	3	1	1	1	6	8	19	3	0	2	0	5	2
	Wood, paper and printing (6)	0	0	1	8	8	133	0	14	12	7	6	3	1	2	20	1	2	11	3	62	25	2	1	6	15	12
	Oil refining, coke and ethanol (7)	13	5	2	7	1	3	45	53	1	2	1	1	1	1	0	20	5	114	35	14	5	8	1	4	9	69
	Chemical and pharmaceutical products (8)	751	67	12	30	13	34	7	476	25	24	43	10	1	5	7	32	32	1	2	23	2	1	4	11	115	23
	Plastic and rubber goods (9)	6	0	1	22	7	18	1	14	27	1	31	16	1	39	21	1	29	16	17	88	0	2	2	0	30	1
	Cement and other non-metallic mineral products (10)	1	1	2	2	1	1	0	15	0	59	18	1	0	14	13	0	353	2	0	9	0	0	0	1	20	3
	Metallurgy (11)	18	2	3	16	5	11	7	28	8	7	180	70	7	65	17	1	83	9	0	9	0	0	1	1	9	24
	Machinery and equipment (12)	0	0	1	1	2	4	4	3	2	2	15	24	0	8	1	0	4	0	0	2	0	0	0	2	0	1
	Electrical and electronic materials (13)	0	0	0	0	0	1	0	1	0	0	1	1	9	1	0	0	1	0	0	1	0	0	0	0	0	0
	Transport materials (14)	0	0	1	0	0	0	0	1	0	0	2	6	0	128	0	0	2	2	3	6	0	0	0	0	0	0
	Miscellaneous industries (15)	0	0	0	0	2	0	0	0	0	0	2	0	0	0	11	0	3	0	4	15	23	1	0	24	0	1
	Power, gas, sewage and public cleaning (16)	50	28	60	331	31	33	23	129	19	68	111	13	1	39	9	1,019	14	218	75	217	29	7	34	136	79	123
	Construction (17)	0	0	0	11	1	1	1	4	2	3	1	1	0	25	0	1	158	11	1	58	26	150	1	219	50	189
	Commerce (18)	453	248	85	1,549	161	44	31	307	43	80	104	45	6	244	43	52	430	341	233	265	43	14	237	78	122	102
	Transport, storage and mail (19)	218	51	135	836	33	31	43	143	21	39	121	25	3	84	11	60	74	423	421	190	32	7	16	30	48	43
	Private services (20)	34	23	58	446	26	37	42	221	19	26	60	23	5	119	7	188	111	606	263	1,604	515	72	34	251	409	722
	Financial and insurance (21)	53	17	25	250	20	20	17	112	15	16	62	30	2	56	7	30	38	139	78	107	391	18	8	6	7	300
	Real estate services (22)	5	1	10	78	10	6	7	23	3	5	10	4	0	3	2	10	12	219	35	147	19	16	19	35	28	111
	Accommodation and food services (23)	1	0	6	12	0	1	4	3	1	4	3	0	0	5	1	1	11	19	26	52	16	3	4	19	69	83
	Public and private education (24)	0	0	0	4	0	0	0	1	0	0	0	0	0	0	0	1	1	9	2	7	5	1	1	6	6	9
	Public and private healthcare (25)	2	1	1	11	1	1	1	3	0	1	1	0	0	1	0	1	2	14	3	10	1	1	2	2	2	7
	Public administration and social security (26)	7	2	5	39	2	3	2	11	1	3	5	1	0	5	1	26	5	29	14	25	11	2	2	8	13	14

Continue

Continuation

		Rest of Brazil																									
		(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*	*(14)*	*(15)*	*(16)*	*(17)*	*(18)*	*(19)*	*(20)*	*(21)*	*(22)*	*(23)*	*(24)*	*(25)*	*(26)*
Goiás State	*Agriculture and forestry (1)*	229	167	1	2,325	117	60	112	15	8	3	2	0	0	0	2	0	1	0	0	15	0	0	43	4	2	8
	Livestock and fishing (2)	20	134	0	1,518	17	2	2	6	1	0	0	0	0	0	2	0	0	0	0	17	0	0	31	4	3	10
	Mining (3)	8	49	47	4	1	6	1	254	0	94	199	8	2	6	1	0	98	0	0	1	0	0	0	0	0	1
	Food, beverages and tobacco (4)	42	344	2	4,559	124	4	92	306	0	0	1	0	0	1	5	3	1	27	3	137	1	2	665	69	52	179
	Textile, clothes and shoes (5)	2	1	4	3	98	2	0	2	2	1	1	2	1	5	2	0	1	5	6	17	3	0	2	0	4	4
	Wood, paper and printing (6)	1	0	10	25	6	61	0	20	4	10	6	4	5	6	21	2	17	20	4	82	22	4	1	7	12	20
	Oil refining, coke and ethanol (7)	11	6	4	6	3	6	270	166	3	4	6	3	8	3	0	8	3	163	36	10	7	14	0	3	12	98
	Chemical and pharmaceutical products (8)	280	77	40	30	17	38	9	363	37	33	117	26	13	15	6	20	61	0	2	25	1	1	4	9	128	39
	Plastic and rubber goods (9)	10	1	7	43	5	9	2	22	5	1	26	13	10	93	12	3	42	18	17	40	0	1	2	0	16	1
	Cement and other non-metallic mineral products (10)	2	2	17	5	1	1	1	24	0	42	38	5	7	22	7	0	261	1	0	3	0	0	0	0	11	3
	Metallurgy (11)	16	3	80	36	4	11	7	31	4	7	321	87	57	163	11	1	74	5	0	5	0	0	1	1	6	32
	Machinery and equipment (12)	0	0	30	9	3	3	3	9	1	5	27	9	2	22	1	1	11	0	0	3	0	1	0	2	0	1
	Electrical and electronic materials (13)	0	0	1	1	0	0	0	2	0	0	1	1	4	3	0	1	1	0	1	2	0	0	0	0	0	0
	Transport materials (14)	1	1	2	1	0	0	0	3	0	1	3	9	1	89	0	0	2	10	15	8	0	0	0	0	0	1
	Miscellaneous industries (15)	0	0	0	1	2	0	0	0	0	0	5	0	0	0	1	0	5	0	2	11	16	0	0	17	1	2
	Power, gas, sewage and public cleaning (16)	6	5	33	37	18	23	9	59	11	31	93	14	15	32	6	143	3	67	28	101	17	2	14	30	29	99
	Construction (17)	0	0	12	1	0	0	1	1	1	1	1	0	1	7	0	0	8	2	0	15	9	27	0	23	7	70
	Commerce (18)	25	20	14	72	25	16	7	48	12	16	34	22	28	89	9	5	37	5	28	45	10	2	27	5	15	18
	Transport, storage and mail (19)	9	3	30	26	5	9	7	18	4	7	33	8	9	27	1	4	4	16	30	17	4	0	1	2	6	6
	Private services (20)	2	1	26	15	2	5	3	25	4	3	14	9	14	25	1	12	7	43	20	77	89	5	3	14	24	89
	Financial and insurance (21)	2	1	6	7	1	1	1	12	1	1	11	5	5	11	1	2	2	9	6	6	0	1	1	0	0	46
	Real estate services (22)	1	0	34	7	1	3	2	5	1	1	4	2	2	3	0	2	2	32	7	28	7	2	3	5	5	35
	Accommodation and food services (23)	0	0	4	1	0	0	1	1	0	1	1	0	0	2	0	0	1	2	3	7	3	0	0	4	9	12
	Public and private education (24)	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	2
	Public and private healthcare (25)	0	0	2	1	0	0	0	1	0	0	0	0	0	1	0	0	0	2	1	2	0	0	0	0	0	2
	Public administration and social security (26)	1	0	2	5	1	1	0	2	0	1	3	1	1	2	0	3	0	3	2	6	3	0	1	1	2	4

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Continuation

		Total Intermediate Consumption	*Goods and services exports*	*Consumption of public administration*	*Consumption of financial institutions*	*Households consumption*	*Gross fixed capital formation*	*Stock change*	*Goods and services exports*	*Consumption of public administration*	*Consumption of financial institutions*	*Households consumption*	*Gross fixed capital formation*	*Stock change*	***Final Demand***	***Total Output***
			Goiás State						***Rest of Brazil***							
Goiás State	*Agriculture and forestry (1)*	6,783	1,644	0	0	834	137	557	0	0	0	742	36	0	3,950	10,732
	Livestock and fishing (2)	4,895	239	0	0	393	380	80	0	0	0	598	141	0	1,831	6,726
	Mining (3)	1,127	701	0	0	12	1	211	0	0	0	17	0	0	942	2,069
	Food, beverages and tobacco (4)	10,723	2,835	0	0	3,913	2	312	0	0	0	8,655	1	0	15,718	26,441
	Textile, clothes and shoes (5)	354	190	0	0	762	1	13	0	0	0	527	0	0	1,493	1,847
	Wood, paper and printing (6)	726	3	0	0	77	6	4	0	0	0	146	4	0	240	966
	Oil refining, coke and ethanol (7)	1,276	2	0	0	1,120	3	36	0	0	0	686	1	0	1,848	3,124
	Chemical and pharmaceutical products (8)	3,137	118	165	0	865	3	-29	0	0	0	912	2	0	2,035	5,173
	Plastic and rubber goods (9)	791	7	0	0	22	1	5	0	0	0	28	1	0	64	855
	Cement and other non-metallic mineral products (10)	972	6	0	0	22	1	79	0	0	0	13	1	0	121	1,093
	Metallurgy (11)	1,545	520	0	0	57	200	481	0	0	0	35	140	0	1,433	2,978
	Machinery and equipment (12)	223	3	0	0	11	141	117	0	0	0	13	368	0	652	875
	Electrical and electronic materials (13)	39	2	0	0	2	4	13	0	0	0	7	17	0	45	83
	Transport materials (14)	304	47	0	0	1,242	665	142	0	0	0	420	285	0	2,801	3,105
	Miscellaneous industries (15)	154	3	0	0	202	56	6	0	0	0	180	60	0	507	661
	Power, gas, sewage and public cleaning (16)	3,820	0	0	0	1,672	1	0	0	0	0	397	0	0	2,070	5,891
	Construction (17)	1,101	49	0	0	16	5,764	0	0	0	0	2	1,016	0	6,847	7,948
	Commerce (18)	5,991	983	0	0	5,106	1,199	-1	0	0	0	432	144	0	7,863	13,854
	Transport, storage and mail (19)	3,428	223	0	0	1,838	124	0	0	0	0	156	9	0	2,351	5,779
	Private services (20)	6,453	67	0	726	4,191	82	0	0	0	0	212	12	0	5,289	11,743
	Financial and insurance (21)	1,961	37	41	0	2,258	1	0	0	0	0	112	0	0	2,448	4,409
	Real estate services (22)	1,016	47	0	0	4,296	107	0	0	0	0	429	27	0	4,906	5,922
	Accommodation and food services (23)	393	299	0	0	1,856	2	0	0	0	0	151	0	0	2,307	2,700
	Public and private education (24)	65	2	3,550	0	609	4	0	0	0	0	28	1	0	4,194	4,260
	Public and private healthcare (25)	84	8	2,836	59	734	11	-0	0	0	0	38	2	0	3,687	3,771
	Public administration and social security (26)	284	8	7,556	1	124	8	1	0	0	0	30	1	0	7,729	8,012

Continue

Continuation

		Goiás State																									
		(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*	*(14)*	*(15)*	*(16)*	*(17)*	*(18)*	*(19)*	*(20)*	*(21)*	*(22)*	*(23)*	*(24)*	*(25)*	*(26)*
Rest of Brazil	*Agriculture and forestry (1)*	505	90	0	2,249	8	29	240	29	2	2	2	0	0	0	2	0	1	0	0	2	0	0	10	2	0	1
	Livestock and fishing (2)	28	51	0	1,687	1	1	5	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	0	0	0
	Mining (3)	2	5	19	5	0	0	790	17	0	14	127	4	0	0	0	215	6	0	0	0	0	0	1	0	0	0
	Food, beverages and tobacco (4)	60	546	2	1,747	3	0	20	22	0	0	0	0	0	0	0	5	1	4	1	12	0	0	155	11	4	8
	Textile, clothes and shoes (5)	19	11	45	8	421	3	3	9	7	7	0	0	0	1	11	1	6	19	11	35	1	0	7	0	7	1
	Wood, paper and printing (6)	32	1	16	160	3	42	3	78	3	24	13	2	0	8	64	7	183	73	11	262	52	13	2	31	20	28
	Oil refining, coke and ethanol (7)	407	128	132	217	9	6	231	263	18	44	31	10	1	13	5	84	95	111	732	31	4	4	3	6	4	20
	Chemical and pharmaceutical products (8)	1,571	166	60	192	39	24	13	435	202	25	78	7	1	22	34	17	166	0	3	17	0	1	5	11	49	17
	Plastic and rubber goods (9)	56	4	57	298	5	3	14	51	7	2	15	3	0	170	3	12	130	52	63	24	0	4	2	0	7	0
	Cement and other non-metallic mineral products (10)	9	0	3	46	0	0	3	21	0	50	2	0	0	12	1	0	639	2	0	1	0	0	0	0	6	0
	Metallurgy (11)	70	10	68	268	1	4	20	30	11	18	564	160	2	303	36	12	400	11	1	16	0	0	1	1	6	3
	Machinery and equipment (12)	1	0	56	107	4	4	18	33	4	12	20	3	0	43	2	4	54	1	2	17	0	3	2	6	1	2
	Electrical and electronic materials (13)	2	1	19	41	1	1	5	17	3	5	3	32	6	108	7	97	83	22	31	128	3	2	0	2	13	6
	Transport materials (14)	15	1	7	16	0	0	1	3	2	2	4	14	0	612	1	8	12	149	187	61	0	4	0	0	0	6
	Miscellaneous industries (15)	0	2	0	7	6	2	0	0	0	0	10	0	0	0	1	0	17	0	4	13	2	1	0	58	1	1
	Power, gas, sewage and public cleaning (16)	10	5	12	65	0	0	3	5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Construction (17)	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Commerce (18)	107	58	20	366	4	1	4	37	1	2	2	1	0	14	1	13	61	10	17	13	3	1	4	3	5	3
	Transport, storage and mail (19)	102	24	64	390	11	7	15	65	5	10	26	6	1	34	2	28	33	201	88	47	11	3	7	10	9	10
	Private services (20)	11	8	23	181	5	5	10	86	2	8	12	3	1	45	1	81	44	245	117	322	69	31	10	76	137	166
	Financial and insurance (21)	56	19	26	267	17	12	18	116	9	15	47	18	1	56	4	32	41	147	83	103	240	19	8	4	4	320
	Real estate services (22)	1	0	3	21	0	0	1	2	0	0	0	0	0	0	0	3	3	9	0	0	0	0	0	0	0	0
	Accommodation and food services (23)	0	0	1	3	0	0	0	1	0	0	0	0	0	1	0	0	2	4	0	0	0	0	0	0	11	0
	Public and private education (24)	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0	5	5	5
	Public and private healthcare (25)	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	Public administration and social security (26)	3	1	2	16	0	0	1	5	0	0	1	0	0	2	0	3	2	12	4	18	4	1	0	3	5	6

Continue

Continuation

		Rest of Brazil																									
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)
Rest of Brazil	*Agriculture and forestry (1)*	9,117	5,659	32	58,544	2,465	6,796	8,155	1,392	401	151	147	5	5	33	182	3	51	31	4	494	3	1	1,643	289	76	192
	Livestock and fishing (2)	740	5,054	1	51,372	337	173	171	89	27	3	4	0	0	1	69	0	0	0	0	366	0	0	780	85	54	155
	Mining (3)	119	703	5,797	102	19	75	74,014	3,769	3	1,749	12,093	459	38	85	33	6,818	1,689	15	9	30	2	2	34	8	22	32
	Food, beverages and tobacco (4)	1,572	15,438	47	49,400	1,923	230	1,092	2,400	30	14	34	12	34	25	94	189	81	833	151	3,310	45	35	25,153	1,647	1,072	2,659
	Textile, clothes and shoes (5)	212	163	351	464	24,511	403	38	297	590	283	57	291	55	180	719	41	198	835	774	2,575	200	9	398	11	789	172
	Wood, paper and printing (6)	350	11	437	2,515	680	17,590	64	2,742	1,018	1,257	900	860	1,018	741	4,963	243	5,125	2,855	556	16,538	4,413	582	146	1,205	1,758	1,954
	Oil refining, coke and ethanol (7)	4,525	2,046	3,208	2,692	816	1,050	24,028	11,391	1,325	1,983	2,637	1,320	2,499	1,900	319	3,287	2,773	7,402	31,373	2,169	530	415	156	540	665	4,224
	Chemical and pharmaceutical products (8)	24,783	3,536	1,900	2,672	4,460	4,777	1,519	42,999	15,484	1,968	7,610	2,120	3,097	2,034	2,429	1,520	5,428	24	164	1,942	137	50	412	871	6,557	1,926
	Plastic and rubber goods (9)	650	71	618	3,796	780	1,800	248	2,508	2,345	124	2,456	2,317	1,716	10,920	1,437	437	4,360	2,310	3,265	5,405	55	204	176	11	2,471	37
	Cement and other non-metallic mineral products (10)	110	21	1,032	570	89	82	45	1,076	17	4,375	1,432	396	607	1,495	877	14	27,193	145	1	478	1	2	1	32	1,328	139
	Metallurgy (11)	937	182	4,695	3,423	318	1,346	854	2,477	1,290	1,090	43,821	25,699	10,670	26,494	3,135	410	13,296	654	61	1,095	7	5	82	61	630	1,304
	Machinery and equipment (12)	14	2	2,763	1,307	464	695	643	1,347	373	595	2,329	3,459	578	3,197	182	145	1,616	40	111	934	4	121	71	457	87	118
	Electrical and electronic materials (13)	23	17	1,256	507	105	183	423	549	253	263	250	3,888	18,027	4,785	437	3,097	2,305	751	1,274	5,957	192	93	5	77	634	326
	Transport materials (14)	168	26	182	196	24	48	54	142	145	94	356	2,049	652	49,182	43	247	368	5,145	7,781	3,441	11	163	5	17	28	321
	Miscellaneous industries (15)	3	32	5	93	269	135	1	23	59	22	919	40	30	26	729	1	552	8	326	1,340	1,402	76	2	2,441	61	99
	Power, gas, sewage and public cleaning (16)	633	504	3,160	4,766	2,315	2,731	1,047	6,142	1,319	2,786	8,299	1,406	1,766	3,006	549	32,234	392	7,371	3,027	10,058	1,642	242	1,501	4,395	3,346	5,965
	Construction (17)	1	0	2,385	162	51	74	117	186	154	136	84	69	214	925	21	23	4,355	389	37	2,658	1,478	5,544	28	6,953	1,642	9,267
	Commerce (18)	6,018	4,715	3,390	23,042	7,769	4,267	1,709	12,153	2,961	3,386	6,834	5,407	7,235	15,107	2,632	2,042	13,548	11,950	10,226	13,469	2,610	555	10,787	2,728	5,773	5,169
	Transport, storage and mail (19)	3,441	1,157	13,462	15,064	2,499	3,454	2,801	7,117	1,765	2,206	10,046	3,687	4,104	6,976	811	2,787	2,981	21,235	20,848	11,053	2,511	358	1,055	1,537	2,592	2,613
	Private services (20)	478	478	13,038	7,825	1,874	3,640	3,078	8,854	1,446	1,479	4,594	3,203	6,629	9,328	466	8,535	4,308	28,959	15,568	91,261	33,489	3,841	1,981	13,286	22,463	43,707
	Financial and insurance (21)	1,177	553	3,396	6,568	2,132	2,776	546	9,463	1,622	1,330	7,532	5,369	4,146	7,458	635	1,943	2,195	9,735	6,584	9,966	36,237	1,341	710	541	697	30,525
	Real estate services (22)	73	21	4,275	1,221	414	493	437	846	217	212	586	413	325	374	149	391	400	7,795	1,455	6,921	1,076	599	859	1,396	1,249	5,513
	Accommodation and food services (23)	7	6	682	203	9	133	225	125	66	184	239	7	89	311	42	29	362	784	1,060	2,402	909	108	190	1,106	3,156	4,065
	Public and private education (24)	3	2	182	63	19	25	23	57	10	10	26	18	20	28	6	28	22	344	73	324	531	29	35	330	379	716
	Public and private healthcare (25)	29	21	265	166	56	46	32	99	25	26	62	46	49	84	20	31	79	506	121	456	72	37	95	92	96	344
	Public administration and social security (26)	102	46	658	668	157	290	145	508	98	138	436	129	237	443	42	908	209	1,399	766	2,097	861	134	111	423	714	967

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Continuation

		Total Intermediate Consumption	*Goods and services exports*	*Consumption of public administration*	*Consumption of financial institutions*	*Households consumption*	*Gross fixed capital formation*	*Stock change*	*Goods and services exports*	*Consumption of public administration*	*Consumption of financial institutions*	*Households consumption*	*Gross fixed capital formation*	*Stock change*	**Final Demand**	**Total Output**
			Goiás State						**Rest of Brazil**							
Rest of Brazil	*Agriculture and forestry (1)*	99,047	0	0	0	192	38	0	24,477	0	0	35,309	3,550	6,579	70,146	169,193
	Livestock and fishing (2)	61,259	0	0	0	79	150	0	3,985	0	0	17,802	8,436	1,363	31,815	93,074
	Mining (3)	108,922	0	0	0	31	0	0	54,501	0	0	1,165	27	-571	55,153	164,075
	Food, beverages and tobacco (4)	110,121	0	0	0	1,213	2	0	52,567	2	0	162,645	155	2,759	219,342	329,462
	Textile, clothes and shoes (5)	35,246	0	0	0	848	1	0	8,790	0	0	57,377	64	3,083	70,163	105,410
	Wood, paper and printing (6)	71,654	0	0	0	445	14	0	14,841	2	0	18,108	781	702	34,892	106,546
	Oil refining, coke and ethanol (7)	117,882	0	0	0	370	2	0	18,107	0	0	37,383	151	468	56,482	174,363
	Chemical and pharmaceutical products (8)	143,576	0	0	0	352	5	0	16,257	6,039	0	40,223	322	1,194	64,392	207,968
	Plastic and rubber goods (9)	51,501	0	0	0	92	3	0	4,376	0	0	3,431	187	859	8,949	60,450
	Cement and other non-metallic mineral products (10)	42,356	0	0	0	30	2	0	3,198	0	0	1,284	110	2,277	6,900	49,256
	Metallurgy (11)	146,048	0	0	0	33	123	0	39,608	0	0	3,146	15,422	9,399	67,731	213,780
	Machinery and equipment (12)	22,054	0	0	0	334	1,288	0	15,456	0	0	11,903	56,984	4,832	90,797	112,850
	Electrical and electronic materials (13)	46,321	0	0	0	460	819	0	12,290	0	0	14,582	41,262	2,637	72,050	118,371
	Transport materials (14)	71,994	0	0	0	445	722	0	42,332	0	0	47,596	52,927	9,531	153,553	225,547
	Miscellaneous industries (15)	8,824	0	0	0	466	127	0	2,116	0	0	23,776	7,777	802	35,064	43,887
	Power, gas, sewage and public cleaning (16)	110,705	0	0	0	0	0	0	89	0	0	48,360	31	26	48,505	159,209
	Construction (17)	36,958	0	0	0	0	0	0	1,451	0	0	484	196,131	0	198,066	235,024
	Commerce (18)	186,232	0	0	0	179	20	0	35,952	0	0	170,482	49,846	-2	256,477	442,709
	Transport, storage and mail (19)	149,369	0	0	0	566	59	0	12,961	0	0	85,916	7,469	2	106,973	256,342
	Private services (20)	335,510	0	0	0	1,317	12	0	25,666	0	31,636	170,719	4,250	0	233,601	569,110
	Financial and insurance (21)	156,856	0	0	0	2,408	0	0	2,271	1,670	0	110,056	39	0	116,444	273,300
	Real estate services (22)	37,753	0	0	0	649	0	0	2,091	0	0	175,746	4,796	1	183,283	221,036
	Accommodation and food services (23)	16,524	0	0	0	96	0	0	11,235	0	0	73,694	66	1	85,091	101,615
	Public and private education (24)	3,327	0	0	0	627	0	0	148	125,705	3	41,843	183	0	168,509	171,836
	Public and private healthcare (25)	2,959	0	0	0	1,173	0	0	335	91,771	2,521	70,308	472	-0	166,580	169,540
	Public administration and social security (26)	12,775	0	0	0	65	2	0	1,155	372,768	40	6,236	378	1	380,645	393,421

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Continuation

	Goiás State																									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)
National production	5,186	2,669	1,114	20,031	1,034	576	2,098	3,088	485	625	1,757	540	54	2,293	353	2,065	3,416	3,289	2,582	4,133	1,542	394	1,053	1,123	1,356	2,500
Imports	757	122	147	627	71	46	214	618	106	70	199	50	9	278	31	142	214	169	200	206	42	14	28	39	101	98
Taxes on Imports	31	6	6	25	16	3	2	15	8	3	9	4	1	14	3	4	25	6	8	16	1	0	3	2	7	5
Taxes on goods and services (ICMS) + Imports	130	126	44	565	29	21	15	113	9	35	44	16	3	76	14	173	133	103	92	298	60	6	112	60	82	182
Zeros (ICMS on Imports, included above)	22	6	4	12	2	1	1	12	1	3	4	1	0	6	1	9	20	6	12	21	2	1	4	3	9	9
Taxes on industrial products (IPI) + Imports	3	10	4	33	2	2	1	8	1	3	4	3	1	9	2	3	18	1	3	13	2	0	31	6	4	2
Zeros (IPI on imports, included above)	1	1	1	1	0	0	0	1	0	0	0	0	0	1	0	1	22	3	1	5	0	0	3	0	1	3
Other Net Indirect Taxes (NIT) + Imports	201	82	49	704	40	21	94	100	17	15	51	18	1	74	9	57	58	74	78	59	25	7	12	24	20	31
Zeros (other NIT on Imports, included above)	25	4	6	19	3	2	13	17	3	1	7	2	0	8	1	3	3	3	4	2	0	0	0	1	1	1
Intermediate Consumption	6,356	3,027	1,375	22,018	1,196	672	2,438	3,971	630	754	2,075	633	69	2,758	413	2,458	3,907	3,654	2,980	4,754	1,675	423	1,247	1,259	1,581	2,831
Remuneration	1,172	1,581	318	2,947	317	117	259	533	128	169	344	121	8	278	89	809	1,374	4,089	919	4,050	1,140	197	456	2,853	1,751	4,471
Wages	998	1,341	249	2,234	263	91	204	395	99	135	265	93	6	202	74	652	1,093	3,163	742	3,458	891	163	390	2,407	1,458	3,213
Effective Social Contributions	174	239	69	713	54	26	55	138	30	35	79	28	2	76	15	157	282	926	177	592	249	34	66	351	214	550
Official Pension plan / FGTS	174	239	66	690	53	25	52	127	29	33	76	28	2	72	15	143	276	916	176	581	228	34	66	346	210	548
Private Pension	0	0	3	23	1	1	3	11	1	1	3	1	0	3	0	14	6	10	0	12	21	0	0	6	4	2
Imputed Social Contributions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	95	79	708
Gross operational surplus and gross mixed revenue	3,142	2,078	356	1,252	315	167	406	622	87	158	534	112	6	47	153	2,583	2,632	5,906	1,835	2,800	1,561	5,296	985	139	430	710
Gross mixed revenue	1,995	1,812	17	138	195	15	0	3	3	9	41	4	0	0	39	0	890	1,775	652	914	17	69	401	33	208	0
Gross operational surplus (GOS)	1,147	266	339	1,114	121	152	406	620	84	149	493	109	5	47	114	2,583	1,742	4,132	1,182	1,885	1,545	5,227	584	106	222	710
Value-added cost factors	4,314	3,659	674	4,198	633	284	665	1,155	216	327	878	233	14	325	242	3,392	4,007	9,996	2,753	6,850	2,701	5,492	1,441	2,993	2,181	5,181
Other taxes on production	63	40	20	230	19	10	21	46	9	12	28	9	1	27	5	51	43	204	52	145	34	7	12	8	10	1
Other production subsidies	-1	0	0	-5	-0	0	0	0	0	0	-2	-1	-0	-5	0	-10	-8	0	-7	-6	0	0	0	0	0	0
Gross value-added (GDP)	4,376	3,699	694	4,423	651	294	686	1,201	225	339	903	242	15	347	247	3,433	4,041	10,200	2,799	6,988	2,735	5,499	1,453	3,000	2,191	5,182
Value of production	10,732	6,726	2,069	26,441	1,847	966	3,124	5,173	855	1,093	2,978	875	83	3,105	661	5,891	7,948	13,854	5,779	11,743	4,409	5,922	2,700	4,260	3,771	8,012
Employed people	556,087	283,616	15,046	127,220	86,855	9,972	16,763	18,150	6,686	17,787	18,402	8,017	518	4,955	22,631	15,137	196,301	456,074	111,623	561,432	16,321	20,131	93,847	135,845	67,184	96,126

Continue

Continuation

	Rest of Brazil																									
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*	*(14)*	*(15)*	*(16)*	*(17)*	*(18)*	*(19)*	*(20)*	*(21)*	*(22)*	*(23)*	*(24)*	*(25)*	*(26)*
National production	55,952	41,283	67,627	246,138	55,008	53,576	122,042	120,146	33,144	26,124	114,727	62,900	64,027	145,763	21,113	65,614	94,531	111,950	105,824	197,423	88,612	14,608	47,217	40,741	58,683	123,293
Imports	9,736	2,763	7,489	9,452	6,290	5,450	30,570	28,984	7,670	3,721	20,951	9,739	16,336	24,064	2,368	6,067	8,357	7,926	11,919	13,683	3,366	706	1,736	2,193	5,953	6,437
Taxes on Imports	190	58	220	253	823	236	60	884	527	97	644	568	849	1,375	166	118	483	144	227	433	32	14	97	58	163	59
Taxes on goods and services (ICMS) + Imports	1,593	2,282	2,306	7,709	1,846	2,212	912	4,333	694	1,511	3,595	2,391	3,194	4,977	869	6,312	3,953	3,717	4,142	12,400	2,846	234	4,647	2,341	3,402	6,026
Zeros (ICMS on Imports, included above)	235	102	124	142	96	106	94	449	72	100	301	171	370	378	46	296	519	203	476	810	96	24	147	126	347	293
Taxes on industrial products (IPI) + Imports	33	172	280	645	121	306	68	438	84	149	406	591	1,319	982	168	143	583	34	137	733	147	23	1,660	236	218	90
Zeros (IPI on imports, included above)	5	7	40	16	9	19	8	51	11	12	42	50	188	89	15	42	497	79	20	155	11	5	89	13	23	24
Other Net Indirect Taxes (NIT) +	1,970	1,111	3,021	9,034	2,249	2,639	7,049	4,717	1,355	1,029	5,202	2,632	2,636	5,996	830	3,041	3,431	5,295	6,992	9,712	5,443	614	1,623	1,677	2,407	6,456
Zeros (other NIT on Imports, included above)	193	45	165	188	130	139	924	620	162	78	548	210	327	521	48	135	161	186	390	338	103	16	33	48	126	172
Intermediate Consumption	69,906	47,824	81,271	273,576	66,572	64,685	161,728	160,622	43,717	32,820	146,415	79,253	89,245	184,145	25,623	81,767	112,514	129,534	130,128	235,688	100,655	16,244	57,250	47,434	71,322	142,850
Remuneration	26,975	20,417	16,004	34,247	21,724	19,407	7,250	23,073	10,913	9,385	26,680	20,855	17,015	30,490	7,260	18,206	44,520	138,669	59,892	178,063	69,538	7,631	18,447	118,091	76,223	216,208
Wages	22,971	17,326	11,329	25,939	17,754	15,461	5,286	17,007	8,386	7,437	20,300	15,932	12,807	22,903	6,036	14,669	35,399	107,269	48,382	149,496	54,351	6,320	15,782	99,710	63,896	155,361
Effective Social Contributions	4,004	3,092	4,675	8,308	3,970	3,946	1,964	6,066	2,526	1,947	6,380	4,923	4,208	7,587	1,224	3,537	9,120	31,400	11,510	28,567	15,187	1,311	2,665	14,806	9,675	26,587
Official Pension plan / FGTS	4,004	3,092	4,123	8,037	3,919	3,858	1,754	5,596	2,456	1,863	6,065	4,783	4,027	7,295	1,201	3,226	8,933	31,051	11,492	28,006	13,883	1,303	2,665	14,450	9,342	26,514
Private Pension	0	0	552	271	51	88	210	470	70	85	315	139	181	293	23	311	187	349	19	560	1,304	8	0	355	333	73
Imputed Social Contributions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3,575	2,652	34,260
Gross operational surplus and gross mixed	71,334	24,277	65,832	18,841	16,122	21,365	4,436	22,483	5,171	6,506	38,866	11,695	11,182	8,971	10,670	58,141	76,965	167,989	64,307	148,481	101,012	196,908	25,464	5,811	21,271	34,317
Gross mixed revenue	45,292	21,167	207	1,947	7,951	2,285	0	85	183	335	1,909	331	621	113	2,725	0	26,034	50,477	22,860	44,395	1,080	2,562	10,355	2,153	11,008	0
Gross operational surplus (GOS)	26,042	3,110	65,625	16,894	8,170	19,080	4,436	22,397	4,988	6,171	36,957	11,363	10,562	8,858	7,945	58,141	50,931	117,511	41,448	104,087	99,931	194,346	15,109	3,658	10,263	34,317
Value-added cost factors	98,309	44,694	81,836	53,089	37,845	40,772	11,686	45,556	16,083	15,891	65,546	32,550	28,197	39,461	17,930	76,347	121,484	306,657	124,200	326,544	170,550	204,540	43,911	123,901	97,494	250,525
Other taxes on production	991	556	968	2,855	1,057	1,089	949	1,791	650	545	1,918	1,200	1,122	2,106	335	1,379	1,276	6,518	2,305	7,224	2,094	252	454	501	723	45
Other production subsidies	-13	0	0	-58	-65	0	0	0	0	0	-100	-152	-194	-165	0	-284	-251	0	-290	-346	0	0	0	0	0	0
Gross value-added (GDP)	99,287	45,250	82,804	55,886	38,838	41,861	12,635	47,347	16,733	16,436	67,365	33,597	29,125	41,402	18,265	77,442	122,510	313,175	126,214	333,423	172,644	204,792	44,365	124,403	98,217	250,570
Value of production	169,193	93,074	164,075	329,462	105,410	106,546	174,363	207,968	60,450	49,256	213,780	112,850	118,371	225,547	43,887	159,209	235,024	442,709	256,342	569,110	273,300	221,036	101,615	171,836	169,540	393,421
Employed people	11,243,518	5,035,728	279,509	2,235,927	3,488,040	1,078,086	152,010	484,127	414,769	613,457	1,061,023	614,619	537,426	582,831	920,014	394,624	6,710,378	15,069,321	4,176,534	19,651,977	931,342	636,595	3,609,867	5,189,185	3,203,648	4,955,328

Continuation

	Total Intermediate Consumption	Goods and services exports	Consumption of public administration	Consumption of financial institutions	Households consumption	Gross fixed capital formation	Stock change	Goods and Services exports	Consumption of public administration	Consumption of financial institutions	Households consumption	Gross fixed capital formation	Stock change	**Final Demand**	**Total Output**
		Goiás State						**Rest of Brazil**							
National production	2,243,419	8,043	14,148	787	44,706	12,289	2,025	406,252	597,957	34,200	1,444,538	454,086	45,941	3,064,972	5,308,391
Imports	258,522	0	0	0	2,544	1,434	0	0	0	0	84,275	61,759	0	150,012	408,534
Taxes on Imports	9,001	0	0	0	112	81	0	0	0	0	3,676	4,203	0	8,073	17,074
Taxes on goods and services (ICMS) + Imports	92,986	0	0	0	2,788	477	0	0	0	0	91,034	17,588	0	111,887	204,873
Zeros (ICMS on Imports, included above)	6,296	0	0	0	145	51	0	0	0	0	4,758	2,668	0	7,623	13,918
Taxes on industrial products (IPI) + Imports	9,938	0	0	0	333	160	0	0	0	0	10,689	5,381	0	16,564	26,502
Zeros (IPI on imports, included above)	1,566	0	0	0	162	74	0	0	0	0	5,311	3,290	0	8,837	10,402
Other Net Indirect Taxes (NIT) + Imports	100,081	0	0	0	1,700	382	0	0	0	0	53,329	14,416	0	69,827	169,908
Zeros (other NIT on Imports, included above)	6,134	0	0	0	52	22	0	0	0	0	1,700	1,168	0	2,943	9,077
Intermediate Consumption	2,727,942	8,043	14,148	787	52,544	14,971	2,025	406,252	597,957	34,200	1,699,309	564,560	45,941	3,440,737	6,168,679
Remuneration	1,267,673	0	0	0	0	0	0	0	0	0	0	0	0	0	1,267,673
Wages	1,001,788	0	0	0	0	0	0	0	0	0	0	0	0	0	1,001,788
Effective Social Contributions	224,516	0	0	0	0	0	0	0	0	0	0	0	0	0	224,516
Official Pension plan / FGTS	218,143	0	0	0	0	0	0	0	0	0	0	0	0	0	218,143
Private Pension	6,373	0	0	0	0	0	0	0	0	0	0	0	0	0	6,373
Imputed Social Contributions	41,369	0	0	0	0	0	0	0	0	0	0	0	0	0	41,369
Gross operational surplus and gross mixed revenue	1,272,729	0	0	0	0	0	0	0	0	0	0	0	0	0	1,272,729
Gross mixed revenue	265,305	0	0	0	0	0	0	0	0	0	0	0	0	0	265,305
Gross operational surplus (GOS)	1,007,424	0	0	0	0	0	0	0	0	0	0	0	0	0	1,007,424
Value-added cost factors	2,540,402	0	0	0	0	0	0	0	0	0	0	0	0	0	2,540,402
Other taxes on production	42,010	0	0	0	0	0	0	0	0	0	0	0	0	0	42,010
Other production subsidies	-1,963	0	0	0	0	0	0	0	0	0	0	0	0	0	-1,963
Gross value-added (GDP)	2,580,449	0	0	0	0	0	0	0	0	0	0	0	0	0	2,580,449
Value of production	5,308,391	0	0	0	0	0	0	0	0	0	0	0	0	0	5,308,391
Employed people	96,232,609	0	0	0	0	0	0	0	0	0	0	0	0	0	96,232,609

Appendix II: Aggregated Input-Output Table for the State of Goiás and the Rest of Brazil

IO table for the state of Goiás and the Rest of Brazil (*X* = *Z* + *Y* matrix). Aggregated from Goiás inter-regional IO table (Guilhoto, 2010), based both on the National and Regional Accounts and by applying the methodology described in Guilhoto and Sesso Filho (2005, 2010) and Guilhoto *et al.* (2010).

		Goiás State													***Rest of Brazil***													
		(1)	***(2)***	***(3)***	***(4)***	***(5)***	***(6)***	***(7)***	***(8)***	***(9)***	***(10)***	***(11)***	***(12)***	***(13)***	***(1)***	***(2)***	***(3)***	***(4)***	***(5)***	***(6)***	***(7)***	***(8)***	***(9)***	***(10)***	***(11)***	***(12)***	***(13)***	***FD***
Goiás State	*Agricultural **(1)*** *	301.93	0.29	1622.08	4.74	13.14	130.00	3.98	2.18	0.84	0.18	0.01	24.20	0.03	170.21	0.21	1189.73	41.57	19.03	35.48	6.45	4.26	1.26	0.63	0.01	42.94	0.01	1789.678
	*Mining **(2)***	16.34	21.56	1.40	0.10	0.29	0.02	31.62	0.43	28.02	5.82	0.01	0.96	0.04	17.69	14.55	1.23	0.38	1.98	0.26	78.51	5.80	59.24	61.71	0.02	1.02	0.01	291.534
	*Food, beverages and tobacco **(3)***	174.81	0.10	857.12	9.28	0.84	7.38	25.38	0.73	0.59	0.09	0.31	192.59	0.98	119.55	0.55	1411.31	38.41	1.26	28.52	94.82	2.49	0.25	0.16	0.78	350.35	1.06	4866.275
	*Textile, clothing and shoes **(4)***	0.16	0.08	0.10	38.46	0.69	0.01	0.19	2.56	0.57	0.31	0.17	11.71	2.52	0.89	1.26	1.05	30.24	0.54	0.08	0.52	3.73	0.80	0.34	0.10	10.85	1.75	462.263
	*Wood, paper and printing **(5)***	0.18	0.20	2.50	2.50	41.13	0.12	4.24	11.77	2.92	1.99	0.13	41.40	0.94	0.38	3.09	7.88	1.91	19.02	0.13	6.27	12.15	8.32	1.88	0.40	52.28	1.12	74.248
	*Oil refining, coke and ethanol **(6)***	5.76	0.48	2.23	0.43	1.06	13.79	16.51	3.12	2.07	0.44	4.70	69.48	10.79	5.51	1.15	1.98	0.92	1.88	83.56	51.49	5.91	2.00	1.97	1.77	94.93	11.04	572.209
	*Chemical and pharmaceutical products **(7)***	253.48	3.68	9.23	4.00	10.44	2.13	147.28	17.09	17.46	13.44	7.32	55.18	0.47	110.76	12.47	9.31	5.23	11.73	2.84	112.47	30.99	29.03	36.35	4.53	63.82	0.56	630.158
	*Other industries **(8)***	8.22	5.62	33.14	6.13	9.73	3.39	16.27	118.58	19.35	23.85	59.56	133.62	13.51	4.87	14.89	19.64	4.46	5.79	2.58	15.69	95.41	23.71	26.23	9.53	76.57	12.95	1387.851
	*Cement, construction and other non-metallic mineral products **(9)***	0.83	0.81	3.97	0.68	0.56	0.50	5.85	18.12	177.47	5.87	0.18	228.75	0.29	1.09	9.14	1.69	0.41	0.45	0.44	7.82	15.61	96.42	11.84	0.05	53.06	0.06	2157.223
	*Metallurgy **(10)***	6.12	1.04	5.03	1.41	3.40	2.03	8.79	51.56	28.15	55.86	0.16	16.70	0.05	5.97	24.72	11.07	1.29	3.48	2.24	9.68	99.44	25.16	99.24	0.13	15.51	0.05	443.731
	*Power sector **(11)***	17.90	13.82	76.87	7.27	7.68	5.26	29.96	78.02	19.17	25.70	177.42	195.63	17.31	2.52	7.77	8.60	4.09	5.34	2.12	13.71	26.44	7.87	21.65	24.94	83.48	6.51	512.795
	*Services **(12)***	262.44	58.80	739.39	68.50	34.37	32.27	211.01	238.36	231.07	76.03	71.17	2302.36	202.48	16.15	27.87	33.31	9.39	8.41	4.40	28.94	80.07	23.04	21.00	5.76	223.36	20.32	11895.831
	*Transport, storage and mail **(13)***	83.45	41.84	258.88	10.11	9.74	13.27	44.16	49.19	35.15	37.50	13.95	244.43	130.44	3.84	9.40	7.98	1.49	2.63	2.11	5.45	15.75	3.27	10.23	1.02	16.66	9.34	727.879
Rest of Brazil	*Agricultural **(1)***	208.54	0.03	1218.54	2.70	9.14	75.99	9.41	1.19	1.00	0.58	0.02	6.18	0.00	6368.62	10.20	34029.81	867.46	2157.66	2577.65	458.57	224.03	63.54	46.66	0.67	1290.80	1.35	31566.750
	*Mining **(2)***	2.35	5.90	1.40	0.01	0.07	244.64	5.40	17.94	6.33	39.27	49.81	0.36	0.04	254.30	1794.62	31.54	5.83	23.22	22914.60	1166.88	719.30	1064.19	3743.90	1583.13	44.45	2.65	17075.134
	*Food, beverages and tobacco **(3)***	187.45	0.59	540.82	0.99	0.09	6.13	6.72	0.51	0.44	0.07	1.10	60.03	0.19	5266.34	14.46	15294.16	595.41	71.35	338.00	743.11	74.68	29.42	10.44	43.97	10759.88	46.73	67907.629
	*Textile, clothing and shoes **(4)***	9.27	13.97	2.53	130.37	1.08	0.91	2.75	5.97	3.83	0.10	0.13	21.51	3.37	116.29	108.52	143.50	7588.57	124.80	11.90	91.82	571.31	148.81	17.52	9.45	1544.35	239.58	21722.349
	*Wood, paper and printing **(5)***	10.12	4.85	49.60	0.84	13.14	0.98	24.26	24.23	64.07	3.90	1.66	149.26	3.29	111.77	135.19	778.62	210.50	5445.87	19.90	849.02	2681.48	1975.98	278.66	56.52	9118.09	172.04	10802.502
	*Oil refining, coke and ethanol **(6)***	165.51	40.99	67.28	2.72	1.89	71.53	81.31	21.11	43.14	9.74	19.39	56.80	226.60	2034.28	993.08	833.57	252.56	325.07	7439.05	3526.53	2533.87	1472.42	816.42	763.16	4984.81	9712.99	17486.534
	*Chemical and pharmaceutical products **(7)***	538.00	18.71	59.54	12.20	7.56	4.11	134.53	83.80	59.17	24.30	3.93	31.04	0.79	8767.32	588.25	827.17	1380.81	1478.84	470.37	13312.45	7908.29	2289.65	2355.98	353.00	3690.22	50.82	19935.661
	*Other industries **(8)***	26.86	43.86	150.47	5.21	3.18	12.16	32.71	326.07	98.47	16.09	28.30	184.75	88.88	399.71	1738.47	2195.43	687.85	1097.25	504.96	1889.70	34637.91	3434.46	2595.61	2782.79	13538.03	4183.50	114585.841
	*Cement, construction and other non-metallic mineral products **(9)***	2.90	1.02	15.10	0.04	0.03	1.05	6.59	4.17	213.34	0.59	0.10	3.09	0.00	41.27	1057.80	226.69	43.54	48.25	50.28	390.75	1481.18	11163.86	469.31	8.72	9313.91	11.99	63456.747
	*Metallurgy **(10)***	24.92	20.94	82.92	0.18	1.26	6.07	9.43	159.24	129.20	174.60	2.84	11.20	0.41	346.34	1453.46	1059.79	98.37	416.81	264.26	766.93	20863.88	4453.84	13566.91	95.23	1188.42	18.79	20969.496
	*Power sector **(11)***	3.50	2.68	15.04	0.00	0.03	0.62	1.22	0.01	0.01	0.17	0.00	0.02	0.00	264.02	733.86	1106.58	537.61	634.12	243.13	1426.25	3739.54	737.92	1927.13	5613.43	8015.79	702.81	12013.511
	*Services **(12)***	82.09	23.22	265.62	8.00	5.69	10.62	76.187	59.823	55.63	19.24	30.60	631.33	68.74	4250.52	8014.60	12308.12	3848.23	3612.83	1917.93	9939.76	24881.73	8634.12	6287.00	3229.26	133436.45	11100.33	492455.217
	*Transport, storage and mail **(13)***	38.78	19.78	120.78	3.28	2.07	4.51	20.153	17.083	13.44	8.12	6.45	92.43	27.28	1423.55	4167.71	4663.86	773.79	1069.47	867.13	2203.45	5585.03	1605.73	3110.31	647.04	13298.58	6454.36	33118.703
	Total Output	*5405.065*	*640.528*	*8185.984*	*571.938*	*299.093*	*967.173*	*1601.436*	*2092.036*	*2799.151*	*921.998*	*1458.693*	*16926.085*	*1789.164*	*81197.102*	*50797.243*	*102000.703*	*32634.563*	*32986.356*	*53982.363*	*64386.489*	*183574.837*	*88012.304*	*66185.741*	*39432.678*	*725252.862*	*79362.849*	

Note: In US$ million; assuming an average exchange rate of 3.23 R$/US$ for a year period (BCB, 2017).

[*] Economy sectors - (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Oil refining, coke and ethanol; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail.

FD: Final Demand

Appendix III: Goiás and Rest of Brazil Technical Coefficients

'A' matrix, where: $A = Zx^{-1}$; $A = [a_{ij}]$.

		Goiás State													***Rest of Brazil***												
		(1)	***(2)***	***(3)***	***(4)***	***(5)***	***(6)***	***(7)***	***(8)***	***(9)***	***(10)***	***(11)***	***(12)***	***(13)***	***(1)***	***(2)***	***(3)***	***(4)***	***(5)***	***(6)***	***(7)***	***(8)***	***(9)***	***(10)***	***(11)***	***(12)***	***(13)***
Goiás State	*Agricultural **(1)****	0.0559	0.0005	0.1982	0.0083	0.0439	0.1344	0.0025	0.0010	0.0003	0.0002	0.0000	0.0014	0.0000	0.0021	0.0000	0.0117	0.0013	0.0006	0.0007	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000
	*Mining **(2)***	0.0030	0.0337	0.0002	0.0002	0.0010	0.0000	0.0197	0.0002	0.0100	0.0063	0.0000	0.0001	0.0000	0.0002	0.0003	0.0000	0.0000	0.0001	0.0000	0.0012	0.0000	0.0007	0.0009	0.0000	0.0000	0.0000
	*Food, beverages and tobacco **(3)***	0.0323	0.0002	0.1047	0.0162	0.0028	0.0076	0.0159	0.0003	0.0002	0.0001	0.0002	0.0114	0.0005	0.0015	0.0000	0.0138	0.0012	0.0000	0.0005	0.0015	0.0000	0.0000	0.0000	0.0000	0.0005	0.0000
	*Textile, clothing and shoes **(4)***	0.0000	0.0001	0.0000	0.0672	0.0023	0.0000	0.0001	0.0012	0.0002	0.0003	0.0001	0.0007	0.0014	0.0000	0.0000	0.0000	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	*Wood, paper and printing **(5)***	0.0000	0.0003	0.0003	0.0044	0.1375	0.0001	0.0026	0.0056	0.0010	0.0022	0.0001	0.0024	0.0005	0.0000	0.0001	0.0001	0.0001	0.0006	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000	0.0001	0.0000
	*Oil refining, coke and ethanol **(6)***	0.0011	0.0008	0.0003	0.0008	0.0035	0.0143	0.0103	0.0013	0.0007	0.0005	0.0034	0.0041	0.0060	0.0001	0.0000	0.0000	0.0000	0.0001	0.0015	0.0008	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001
	*Chemical and pharmaceutical products **(7)***	0.0469	0.0057	0.0011	0.0070	0.0349	0.0022	0.0920	0.0079	0.0062	0.0146	0.0054	0.0033	0.0003	0.0014	0.0002	0.0001	0.0002	0.0004	0.0001	0.0017	0.0002	0.0003	0.0005	0.0001	0.0001	0.0000
	*Other industries **(8)***	0.0013	0.0073	0.0034	0.0099	0.0308	0.0031	0.0089	0.0527	0.0065	0.0240	0.0349	0.0071	0.0069	0.0001	0.0003	0.0002	0.0001	0.0002	0.0000	0.0002	0.0005	0.0003	0.0004	0.0002	0.0001	0.0002
	*Cement, construction and other non-metallic mineral products **(9)***	0.0002	0.0013	0.0005	0.0012	0.0019	0.0005	0.0037	0.0087	0.0634	0.0064	0.0001	0.0135	0.0002	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0011	0.0002	0.0000	0.0001	0.0000
	*Metallurgy **(10)***	0.0011	0.0016	0.0006	0.0025	0.0114	0.0021	0.0055	0.0246	0.0101	0.0606	0.0001	0.0010	0.0000	0.0001	0.0005	0.0001	0.0000	0.0001	0.0000	0.0002	0.0005	0.0003	0.0015	0.0000	0.0000	0.0000
	*Power sector **(11)***	0.0035	0.0230	0.0100	0.0136	0.0274	0.0058	0.0200	0.0338	0.0073	0.0297	0.1384	0.0123	0.0103	0.0000	0.0002	0.0001	0.0001	0.0002	0.0000	0.0002	0.0001	0.0001	0.0003	0.0007	0.0001	0.0001
	*Services **(12)***	0.0486	0.0918	0.0903	0.1198	0.1149	0.0334	0.1318	0.1117	0.0825	0.0825	0.0520	0.1360	0.1132	0.0002	0.0005	0.0003	0.0003	0.0003	0.0001	0.0004	0.0004	0.0003	0.0003	0.0002	0.0003	0.0003
	*Transport, storage and mail **(13)***	0.0154	0.0653	0.0316	0.0177	0.0326	0.0137	0.0276	0.0231	0.0126	0.0407	0.0102	0.0144	0.0729	0.0000	0.0002	0.0001	0.0000	0.0001	0.0000	0.0001	0.0001	0.0000	0.0002	0.0000	0.0000	0.0001
Rest of Brazil	*Agricultural **(1)***	0.0386	0.0001	0.1489	0.0047	0.0306	0.0786	0.0059	0.0006	0.0004	0.0006	0.0000	0.0004	0.0000	0.0784	0.0002	0.3336	0.0266	0.0654	0.0477	0.0071	0.0012	0.0007	0.0007	0.0000	0.0018	0.0000
	*Mining **(2)***	0.0004	0.0092	0.0002	0.0000	0.0002	0.2529	0.0034	0.0070	0.0023	0.0426	0.0364	0.0000	0.0000	0.0031	0.0353	0.0003	0.0002	0.0007	0.4245	0.0181	0.0033	0.0121	0.0566	0.0428	0.0001	0.0000
	*Food, beverages and tobacco **(3)***	0.0347	0.0009	0.0661	0.0017	0.0003	0.0063	0.0042	0.0002	0.0002	0.0001	0.0008	0.0035	0.0001	0.0649	0.0003	0.1499	0.0182	0.0022	0.0063	0.0115	0.0004	0.0003	0.0002	0.0012	0.0148	0.0006
	*Textile, clothing and shoes **(4)***	0.0017	0.0218	0.0003	0.2279	0.0036	0.0009	0.0017	0.0028	0.0014	0.0001	0.0001	0.0013	0.0019	0.0014	0.0021	0.0014	0.2325	0.0038	0.0002	0.0014	0.0031	0.0017	0.0003	0.0003	0.0021	0.0030
	*Wood, paper and printing **(5)***	0.0019	0.0076	0.0061	0.0015	0.0439	0.0010	0.0151	0.0115	0.0229	0.0042	0.0012	0.0088	0.0018	0.0014	0.0027	0.0076	0.0065	0.1651	0.0004	0.0132	0.0146	0.0225	0.0042	0.0015	0.0126	0.0022
	*Oil refining, coke and ethanol **(6)***	0.0306	0.0640	0.0082	0.0048	0.0063	0.0740	0.0508	0.0095	0.0154	0.0106	0.0142	0.0034	0.1267	0.0251	0.0195	0.0082	0.0077	0.0099	0.1378	0.0548	0.0135	0.0167	0.0123	0.0206	0.0069	0.1224
	*Chemical and pharmaceutical products **(7)***	0.0995	0.0292	0.0073	0.0213	0.0253	0.0043	0.0840	0.0399	0.0211	0.0264	0.0029	0.0018	0.0004	0.1080	0.0116	0.0081	0.0423	0.0448	0.0087	0.2068	0.0430	0.0260	0.0356	0.0095	0.0051	0.0006
	*Other industries **(8)***	0.0049	0.0682	0.0183	0.0091	0.0106	0.0125	0.0204	0.1550	0.0352	0.0174	0.0207	0.0109	0.0497	0.0047	0.0333	0.0208	0.0200	0.0320	0.0091	0.0279	0.1865	0.0385	0.0373	0.0652	0.0179	0.0521
	*Cement, construction and other non-metallic mineral products **(9)***	0.0005	0.0016	0.0018	0.0001	0.0001	0.0011	0.0041	0.0020	0.0762	0.0006	0.0001	0.0002	0.0000	0.0005	0.0208	0.0022	0.0013	0.0015	0.0009	0.0061	0.0081	0.1268	0.0071	0.0002	0.0128	0.0002
	*Metallurgy **(10)***	0.0046	0.0327	0.0101	0.0003	0.0042	0.0063	0.0059	0.0760	0.0462	0.1894	0.0021	0.0007	0.0002	0.0043	0.0286	0.0104	0.0030	0.0126	0.0049	0.0119	0.1136	0.0506	0.2050	0.0026	0.0016	0.0002
	*Power sector **(11)***	0.0007	0.0045	0.0020	0.0000	0.0001	0.0007	0.0008	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0035	0.0154	0.0116	0.0176	0.0205	0.0048	0.0236	0.0196	0.0089	0.0311	0.1620	0.0118	0.0094
	*Services **(12)***	0.0152	0.0362	0.0324	0.0140	0.0190	0.0110	0.0476	0.0276	0.0199	0.0209	0.0224	0.0373	0.0384	0.0523	0.1578	0.1207	0.1179	0.1095	0.0355	0.1544	0.1344	0.0981	0.0950	0.0874	0.1840	0.1399
	*Transport, storage and mail **(13)***	0.0072	0.0309	0.0148	0.0057	0.0069	0.0047	0.0126	0.0080	0.0048	0.0088	0.0047	0.0055	0.0152	0.0175	0.0820	0.0457	0.0237	0.0324	0.0161	0.0342	0.0302	0.0182	0.0470	0.0175	0.0183	0.0813

*Note: *Economy sectors - (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Oil refining, coke and ethanol; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail.*

Appendix IV: Goiás and Rest of Brazil (*I* - *A*) Matrix

		Goiás State													***Rest of Brazil***												
		(1)	***(2)***	***(3)***	***(4)***	***(5)***	***(6)***	***(7)***	***(8)***	***(9)***	***(10)***	***(11)***	***(12)***	***(13)***	***(1)***	***(2)***	***(3)***	***(4)***	***(5)***	***(6)***	***(7)***	***(8)***	***(9)***	***(10)***	***(11)***	***(12)***	***(13)***
Goiás State	*Agricultural **(1)****	0.9441	(0.0005)	(0.1982)	(0.0083)	(0.0439)	(0.1344)	(0.0025)	(0.0010)	(0.0003)	(0.0002)	(0.0000)	(0.0014)	(0.0000)	(0.0021)	(0.0000)	(0.0117)	(0.0013)	(0.0006)	(0.0007)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0001)	(0.0000)
	*Mining **(2)***	(0.0030)	0.9663	(0.0002)	(0.0002)	(0.0010)	(0.0000)	(0.0197)	(0.0002)	(0.0100)	(0.0063)	(0.0000)	(0.0001)	(0.0000)	(0.0002)	(0.0003)	(0.0000)	(0.0000)	(0.0001)	(0.0000)	(0.0012)	(0.0000)	(0.0007)	(0.0009)	(0.0000)	(0.0000)	(0.0000)
	*Food, beverages and tobacco **(3)***	(0.0323)	(0.0002)	0.8953	(0.0162)	(0.0028)	(0.0076)	(0.0159)	(0.0003)	(0.0002)	(0.0001)	(0.0002)	(0.0114)	(0.0005)	(0.0015)	(0.0000)	(0.0138)	(0.0012)	(0.0000)	(0.0005)	(0.0015)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0005)	(0.0000)
	*Textile, clothing and shoes **(4)***	(0.0000)	(0.0001)	(0.0000)	0.9328	(0.0023)	(0.0000)	(0.0001)	(0.0012)	(0.0002)	(0.0003)	(0.0001)	(0.0007)	(0.0014)	(0.0000)	(0.0000)	(0.0000)	(0.0009)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
	*Wood, paper and printing **(5)***	(0.0000)	(0.0003)	(0.0003)	(0.0044)	0.8625	(0.0001)	(0.0026)	(0.0056)	(0.0010)	(0.0022)	(0.0001)	(0.0024)	(0.0005)	(0.0000)	(0.0001)	(0.0001)	(0.0001)	(0.0006)	(0.0000)	(0.0001)	(0.0001)	(0.0001)	(0.0000)	(0.0000)	(0.0001)	(0.0000)
	*Oil refining, coke and ethanol **(6)***	(0.0011)	(0.0008)	(0.0003)	(0.0008)	(0.0035)	0.9857	(0.0103)	(0.0013)	(0.0007)	(0.0005)	(0.0034)	(0.0041)	(0.0060)	(0.0001)	(0.0000)	(0.0000)	(0.0000)	(0.0001)	(0.0015)	(0.0008)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0001)	(0.0001)
	*Chemical and pharmaceutical products **(7)***	(0.0469)	(0.0057)	(0.0011)	(0.0070)	(0.0349)	(0.0022)	0.9080	(0.0079)	(0.0062)	(0.0146)	(0.0054)	(0.0033)	(0.0003)	(0.0014)	(0.0002)	(0.0001)	(0.0002)	(0.0004)	(0.0001)	(0.0017)	(0.0002)	(0.0003)	(0.0005)	(0.0001)	(0.0001)	(0.0000)
	*Other industries **(8)***	(0.0013)	(0.0073)	(0.0034)	(0.0099)	(0.0308)	(0.0031)	(0.0089)	0.9473	(0.0065)	(0.0240)	(0.0349)	(0.0071)	(0.0069)	(0.0001)	(0.0003)	(0.0002)	(0.0001)	(0.0002)	(0.0000)	(0.0002)	(0.0005)	(0.0003)	(0.0004)	(0.0002)	(0.0001)	(0.0002)
	*Cement, construction and other non-metallic mineral products **(9)***	(0.0002)	(0.0013)	(0.0005)	(0.0012)	(0.0019)	(0.0005)	(0.0037)	(0.0087)	0.9366	(0.0064)	(0.0001)	(0.0135)	(0.0002)	(0.0000)	(0.0002)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0001)	(0.0001)	(0.0011)	(0.0002)	(0.0000)	(0.0001)	(0.0000)
	*Metallurgy **(10)***	(0.0011)	(0.0016)	(0.0006)	(0.0025)	(0.0114)	(0.0021)	(0.0055)	(0.0246)	(0.0101)	0.9394	(0.0001)	(0.0010)	(0.0000)	(0.0001)	(0.0005)	(0.0001)	(0.0000)	(0.0001)	(0.0000)	(0.0002)	(0.0005)	(0.0003)	(0.0015)	(0.0000)	(0.0000)	(0.0000)
	*Power sector **(11)***	(0.0035)	(0.0230)	(0.0100)	(0.0136)	(0.0274)	(0.0058)	(0.0200)	(0.0338)	(0.0073)	(0.0297)	0.8616	(0.0123)	(0.0103)	(0.0000)	(0.0002)	(0.0001)	(0.0001)	(0.0002)	(0.0000)	(0.0002)	(0.0001)	(0.0001)	(0.0003)	(0.0007)	(0.0001)	(0.0001)
	*Services **(12)***	(0.0486)	(0.0918)	(0.0903)	(0.1198)	(0.1149)	(0.0334)	(0.1318)	(0.1117)	(0.0825)	(0.0825)	(0.0520)	0.8640	(0.1132)	(0.0002)	(0.0005)	(0.0003)	(0.0003)	(0.0003)	(0.0001)	(0.0004)	(0.0004)	(0.0003)	(0.0003)	(0.0002)	(0.0003)	(0.0003)
	*Transport, storage and mail **(13)***	(0.0154)	(0.0653)	(0.0316)	(0.0177)	(0.0326)	(0.0137)	(0.0276)	(0.0231)	(0.0126)	(0.0407)	(0.0102)	(0.0144)	0.9271	(0.0000)	(0.0002)	(0.0001)	(0.0000)	(0.0001)	(0.0000)	(0.0001)	(0.0001)	(0.0000)	(0.0002)	(0.0000)	(0.0000)	(0.0001)
Rest of Brazil	*Agricultural **(1)***	(0.0386)	(0.0001)	(0.1489)	(0.0047)	(0.0306)	(0.0786)	(0.0059)	(0.0006)	(0.0004)	(0.0006)	(0.0000)	(0.0004)	(0.0000)	0.9216	(0.0002)	(0.3336)	(0.0266)	(0.0654)	(0.0477)	(0.0071)	(0.0012)	(0.0007)	(0.0007)	(0.0000)	(0.0018)	(0.0000)
	*Mining **(2)***	(0.0004)	(0.0092)	(0.0002)	(0.0000)	(0.0002)	(0.2529)	(0.0034)	(0.0070)	(0.0023)	(0.0426)	(0.0364)	(0.0000)	(0.0000)	(0.0031)	0.9647	(0.0003)	(0.0002)	(0.0007)	(0.4245)	(0.0181)	(0.0033)	(0.0121)	(0.0566)	(0.0428)	(0.0001)	(0.0000)
	*Food, beverages and tobacco **(3)***	(0.0347)	(0.0009)	(0.0661)	(0.0017)	(0.0003)	(0.0063)	(0.0042)	(0.0002)	(0.0002)	(0.0001)	(0.0008)	(0.0035)	(0.0001)	(0.0649)	(0.0003)	0.8501	(0.0182)	(0.0022)	(0.0063)	(0.0115)	(0.0004)	(0.0003)	(0.0002)	(0.0012)	(0.0148)	(0.0006)
	*Textile, clothing and shoes **(4)***	(0.0017)	(0.0218)	(0.0003)	(0.2279)	(0.0036)	(0.0009)	(0.0017)	(0.0028)	(0.0014)	(0.0001)	(0.0001)	(0.0013)	(0.0019)	(0.0014)	(0.0021)	(0.0014)	0.7675	(0.0038)	(0.0002)	(0.0014)	(0.0031)	(0.0017)	(0.0003)	(0.0003)	(0.0021)	(0.0030)
	*Wood, paper and printing **(5)***	(0.0019)	(0.0076)	(0.0061)	(0.0015)	(0.0439)	(0.0010)	(0.0151)	(0.0115)	(0.0229)	(0.0042)	(0.0012)	(0.0088)	(0.0018)	(0.0014)	(0.0027)	(0.0076)	(0.0065)	0.8349	(0.0004)	(0.0132)	(0.0146)	(0.0225)	(0.0042)	(0.0015)	(0.0126)	(0.0022)
	*Oil refining, coke and ethanol **(6)***	(0.0306)	(0.0640)	(0.0082)	(0.0048)	(0.0063)	(0.0740)	(0.0508)	(0.0095)	(0.0154)	(0.0106)	(0.0142)	(0.0034)	(0.1267)	(0.0251)	(0.0195)	(0.0082)	(0.0077)	(0.0099)	0.8622	(0.0548)	(0.0135)	(0.0167)	(0.0123)	(0.0206)	(0.0069)	(0.1224)
	*Chemical and pharmaceutical products **(7)***	(0.0995)	(0.0292)	(0.0073)	(0.0213)	(0.0253)	(0.0043)	(0.0840)	(0.0399)	(0.0211)	(0.0264)	(0.0029)	(0.0018)	(0.0004)	(0.1080)	(0.0116)	(0.0081)	(0.0423)	(0.0448)	(0.0087)	0.7932	(0.0430)	(0.0260)	(0.0356)	(0.0095)	(0.0051)	(0.0006)
	*Other industries **(8)***	(0.0049)	(0.0682)	(0.0183)	(0.0091)	(0.0106)	(0.0125)	(0.0204)	(0.1550)	(0.0352)	(0.0174)	(0.0207)	(0.0109)	(0.0497)	(0.0047)	(0.0333)	(0.0208)	(0.0200)	(0.0320)	(0.0091)	(0.0279)	0.8135	(0.0385)	(0.0373)	(0.0652)	(0.0179)	(0.0521)
	*Cement, construction and other non-metallic mineral products **(9)***	(0.0005)	(0.0016)	(0.0018)	(0.0001)	(0.0001)	(0.0011)	(0.0041)	(0.0020)	(0.0762)	(0.0006)	(0.0001)	(0.0002)	(0.0000)	(0.0005)	(0.0208)	(0.0022)	(0.0013)	(0.0015)	(0.0009)	(0.0061)	(0.0081)	0.8732	(0.0071)	(0.0002)	(0.0128)	(0.0002)
	*Metallurgy **(10)***	(0.0046)	(0.0327)	(0.0101)	(0.0003)	(0.0042)	(0.0063)	(0.0059)	(0.0760)	(0.0462)	(0.1894)	(0.0021)	(0.0007)	(0.0002)	(0.0043)	(0.0286)	(0.0104)	(0.0030)	(0.0126)	(0.0049)	(0.0119)	(0.1136)	(0.0506)	0.7950	(0.0026)	(0.0016)	(0.0002)
	*Power sector **(11)***	(0.0007)	(0.0045)	(0.0020)	(0.0000)	(0.0001)	(0.0007)	(0.0008)	(0.0000)	(0.0000)	(0.0002)	(0.0000)	(0.0000)	(0.0000)	(0.0035)	(0.0154)	(0.0116)	(0.0176)	(0.0205)	(0.0048)	(0.0236)	(0.0196)	(0.0089)	(0.0311)	0.8380	(0.0118)	(0.0094)
	*Services **(12)***	(0.0152)	(0.0362)	(0.0324)	(0.0140)	(0.0190)	(0.0110)	(0.0476)	(0.0276)	(0.0199)	(0.0209)	(0.0224)	(0.0373)	(0.0384)	(0.0523)	(0.1578)	(0.1207)	(0.1179)	(0.1095)	(0.0355)	(0.1544)	(0.1344)	(0.0981)	(0.0950)	(0.0874)	0.8160	(0.1399)
	*Transport, storage and mail **(13)***	(0.0072)	(0.0309)	(0.0148)	(0.0057)	(0.0069)	(0.0047)	(0.0126)	(0.0080)	(0.0048)	(0.0088)	(0.0047)	(0.0055)	(0.0152)	(0.0175)	(0.0820)	(0.0457)	(0.0237)	(0.0324)	(0.0161)	(0.0342)	(0.0302)	(0.0182)	(0.0470)	(0.0175)	(0.0183)	0.9187

Note: *Economy sectors - (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Oil refining, coke and ethanol; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail.

Appendix V: Goiás and Rest of Brazil Leontief Inverse Matrix

		Goiás State													Rest of Brazil												
		(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*	*(1)*	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*	*(11)*	*(12)*	*(13)*
Goiás State	*Agricultural* ***(1)****	1.06963	0.00189	0.23991	0.01591	0.05776	0.14874	0.01050	0.00304	0.00147	0.00158	0.00136	0.00612	0.00229	0.00458	0.00029	0.02059	0.00308	0.00147	0.00184	0.00146	0.00041	0.00031	0.00031	0.00025	0.00072	0.00044
	Mining ***(2)***	0.00479	1.03524	0.00153	0.00065	0.00268	0.00099	0.02296	0.00108	0.01158	0.00784	0.00028	0.00042	0.00017	0.00055	0.00044	0.00039	0.00020	0.00029	0.00030	0.00176	0.00038	0.00101	0.00141	0.00010	0.00006	0.00008
	Food, beverages and tobacco ***(3)***	0.04206	0.00250	1.13029	0.02324	0.00958	0.01582	0.02312	0.00312	0.00216	0.00243	0.00172	0.01547	0.00304	0.00387	0.00039	0.02077	0.00287	0.00086	0.00141	0.00293	0.00054	0.00038	0.00044	0.00033	0.00116	0.00045
	Textile, clothing and shoes ***(4)***	0.00016	0.00041	0.00023	1.07262	0.00317	0.00012	0.00039	0.00160	0.00038	0.00062	0.00030	0.00093	0.00177	0.00003	0.00005	0.00004	0.00131	0.00004	0.00003	0.00003	0.00005	0.00003	0.00003	0.00002	0.00003	0.00004
	Wood, paper and printing ***(5)***	0.00054	0.00094	0.00100	0.00612	1.16057	0.00046	0.00414	0.00756	0.00181	0.00338	0.00070	0.00347	0.00119	0.00007	0.00013	0.00020	0.00016	0.00086	0.00009	0.00023	0.00018	0.00020	0.00012	0.00006	0.00014	0.00007
	Oil refining, coke and ethanol ***(6)***	0.00252	0.00225	0.00189	0.00203	0.00619	1.01542	0.01304	0.00277	0.00167	0.00190	0.00471	0.00520	0.00763	0.00036	0.00019	0.00034	0.00023	0.00028	0.00198	0.00131	0.00026	0.00019	0.00024	0.00020	0.00023	0.00048
	Chemical and pharmaceutical products ***(7)***	0.05624	0.00776	0.01519	0.01053	0.04954	0.01097	1.10373	0.01146	0.00857	0.01877	0.00777	0.00509	0.00137	0.00232	0.00049	0.00219	0.00075	0.00099	0.00059	0.00275	0.00066	0.00071	0.00109	0.00034	0.00027	0.00018
	Other industries ***(8)***	0.00344	0.01106	0.00687	0.01401	0.04232	0.00496	0.01403	1.06014	0.00942	0.03048	0.04385	0.01005	0.00982	0.00027	0.00051	0.00062	0.00038	0.00043	0.00039	0.00058	0.00093	0.00054	0.00079	0.00046	0.00022	0.00034
	Cement, construction and other non-metallic mineral products ***(9)***	0.00166	0.00344	0.00289	0.00396	0.00574	0.00162	0.00730	0.01236	1.06969	0.00948	0.00180	0.01702	0.00245	0.00011	0.00031	0.00019	0.00011	0.00011	0.00020	0.00030	0.00026	0.00143	0.00037	0.00007	0.00015	0.00007
	Metallurgy ***(10)***	0.00197	0.00255	0.00165	0.00367	0.01590	0.00302	0.00739	0.02870	0.01215	1.06624	0.00157	0.00182	0.00065	0.00022	0.00072	0.00038	0.00018	0.00031	0.00047	0.00041	0.00111	0.00061	0.00220	0.00018	0.00010	0.00015
	Power sector ***(11)***	0.00805	0.03131	0.01763	0.02112	0.04410	0.00943	0.03083	0.04598	0.01239	0.04142	1.16402	0.01808	0.01575	0.00034	0.00043	0.00080	0.00047	0.00050	0.00038	0.00073	0.00056	0.00039	0.00088	0.00114	0.00029	0.00027
	Services ***(12)***	0.07828	0.12593	0.14305	0.16198	0.18393	0.05572	0.18542	0.15188	0.11115	0.12080	0.08005	1.16789	0.14578	0.00174	0.00134	0.00493	0.00164	0.00126	0.00130	0.00228	0.00152	0.00121	0.00163	0.00073	0.00085	0.00081
	Transport, storage and mail ***(13)***	0.02287	0.07617	0.04594	0.02547	0.04909	0.01982	0.03981	0.03166	0.01843	0.05147	0.01569	0.01999	1.08182	0.00048	0.00040	0.00145	0.00038	0.00034	0.00040	0.00061	0.00037	0.00030	0.00059	0.00016	0.00015	0.00026
Rest of Brazil	*Agricultural* ***(1)***	0.07902	0.01244	0.24189	0.02894	0.05582	0.11354	0.02706	0.00973	0.00831	0.00791	0.00464	0.00919	0.01360	1.12411	0.00683	0.45126	0.05629	0.09500	0.07067	0.02806	0.01065	0.00881	0.00776	0.00587	0.01398	0.01298
	Mining ***(2)***	0.03596	0.06623	0.02989	0.01628	0.02507	0.32467	0.05648	0.04070	0.02860	0.08691	0.06064	0.00952	0.08063	0.03196	1.06290	0.02880	0.01890	0.02305	0.52993	0.07331	0.03819	0.03880	0.09842	0.07434	0.01052	0.07547
	Food, beverages and tobacco ***(3)***	0.05813	0.00779	0.12106	0.01755	0.01228	0.02816	0.01613	0.00646	0.00451	0.00522	0.00382	0.00879	0.00584	0.09149	0.00645	1.21987	0.03852	0.01618	0.01883	0.02623	0.00820	0.00591	0.00635	0.00617	0.02369	0.00762
	Textile, clothing and shoes ***(4)***	0.00418	0.03158	0.00337	0.31999	0.00858	0.00401	0.00529	0.00687	0.00394	0.00244	0.00134	0.00293	0.00469	0.00343	0.00464	0.00489	1.30500	0.00760	0.00328	0.00439	0.00676	0.00406	0.00236	0.00187	0.00406	0.00578
	Wood, paper and printing ***(5)***	0.01047	0.01771	0.01750	0.01106	0.06925	0.00869	0.02962	0.02642	0.03788	0.01425	0.00607	0.01551	0.00844	0.00841	0.01044	0.01949	0.01712	1.20488	0.00808	0.02760	0.02962	0.03696	0.01366	0.00801	0.02083	0.00897
	Oil refining, coke and ethanol ***(6)***	0.06621	0.10899	0.05228	0.02677	0.03754	0.12138	0.09574	0.03926	0.03751	0.04328	0.03014	0.01404	0.17213	0.05310	0.04698	0.04919	0.03138	0.03630	1.19241	0.10031	0.04284	0.03807	0.04288	0.04196	0.01835	0.16488
	Chemical and pharmaceutical products ***(7)***	0.15806	0.05772	0.08510	0.05982	0.07068	0.05419	0.13479	0.08195	0.04730	0.06113	0.01416	0.01054	0.01426	0.15992	0.02696	0.08624	0.08566	0.09006	0.03839	1.27772	0.08441	0.05204	0.06884	0.02595	0.01544	0.01402
	Other industries ***(8)***	0.02891	0.11587	0.05312	0.03825	0.04609	0.04848	0.05785	0.22949	0.07061	0.06306	0.04827	0.02594	0.08366	0.02494	0.06471	0.05618	0.05118	0.06714	0.05200	0.06786	1.25958	0.07329	0.08263	0.10941	0.03571	0.08547
	Cement, construction and other non-metallic mineral products ***(9)***	0.00533	0.00811	0.00762	0.00414	0.00452	0.01276	0.01152	0.01072	0.09740	0.00907	0.00365	0.00360	0.00513	0.00533	0.03051	0.00961	0.00750	0.00758	0.01809	0.01635	0.01895	1.15112	0.01742	0.00625	0.01941	0.00677
	Metallurgy ***(10)***	0.01852	0.06669	0.03166	0.01304	0.02647	0.03303	0.02823	0.14680	0.08585	0.27278	0.01797	0.00887	0.01888	0.01571	0.05137	0.03123	0.01678	0.03316	0.03708	0.03522	0.18593	0.08772	1.27732	0.02399	0.01054	0.01790
	Power sector ***(11)***	0.01119	0.01808	0.01432	0.01288	0.00902	0.01535	0.01291	0.01762	0.01077	0.01833	0.00498	0.00338	0.00803	0.01529	0.02965	0.02996	0.03743	0.04016	0.02503	0.04737	0.04553	0.02400	0.05809	1.20247	0.02118	0.02181
	Services ***(12)***	0.09956	0.13471	0.14327	0.11252	0.09829	0.13707	0.15063	0.14369	0.09589	0.12579	0.07027	0.07411	0.11198	0.14182	0.25846	0.27056	0.24584	0.22519	0.20239	0.30525	0.28000	0.19672	0.22346	0.18113	1.25631	0.23791
	Transport, storage and mail ***(13)***	0.03026	0.05973	0.04685	0.02780	0.02781	0.05122	0.03966	0.03900	0.02496	0.04376	0.01837	0.01365	0.03707	0.04116	0.10884	0.08700	0.05114	0.06078	0.08084	0.07038	0.06694	0.04217	0.08721	0.04060	0.03174	1.10882

$(I – A)^{-1}$ matrix.

Note: *Economy sectors - (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Oil refining, coke and ethanol; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail.

The Leontief model's solution can be represented by $X = (I – A)^{-1}.Y$

Appendix VI: Goiás Economic-Ecological Hybrid Input-Output Matrix

		Goiás State													*Emissions*
		(1)	***(2)***	***(3)***	***(4)***	***(5)***	***(6)***	***(7)***	***(8)***	***(9)***	***(10)***	***(11)***	***(12)***	***(13)***	*($TgCO_{2e}$)*
Goiás State	*Agricultural **(1)****	301.93	0.29	1622.08	4.74	13.14	130.00	3.98	2.18	0.84	0.18	0.01	24.20	0.03	89.402
	*Mining **(2)***	16.34	21.56	1.40	0.10	0.29	0.02	31.62	0.43	28.02	5.82	0.01	0.96	0.04	0.189
	*Food, beverages and tobacco **(3)***	174.81	0.10	857.12	9.28	0.84	7.38	25.38	0.73	0.59	0.09	0.31	192.59	0.98	0.591
	*Textile, clothing and shoes **(4)***	0.16	0.08	0.10	38.46	0.69	0.01	0.19	2.56	0.57	0.31	0.17	11.71	2.52	0.0005
	*Wood, paper and printing **(5)***	0.18	0.20	2.50	2.50	41.13	0.12	4.24	11.77	2.92	1.99	0.13	41.40	0.94	0.026
	*Oil refining, coke and ethanol **(6)***	5.76	0.48	2.23	0.43	1.06	13.79	16.51	3.12	2.07	0.44	4.70	69.48	10.79	0.154
	*Chemical and pharmaceutical products **(7)***	253.48	3.68	9.23	4.00	10.44	2.13	147.28	17.09	17.46	13.44	7.32	55.18	0.47	0.067
	*Other industries **(8)***	8.22	5.62	33.14	6.13	9.73	3.39	16.27	118.58	19.35	23.85	59.56	133.62	13.51	2.458
	*Cement, construction and other non-metallic mineral products **(9)***	0.83	0.81	3.97	0.68	0.56	0.50	5.85	18.12	177.47	5.87	0.18	228.75	0.29	0.439
	*Metallurgy **(10)***	6.12	1.04	5.03	1.41	3.40	2.03	8.79	51.56	28.15	55.86	0.16	16.70	0.05	0.765
	*Power sector **(11)***	17.90	13.82	76.87	7.27	7.68	5.26	29.96	78.02	19.17	25.70	177.42	195.63	17.31	0.074
	*Services **(12)***	262.44	58.80	739.39	68.50	34.37	32.27	211.01	238.36	231.07	76.03	71.17	2302.36	202.48	0.068
	*Transport, storage and mail **(13)***	83.45	41.84	258.88	10.11	9.74	13.27	44.16	49.19	35.15	37.50	13.95	244.43	130.44	5.924
	Value added	2500.03	214.93	1369.37	201.52	90.97	212.43	371.92	545.52	1356.23	279.63	850.27	11531.79	866.45	
	Jobs (Thousands)	839.70	15.05	1276.22	86.86	9.97	16.76	18.15	45.83	214.09	18.40	12.11	1446.96	111.62	
	Land use (km²)	204517.41	30.12	6.90	-	3.65	0.09	3.69	1.57	4.23	7.12	2755.16	0.62	-	
	Water (hm³)	3721.594	64.093	22.491	2.012	13.165	1.673	21.027	0.175	1.358	74.501	699.264	38.474	-	
	Energy (PJ)	13.523	7.034	30.857	0.126	0.754	149.552	2.386	2.973	15.240	0.126	99.018	7.536	143.482	
	Total Output	*5405.065*	*640.528*	*8185.984*	*571.938*	*299.093*	*967.173*	*1601.436*	*2092.036*	*2799.151*	*921.998*	*1458.96*	*16926.085*	*1789.164*	

Note: Economic variables in million US$; assuming an average exchange rate of 3.23 R$/US$ for a year period (BCB, 2017. Environmental variables in physical units.
**Economy sectors - (1) Agricultural; (2) Mining; (3) Food, beverages and tobacco; (4) Textile, clothing and shoes; (5) Wood, paper and printing; (6) Oil refining, coke and ethanol; (7) Chemical and pharmaceutical products; (8) Other industries; (9) Cement, construction and other non-metallic mineral products; (10) Metallurgy; (11) Power sector; (12) Services; (13) Transport, storage and mail*

Appendix VII: Useful Volume of Hydropower Reservoir

Useful volume: Monthly average.

Useful volume (%)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Emborcação	0.49	0.57	0.64	0.67	0.66	0.64	0.61	0.55	0.49	0.42	0.38	0.41
Itumbiara	0.49	0.57	0.68	0.74	0.76	0.73	0.67	0.56	0.45	0.36	0.34	0.39
Nova Ponte	0.54	0.59	0.65	0.68	0.68	0.67	0.64	0.60	0.55	0.51	0.48	0.50
São Simão	0.60	0.77	0.87	0.85	0.82	0.78	0.73	0.63	0.55	0.44	0.44	0.48
Average of four power stations	*0.53*	*0.62*	*0.71*	*0.73*	*0.73*	*0.71*	*0.66*	*0.59*	*0.51*	*0.43*	*0.41*	*0.45*

Note: The ONS has made available data for Emborcação, Itumbiara, Nova Ponte and São Simão reservoirs only. Due to the lack of data, the monthly average of useful volume for the other reservoirs in the region of study was estimated from the average found to these four reservoirs.
Source: ONS (2017).

Appendix VIII: Useful Monthly Volume

Real monthly average[*]. Historical series (2000 – 2015).

Hydropower reservoir	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UHE Batalha	1148.9	1272.5	1391.0	1422.9	1417.6	1383.3	1325.0	1220.8	1118.3	1012.2	987.0	1031.6
UHE Nova Ponte	8007.3	8531.1	9163.7	9440.3	9478.4	9368.0	9091.7	8629.9	8142.6	7666.2	7375.7	7611.9
UHE Corumbá I	1017.8	1112.0	1202.4	1226.6	1222.6	1196.4	1152.1	1072.6	994.5	913.6	894.4	928.4
UHE Barra dos Coqueiros	325.4	329.8	334.0	335.1	334.9	333.7	331.7	328.0	324.3	320.6	319.7	321.3
UHE Salto	826.1	826.1	826.1	826.1	826.1	826.1	826.1	826.1	826.1	826.1	826.1	826.1
UHE Emborcação	11089.6	12059.9	12972.0	13406.0	13324.0	13060.8	12609.4	11867.6	11026.8	10162.9	9680.0	10019.3
UHE Cachoeira Dourada	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0
Queimado	340.8	383.1	423.6	434.5	432.7	420.9	401.0	365.4	330.4	294.1	285.5	300.7
Corumbá IV	3346.9	3417.4	3485.1	3503.3	3500.3	3480.7	3447.4	3387.9	3329.4	3268.8	3254.5	3279.9
Corumbá III	848.9	872.9	896.0	902.2	901.2	894.5	883.2	862.9	842.9	822.3	817.4	826.0
Serra do Facão	3585.3	3900.6	4202.9	4284.2	4270.7	4183.1	4034.6	3768.8	3507.4	3236.6	3172.3	3286.1
Itumbiara	10722.2	11697.8	13085.5	13823.4	13983.9	13637.2	12862.1	11568.9	10174.3	9041.0	8854.2	9386.9
Salto Verdinho	264.5	264.5	264.5	264.5	264.5	264.5	264.5	264.5	264.5	264.5	264.5	264.5
Cacu	215.6	218.8	221.8	222.6	222.5	221.6	220.1	217.5	214.8	212.1	211.5	212.6
Espora	144.4	157.0	169.1	172.4	171.8	168.3	162.4	151.7	141.3	130.4	127.9	132.4
Castelo Branco II	878.5	878.6	878.7	878.7	878.7	878.7	878.7	878.6	878.5	878.4	878.4	878.4
Castelo Branco I	235.1	236.3	237.4	237.7	237.7	237.3	236.8	235.8	234.8	233.8	233.6	234.0
Miranda	1051.6	1065.0	1077.8	1081.3	1080.7	1077.0	1070.7	1059.4	1048.4	1036.9	1034.2	1039.0
São Simão	10339.5	11241.3	11843.1	11705.3	11562.0	11323.7	11052.6	10480.4	10037.0	9421.2	9451.0	9675.2

*Note: Useful volume, monthly average (UVMA), from **Appendix VII**; Real useful volume (RUV), from **Table** 7; Minimum volume (MINV), from **Table** 7.*

[*] *Useful monthly volume, Real monthly average = UVMA x RUV – MINV*

Source: Author's calculation from the variables made available from ONS (2017).

Appendix IX: Polynomials for Reservoir Calculation

Hydropower reservoir	a_{QVP}	b_{QVP}	c_{QVP}	d_{QVP}	e_{QVP}	a_{QAP}	b_{QAP}	c_{QAP}	d_{QAP}	e_{QAP}
UHE Batalha	7.75E+02	2.64E-02	-1.06E-05	1.99E-09	0.00E+00	-4.58E+03	5.89E+00	-4.65E-09	-6.03E-13	0.00E+00
UHE Nova Ponte	7.52E+02	1.23E-02	-1.26E-06	7.85E-11	-1.98E-15	-3.23E+05	9.30E+02	-3.85E-01	-8.80E-04	6.76E-07
UHE Corumbá I	5.46E+02	6.47E-02	-3.24E-05	7.39E-09	0.00E+00	-3.89E+04	2.13E+02	-3.90E-01	2.39E-04	0.00E+00
UHE Barra dos Coqueiros	4.18E+02	1.73E-01	-4.19E-04	5.91E-07	-3.20E-10	1.27E+06	-1.13E+04	3.79E+01	-5.64E-02	3.15E-05
UHE Salto	4.47E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.02E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
UHE Emborcação	5.68E+02	1.45E-02	-1.20E-06	5.83E-11	-1.12E-15	-1.82E+04	5.66E+01	4.52E-02	-2.91E-04	2.39E-07
UHE Cachoeira Dourada	4.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.90E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Queimado	8.02E+02	1.14E-01	-1.98E-04	1.44E-07	-2.49E-17	-7.22E+06	2.65E+04	-3.25E+01	1.33E-02	0.00E+00
Corumbá IV	7.89E+02	3.97E-02	-1.50E-05	3.07E-09	-2.37E-13	-2.44E+05	9.31E+02	-1.19E+00	5.06E-04	0.00E+00
Corumbá III	7.50E+02	2.03E-02	4.57E-05	-7.84E-08	3.52E-11	4.18E+04	-1.12E+02	7.50E-02	0.00E+00	0.00E+00
Serra do Facão	6.83E+02	4.87E-02	-1.59E-05	2.67E-09	-1.71E-13	-8.18E+05	3.33E+03	-4.53E+00	2.05E-03	0.00E+00
Itumbiara	4.71E+02	7.28E-03	-5.61E-07	2.60E-11	-4.85E-16	-8.75E+05	5.33E+03	-1.09E+01	7.38E-03	0.00E+00
Salto Verdinho	3.71E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.66E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cacu	4.53E+02	2.00E-01	-7.76E-04	2.17E-06	-2.59E-09	4.50E+05	-3.90E+03	1.27E+01	-1.84E-02	1.00E-05
Espora	5.59E+02	4.00E-01	-2.78E-03	9.26E-06	-1.15E-08	-1.08E+04	6.50E+01	-9.14E-02	-4.83E-05	1.18E-07
Castelo Branco II	5.27E+02	1.10E-01	-1.89E-04	1.93E-07	-7.45E-11	1.07E+06	-7.79E+03	2.12E+01	-2.58E-02	1.17E-05
Castelo Branco I	5.94E+02	3.52E-01	-2.16E-03	7.36E-06	-9.60E-09	-3.58E+06	2.35E+04	-5.79E+01	6.34E-02	-2.60E-05
Miranda	6.85E+02	-4.02E-03	-7.94E-07	2.79E-08	-1.42E-11	6.34E+04	-9.56E+01	-6.59E-02	2.46E-05	1.14E-07
São Simão	3.58E+02	8.62E-03	-8.84E-07	5.29E-11	-1.24E-15	-1.85E+05	1.54E+03	-4.30E+00	4.02E-03	0.00E+00

Source: ONS (2017).

Appendix X: Relative Quota

Quota-Volume polynomial (in hm^3*): Quota =* $a_{QVP} + b_{QVP}.Vol + c_{QVP}.Vol^2 + d_{QVP}.Vol^3 + e_{QVP}.Vol^4$

Hydropower reservoir	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
UHE Batalha	794.36	795.52	796.55	796.82	796.77	796.49	795.99	795.05	794.06	792.94	792.66	793.15
UHE Nova Ponte	802.10	803.74	805.64	806.45	806.56	806.24	805.43	804.04	802.53	801.00	800.03	800.82
UHE Corumbá I	586.01	587.99	589.75	590.20	590.13	589.64	588.78	587.18	585.50	583.63	583.16	583.98
UHE Barra dos Coqueiros	447.05	447.24	447.42	447.46	447.46	447.40	447.32	447.16	447.00	446.84	446.80	446.87
UHE Salto	446.50	446.50	446.50	446.50	446.50	446.50	446.50	446.50	446.50	446.50	446.50	446.50
UHE Emborcação	643.54	646.57	649.29	650.54	650.31	649.55	648.22	645.98	643.34	640.49	638.81	639.99
UHE Cachoeira Dourada	434.12	434.12	434.12	434.12	434.12	434.12	434.12	434.12	434.12	434.12	434.12	434.12
Queimado	823.47	824.64	825.66	825.92	825.88	825.60	825.10	824.17	823.15	821.95	821.64	822.18
Corumbá IV	839.99	840.50	840.99	841.12	841.10	840.96	840.72	840.29	839.86	839.42	839.31	839.50
Corumbá III	770.16	770.51	770.85	770.94	770.92	770.82	770.66	770.37	770.08	769.78	769.71	769.83
Serra do Facão	747.31	749.16	750.88	751.33	751.26	750.77	749.93	748.40	746.85	745.18	744.76	745.49
Itumbiara	510.35	512.08	514.38	515.54	515.78	515.25	514.02	511.85	509.34	507.09	506.70	507.80
Salto Verdinho	370.50	370.50	370.50	370.50	370.50	370.50	370.50	370.50	370.50	370.50	370.50	370.50
Cacu	476.20	476.40	476.59	476.64	476.63	476.58	476.48	476.32	476.15	475.98	475.93	476.01
Espora	581.63	582.05	582.41	582.50	582.49	582.39	582.21	581.88	581.52	581.09	580.97	581.17
Castelo Branco II	564.99	565.00	565.00	565.00	565.00	565.00	565.00	564.99	564.99	564.99	564.99	564.99
Castelo Branco I	623.75	623.82	623.88	623.90	623.90	623.88	623.85	623.79	623.73	623.67	623.66	623.68
Miranda	694.62	694.90	695.16	695.23	695.21	695.14	695.01	694.78	694.55	694.32	694.26	694.36
São Simão	397.21	398.82	399.85	399.62	399.37	398.96	398.48	397.46	396.66	395.51	395.56	395.98

Source: Author's calculation, from ONS (2017) polynomials data.

Appendix XI: Average Monthly Area

Area in $km^2 = a_{QAP} + b_{QAP}.Quota + c_{QAP}.Quota^2 + d_{QAP}.Quota^3 + e_{QAP}.Quota^4$

Hydropower reservoir	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual average**
UHE Batalha	104.89	111.75	117.81	119.37	119.11	117.42	114.49	108.96	103.10	96.51	94.86	97.75	108.83
UHE Nova Ponte	308.25	323.00	340.84	348.67	349.75	346.63	338.81	325.79	312.07	298.63	290.41	297.10	323.33
UHE Corumbá I	45.52	49.18	52.65	53.58	53.43	52.42	50.72	47.66	44.61	41.40	40.63	41.99	47.82
UHE Barra dos Coqueiros	26.34	26.59	26.83	26.89	26.88	26.81	26.69	26.48	26.27	26.06	26.00	26.10	26.49
UHE Salto	60.24	60.24	60.24	60.24	60.24	60.24	60.24	60.24	60.24	60.24	60.24	60.24	60.24
UHE Emborcação	316.69	340.97	363.99	375.00	372.92	366.24	354.81	336.14	315.13	293.63	281.59	290.05	333.93
UHE Cachoeira Dourada	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00	69.00
Queimado	35.43	39.55	43.88	45.13	44.92	43.59	41.42	37.79	34.47	31.31	30.61	31.87	38.33
Corumbá IV	153.67	156.67	159.58	160.37	160.24	159.39	157.95	155.41	152.94	150.41	149.82	150.87	155.61
Corumbá III	65.58	66.83	68.05	68.38	68.33	67.97	67.37	66.31	65.27	64.21	63.96	64.40	66.39
Serra do Facão	160.63	170.74	180.69	183.40	182.96	180.04	175.12	166.49	158.16	149.58	147.53	151.16	167.21
Itumbiara	534.31	573.97	631.44	662.56	669.37	654.67	622.09	568.70	512.20	466.48	458.91	480.46	569.60
Salto Verdinho	36.55	36.55	36.55	36.55	36.55	36.55	36.55	36.55	36.55	36.55	36.55	36.55	36.55
Cacu	15.51	15.67	15.83	15.87	15.87	15.82	15.74	15.61	15.47	15.33	15.30	15.35	15.61
Espora	25.66	26.69	27.60	27.84	27.80	27.55	27.10	26.28	25.39	24.35	24.08	24.55	26.24
Castelo Branco II	54.48	54.49	54.49	54.49	54.49	54.49	54.49	54.48	54.48	54.48	54.48	54.48	54.48
Castelo Branco I	30.84	30.90	30.96	30.98	30.98	30.96	30.93	30.88	30.82	30.77	30.76	30.78	30.88
Miranda	47.84	48.28	48.75	48.88	48.86	48.72	48.48	48.09	47.74	47.40	47.33	47.46	48.15
São Simão	560.16	602.86	631.76	625.13	618.24	606.81	593.86	566.77	546.03	517.61	518.97	529.28	576.46
Total area													**2,755.16**

Source: Author's calculation, from ONS (2017) polynomials data.

Appendix XII: Water Use Coefficients, Total Production and Total Water Use by Sector

Water-use coefficients, total production and total water-use by sector in the state of Goiás, in 2008.

Unit	*Economy sectors*	*Water use coefficients**									*Production (2008)*	*Total water-use (hm³)*	
		Withdrawal (m³)			*Consumption (m³)*			*Effluent (m³)*					
		Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*		*Brazil*	*Goiás*
	Agricultural											**-**	**3,721.59**
t produced	Sugarcane[1;2;3]			168			75				33,112,209		2,494.84
t produced	Soybeans[1;2;3]			954			7				6,604,805		46.23
t produced	Corn[4;5]			478			81				5,101,543		413.22
t produced	Beans[4;5]						89.5				220,449		19.73
t produced	Other culture[4;5]						117				3,596,904		420.84
head/day	Bovine[6]						0.04229				20,466,360		315.92
head/day	Swine[6]						0.01142				1,592,760		6.64
head/day	Poultry[6]						0.00024				47,651,370		4.17
	Industry											**-**	**200.49**
	Mining[7]											***1,125.77***	***64.09***
t produced	Coal extraction			6.25			1.25			5		9.04	0.00
t produced	Iron ore extraction			1.05	0.18	1	0.59			0.87	55,631	241.36	0.03
t produced	Aluminium ore extraction			3.42			2.91			0.51		112.25	0.00
t produced	Tin ore extraction			6.25			1.25			5		0.02	0.00
t produced	Manganese ore extraction			6.25			1.25			5	1,200	4.59	0.00
t produced	Precious metals ores extraction	0.14	1.78	0.96	0.05	1.67	0.86	0.14	0.37	0.255	12.3	1.26	0.00
t produced	Radioactive ores extraction			6.25			1.25			5		0.00	0.00
t produced	Non-ferrous metal ores extraction			1.86			1.58			0.28	43,526	2.37	0.07
t produced	Stone, sand and clay extractions	0.04	7.64	3.84	0.03	7.42	3.725	0.01	0.22	0.115	6,953,183	681.96	25.90
t produced	Extraction of minerals for the manufacture of fertilizers and other chemical products	16.4	47.5	31.95	6.6	13.8	10.2	2.6	36.8	19.7	3,542,870	63.87	36.14
t produced	Sea salt extraction and refining			6.25			1.25			5		5.56	0.00
t produced	Gemstones extractions (precious and semi-precious stones)			6.25			1.25			5	10.23	0.00	0.00
t produced	Extraction of non-metallic minerals not previously specified			6.25			1.25			5	1,561,801	3.50	1.95
	Food, beverages and tobacco											***858.45***	***22.49***
t of live animal	Slaughter of cattle except swine			2			0.25			1.75	7,136,568	1.78	0.05
t of live animal	Slaughter of swine, poultry and other small animals	4	12	8	0.5	1.5	1	3.5	10.5	7	12,395,702	12.40	0.32
t produced	Manufacture of meat products			12			1.5			10.5	1,828,366	2.74	0.07

t produced	Preservation of fish and manufacture of fish products			12.5			2.5			10	327,759	0.82	0.02
t of feedstock	Manufacture of canned fruit and vegetables			18.75			3.75			15	2,174,600	8.15	0.21
t of feedstock	Manufacture of vegetable oils and fats	0.2	14	7.1				0.2	14	7.1	31,815,133	0.00	0.00
m^3 of milk	Dairy products	1.1	2	1.55				1.6	2.2	1.9	10,072,008	0.00	0.00
t produced	Grinding, manufacture of starch products and animal feed	1.7	3	2.35	0.3	1.2	0.75	1.4	1.8	1.6	34,136,289	25.60	0.67
t of sugar	Manufacture and refining of sugar			17			17				45,169,130	767.88	20.12
t produced	Manufacture of other food products			4.72			0.95			3.78	9,292,352	8.83	0.23
m^3 produced	Manufacture of spirits and other distilled beverages			1.24			0.47			0.77	1,506,552	0.71	0.02
t of grape	Manufacture of wine[8]			2.5			0.5			2	283,190	0.14	0.00
m^3 produced	Manufacture of malt, beer and draft beer	4	5.4	4.7	0.8	1.2	1	3.2	4.3	3.75	10,848,516	10.85	0.28
m^3 produced	Manufacture of non-alcoholic beverages	1.4	3	2.2			0.9	0.5	2.1	1.3	14,114,237	12.70	0.33
t of feedstock	Manufacture of tobacco products			31.25			6.25			25	935,666	5.85	0.15
	Textile, clothes and shoes											***76.78***	***2.01***
t produced	Manufacture and spinning of textile fibres	115	118	116.5	22	23	22.5	93	96	94.5	982,190	22.10	0.58
t produced	Weaving, except knitted	42	48	45	7	8	7.5	35	40	37.5	1,377,733	10.33	0.27
t produced	Manufacture of knitted fabrics			36			6			30	274,473	1.65	0.04
t produced	Textile yarn, fabric and textile finishing	19	104	61.5	3.5	20	11.75	15	83	49	-	0.00	0.00
Thousand pieces	Manufacture of other textile products, except apparel	2.1	8.2	5.15	1.8	6.9	4.35	0.3	1.3	0.8	1,251,334	5.44	0.14
Thousand pieces	Manufacture of wearing apparel and accessories			11.9			2.2			9.8	1,269,363	2.79	0.07
Thousand pieces	Manufacture of knitted and crocheted articles			3.32			0.64			2.68	6,849	0.00	0.00
Skin processed	Tanning and other leather preparations[9]	0.47	1	0.735			0.735	0.47	1	0.735	45,908,697	33.74	0.88
Pair of shoes	Manufacture of shoes			0.0021			0.0004			0.0017	778,164,312	0.31	0.01
Pair of shoes	Manufacture of parts for footwear, of any material			0.0038			0.0008			0.003	514,221,340	0.41	0.01
	Wood, paper and printing											***502.47***	***13.16***
Thousand m^3 of wood	Manufacture of products of wood, cork and plaited materials, other than furniture[10]			3.2			0.84			2.36	26,270	0.02	0.00
Air dried t	Manufacture of pulp and paper pulp	25.9	46.8	36.35	3.2	5.8	4.5	22.7	41	31.85	9,645,659	43.41	1.14
t of paper	Manufacture of paper and paperboard	10	46.3	28.15	1.8	8.4	5.1	8.2	37.9	23.05	80,179,983	408.92	10.71
t of paper	Manufacture of paper packaging, cardboard, corrugated paperboard and paperboard			0.46			0.33			0.13	4,867,168	1.61	0.04
t of paper	Manufacture of other products from paper, paperboard, cardboard and corrugated paperboard	13	27	20	4	9	6.5	9	18	13.5	7,464,755	48.52	1.27
t of finished material	Printing and reproduction of recordings	0.17	9	4.585	0.03	1.8	0.915	0.14	7.2	3.67	2,602	0.00	0.00
	Oil refining, coke and alcohol[1;11]											***436.12***	***1.67***
t of coke	Manufacture of coke			12.4			2.5			9.9	649.60	0.42	0.00
Barrels of oil	Manufacture of petroleum products			0.188			0.038			0.15		0.00	0.00
m^3/GJ	Manufacture of biofuels (ethanol)						45				37,139	435.70	1.67

	Chemical and pharmaceutical products											***802.55***	***21.03***
t produced	Manufacture of inorganic products	3	16	9.5	2	4	3	2	12	7	32,562,593	97.69	2.56
t produced	Manufacture of organic products	2	70	36	1	40	20.5	1	30	15.5	32,500,860	666.27	17.46
t produced	Manufacture of resins and elastomers	2	15	8.5	1	4	2.5	1	11	6	3,808,384	9.52	0.25
t produced	Manufacture of artificial and synthetic fibres			1.25			0.25			1	368,064	0.09	0.00
t produced	Manufacture of pesticides and disinfectants			10.3			3.3			7	778,477	2.57	0.07
t produced	Manufacture of soap, detergents, cleaning products, cosmetics, perfumery and personal care products	1.2	1.7	1.45	0.6	0.8	0.7	0.6	0.9	0.75	6,073,451	4.25	0.11
t produced	Manufacture of paints, varnishes, enamels, lacquers and related products			1			0.7			0.3	1,468,857	1.03	0.03
t produced	Manufacture of other chemical products and preparations	0.5	60	30.25	0	10	5	0.5	50	25.25	3,587,391	17.94	0.47
t produced	Manufacture of pharmaceutical and chemical products			312.5			62.5			250	51,086	3.19	0.08
	Other industries											***6.67***	***0.17***
t produced	Manufacture of rubber products			16.2			3.2			13	1,888,193	6.04	0.16
t produced	Manufacture of plastic materials			0.23			0.05			0.18	12,603,992	0.63	0.02
	Cement, construction and other non-metallic minerals											41.21	1.36
t produced	Manufacture of glass and glass products	0.3	10	5.15			0.1	0.2	9.9	5.05	768,911	0.08	0.00
t produced	Manufacture of cement	0.08	0.4	0.24	0.08	0.4	0.24				52,279,324	12.55	0.41
m³ of concrete	Manufacture of articles of concrete, cement, asbestos cement, plaster and similar materials			0.25			0.25				27,847,966	6.96	0.23
Piece	Manufacture of ceramic products			0.0471			0.01			0.00371	706,566,254	7.07	0.23
t produced	Stone working and other non-metallic mineral products manufacturing	0.41	7.27	3.84	0.08	1.45	0.765	0.33	5.82	3.075	19,036,665	14.56	0.48
	Metallurgy											***2,862.33***	***74.50***
t produced	Manufacture of pig iron and iron-alloys			1.25			0.25			1	11,059,906	2.76	0.00
t of crude steel	Steel industry			33.6			8.7			24.9	118,248,271	1,028.76	26.95
t produced	Manufacture of steel tubes	1.25	52.5	26.875	0.25	10.5	5.375	1	42	21.5	2,981,729	16.03	0.00
t produced	Metallurgy of non-ferrous metals	1.24	3.5	2.37	0.25	0.7	0.475	0.99	2.8	1.895	11,460,190	5.44	0.14
t produced	Foundry			5			1			4	1,329,157	1.33	0.03
t produced	Manufacture of metal products, except machinery and equipment			2.65			1.24			1.41	11,998,958	14.88	0.39
Unit produced	Manufacture of computers, electronics and optical products			0.0985			0.0197			0.0788	7,977,494,924	1,57.16	4.12
Unit produced	Manufacture of machinery and equipment	2.2	9.7	5.95	0.4	1.9	1.15	1.8	7.8	4.8	690,725,562	794.33	20.81
Unit produced	Manufacture of cars, vans and commercial vehicles	2.6	5	3.8	0.47	0.9	0.685	2.13	4.1	3.115	5,364,948	3.67	0.10
Unit produced	Manufacture of trucks and buses			9			1.6			7.4	866,138	1.39	0.04
t produced	Manufacture of parts and accessories for motor vehicles			1.39			0.53			0.87	1,578,448,061	836.58	21.92
	Power sector											**-**	**699.26**
m³/MWh	Water footprint of hydro plants of the Paranaíba basin[11;12]						28.742				24,329,000		699.26

	Services		-	**38.47**
m³/s	Human supply[13]	6.10		38.47

*Source: [1]Fachinelli and Pereira (2015); [2]IBGE (2009); [3]IBGE (2009a); [4]FAO (2017); [5]Mekonnen and Hoekstra (2011); [6]EMBRAPA (2013); [7]DNPM (2009); [8]EMBRAPA (2016); [9]CETESB (2014); [10]IPT (2013); [11]Goiás (2010); [12]**Appendix XV**; [13]ANA (2015).*

Assumptions:

- **The water use coefficient applied in all estimates was the average of water consumption. The choice was based on the available data and because of the purpose of the study which aims to identify the water used by the sectors of the economy. The water use (consumption), therefore, suits better when estimating the water unavailable for other uses.*
- *First, the water consumption was calculated for the whole country due to most of the production data (physical/bulk production) be available for Brazil and not for states or regions of the country. Thus, it was applied a production ratio that represents the share of the state of Goiás on the national production, in 2008. The share applied was based on both Brazilian National and Regional accounts (IBGE, 2010, 2011), which accounted for 26% for Food, beverages and tobacco, Textile, clothes and shoes, Wood, paper and printing, Chemical and pharmaceutical products, Other industries and Metallurgy sectors. Goiás Cement, construction and other non-metallic minerals sector accounted for 33% of the National production, in 2008 (IBGE, 2010).*
- *The total production data for the Mining sector was obtained from the National Department of Mineral Production - DNPM (2009). The DNPM published a report of the mineral sector's performance of the state of Goiás for the year 2008.*
- *Data for the Oil refining, coke and ethanol sector was obtained from the Goiás Energy Balance (Brasil, 2010). There is no refineries and coke production in the state of Goiás. Despite of that, the firewood production in the IO model was included in the activity "Manufacture of coke". It was assumed that: 1t of sugarcane = 85 L of ethanol; 1t of sugarcane consumes 9.1 L of water; 50% of processed sugarcane was used to produce ethanol in 2008. In the activity "Manufacture of coke", it was assumed that 545 toe (firewood) = 5.450 x 10^6 kcal / 8.390 = 649.6 t of coke; 1kg of coke = 8,390 kcal. Regarding biofuels production (ethanol), 968,232 t of ethanol x 0.85 g/cm³ (ethanol density) = 822,997,200 L of ethanol, divided by 85 L/t of sugarcane = 9,682,320 t of sugarcane. Finally, 1TEP = 41.87 GJ; from Brasil (2010), 887 TEP = 37,139 GJ.*
- *In the Food, beverages and tobacco sector, activity "Manufacture of wine", the amount of wine declared by IBGE (2009b) – 381.658m³ of wine, was multiplied by 0.742 m³ of wine by tonnes of grape (equals to 283,190 t of grape), according to EMBRAPA (2016).*
- *In the Textile, clothes and shoes sector, for the activity "Tanning and other leather preparation" was assumed that: 1 skin = 37.5 kg; 1kg of skin = 0.225 kg of finished leather (yield of 22.5%), according to CETESB (2014); Total production of 166,096 t of finished leather (IBGE, 2009b). Multiplying the total production by 1.775 (+77.5%) = 294,820 t; divided by 37.5 kg (average weight of one skin) = 7,861,887 skins. 1skin = 7.1 m²; 270,132,357 m² (IBGE, 2009b) divided by 7.1 = 38,046,810 skins. Total = 7,861,887 + 38,046,810 = 45,908,697 skins processed in 2008.*
- *In the Wood, paper and printing sector, for the activity "Manufacture of products of wood, cork and plaited materials, other than furniture" was assumed that: The average density of 20 species used in construction sector = 682 kg/m³; of 17,093 t of wood produced, it results in about 26,270 m³, according to IPT (2013).*
- *According to Brasil (2010) – Energy Balance for the Goiás State, hydropower plants produced 24,329,00 MWh in the state in 2008, accounting for 96.4% of total power production. It was assumed a water footprint of 28.742 m³ of water/MWh produced. Therefore, 699.26 hm³ of water was consumed through evaporation (see **Appendices XII**, **XIII**, **XIV** and **XV**.*
- *In the Services sector, for the activity "Human supply" was assumed: 1 year = 31,536,000 seconds x 6.1 m³ of water consumption per second (from ANA, 2015) = 192,369,600 x 20% (the estimated share of consumption in the commercial sector) = 38.47 hm³ of water.*

Appendix XIII: Evaporation Coefficients

Net evapotranspiration in reservoirs, by month (in *mm*).

Hydropower reservoir	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
UHE Batalha	10	6	21	39	58	62	63	63	61	26	10	29
UHE Nova Ponte	16	7	23	40	61	65	67	66	54	25	13	33
UHE Corumbá I	2	1	17	37	53	56	58	54	55	21	8	21
UHE Barra dos Coqueiros	12	7	22	42	64	70	68	68	67	20	6	25
UHE Salto	12	8	23	42	64	70	68	69	66	19	5	25
UHE Emborcação	0	2	16	36	53	54	54	50	45	16	5	19
UHE Cachoeira Dourada	11	5	24	44	59	63	61	62	65	27	11	30
Queimado	21	4	21	33	59	70	77	79	80	51	17	51
Corumbá IV	19	8	19	32	56	64	73	84	86	53	13	44
Corumbá III	12	11	19	32	57	63	68	72	72	42	21	37
Serra do Facão	6	8	20	35	55	57	57	59	52	24	16	31
Itumbiara	6	1	19	42	58	62	60	56	58	22	5	23
Salto Verdinho	14	14	27	46	65	67	63	64	65	23	9	30
Cacu	12	5	21	39	62	69	69	69	68	19	7	24
Espora	10	5	24	37	55	61	64	75	71	25	19	28
Castelo Branco II	2	0	18	40	55	56	53	49	50	19	4	23
Castelo Branco I	2	0	18	38	51	51	48	46	45	18	6	25
Miranda	7	4	18	37	54	54	53	52	41	15	5	26
São Simão	13	11	25	46	67	72	68	66	64	22	4	25

Source: ONS (2004) – Net evaporation in hydropower plants.

Appendix XIV: Net Evaporation of Reservoirs

Net evaporation, monthly average (in *hm³*).

Hydropower reservoir	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual average**
UHE Batalha	1.0	0.6	2.4	4.6	6.9	7.3	7.2	6.9	6.3	2.5	0.9	2.8	*48.6*
UHE Nova Ponte	4.9	2.3	7.8	13.9	21.3	22.5	22.7	21.5	16.9	7.5	3.8	9.8	*150.0*
UHE Corumbá I	0.1	0.0	0.9	2.0	2.8	2.9	2.9	2.6	2.5	0.9	0.3	0.9	*18.7*
UHE Barra dos Coqueiros	0.3	0.2	0.6	1.1	1.7	1.9	1.8	1.8	1.8	0.5	0.2	0.7	*12.2*
UHE Salto	0.7	0.5	1.4	2.5	3.9	4.2	4.1	4.2	4.0	1.1	0.3	1.5	*27.7*
UHE Emborcação	0.0	0.7	5.8	13.5	19.8	19.8	19.2	16.8	14.2	4.7	1.4	5.5	*121.3*
UHE Cachoeira Dourada	0.8	0.3	1.7	3.0	4.1	4.3	4.2	4.3	4.5	1.9	0.8	2.1	*31.1*
Queimado	0.7	0.2	0.9	1.5	2.7	3.1	3.2	3.0	2.8	1.6	0.5	1.6	*20.9*
Corumbá IV	2.9	1.3	3.0	5.1	9.0	10.2	11.5	13.1	13.2	8.0	1.9	6.6	*82.9*
Corumbá III	0.8	0.7	1.3	2.2	3.9	4.3	4.6	4.8	4.7	2.7	1.3	2.4	*32.9*
Serra do Facão	1.0	1.4	3.6	6.4	10.1	10.3	10.0	9.8	8.2	3.6	2.4	4.7	*70.4*
Itumbiara	3.2	0.6	12.0	27.8	38.8	40.6	37.3	31.8	29.7	10.3	2.3	11.1	*242.3*
Salto Verdinho	0.5	0.5	1.0	1.7	2.4	2.4	2.3	2.3	2.4	0.8	0.3	1.1	*17.3*
Cacu	0.2	0.1	0.3	0.6	1.0	1.1	1.1	1.1	1.1	0.3	0.1	0.4	*7.1*
Espora	0.3	0.1	0.7	1.0	1.5	1.7	1.7	2.0	1.8	0.6	0.5	0.7	*12.3*
Castelo Branco II	0.1	0.0	1.0	2.2	3.0	3.1	2.9	2.7	2.7	1.0	0.2	1.3	*20.0*
Castelo Branco I	0.1	0.0	0.6	1.2	1.6	1.6	1.5	1.4	1.4	0.6	0.2	0.8	*10.7*
Miranda	0.3	0.2	0.9	1.8	2.6	2.6	2.6	2.5	2.0	0.7	0.2	1.2	*17.4*
São Simão	7.3	6.6	15.8	28.8	41.4	43.7	40.4	37.4	34.9	11.4	2.1	13.2	*275.7*
Average net annual evaporation (hm³)													**1,219.47**

Note: $EVAV = 10^{-3}. Area . EVAC_i$

Area, from ***Appendix XI: Average Monthly Area.***

EVAC, from ***Appendix XIII: Evaporation Coefficients.***

Appendix XV: Water Footprint of Power Plants in the Region of Study

Hydropower station	**Power generation**				**Water footprint**		
	$MW_{average}$	**MW(month)**	**MWh (year)**	**kWh (year)**	**m^3/MWh**	**m^3/kWh**	**GJ (year)**
UHE Batalha	48.8	36307	427,488	427,488,000	**113.7**	**0.114**	1,538,957
UHE Nova Ponte	276	205344	2,417,760	2,417,760,000	**62.0**	**0.062**	8,703,936
UHE Corumbá I	209	155496	1,830,840	1,830,840,000	**10.2**	**0.010**	6,591,024
UHE Barra dos Coqueiros	57.3	42631	501,948	501,948,000	**24.3**	**0.024**	1,807,013
UHE Salto	63.8	47467	558,888	558,888,000	**49.5**	**0.049**	2,011,997
UHE Emborcação	497	369768	4,353,720	4,353,720,000	**27.9**	**0.028**	15,673,392
UHE Cachoeira Dourada	415	308760	3,635,400	3,635,400,000	**8.6**	**0.009**	13,087,440
Queimado	58	43152	508,080	508,080,000	**41.2**	**0.041**	1,829,088
Corumbá IV	76.6	56990	671,016	671,016,000	**123.5**	**0.124**	2,415,658
Corumbá III	50.9	37870	445,884	445,884,000	**73.7**	**0.074**	1,605,182
Serra do Facão	182.4	135706	1,597,824	1,597,824,000	**44.1**	**0.044**	5,752,166
Itumbiara	1015	755160	8,891,400	8,891,400,000	**27.3**	**0.027**	32,009,040
Salto Verdinho	58.2	43301	509,832	509,832,000	**33.9**	**0.034**	1,835,395
Cacu	42.9	31918	375,804	375,804,000	**18.9**	**0.019**	1,352,894
Espora	23.5	17484	205,860	205,860,000	**59.7**	**0.060**	741,096
Castelo Branco II	131	97464	1,147,560	1,147,560,000	**17.4**	**0.017**	4,131,216
Castelo Branco I	155	115320	1,357,800	1,357,800,000	**7.9**	**0.008**	4,888,080
Miranda	202	150288	1,769,520	1,769,520,000	**9.8**	**0.010**	6,370,272
São Simão	1281	953064	11,221,560	11,221,560,000	**24.6**	**0.025**	40,397,616
Total Paranaíba basin	**4843.4**	**3603490**	**42,428,184**	**42,428,184,000**	**28.742**	**0.029**	**152,741,462**

Note: Total WF = Average annual total evaporation/MWh (year)

Average annual total, from ***Appendix XIV: Net Evaporation of Reservoirs***

The total estimated water footprint of hydropower plants in the Paranaíba basin was 28.742 m^3/MWh. This indicator was applied to estimate the water use from the power sector in 2008, according to the generation of 24,329 GWh of power and by consuming 699.27 hm^3 of water through evaporation processes (24,329,000 MWh x 28.742 m^3/MWh).

Source: Own elaboration based on ANEEL (2017).

Appendix XVI: GHG Emissions References

References used to determine GHG emissions in the state of Goiás, in 2008.

Economy sectors	*Brazil*									*Goiás State*						
	(1) in Gg			*(2) in Gg*					*(3)in Gg*	*(4) in Gg*			*(5) in t*			
	Co_2	*CH_4*	*N_2O*	*Co_2*	*CH_4*	*N_2O*	*CO*	*NO_x*	*GgCO2e GWP-AR2*	*GgCO2e GWP-AR2*	*CH_4*	*N_2O*	*GgCO2e GWP-AR2*	*Co_2*	*CH_4*	*N_2O*
Agricultural	17,296	12,678.1	495.26	17,473	11,955.4	448.06	5,980.4	162.5	408,234.2	34,409.55	1,079.89	37.84	34,360,642		441,107	1,079,893
Sugarcane																
Soybeans																
Corn																
Beans																
Rice crops		430			474.2											
Other culture									9,958.20							
Burning of agricultural wastes		169.7	8.37		175.5	4.55	5,980.4	162.5	5,096							
Agricultural soils			472						133,052							
Enteric fermentation		11,296.8			10,730.3	429.20			225,336.30							
Waste management		760.8	14.31		575.4	14.31			16,520							
Bovine																
Swine																
Poultry																
Industrial processes	163,285	11,381.64	8.12	142,720	89.40	8.95	2,568.9	408.50	153,685.07				382,258	382,258		
Mining	8,168	0.13	0.07	1,658	58.6											
Coal extraction	1,784	72.34							2,888.60							
Iron ore extraction																
Aluminium ore extraction																
Tin ore extraction																
Manganese ore extraction																
Precious metals ores extraction																
Radioactive ores extraction																
Non-ferrous metal ores extraction																
Stone, sand and clay extractions																
Extraction of minerals for the manufacture of fertilizers and other chemical products																
Sea salt extraction and refining																
Gemstones extractions (precious and semi-precious stones)																

Extraction of non-metallic minerals not previously specified				
Food, beverages and tobacco	3,834	21.82	3.13	230.5
Slaughter of cattle except swine				
Slaughter of swine, poultry and other small animals				
Manufacture of meat products				
Preservation of fish and manufacture of fish products				
Manufacture of canned fruit and vegetables				
Manufacture of vegetable oils and fats				
Dairy products				
Grinding, manufacture of starch products and animal feed				
Manufacture and refining of sugar				
Manufacture of other food products				
Manufacture of spirits and other distilled beverages				
Manufacture of wine				
Manufacture of malt, beer and draft beer				
Manufacture of non-alcoholic beverages				
Manufacture of tobacco products				
Textile, clothes and shoes	**1,128**	**0.28**	**0.03**	
Manufacture and spinning of textile fibres				
Weaving, except knitted				
Manufacture of knitted fabrics				
Textile yarn, fabric and textile finishing				
Manufacture of other textile products, except apparel				
Manufacture of wearing apparel and accessories				
Manufacture of knitted and crocheted articles				
Tanning and other leather preparations[9]				
Manufacture of shoes				
Manufacture of parts for footwear, of any material				
Wood, paper and printing	**3,383**	**2.24**	**0.60**	
Manufacture of products of wood, cork and plaited materials, other than furniture				
Manufacture of pulp and paper pulp				
Manufacture of paper and paperboard				
Manufacture of paper packaging, cardboard, corrugated paperboard and paperboard				

Manufacture of other products from paper, paperboard, cardboard and corrugated paperboard								
Printing and reproduction of recordings								
Oil refining, coke and alcohol[1]	**12,374**	**111.73**	**0.17**	**12,549**	**114.3**			
Manufacture of coke								
Manufacture of ethanol	59	0.498						
Manufacture of ethene	5	10.278						
Manufacture of ethene oxide	139	0.478						
Manufacture of petroleum products								
Manufacture of biofuels (ethanol)								
Chemical and pharmaceutical products	**23,665**	**0.57**	**0.10**	**14,283**	**11.5**	**2.28**		
Use of kelp	357							
Production of ammonia	1,811			1,811				
Production of calcium carbide	43							
Production of vinyl chloride	198	0.015						
Production of actinonitrile	16	0.012						
Production of carbon black	632	0.023						
Production of phosphoric acid	114							
Production of nitric acid			1.58			1.58		
Production of adipic acid			0.37			0.37		
Production of caprolactam			0.33					
Use of HFC, PFC, SF6								
Production of magnesium								
Manufacture of inorganic products								
Manufacture of organic products								
Manufacture of resins and elastomers								
Manufacture of artificial and synthetic fibres								
Manufacture of pesticides and disinfectants								
Manufacture of soap, detergents, cleaning products, cosmetics, perfumery and personal care products								
Manufacture of paints, varnishes, enamels, lacquers and related products								
Manufacture of other chemical products and preparations								
Manufacture of pharmaceutical and chemical products								
Other industries	**7,879**	**1.35**	**0.23**	**50,708**	**32.7**		**1,364.9**	**278.8**
Manufacture of rubber products								
Manufacture of plastic materials								
Cement, construction and other non-metallic minerals								

Manufacture of glass and glass products																
Manufacture of cement	31,073	2.36	0.14	18,884												
Manufacture of articles of concrete, cement, asbestos cement, plaster and																
Manufacture of ceramic products	4,602	2.82	0.38													
Stone working and other non-metallic mineral products manufacturing																
Lime production	5,690			5,690												
Other uses of limestone and dolomite	1,731															
Metallurgy				**5,811**	**45.2**	**1.47**	**12.3**	**129.7**								
Manufacture of pig iron and iron-alloys	57,527	44.83	1.10	40,967			956.3									
Steel industry																
Manufacture of steel tubes																
Manufacture of aluminium	2,749			2,753												
Metallurgy of non-ferrous metals	8,480	0.24	0.05	1,813			4.9									
Foundry																
Manufacture of metal products, except machinery and equipment																
Manufacture of computers, electronics and optical products																
Manufacture of machinery and equipment																
Manufacture of cars, vans and commercial vehicles																
Manufacture of trucks and buses																
Manufacture of parts and accessories for																
Power sector	**62,651**	**173.31**	**2.83**	**58,186**	**36.7**		**1,778.4**	**584**	**60,599.7**				**9,385,520**	**9,178,137**	**72,132**	**1,798**
Integrated National System[2]	0.0484															
Transport	**148,416**	**12.68**	**3.32**	**150,798**	**67.9**	**13.42**	**3,065.2**	**1,456.5**	**156,384.10**							
Services/commercial	**1,772**	**1.48**	**0.03**						**1,869.70**							
Waste treatment	**122,397**	**1,843,856**	**14.40**	**159**	**2,277.4**	**6.96**			**50,142**				**2,374,186**	**20,123**		**108,800**
Solid waste		1,175,199			1,266.4				26,755.50							
Effluent		668,657	14.40		1,011				23,385.50							

Note: [1]Fugitive emissions. [2]Emission factor of the National Integrated System (SIN, in Portuguese). Blank cells mean there is no data available for the corresponding sector or activity, according to available sources.

Source: (1) Annual estimates of GHG emissions in Brazil (MCTI, 2014);

(2) Third National Communication of Brazil to the United Nations Framework Convention on Climate Change (MCTI, 2016);

(3) National Emissions Record System – SIRENE (SIRENE, 2017);

(4) National Emissions Record System – SIRENE, Goiás, 2008 (SIRENE, 2017) (available at: http://sirene.mcti.gov.br/web/guest/emissoes-por-unidade-federativa) ;

(5) Emission Estimating System for GHG – SEEG, Goiás, 2008 (SEEG, 2017) (available at: http://plataforma.seeg.eco.br/total_emission).

For a deeper understanding on the methodological approach used in the official estimates presented here, please refer to MCT (2010, 2010a, 2010b, 2010c, 2010d, 2010e), MCTI (2014, 2016) and SEEG (2016, 2016a, 2016b, 2017b).

Appendix XVII: Goiás' GHG Emissions

GHG emissions in the state of Goiás, in 2008. The source SEEG (2017) was chosen because of the best available data for the state of Goiás.

Economy sectors	*GHG emissions (t)*		
	$CO_{2e\ GWP\text{-}AR2}$	*$CO_{2e\ GWP\text{-}AR5}$*	*$CO_{2e\ GTP\text{-}AR5}$*
Agricultural	**35,776,828**	**41,674,079**	**14,461,701**
Sugarcane	484,056	543,872	211,958
Soybeans	498,819	426,410	376,528
Corn	257,723	220,311	194,539
Beans	23,665	20,230	17,863
Rice crops	49,632	62,112	14,246
Other crops	103,558	88,526	78,169
Organic soils	149,549	127,840	112,885
Synthetic fertilizers	1,599,789	1,367,562	1,207,583
Asinos	4,980	4,943	2,950
Poultry	282,723	255,615	196,977
Buffaloes	52,508	61,978	19,475
Goats	9,275	9,981	4,580
Equine	429,235	453,304	222,124
Beef cattle	25,067,188	30,510,855	8,209,345
Milk cattle	4,870,210	5,554,702	2,035,061
Mules	35,076	34,812	20,782
Sheep	43,084	46,355	21,286
Swine	508,364	579,645	212,622
Industrial processes	**3,973,664**	**4,689,223**	**2,194,165**
Mining	***189,469***	***189,455***	***189,238***
Food, beverages and tobacco	***497,111***	***590,789***	***269,398***
Dairy products	158,476	211,301	30,185
Manufacture and refining of sugar	119,775	159,701	22,814
Manufacture of malt, beer and draft beer	2,767	3,690	527
Textile, clothes and shoes	***462***	***461***	***461***
Wood, paper and printing	***19,488***	***25,620***	***4,596***
Manufacture of pulp and paper pulp	18,394	24,526	3,503
Oil refining, coke and alcohol	***115,463***	***153,951***	***21,993***
Manufacture of biofuels (ethanol)	115,463	153,951	21,993
Chemical and pharmaceutical products	***66,522***	***66,519***	***66,438***
Other industries	***1,881,011***	***2,458,324***	***438,838***
Cement, construction and other non-metallic minerals	***439,186***	***439,155***	***438,999***
Manufacture of cement	5,148	5,148	5,142
Manufacture of ceramic products	51,780	51,749	51,702
Metallurgy	***764,947***	***764,943***	***764,096***
Manufacture of pig iron and iron-alloys	136,825	136,814	136,662
Metallurgy of non-ferrous metals	628,122	628,129	627,434
Power sector	**73,586**	**73,584**	**73,497**
Transport sector	**5,933,334**	**5,924,289**	**5,868,748**
Services / Commercial	**67,941**	**67,918**	**67,861**
Waste	**2,374,184**	**3,125,738**	**507,596**
Domestic effluents	381,241	476,253	110,442
Industrial liquid effluents	523,678	698,238	99,748
Solid waste final disposal	1,446,915	1,929,220	275,602
Waste incineration	22,350	22,027	21,804
Land-use, land-use change and forests	**47,046,802**	**47,728,325**	**44,541,099**
Land-use changes	41,679,890	41,679,890	41,679,890
Liming	1,279,520	1,279,520	1,279,520
Forestry residues	4,087,392	4,768,915	1,581,689

Note: The GHG emissions indicator chosen by this work was the $CO_{2e\ GWP\text{-}AR5}$.

Source: SEEG (2017), Annual estimates of GHG emissions in Brazil, 2008. Available at: http://plataforma.seeg.eco.br/total_emission.

Assumptions (all the following assumptions were considered for the $CO_{2e\ GWP\text{-}AR5}$ *indicator):*

- *Agricultural: 40,223,988 t (from agricultural sector) + 1,305,026 t (from the energy used by the sector) + 145,065 t (waste/effluent from agricultural);*
- *Sugarcane: 480,778 t (from sugarcane crops) + 63,094 t (vinasse);*
- *Other cultures: 74,862 t (other cultures crops) + 13,664 t (cassava);*
- *Poultry: 240,858 t (from agricultural sector) + 14,757 t (from waste/effluent);*
- *Beef cattle: 30,407,153 t (from agricultural sector) + 103,702 t (from waste/effluent);*
- *Swine: 553,039 t (from agricultural sector) + 26,606 t (waste/effluent);*
- *Industrial processes: 382,258 t (from industrial processes) + 1,348,323 t (from the energy used by the sector) + 2,519,481 t (waste/effluent);*
- *Food, beverages and tobacco: 216,097 t (from the energy used by the sector) + 374,692 t (waste/effluent);*
- *Dairy products: 190,303 t (waste/effluent from the raw milk) + 20,998 t (effluent from pasteurized milk);*
- *Manufacture and refining of sugar: 159,701 t (from waste/effluent);*
- *Manufacture of malt, beer and draft beer: 3,690 t (from waste/effluent);*
- *Wood, paper and printing: 1,094 t (from the energy used by the sector) + 24,526 t (effluent);*
- *Manufacture of pulp and paper pulp: 24,526 t (effluent);*
- *Manufacture of biofuels (ethanol): 153,951 t (waste/effluent);*
- *Other industries: 52,851 t (from the energy used by the sector) +476,253 t (residential effluent) + 1,929,220 t (waste disposal);*
- *Cement, construction and other non-metallic minerals: 382,258 t (industrial processes) + 5,148 t (from the energy used by the sector) + 51,749 t (energy used by the activity ceramics);*
- *Metallurgy: It does not consider state emissions from melting carbonates process (lack of data on state consumption of dolomite and limestone). It only considers emissions of the use of fuels (coke, coal) in the state;*
- *Manufacture of pig iron and iron-alloys: 97,269 t (from the energy used by pig iron activity) + 39,545 t (energy used by iron-alloys activity);*
- *Power sector: 29,988 t (from public producers) + 43,596 t (from private/self-producers);*
- *Emissions from land-use, land-use change, and forests were included in the Agricultural sector of the Goiás hybrid IO model because of the origin of the emissions (i.e. land-use change, liming and forestry residues).*

For a deeper understanding of the methodological approach used in the official estimates presented here, please refer to MCT (2010, 2010a, 2010b, 2010c, 2010d, 2010e), MCTI (2014, 2016) and SEEG (2016, 2016a, 2016b, 2017b).

Appendix XVIII: Price- and income-elasticities of different expenditure

Region: **Brazil** (Pintos-Payeras, 2009)	*income-elasticity*	*price-elasticity*
Alcoholic beverages	0.928	-1.105
All chicken meat products and by-products	0.381	-0.723
All dairy, coffee, breads, and biscuits	0.484	-1.001
All types of rice	0.311	-0.863
Beef	0.725	-0.899
Chicken eggs, pasta, wheat flour, cassava flour, canned, mayonnaise, refined salt, soybean oil, prepared foods	0.536	-0.884
Cigarettes	0.423	-1.025
Cleaning products: bleach, alcohol, detergent, soap, among others	0.671	-0.906
Clothing: trousers, sweatpants, shorts, t-shirt, skirt, diaper, shoes, etc.	0.617	-0.863
Education: regular courses, books, newspaper, magazine, notebook and stationery	0.865	-0.676
Fish and seafood	0.521	-1.025
Furniture and household articles: living room furniture, kitchen, bedroom, bed linen, etc.	0.717	-0.773
Health: health plan, medicines, medical and dental consultation, laboratory tests, glasses, etc.	1.031	-0.928
Hygiene: Soap, hair products, toothpaste, deodorant	0.786	-0.945
Land telephone, cell phone and public telephone	0.821	-1.044
Lottery games, cinema, theatre, show, toys, animal products, etc.	0.906	-0.861
Other Cereals: Beans, oats, barley, corn, wheat in grain, peanuts	0.351	-0.956
Other Meat: pork, eggs and meat of other birds and exotic meats	0.467	-0.889
Personal Services: Seamstress, manicure, hairdresser, notary, etc.	0.943	-0.939
Prime beef	0.725	-0.898
Private transport: new car, fuel, oil, tire, repair, etc.	1.104	-1.057
Public transportation: urban, intercity and interstate bus, taxi, subway, airplane, etc.	0.463	-0.790
Refreshments: Soda, coconut water, guarana powder, cane juice, etc.	0.701	-1.069
Rent, strata, water and sewage, among others;	0.633	-0.961
Stove, refrigerator, air conditioner, washing machine, lamp, etc.	0.626	-0.837
Vegetables, fruits and roots	0.671	-0.997
White refined sugar and white crystal sugar	0.286	-0.534
Average	**0.655**	**-0.905**

Region: **Brazil** (Hoffman, 2007)	*income-elasticity*
Beer and other alcoholic beverages (outside home)	0.561
Clothing	0.639
Consumption expenditures	0.758
Current expenses	0.816
Education	1.072
Food	0.481
Food (outside home)	0.798
Food at home	0.381
Health care	0.924
Housing	0.741
Hygiene and personal care	0.587
Lunch and dinner out	1.043
Miscellaneous expenses	0.946
Other current expenditure	1.263
Personal services	0.871
Recreation and culture	0.989
Tobacco	0.424
Total expenditure	0.841
Transport	0.966
Average	**0.795**

Region: **World** (Belgium, France, German, Italy, Netherlands, UK and US (Nordhaus, 1977)
*price-elasticity (long-run): **- 0.85***
*income-elasticity (long-run): **0.79***

Appendix XIX: Leontief Input-Output Price Model

Leontief IO price model and different carbon price scenarios

		Goiás													*Rest of Brazil*												
L^0		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
Goiás	*1*	1.0696	0.0048	0.0421	0.0002	0.0005	0.0025	0.0562	0.0039	0.0017	0.0020	0.0075	0.0783	0.0229	0.0790	0.0359	0.0581	0.0042	0.0105	0.0662	0.1581	0.0297	0.0053	0.0186	0.0105	0.0996	0.0303
	2	0.0019	1.0352	0.0025	0.0004	0.0009	0.0023	0.0078	0.0130	0.0035	0.0026	0.0292	0.1260	0.0762	0.0124	0.0662	0.0078	0.0316	0.0177	0.1090	0.0578	0.1172	0.0081	0.0668	0.0170	0.1348	0.0598
	3	0.2399	0.0015	1.1303	0.0002	0.0010	0.0019	0.0152	0.0080	0.0029	0.0017	0.0164	0.1431	0.0460	0.2419	0.0299	0.1211	0.0034	0.0175	0.0523	0.0852	0.0542	0.0076	0.0318	0.0134	0.1433	0.0469
	4	0.0159	0.0007	0.0232	1.0726	0.0061	0.0020	0.0105	0.0153	0.0040	0.0037	0.0197	0.1620	0.0255	0.0289	0.0163	0.0175	0.3200	0.0111	0.0268	0.0599	0.0392	0.0042	0.0132	0.0120	0.1126	0.0278
	5	0.0578	0.0027	0.0096	0.0032	1.1606	0.0062	0.0495	0.0451	0.0057	0.0159	0.0412	0.1840	0.0491	0.0558	0.0251	0.0123	0.0086	0.0693	0.0375	0.0707	0.0468	0.0045	0.0266	0.0085	0.0983	0.0278
	6	0.1487	0.0010	0.0158	0.0001	0.0005	1.0154	0.0110	0.0055	0.0016	0.0030	0.0088	0.0557	0.0198	0.1135	0.3246	0.0282	0.0040	0.0087	0.1214	0.0542	0.0495	0.0128	0.0331	0.0143	0.1371	0.0512
	7	0.0105	0.0230	0.0231	0.0004	0.0041	0.0130	1.1037	0.0160	0.0073	0.0074	0.0288	0.1855	0.0398	0.0271	0.0565	0.0161	0.0053	0.0297	0.0957	0.1349	0.0589	0.0115	0.0284	0.0121	0.1507	0.0397
	8	0.0030	0.0010	0.0031	0.0016	0.0073	0.0029	0.0113	1.0626	0.0119	0.0276	0.0477	0.1489	0.0310	0.0095	0.0416	0.0064	0.0066	0.0255	0.0389	0.0791	0.2228	0.0104	0.1412	0.0163	0.1405	0.0381
	9	0.0015	0.0116	0.0022	0.0004	0.0018	0.0017	0.0086	0.0102	1.0697	0.0122	0.0116	0.1112	0.0184	0.0083	0.0286	0.0045	0.0039	0.0379	0.0375	0.0473	0.0713	0.0974	0.0859	0.0101	0.0959	0.0250
	10	0.0016	0.0078	0.0024	0.0006	0.0034	0.0019	0.0188	0.0331	0.0095	1.0663	0.0387	0.1209	0.0515	0.0079	0.0869	0.0052	0.0025	0.0143	0.0433	0.0612	0.0645	0.0091	0.2730	0.0172	0.1259	0.0438
	11	0.0014	0.0003	0.0017	0.0003	0.0008	0.0047	0.0078	0.0542	0.0019	0.0018	1.1529	0.0806	0.0158	0.0047	0.0605	0.0038	0.0014	0.0062	0.0302	0.0147	0.0500	0.0037	0.0189	0.0048	0.0708	0.0185
	12	0.0061	0.0004	0.0155	0.0009	0.0035	0.0052	0.0051	0.0112	0.0170	0.0018	0.0169	1.1679	0.0200	0.0092	0.0095	0.0088	0.0029	0.0155	0.0140	0.0106	0.0263	0.0036	0.0089	0.0032	0.0741	0.0137
	13	0.0023	0.0002	0.0030	0.0018	0.0012	0.0076	0.0014	0.0108	0.0025	0.0007	0.0147	0.1458	1.0818	0.0136	0.0806	0.0058	0.0047	0.0084	0.1721	0.0143	0.0842	0.0051	0.0188	0.0076	0.1120	0.0371
Rest of Brazil	*1*	0.0046	0.0006	0.0039	0.0000	0.0001	0.0004	0.0023	0.0003	0.0001	0.0002	0.0003	0.0017	0.0005	1.1241	0.0319	0.0915	0.0034	0.0084	0.0531	0.1600	0.0260	0.0053	0.0158	0.0142	0.1419	0.0412
	2	0.0003	0.0004	0.0004	0.0000	0.0001	0.0002	0.0005	0.0005	0.0003	0.0007	0.0004	0.0013	0.0004	0.0068	1.0629	0.0064	0.0046	0.0105	0.0470	0.0270	0.0667	0.0305	0.0515	0.0277	0.2586	0.1089
	3	0.0206	0.0004	0.0208	0.0000	0.0002	0.0003	0.0022	0.0007	0.0002	0.0004	0.0007	0.0049	0.0015	0.4513	0.0288	1.2199	0.0049	0.0195	0.0492	0.0863	0.0582	0.0096	0.0314	0.0279	0.2707	0.0870
	4	0.0031	0.0002	0.0029	0.0013	0.0002	0.0002	0.0007	0.0004	0.0001	0.0002	0.0004	0.0016	0.0004	0.0563	0.0188	0.0385	1.3050	0.0172	0.0314	0.0858	0.0537	0.0075	0.0170	0.0349	0.2460	0.0512
	5	0.0015	0.0003	0.0009	0.0000	0.0009	0.0003	0.0010	0.0005	0.0001	0.0003	0.0005	0.0013	0.0003	0.0950	0.0230	0.0162	0.0076	1.2049	0.0363	0.0902	0.0699	0.0076	0.0334	0.0374	0.2253	0.0608
	6	0.0018	0.0003	0.0014	0.0000	0.0001	0.0020	0.0006	0.0004	0.0002	0.0005	0.0004	0.0013	0.0004	0.0707	0.5299	0.0188	0.0033	0.0081	1.1924	0.0384	0.0537	0.0181	0.0372	0.0233	0.2025	0.0809
	7	0.0015	0.0018	0.0029	0.0000	0.0002	0.0013	0.0027	0.0006	0.0003	0.0004	0.0007	0.0023	0.0006	0.0281	0.0732	0.0262	0.0044	0.0276	0.1003	1.2778	0.0711	0.0164	0.0355	0.0441	0.3055	0.0704
	8	0.0004	0.0004	0.0005	0.0000	0.0002	0.0003	0.0007	0.0010	0.0003	0.0011	0.0005	0.0015	0.0004	0.0106	0.0387	0.0082	0.0067	0.0293	0.0428	0.0836	1.2605	0.0188	0.1837	0.0447	0.2786	0.0666
	9	0.0003	0.0010	0.0004	0.0000	0.0002	0.0002	0.0007	0.0006	0.0014	0.0006	0.0004	0.0012	0.0003	0.0088	0.0388	0.0059	0.0041	0.0370	0.0381	0.0521	0.0749	1.1511	0.0878	0.0224	0.1968	0.0422
	10	0.0003	0.0014	0.0004	0.0000	0.0001	0.0002	0.0011	0.0008	0.0004	0.0022	0.0008	0.0016	0.0006	0.0078	0.0983	0.0064	0.0024	0.0137	0.0429	0.0690	0.0866	0.0174	1.2777	0.0541	0.2237	0.0873
	11	0.0002	0.0001	0.0003	0.0000	0.0001	0.0002	0.0003	0.0005	0.0001	0.0002	0.0011	0.0007	0.0002	0.0059	0.0739	0.0062	0.0019	0.0083	0.0420	0.0266	0.1236	0.0064	0.0258	1.1882	0.1822	0.0409
	12	0.0007	0.0001	0.0012	0.0000	0.0001	0.0002	0.0003	0.0002	0.0001	0.0001	0.0003	0.0009	0.0002	0.0140	0.0105	0.0237	0.0041	0.0209	0.0184	0.0155	0.0372	0.0194	0.0107	0.0197	1.2564	0.0318
	13	0.0004	0.0001	0.0004	0.0000	0.0001	0.0005	0.0002	0.0004	0.0001	0.0002	0.0003	0.0008	0.0003	0.0130	0.0755	0.0076	0.0058	0.0090	0.1649	0.0140	0.0869	0.0068	0.0179	0.0204	0.2379	1.1088

Note: Numbers 1 to 13 represent Goiás economy sectors, as previously defined.

Continue

Continuation

Value added coefficients, assuming taxes and imports for each economy sector.

Economy sectors	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
Imports + taxes	473	81	615	50	30	105	274	272	192	99	91	629	123	6,345	4,224	8,495	3,580	3,439	12,287	12,531	30,673	7,641	9,811	3,751	36,672	7,524
Gross value-added (GDP)	2,500	215	1,369	202	91	212	372	599	1,356	280	797	11,532	866	44,748	25,636	17,302	12,024	12,960	3,912	14,658	49,066	43,017	20,856	17,982	477,272	39,076
GDP + Imports	2,973	296	1,984	252	121	318	646	870	1,548	378	888	12,161	990	51,093	29,860	25,797	15,604	16,399	16,198	27,189	79,739	50,658	30,667	21,733	513,944	46,600
Value of Production	5,405	641	8,186	572	299	967	1,601	2,183	2,799	922	1,368	16,926	1,789	81,197	50,797	102,001	32,635	32,986	53,982	64,386	186,039	88,012	66,186	36,968	725,253	79,363
Value-added coefficient (v_c^0)	0.5501	0.4616	0.2424	0.4402	0.4039	0.3285	0.4031	0.3987	0.5531	0.4101	0.6495	0.7185	0.5532	0.6293	0.5878	0.2529	0.4782	0.4972	0.3001	0.4223	0.4286	0.5756	0.4633	0.5879	0.7086	0.5872
Emissions intensity ($TgCO_2$/Output)	0.0165	0.0003	0.0001	0.0000	0.0001	0.0002	0.0000	0.0011	0.0002	0.0008	0.0001	0.0000	0.0033													
Carbon tax (Carbon price 5 $)	0.0827	0.0015	0.0004	0.0000	0.0004	0.0008	0.0002	0.0056	0.0008	0.0041	0.0003	0.0000	0.0166													
Carbon tax (Carbon price 10 $)	0.1654	0.0030	0.0007	0.0000	0.0009	0.0016	0.0004	0.0113	0.0016	0.0083	0.0005	0.0000	0.0331													
Carbon tax (Carbon price 25 $)	0.4135	0.0074	0.0018	0.0000	0.0021	0.0040	0.0010	0.0282	0.0039	0.0207	0.0013	0.0001	0.0828													
Carbon tax (Carbon price 50 $)	0.8270	0.0148	0.0036	0.0000	0.0043	0.0080	0.0021	0.0563	0.0078	0.0415	0.0027	0.0002	0.1656													
New value-added (+ Carbon tax 5 $)	0.6328	0.4631	0.2428	0.4402	0.4044	0.3293	0.4033	0.4043	0.5539	0.4143	0.6498	0.7185	0.5697													
New value-added (+ Carbon tax 10 $)	0.7155	0.4646	0.2431	0.4403	0.4048	0.3301	0.4035	0.4099	0.5547	0.4184	0.6500	0.7185	0.5863													
New value-added (+ Carbon tax 25 $)	0.9636	0.4690	0.2442	0.4403	0.4061	0.3324	0.4041	0.4268	0.5570	0.4309	0.6508	0.7186	0.6360													
New value-added (+ Carbon tax 50 $)	1.3771	0.4764	0.2460	0.4403	0.4082	0.3364	0.4052	0.4550	0.5610	0.4516	0.6522	0.7187	0.7187													

Note:

Continue

Original value added coefficient (v_c^0) = GDP + Imports / Value of production

Emissions intensity given by Eq. 3.38; $EI = E / X$

Carbon tax (e.g. carbon price at 5 USD), given by Eq. 3.39; $t^n = Tax^5 \,.\, Emission\ intensity^5$

New value added coefficient (v_c') at 5 USD = $v_c^5 = v_c^0 + Carbon\ tax^5$

Continuation

		v_c^0	***P***	*New value added coefficient (v_c')*				***Price$_{New}$*** *(Value added + Carbon tax)*				***Price change***			
				5 USD	10 USD	25 USD	50 USD	5 USD	10 USD	25 USD	50 USD	5 USD	**10 USD**	25 USD	50 USD
Goiás	*Agricultural*	*0.5501*	**0.7017**	0.6328	0.7155	0.9636	1.3771	0.7906	0.8795	1.1462	1.5908	*12.67%*	***25.34%***	*63.36%*	*126.72%*
	Mining	*0.4616*	**0.6438**	0.4631	0.4646	0.4690	0.4764	0.6468	0.6499	0.6590	0.6743	*0.47%*	***0.95%***	*2.37%*	*4.74%*
	Food, beverages and tobacco	*0.2424*	**0.5583**	0.2428	0.2431	0.2442	0.2460	0.5794	0.6005	0.6637	0.7691	*3.78%*	***7.55%***	*18.88%*	*37.75%*
	Textile, clothes and shoes	*0.4402*	**0.6474**	0.4402	0.4403	0.4403	0.4403	0.6493	0.6512	0.6568	0.6661	*0.29%*	***0.58%***	*1.45%*	*2.89%*
	Wood, paper and printing	*0.4039*	**0.7414**	0.4044	0.4048	0.4061	0.4082	0.7478	0.7543	0.7736	0.8059	*0.87%*	***1.74%***	*4.35%*	*8.70%*
	Oil refining, coke and ethanol	*0.3285*	**0.4854**	0.3293	0.3301	0.3324	0.3364	0.4989	0.5124	0.5529	0.6204	*2.78%*	***5.56%***	*13.90%*	*27.80%*
	Chemical and pharmaceutical products	*0.4031*	**0.6605**	0.4033	0.4035	0.4041	0.4052	0.6624	0.6644	0.6702	0.6800	*0.30%*	***0.59%***	*1.48%*	*2.95%*
	Other industries	*0.3987*	**0.6086**	0.4043	0.4099	0.4268	0.4550	0.6155	0.6224	0.6431	0.6775	*1.13%*	***2.26%***	*5.66%*	*11.32%*
	Cement, construction and other non-metallic mineral products	*0.5531*	**0.7099**	0.5539	0.5547	0.5570	0.5610	0.7113	0.7127	0.7169	0.7239	*0.20%*	***0.39%***	*0.99%*	*1.97%*
	Metallurgy	*0.4101*	**0.6111**	0.4143	0.4184	0.4309	0.4516	0.6168	0.6224	0.6393	0.6675	*0.92%*	***1.84%***	*4.61%*	*9.22%*
	Power sector	*0.6495*	**0.8453**	0.6498	0.6500	0.6508	0.6522	0.8463	0.8473	0.8503	0.8554	*0.12%*	***0.24%***	*0.60%*	*1.19%*
	Services	*0.7185*	**0.8887**	0.7185	0.7185	0.7186	0.7187	0.8896	0.8906	0.8935	0.8983	*0.11%*	***0.22%***	*0.54%*	*1.08%*
	Transport, storage and mail	*0.5532*	**0.7251**	0.5697	0.5863	0.6360	0.7187	0.7433	0.7615	0.8160	0.9069	*2.51%*	***5.01%***	*12.54%*	*25.07%*
Rest of Brazil	*Agricultural*	0.6293													
	Mining	0.5878													
	Food, beverages and tobacco	0.2529													
	Textile, clothes and shoes	0.4782													
	Wood, paper and printing	0.4972													
	Oil refining, coke and ethanol	0.3001													
	Chemical and pharmaceutical products	0.4223													
	Other industries	0.4286													
	Cement, construction and other non-metallic mineral products	0.5756													
	Metallurgy	0.4633													
	Power sector	0.5879													
	Services	0.7086													
	Transport, storage and mail	0.5872													

Note:

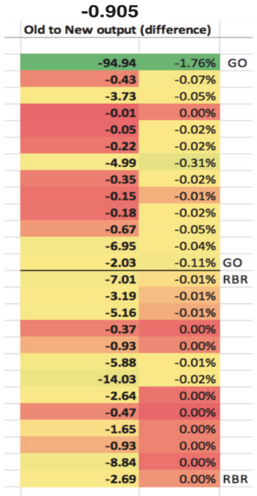
P *=* $L^{0\prime} \cdot v_c^0$; *Eq. 3.35.*

New value added coefficient (v_c^5) *at 5 USD* = $v_c^5 = v_c^0 + \text{Carbon tax}^5$

Price$_{New}$ = $L^{0\prime} \cdot v_c^5$; *Eq. 3.33.*

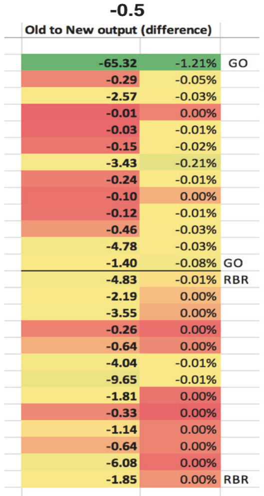
Price change = $(\text{Price}_{New} - \text{Price}_{Old}) / \text{Price}_{Old}$; *Eq. 3.37.*

Appendix XX: Comparisons between old (original) to new output in Goiás and the Rest of Brazil, by sector



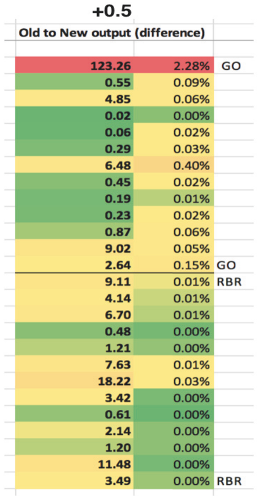
-0.905

Old to New output (difference)		
-94.94	-1.76%	GO
-0.43	-0.07%	
-3.73	-0.05%	
-0.01	0.00%	
-0.05	-0.02%	
-0.22	-0.02%	
-4.99	-0.31%	
-0.35	-0.02%	
-0.15	-0.01%	
-0.18	-0.02%	
-0.67	-0.05%	
-6.95	-0.04%	
-2.03	-0.11%	GO
-7.01	-0.01%	RBR
-3.19	-0.01%	
-5.16	-0.01%	
-0.37	0.00%	
-0.93	0.00%	
-5.88	-0.01%	
-14.03	-0.02%	
-2.64	0.00%	
-0.47	0.00%	
-1.65	0.00%	
-0.93	0.00%	
-8.84	0.00%	
-2.69	0.00%	RBR



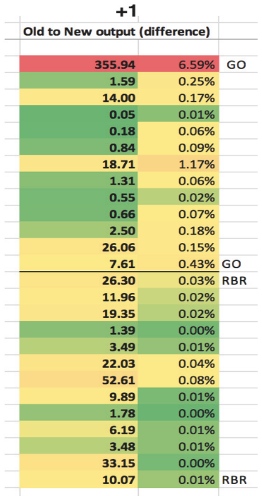
-0.5

Old to New output (difference)		
-65.32	-1.21%	GO
-0.29	-0.05%	
-2.57	-0.03%	
-0.01	0.00%	
-0.03	-0.01%	
-0.15	-0.02%	
-3.43	-0.21%	
-0.24	-0.01%	
-0.10	0.00%	
-0.12	-0.01%	
-0.46	-0.03%	
-4.78	-0.03%	
-1.40	-0.08%	GO
-4.83	-0.01%	RBR
-2.19	0.00%	
-3.55	0.00%	
-0.26	0.00%	
-0.64	0.00%	
-4.04	-0.01%	
-9.65	-0.01%	
-1.81	0.00%	
-0.33	0.00%	
-1.14	0.00%	
-0.64	0.00%	
-6.08	0.00%	
-1.85	0.00%	RBR



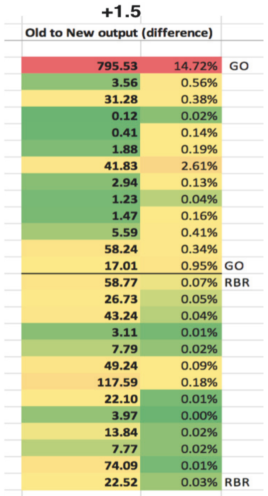
+0.5

Old to New output (difference)		
123.26	2.28%	GO
0.55	0.09%	
4.85	0.06%	
0.02	0.00%	
0.06	0.02%	
0.29	0.03%	
6.48	0.40%	
0.45	0.02%	
0.19	0.01%	
0.23	0.02%	
0.87	0.06%	
9.02	0.05%	
2.64	0.15%	GO
9.11	0.01%	RBR
4.14	0.01%	
6.70	0.01%	
0.48	0.00%	
1.21	0.00%	
7.63	0.01%	
18.22	0.03%	
3.42	0.00%	
0.61	0.00%	
2.14	0.00%	
1.20	0.00%	
11.48	0.00%	
3.49	0.00%	RBR



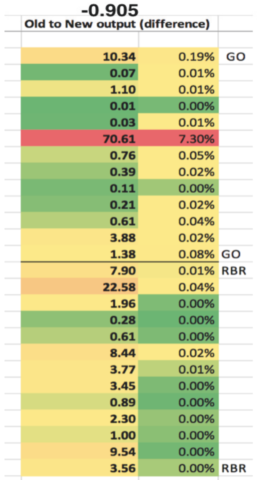
+1

Old to New output (difference)		
355.94	6.59%	GO
1.59	0.25%	
14.00	0.17%	
0.05	0.01%	
0.18	0.06%	
0.84	0.09%	
18.71	1.17%	
1.31	0.06%	
0.55	0.02%	
0.66	0.07%	
2.50	0.18%	
26.06	0.15%	
7.61	0.43%	GO
26.30	0.03%	RBR
11.96	0.02%	
19.35	0.02%	
1.39	0.00%	
3.49	0.01%	
22.03	0.04%	
52.61	0.08%	
9.89	0.01%	
1.78	0.00%	
6.19	0.01%	
3.48	0.01%	
33.15	0.00%	
10.07	0.01%	RBR



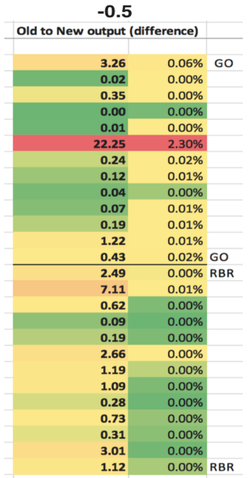
+1.5

Old to New output (difference)		
795.53	14.72%	GO
3.56	0.56%	
31.28	0.38%	
0.12	0.02%	
0.41	0.14%	
1.88	0.19%	
41.83	2.61%	
2.94	0.13%	
1.23	0.04%	
1.47	0.16%	
5.59	0.41%	
58.24	0.34%	
17.01	0.95%	GO
58.77	0.07%	RBR
26.73	0.05%	
43.24	0.04%	
3.11	0.01%	
7.79	0.02%	
49.24	0.09%	
117.59	0.18%	
22.10	0.01%	
3.97	0.00%	
13.84	0.02%	
7.77	0.02%	
74.09	0.01%	
22.52	0.03%	RBR



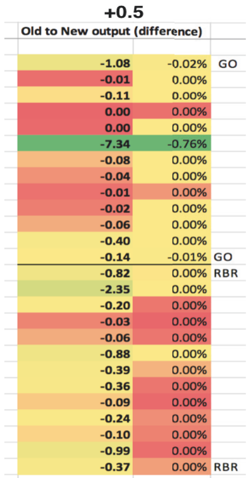
-0.905

Old to New output (difference)		
10.34	0.19%	GO
0.07	0.01%	
1.10	0.01%	
0.01	0.00%	
0.03	0.01%	
70.61	7.30%	
0.76	0.05%	
0.39	0.02%	
0.11	0.00%	
0.21	0.02%	
0.61	0.04%	
3.88	0.02%	
1.38	0.08%	GO
7.90	0.01%	RBR
22.58	0.04%	
1.96	0.00%	
0.28	0.00%	
0.61	0.00%	
8.44	0.02%	
3.77	0.01%	
3.45	0.00%	
0.89	0.00%	
2.30	0.00%	
1.00	0.00%	
9.54	0.00%	
3.56	0.00%	RBR



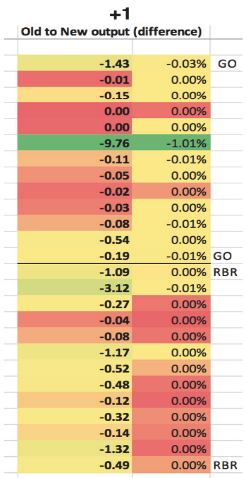
-0.5

Old to New output (difference)		
3.26	0.06%	GO
0.02	0.00%	
0.35	0.00%	
0.00	0.00%	
0.01	0.00%	
22.25	2.30%	
0.24	0.02%	
0.12	0.01%	
0.04	0.00%	
0.07	0.01%	
0.19	0.01%	
1.22	0.01%	
0.43	0.02%	GO
2.49	0.00%	RBR
7.11	0.01%	
0.62	0.00%	
0.09	0.00%	
0.19	0.00%	
2.66	0.00%	
1.19	0.00%	
1.09	0.00%	
0.28	0.00%	
0.73	0.00%	
0.31	0.00%	
3.01	0.00%	
1.12	0.00%	RBR



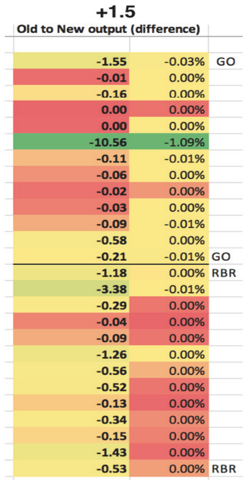
+0.5

Old to New output (difference)		
-1.08	-0.02%	GO
-0.01	0.00%	
-0.11	0.00%	
0.00	0.00%	
0.00	0.00%	
-7.34	-0.76%	
-0.08	0.00%	
-0.04	0.00%	
-0.01	0.00%	
-0.02	0.00%	
-0.06	0.00%	
-0.40	0.00%	
-0.14	-0.01%	GO
-0.82	0.00%	RBR
-2.35	0.00%	
-0.20	0.00%	
-0.03	0.00%	
-0.06	0.00%	
-0.88	0.00%	
-0.39	0.00%	
-0.36	0.00%	
-0.09	0.00%	
-0.24	0.00%	
-0.10	0.00%	
-0.99	0.00%	
-0.37	0.00%	RBR



+1

Old to New output (difference)		
-1.43	-0.03%	GO
-0.01	0.00%	
-0.15	0.00%	
0.00	0.00%	
0.00	0.00%	
-9.76	-1.01%	
-0.11	-0.01%	
-0.05	0.00%	
-0.02	0.00%	
-0.03	0.00%	
-0.08	-0.01%	
-0.54	0.00%	
-0.19	-0.01%	GO
-1.09	0.00%	RBR
-3.12	-0.01%	
-0.27	0.00%	
-0.04	0.00%	
-0.08	0.00%	
-1.17	0.00%	
-0.52	0.00%	
-0.48	0.00%	
-0.12	0.00%	
-0.32	0.00%	
-0.14	0.00%	
-1.32	0.00%	
-0.49	0.00%	RBR



+1.5

Old to New output (difference)		
-1.55	-0.03%	GO
-0.01	0.00%	
-0.16	0.00%	
0.00	0.00%	
0.00	0.00%	
-10.56	-1.09%	
-0.11	-0.01%	
-0.06	0.00%	
-0.02	0.00%	
-0.03	0.00%	
-0.09	-0.01%	
-0.58	0.00%	
-0.21	-0.01%	GO
-1.18	0.00%	RBR
-3.38	-0.01%	
-0.29	0.00%	
-0.04	0.00%	
-0.09	0.00%	
-1.26	0.00%	
-0.56	0.00%	
-0.52	0.00%	
-0.13	0.00%	
-0.34	0.00%	
-0.15	0.00%	
-1.43	0.00%	
-0.53	0.00%	RBR

- impact 🟩🟨🟥 *+ impact*

Appendix XXI: Impacts of Carbon Pricing on Sectoral Value Added

Emissions intensity and Goiás sectoral value added. Different carbon prices (US$5, US$10, US$25 and US$50) and carbon costs to sectoral value added (%).

	Goiás economy sectors												
	Agricultural	*Mining*	*Food & beverages*	*Textile*	*Wood & paper*	*Biofuels*	*Chemical products*	*Other industries*	*Cement & construction*	*Metallurgy*	*Power sector*	*Services*	*Transport*
Emissions ($TgCO_{2e}$)	89.404	0.189	0.590	0.0004	0.026	0.154	0.067	2.458	0.439	0.765	0.074	0.068	5.924
Value-added (US$ million)	2,973	296	1,984	252	121	318	646	870	1,548	378	888	12,161	990
Emissions Intensity ($TgCO_{2e}$*/US$ million)*	0.0301	0.0006	0.0003	0.0000	0.0002	0.0005	0.0001	0.0028	0.0003	0.0020	0.0001	0.0000	0.0060
Carbon cost (US$5/$tCO_2$)	447.02	0.95	2.95	0.00	0.13	0.77	0.33	12.29	2.20	3.82	0.37	0.34	29.62
Carbon cost / VA (%)	15.04	0.32	0.15	0.00	0.11	0.24	0.05	1.41	0.14	1.01	0.04	0.00	2.99
Carbon cost (US$10/$tCO_2$)	894.04	1.89	5.91	0.00	0.26	1.54	0.67	24.58	4.39	7.65	0.74	0.68	59.24
Carbon cost / VA (%)	30.07	0.64	0.30	0.00	0.21	0.48	0.10	2.82	0.28	2.02	0.08	0.01	5.99
Carbon cost (US$25/$tCO_2$)	2235.10	4.74	14.77	0.01	0.64	3.85	1.66	61.46	10.98	19.12	1.84	1.70	148.11
Carbon cost / VA (%)	75.18	1.60	0.74	0.00	0.53	1.21	0.26	7.06	0.71	5.06	0.21	0.01	14.96
Carbon cost (US$50/$tCO_2$)	4470.20	9.47	29.54	0.02	1.28	7.70	3.33	122.92	21.96	38.25	3.68	3.40	296.21
Carbon cost / VA (%)	150.35	3.20	1.49	0.01	1.06	2.42	0.52	14.12	1.42	10.11	0.41	0.03	29.93

Note: Emissions intensity = Emissions / Value added;
Carbon cost = Carbon price . Emissions

Impact on sectorial VA (%) according to carbon price (in US\$/tCO$_{2e}$) and emissions reduction (% over total), year 2008.

	Goiás economy sectors												
	Agricultural	*Mining*	*Food & beverages*	*Textile*	*Wood& paper*	*Biofuels*	*Chemical products*	*Other industries*	*Cement & construction*	*Metallurgy*	*Power sector*	*Services*	*Transport*
Carbon cost / VA							***US\$5/tCO$_{2e}$***						
No reduction	15.04%	0.32%	0.15%	0.00%	0.11%	0.24%	0.05%	1.41%	0.14%	1.01%	0.04%	0.00%	2.99%
5% reduction	14.28%	0.30%	0.14%	0.00%	0.10%	0.23%	0.05%	1.34%	0.13%	0.96%	0.04%	0.00%	2.84%
15% reduction	12.78%	0.27%	0.13%	0.00%	0.09%	0.21%	0.04%	1.20%	0.12%	0.86%	0.04%	0.00%	2.54%
25% reduction	11.28%	0.24%	0.11%	0.00%	0.08%	0.18%	0.04%	1.06%	0.11%	0.76%	0.03%	0.00%	2.24%
35% reduction	9.77%	0.21%	0.10%	0.00%	0.07%	0.16%	0.03%	0.92%	0.09%	0.66%	0.03%	0.00%	1.95%
45% reduction	8.27%	0.18%	0.08%	0.00%	0.06%	0.13%	0.03%	0.78%	0.08%	0.56%	0.02%	0.00%	1.65%
Carbon cost / VA							***US\$10/tCO$_{2e}$***						
No reduction	*30.07%*	*0.64%*	*0.30%*	*0.00%*	*0.21%*	*0.48%*	*0.10%*	*2.82%*	*0.28%*	*2.02%*	*0.08%*	*0.01%*	*5.99%*
5% reduction	*28.57%*	*0.61%*	*0.28%*	*0.00%*	*0.20%*	*0.46%*	*0.10%*	*2.68%*	*0.27%*	*1.92%*	*0.08%*	*0.01%*	*5.69%*
15% reduction	*25.56%*	*0.54%*	*0.25%*	*0.00%*	*0.18%*	*0.41%*	*0.09%*	*2.40%*	*0.24%*	*1.72%*	*0.07%*	*0.00%*	*5.09%*
25% reduction	*22.55%*	*0.48%*	*0.22%*	*0.00%*	*0.16%*	*0.36%*	*0.08%*	*2.12%*	*0.21%*	*1.52%*	*0.06%*	*0.00%*	*4.49%*
35% reduction	*19.55%*	*0.42%*	*0.19%*	*0.00%*	*0.14%*	*0.31%*	*0.07%*	*1.84%*	*0.18%*	*1.31%*	*0.05%*	*0.00%*	*3.89%*
45% reduction	*16.54%*	*0.35%*	*0.16%*	*0.00%*	*0.12%*	*0.27%*	*0.06%*	*1.55%*	*0.16%*	*1.11%*	*0.05%*	*0.00%*	*3.29%*
Carbon cost / VA							***US\$25/tCO$_{2e}$***						
No reduction	75.18%	1.60%	0.74%	0.00%	0.53%	1.21%	0.26%	7.06%	0.71%	5.06%	0.21%	0.01%	14.96%
5% reduction	71.42%	1.52%	0.71%	0.00%	0.50%	1.15%	0.24%	6.71%	0.67%	4.80%	0.20%	0.01%	14.22%
15% reduction	63.90%	1.36%	0.63%	0.00%	0.45%	1.03%	0.22%	6.00%	0.60%	4.30%	0.18%	0.01%	12.72%
25% reduction	56.38%	1.20%	0.56%	0.00%	0.40%	0.91%	0.19%	5.30%	0.53%	3.79%	0.16%	0.01%	11.22%
35% reduction	48.86%	1.04%	0.48%	0.00%	0.34%	0.79%	0.17%	4.59%	0.46%	3.29%	0.13%	0.01%	9.73%
45% reduction	41.35%	0.88%	0.41%	0.00%	0.29%	0.67%	0.14%	3.88%	0.39%	2.78%	0.11%	0.01%	8.23%
Carbon cost / VA							***US\$50/tCO$_{2e}$***						
No reduction	150.35%	3.20%	1.49%	0.01%	1.06%	2.42%	0.52%	14.12%	1.42%	10.11%	0.41%	0.03%	29.93%
5% reduction	142.83%	3.04%	1.41%	0.01%	1.01%	2.30%	0.49%	13.42%	1.35%	9.61%	0.39%	0.03%	28.43%
15% reduction	127.80%	2.72%	1.27%	0.01%	0.90%	2.06%	0.44%	12.00%	1.21%	8.60%	0.35%	0.02%	25.44%
25% reduction	112.76%	2.40%	1.12%	0.01%	0.80%	1.82%	0.39%	10.59%	1.06%	7.59%	0.31%	0.02%	22.45%
35% reduction	97.73%	2.08%	0.97%	0.01%	0.69%	1.57%	0.33%	9.18%	0.92%	6.57%	0.27%	0.02%	19.45%
45% reduction	82.69%	1.76%	0.82%	0.01%	0.58%	1.33%	0.28%	7.77%	0.78%	5.56%	0.23%	0.02%	16.46%

Appendix XXII: Publications Included

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Publication Included

Biomass and Bioenergy 115 (2018) 108–119

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Research paper

Water-energy-food nexus of sugarcane ethanol production in the state of Goiás, Brazil: An analysis with regional input-output matrix

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ABSTRACT

Concerns about impacts of biomass growth for biofuel production emphasize the importance of planning energy crops expansion considering land, water, food and biodiversity. Brazil is the second largest ethanol producer worldwide and sugarcane is cultivated in many regions, including the Brazilian Cerrado (a Savannah-type biome). This paper analyses the impacts of first-generation sugarcane expansion in the Paranaíba basin (Goiás State), focusing on how future demand for ethanol could affect local resources availability. The study area is a sugarcane expansion frontier in Brazil, thus, the Cerrado biome should be focus of research considering competition for land and water uses. An economic-ecologic Input-Output (IO) framework was applied to develop a water-energy-food (WEF) nexus analysis. The Goiás' IO table was expanded to assess water, energy and land uses, GHG emissions and employment levels through six different ethanol supply scenarios.

Results show that if sugarcane expansion projected to 2030 considers the Goiás' extended IO structure for the year 2008, it should cause little impact on land and water availability in the state, due to both the ample availability of suitable pasturelands for sugarcane expansion as well as water in most of the Paranaíba basin. The WEF nexus analysis is a valuable tool on guiding the sustainable management of natural resources considering water, energy, land use and GHG emissions as goals to the same policy. In particular, the hybrid extended IO-WEF nexus framework is useful to design effective biofuel policies, collectively addressing impacts on environmental, social and economic spheres, in a local or broader context.

1. Introduction

Debates on energy security, oil price variability and the growing global commitment to address climate change have intensified throughout the 21st century, motivating increasing investments in renewable energy resources. Researchers have focused on liquid biofuels, which in Brazil have long contributed to reduce greenhouse gas emissions (GHG) from the transport sector, besides contributing to agricultural development and reducing oil imports dependency.

Biofuel production has attracted the attention of policy makers and the current debate is largely focused on the environmental and socioeconomic implications of first-generation (1G) biofuel crops, since they impact food production, water security and biodiversity [1–10].

Concerns about the impacts of biofuel production emphasize the importance of planning the expansion of energy crops considering all the resources involved [11–13]. In this context, a water, energy and food nexus approach (WEF nexus) is currently quite popular in environmental management [14–18], finding fertile ground in policy-making and science. The logic behind the WEF nexus concept is that it shifts attention from a one-sector view to a more integrated one [18].

Brazil is the second largest producer of fuel ethanol worldwide, with a record production of 30.23 hm^3 in 2015 [19]. Considering the country's still wide availability of land for energy crops, Brazilian 1G sugarcane ethanol is a well-known success story of commercial use of biomass for energy purposes, given its low “well-to-wheels” GHG emissions, the crop's very high yield (typical of C4 plants), low water footprint and its low induced deforestation [20–22].

The use of ethanol as an alternative fuel in Brazil expanded after the first oil crisis, with the PROALCOOL Program in 1975. First it was employed as an octane booster to gasoline and later as a complete

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substitute in properly adapted engines. The program has attracted significant investments in agricultural and industrial processes related to 1G ethanol production, stimulating sugarcane growing and the construction of ethanol plants in the country. Additionally, an important domestic ethanol market was consolidated through a huge investment cycle focusing on promoting flex-fuel engines, which gives to consumers the choice of fuelling their car with petrol or ethanol in any proportion, according to their selling prices. Brazilian ethanol can be produced both in autonomous distilleries and in the most common mixed-sugar ethanol plants.

Brazilian 1G ethanol production rose from 10.6 hm^3 in 2000/01 to 17.8 hm^3 in 2006/07, and then to 30.2 hm^3 in 2015/16, with significant increases in agricultural and industrial productivity [19]. In 2016, sugarcane biomass energy accounted for 17.5% of Brazil's internal energy supply, whereas ethanol had a 5.6% share of the final energy consumption [23]. Currently, anhydrous ethanol is employed as an oxygenated additive to gasoline (from 18% to 27% blending). Hydrous ethanol is employed in dedicated engines or in flex-fuel engines (up to E100).

As stated by Brazil's National Agency of Petroleum, Natural Gas and Biofuels – ANP [24], as of February 2017, the country had 384 ethanol mills, producing 334 $dam^3\,d^{-1}$, with sugarcane being the feedstock used in 97% of authorized mills [24]. According to ANP [25], 36.7% of all ethanol produced in the country between 2008 and 2015 was anhydrous ethanol, while the hydrous ethanol share was 63.3%. In the same period, 95% of all ethanol consumed was for energy purposes [25].

Sugarcane is cultivated in many Brazilian states, being the top crop in terms of raw biomass production and third in terms of area, after soybeans and corn. The largest sugarcane-producing area is the Centre-South region, accounting for more than 90% of the country's production [19,26]. Sugarcane is also the most irrigated crop in the country (30% of total), with about 17,000 km^2 [27], and the National Irrigation Policy [28] encourages the expansion of irrigated areas. However, 98% of that is the so-called salvage irrigation, i.e. 20–80 $mm\,year^{-1}$ irrigation aiming to partially reduce the water stress in the dry season, which corresponds to the application of vinasse in the soil. Vinasse is a potassium-rich ethanol distillation by-product produced in large amounts (about 10 L for each litre of ethanol) and diluted with water recycled from the process (when necessary) [29]. Therefore, despite the significant share of sugarcane in the total irrigated area, it is noteworthy that the water demand by km^2 is much lower than other crops mainly due to low application levels (salvage irrigation) and high water reuse of industrial processes (vinasse application).

The projected increase in ethanol consumption in the transport sector over the next decade (about 54 hm^3) [30] is inducing the expansion of sugarcane production to areas such as the Brazilian Cerrado (a Savannah-type biome, located mainly in the Centre-West region) [31,32]. There has been a rapid growth of sugarcane crop in this region, from about 3700 km^2 in 2000 to about 19,600 km^2 in 2015, a 5-fold increase [19]. Goiás and Mato Grosso do Sul states were the main drivers behind this increase, accounting for 85% of the region's current production [19]. The growing demand for new production sites has led to the exploration of water-stressed areas and it justifies further analysis on the Paranaíba basin, a river basin located in the state of Goiás which has recently raised concerns on water and land resources availability.

Although the country has great potential for expanding sugarcane production, as well as the logistics required for ethanol production and export in large scale [33], sugarcane crops impact the soil and water through erosion, and its irrigation can reduce the water availability to irrigate food crops, meet human consumption, as well as industrial and power generation demands. Water, energy and land are basic resources to any production process, but the intensity by which they are being exploited has led to growing environmental impacts.

Thereby, this paper analyses the impacts of the ongoing 1G sugarcane ethanol production expansion towards the Brazilian Cerrado (specifically to the Paranaíba basin, Goiás State), aiming to understand how the interlinkages between the local economic sectors may influence the availability of resources in the region and how future demand for ethanol could impact local resources availability, based on current Brazilian ethanol policies and targets. The analysis performed herein is based on the WEF nexus approach, which is carried out through Input-Output (IO) model concepts.

Since there is no uniform framework to analyse the issues of WEF nexus [10,15–18,34–39], researchers have been seeking for a suitable method to analyse it. Due to its robustness, the IO model is one of the most widely applied methods in economics. It analyses the interdependence of sectors in an economy, showing how the output of a given sector is an input to another, on a national or regional level [39]. IO models can also be expanded to account for energy and environmental impacts [40,41], by considering a proportion between the sector's output and the corresponding impact levels. Additionally, some IO model interactions of the Brazilian ethanol sector with the national economic system has been applied to analyse the impacts of ethanol and sugar exports [42,43], impacts from adding ethanol plants to system [44], studies on ethanol demand forecasts [45] and socioeconomic analyses from different technological approaches for producing ethanol [46–48]. Since most of these studies have focused on economic aspects of the ethanol sector, they unfortunately could not properly address environmental issues regarding the sector itself and the Brazilian economy.

Conversely, some studies have developed IO analysis considering energy and carbon intensities of different ethanol technological routes [49,50] and by integrating IO models with Life Cycle Analysis (LCA) to appraise economic and GHG emissions of 1G and 2G ethanol production in Brazil [51]. Also, some studies have applied IO models coupled with linear programming approaches for distinct objectives [52,53]. Finally, the use of hybrid IO models with multi-objective linear programming [54–56] focusing on the analysis of the economic-energy-environmental-social spheres coupled with LCA estimates for ethanol production in Brazil was carried out by Carvalho et al. [56]. These authors have concluded that hybrid IO models are useful tools to assess the impacts from changes in the output of economic sectors in ethanol prospective scenarios, highlighting the importance on analysing direct and indirect impacts from technical and political choices [56].

As stated, while IO models have many applications, there has been little investigation considering environmental commodities in hybrid IO models applied to WEF nexus [52,56–60]. However, despite some relevant recent studies considering hybrid IO models focusing on the analysis of environmental impacts of the Brazilian ethanol system [51,54,56], they only consider GHG emissions and one single resource of the WEF nexus, i.e. excluding water and land resources. Indeed, studies on hybrid IO models considering GHG emissions and water, energy and land uses as variables to the same nexus analysis (as explored herein) are rare (see Ref. [60], which have not analysed GDP and employment indicators). In this context, we justify the use of hybrid IO models as a WEF nexus tool aiming to analyse 1G sugarcane ethanol expansion in the Paranaíba basin, located in the Brazilian Cerrado. Additionally, this work overcomes the lack of integrated analysis focusing on water-energy-land resources, as well as GHG emissions and socioeconomic aspects from a river basin/state perspective, i.e. IO model concepts coupled with WEF nexus approach. This hybrid IO-WEF nexus framework was chosen because of its wide potential to assess integrated impacts throughout the economy, besides being a reliable decision-making tool for planning purposes and it can also be applied to other energy commodities and target sectors, as well as economic systems and regions to promote the sustainability of biofuels and policy integration. The WEF nexus approach; IO model concepts; the hybrid IO modelling and data sources are presented in section 2. Section 3 covers Brazilian sugarcane industry status; study site; Brazilian ethanol outlook and policy scenarios. Section 4 presents the results of Goiás State case study, and discussions about the potential impacts of sugarcane crops expansion in the region are presented in section 5. Section 6 provides conclusions on the hybrid IO-WEF nexus framework applied to the 1G sugarcane ethanol expansion in Goiás State.

2. Methodology

2.1. The water-energy-food nexus

Focusing on the promotion of inseparable links between the use of resources to provide basic rights to food, water and energy security, the 2011 World Economic Forum has first postulated the 'nexus thinking'. This approach has become an advanced tool on sector-specific governance of natural resource use [34].

There are three reasons for the need for WEF nexus debate [18]:

a) increasing resource interlinks due to growing scarcities. As an example, many dams worldwide are primarily built for energy purposes, although their benefits extend to other issues (e.g. flood control, irrigation and drought management) [18].
b) resource supply crises. This concern lies in recent water and food crises, as well as drought and heat waves across the globe. Since 2013, Brazil has experienced a severe water crisis that has impacted large sections of the country through water rationing for agriculture and human consumption, as well as hydropower supply, resulting in high energy prices and low reservoir levels.
c) failures of sector-driven management strategies. Increasing demands for food and energy, for example, are ultimately converted into increasing pressures on water resources, emphasizing the natural interlinkages between resources [18].

In fact, assessments of land use, energy and water are often carried out in isolation by disconnected institutions. An institution focusing on water resources is likely to consider food and energy systems as end users [61]. Assessments on agriculture might see energy and water as resources [62,63], whereas energy sector is likely to treat biomass and water as inputs. Thus, promoting biofuel expansion through the current sector-driven approach, disregarding indirect impacts on water resources and GHG emissions could counteract one of the main objectives of biofuel policies [10].

Since there is no uniform integrated framework to analyse the issues of WEF, analyses will depend on the existing resource links and the purpose of the analysis. The WEF nexus approach is conceived and measured using varying methods, among others: indicators for macro-level assessments [64]; integrated modelling approach (LCA) [15]; Climate, Land, Energy and Water model – CLEW (resource planning use) [10]; and hybrid Input-Output (IO) approach by adding WEF commodities [54,65], which was applied to the current work.

The IO approach was chosen because of its wide potential to assess integrated impacts throughout the economy, besides being a reliable decision-making tool for planning purposes. Another reason was the data availability for the region under study. Environmental impacts have been accounted through modified IO models using three basic modelling approaches: generalized IO models [36]; economic-ecological models [37]; and hybrid IO models [39]. The economic-ecological model results from extending the interindustry framework to include additional "ecosystem" sectors, where flows will be recorded between economic and ecosystem sectors along the lines of an inter-regional IO model [39]. To analyse the WEF nexus through a case study, this paper applies a hybrid economic-ecological IO approach in attributing water, energy, land use and emissions to the various sectors, and in calculating the interdependence of sectors regarding changes in final demand. It is noteworthy mentioning that "hybrid" does not refer here to the linkage between IO models and other methodologies, but to the combination of physical and monetary units in the IO model. Although our estimates generate results in hybrid units, as explained below, we will refer to the applied model as an extended IO model hereafter, to avoid misapprehension.

2.2. The Input-Output model

Firstly, an IO model (also named Leontief model) is understood as a direct technical coefficients matrix that denotes how much a given economic activity needs to consume from other activities, so that it can produce an additional monetary unit [66]. In the model, the economy is constituted by sectors which produce goods and services (outputs), but to do so, they also consume goods and services from other sectors (inputs). Thus, there are monetary flows of products from a given sector to another in a given period and site [39]. By providing economic and environmental data in a consistent Leontief-type framework, the extended IO matrix is well suited for analytical purposes [67].

It is noteworthy that there are two fundamental hypotheses regarding the economic system in the IO model [39]: 1) Homogeneity – each product is supplied by a single activity (and only one technology is used to produce a product) and; 2) Proportionality – the inputs consumed by each activity are to be as a function of the production level of the activity itself. Therefore, the constraints considered and the corresponding solutions are to be viewed as policy targets.

The basic equation of the IO model can be expressed as follows:

$$X = Z + f \tag{1}$$

where X is the total output, Z is the intermediate input matrix, and f is the final demand. The matrix A, called the direct technical coefficient matrix, is given by:

$$A = Zx^{-1} \tag{2}$$

where $A = [a_{ij}]$ coefficient denotes the quantity of sector i's product required as input to produce a unit of sector j's final product. Thus, Leontief model's solution can be represented by equation (3):

$$X = (I - A)^{-1} f \tag{3}$$

where $(I - A)^{-1}$ is the total impact matrix or Leontief Inverse matrix. For a better understanding on IO theory, see Refs. [39] [67], and [68].

Guilhoto [69] has developed an inter-regional IO table for Goiás State and the rest of Brazil, based both on the National and Regional Accounts for the year 2000, considering 26 sectors of the economy. To perform it, the methodology described in Refs. [70–72] was applied. Focusing on the analysis proposed herein, these 26 Goiás' economy sectors were aggregated into 13 target sectors, as follows: agricultural; mining; food, beverages and tobacco; textile, clothing and shoes; wood, paper and printing; oil refining, coke and ethanol (biofuel sector, hereafter); chemical and pharmaceutical products; other industries; cement, construction and other non-metallic mineral products; metallurgy; power sector; services and; transport, storage and mail.

Next, a nexus framework was developed by applying the Goiás' extended inter-regional IO model to analyse its direct and indirect relationships while considering the water, energy, land use and GHG emissions that would be required due to any change in final demand.

2.3. The Goiás' economic-ecologic Input-Output model

There are no market transactions of environmental requirements (e.g. water, energy, land and emissions) and, therefore, they are not represented in the standard national accounts [52]. In order to assess environmental requirements, Goiás' IO table was rearranged to include them into the analysis (see Refs. [39,52,54,65]). In this regard, production and consumption of water, energy, land and emissions were incorporated into the original Goiás' IO table as an 'extended environmental account' to allocate the environmental flows between sectors.

This procedure generates an extended IO table with hybrid units, where environmental flows are considered in physical units (i.e. hm^3,

Table 1
General structure of an Input-Output table with hybrid units.

	Interindustry Transactions				Environmental Commodity Output[b]
	Consuming Sectors				
	Sector 1	Sector *n*	Final Demand	Total Output	Emissions[c]
Producing Sectors					
Sector 1	*Z ($)*		*f ($)*	*X ($)*	*Tg*
Sector *n*					
Environmental Commodity[a]					
Land	*km²*				
Water	*hm³*				
Energy	*PJ*				

Source: Adapted from Ref. [39].

[a] Land, water and energy represent the input matrix $M = [m_{kj}]$.

[b] GHG emissions represent the output matrix $N = [n_{kj}]$.

[c] As mass of CO_{2eq}.

PJ, km^2, Tg) and all non-environmental sector flows are measured in monetary units (US Dollar - $); assuming an average exchange rate of 3.23 R$ US$$^{-1}$, for a year period [73]) (Table 1).

Therefore, we can estimate the environmental requirements of productive sectors as well as the requirements to produce goods and services in the economy, resulting in estimates of all resources used by each sector, from changes in the final demand. To perform it, we have defined a set of ecological commodity inputs, i.e. $M = [m_{kj}]$, an element of which reflects the amount of ecological input of type k used in the production of economic sector j's total output. Similarly, the same logic can be applied to ecological outputs, i.e. $N = [n_{kj}]$. Thus, the matrices of ecological commodity input and output coefficients can be defined as:

$$R = Mx^{-1}\text{ , and} \tag{4}$$

$$Q = N'x^{-1} \tag{5}$$

That is, the elements of $R = [r_{kj}]$ and $Q = [q_{kj}]$ specify the amount of commodity k required or generated per dollar's worth of output of industry j (Table 1) [39]. Note that N' is the transpose of the matrix of ecological commodity output flows. Thus, using R and Q as computed above, total impact coefficients – in this case ecological commodity input and output coefficients as a function of final demands – can be written as:

$$R^* = R(I - A)^{-1}\text{ , and} \tag{6}$$

$$Q^* = Q(I - A)^{-1} \tag{7}$$

The elements in $R^* = [r_{ij}{}^*]$ reflect the amount of ecologic input i required directly and indirectly to deliver a dollar's worth of industry j's output to final demand [39]. Similarly, the elements in Q^*, i.e. ecological outputs, can be interpreted in the same way.

Therefore, this framework allows tracing the impacts associated with interindustry production generated in response to any new vector of final demands. To carry it out, a linear programming problem is defined aiming at maximizing the GDP (Eq. (8)):

$$\text{Max GDP} = c^T X \tag{8}$$

where $c^T = [1,1, \ldots,1]^T$ (so that c is the column-sum of the IO matrix). The matrix of technology coefficients (Eq. (2)) is obtained from the IO matrix and, through some algebraic manipulation, it derives in the basic linear Leontief model (Eq. (3)). Thus, the maximization of GDP was subject to the following (linear) constraints:

a) $c^T (I - A) X \le c^T (f_{\min} - M)$; where M represents imports and $f_{\min}$ is a lower bound on the total sum of demand met across all sectors;
b) $X \ge X_{\min}$, where $X_{\min}$ is the lower production bound;
c) $X \ge 0$, representing that gross value of production must be non-negative in every sector;
d) $R^* \le R_{\min}$, where $R_{\min}$ is the current use of environmental resources, i.e. water, energy and land;
e) $N'^* \le N'_{min}$, where N'_{min} is the current GHG emissions;
f) $J^* \le J_{\min}$, where $J_{\min}$ is the current employment level.

Additionally, prospective ethanol scenarios were considered as the main changing variable in the IO model. After estimating these scenarios (in terms of % change from current levels – 2015), the new ethanol final demand requirement was incorporated into the extended IO model aiming to estimate the impacts on energy, environmental and economic systems to better understand whether ethanol expansion in the region would threat local environmental resources.

Thus, this work addresses the nexus approach through the application of the Goiás' extended IO model, considering as environmental aspects (i) inputs: water withdrawal (hm^3), land use (km^2) and energy use (PJ); and (ii) outputs: GHG emissions (as mass of $CO_{2eq\ \text{GWP-AR5}}$ – in Tg). Also, since the Goiás' IO model considers official jobs data, the model can be used to estimate social impacts from future changes in final demand for ethanol. Finally, the IO tables were processed through multiple spread-sheets workbook structure (using *Microsoft Excel*) and the optimizations were performed through the *Opensolver*. The *Opensolver* is a free preprogrammed software, i.e. a closed non-editable software, which uses the simplex linear programming method in solving problems, where formulas depend on the variable cells and linear program constraints (defined above).

2.4. Data sources

Due to Goiás' IO table having been estimated for the year 2008, all other data required to formulate the extended IO model (water, energy, land use and GHG emissions) are also analysed for the same year to calibrate the model.

Land use data for the agriculture sector covers all the crop area used in Goiás State, i.e. mainly soybean, corn and sugarcane crops, which, altogether, accounted for 71% of the total agriculture area in 2008 [74,75]. Also, total area used by livestock production was estimated [75–77]. Despite the lower land footprint compared to agriculture, data on total industry area was estimated from state government agencies [78–80]. Both the land and water used by Goiás' power sector was estimated from the National Electrical System Operator – ONS [81–83].

Regarding water use, there is an issue to determine the sectoral technical coefficients, which ideally should be differentiated by productive sectors, micro-region and by technological process [84]. Many studies [82,84–86] have tried to find some water use coefficients related to water withdrawals. The industrial water use coefficients applied to this paper were related to water withdrawal (m^3) per unit of production, considering the findings of [84]. In this context, the total national production for 2008 was obtained from Refs. [69] and [87], by sector.

The water used by the agriculture (blue water) and livestock sectors was based on [74] and [88–90]. Regarding sugarcane production in Goiás State, the blue water coefficient applied was 0.075 m^3 kg^{-1} of sugarcane [32].

Data on both Brazil's and Goiás' energy balances were obtained from Goiás State government [91] and the Ministry of Energy and Mines [23,92]. Ethanol and gasoline demand and supply forecasts were obtained from the Brazilian Energy Research Centre – EPE [30], a Ministry of Energy and Mines agency responsible for the energy planning in the country. Additionally, GHG emissions for Brazil and Goiás State were obtained from the Brazilian National GHG Inventory [93], the National Emissions Record System – SIRENE [94] and the Emission Estimating System for GHG – SEEG [95]. Direct and indirect land use change – DLUC and ILUC, respectively – GHG emissions were excluded due to data constraints. However, due to its importance in a country such as

Brazil, LUC issues were considered in this paper's discussion.

With such information and by applying IO concepts, it is possible to estimate future changes related to GHG emissions, water, energy and land use, value added and job creation, when the final demand in any sector of the economy increases by a monetary unit (in this case, 1 M$). Therefore, the IO model helps analysing future scenarios regarding changes for ethanol demand and how it could impact the use of inputs and outputs production throughout the whole economy, by applying an integrated analysis considering water, energy, land and emissions as targets for a given policy goal.

3. Case study

3.1. Sugarcane industry and environmental concerns in Brazil

According to the Brazilian Sugarcane Industry Association – UNICA [19], Brazil's 2014/2015 sugarcane planted area amounted to 103,000 km^2. This represents about 14% of total cultivated area in the country, 3% of all agricultural properties, 5% of pasturelands and 1% of Brazil's total area [26,76].

The Brazilian sugarcane agro-ecological zoning indicates the Centre-West region as the one with the largest total of suitable areas for sugarcane expansion [31]. The "Agribusiness Outlook in Brazil, 2015/16 to 2025/26" [96], estimates an expansion of 19,000 km^2 of sugarcane crops in the country by 2026, 8000 km^2 of which in the Centre-West. The states of Mato Grosso do Sul (45.6%) and Goiás (34.3%) are projected to present the highest growth rates regarding sugarcane planted area, which confirms the sector's tendency in expanding near traditional producing areas (Fig. 1).

However, the Brazilian Cerrado is typified by water shortage periods and watersheds with economic, social and environmental conflicts related to multiple water uses. Thus, the expansion of sugarcane crops towards Centre-West region may trigger a water constraint on ethanol production.

While São Paulo State has shown less available areas for expansion, sugarcane area in Goiás State soared 18%, twice the Centre-West region's growth rate (Table 2 and Fig. 2). Also, Goiás' sugarcane production accounts for about half the entire Centre-West's sugarcane area and production.

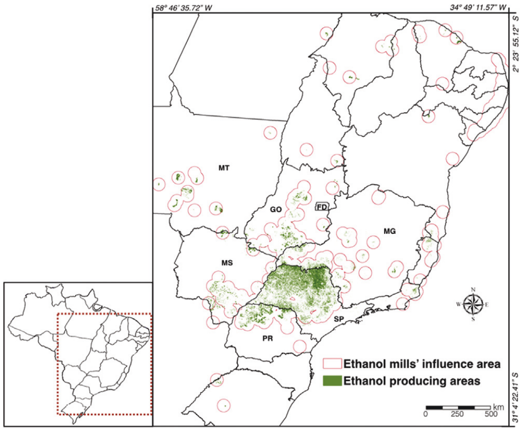

Fig. 1. Sugarcane crops and ethanol plants' influence areas in Brazil. Note that the current study focuses on sugarcane expansion in Goiás State (GO). *Source: Adapted from Ref.* [97].

Table 2
Sugarcane crop area and outputs in Brazil.

Site	Crop area (km^2)			Output (Gg)		
	2013	2014	(%)	2013	2014	(%)
Brazil	102,230	106,457	4.1	588,480	651,290	10.7
São Paulo State	54,150	54,174	0.0	329,920	367,450	11.4
Centre-West region	17,864	19,479	9.0	106,380	120,500	13.3
Goiás State	8,605	10,183	18.3	52,730	62,018	17.6

Source: [19], [26].

3.2. Study site

As one of the leading states in sugarcane expansion, this work focus on the Goiás State (Fig. 1), situated in Brazil's Centre-West region. The Paranaíba basin covers about 220,000 km^2 in this region (Fig. 2), and it comprises parts of the states of Goiás (63%), Minas Gerais (32%), Mato Grosso do Sul (3.5%) and the Federal District (1.5%) [82]. This is an important basin from both an energy and agricultural point of view.

The activities developed in the Paranaíba basin result in growing water demand, 89.5% of which for irrigation. Moreover, most industrial water demand (3.5%) comes from agribusiness, specifically the sugarcane industry [99]. The basin has been undergoing rapid agricultural expansion, with sugarcane replacing pasturelands, corn and soybean crops. Irrigated sugarcane has expanded 2300 km^2 since 2010; overall, irrigated area in the basin rose from 2100 km^2 in 1995 to 6100 km^2 in 2010, virtually tripling the area in 15 years [99]. However, as previously mentioned, most of the irrigated sugarcane in the region is the so-called salvage irrigation which corresponds to the application of vinasse in the soil. Conversely, although about 3800 km^2 of irrigated sugarcane crops were identified in Goiás in 2016 through analysing recent geospatial images, the National Water Agency states that the water used in irrigated sugarcane is relatively unknown [29].

Also, there are 20 hydropower stations in Goiás with 4.8 GW total capacity plus 309 MW from small hydroelectric plants (SHP) [100], which were omitted from this study. In addition, there are 163 hydropower plants in planning stage, totalizing 3.2 GW [99].

In Brazil, sugarcane bagasse (a by-product) is used to co-generate electricity (and heat) to be used in ethanol plants and the surplus exported to the national electricity grid. As stated by the Ministry of Energy and Mines [92], hydropower generation accounted for 81% of the total electricity supply in 2015 in Goiás State (28,468 GWh), while sugarcane by-products represented 15%. Additionally, Goiás is the nation's second largest ethanol producer with 37 mills, which produced 4.72 hm^3 of fuel in 2015 (an 11% increase over 2014) [19,24].

Goiás main economic activities contribute little to GHG emissions, as renewable sources are predominant in the power grid. In 2015, the highest emissions have occurred in the agricultural sector (71%), transport (22%) and waste (6%), had the highest emissions, with little contribution from industries [93,95].

Current land use in the Paranaíba basin shows the predominance of livestock (35%) and agriculture (34%), with emphasis on soybeans, corn and sugarcane. The basin still has about 27% of native vegetation coverage [99].

3.3. Ethanol policy scenarios

The analysis uses the 2008 IO table for the Goiás economy as a baseline for making comparisons with a set of policy scenarios which will be briefly described next. As stated, this paper's aim is to analyse both the environmental impacts of sugarcane expansion on Paranaíba basin and its consequences on Goiás' economy.

As previously mentioned, sugarcane crops have steadily grown in recent times, mainly because of ethanol demand by flex-fuel vehicles, but also because of growing worldwide sugar demand. EPE [30] has

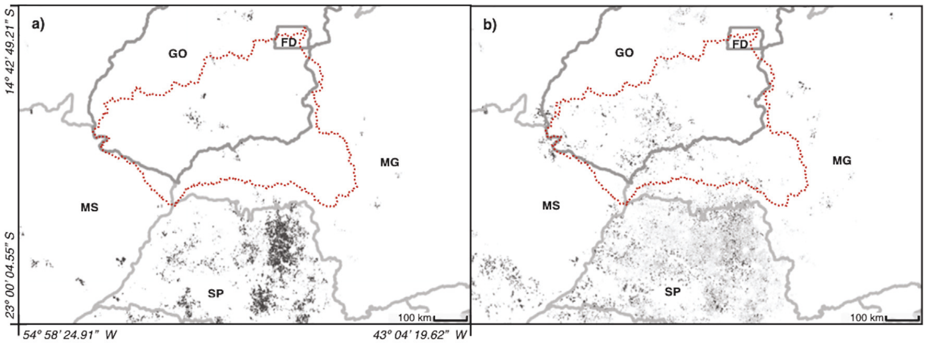

Fig. 2. Crop area in Centre-South region of Brazil, highlighting the Paranaíba basin (dotted) and the states of São Paulo (SP) and Goiás (GO) in *a)* 2003 and *b)* 2011. Different grey scales represent different crop growth stages, unimportant to the current analysis. *Source: Adapted from Ref.* [98].

elaborated three different scenarios for ethanol supply in Brazil to 2030, i.e. low, intermediate and high supply scenario. Since the current study focuses on the environmental impacts from changes in ethanol production, we have selected the EPE high supply scenario, i.e. 12.4 hm^3 of additional ethanol, totalling 54 hm^3, as reference when estimating our prospective ethanol scenarios.

As mentioned, Brazil has 334 $dam^3\,d^{-1}$ of ethanol installed capacity and Goiás accounts for 14%. This share of overall domestic installed capacity was used as a proxy to determine future ethanol supply. Brazil produces both anhydrous ethanol (gasoline additive) and hydrous (employed mainly in flex-fuel engines, up to E100). Anhydrous ethanol must have less than 0.4% water content, while hydrated ethanol has between 4 and 4.9% water content; therefore, their lower heating values (LHV) differ. According to [23], Brazilian anhydrous ethanol has a LHV = 22.36 $GJ\,m^{-3}$, whereas hydrated ethanol's LHV = 21.35 $GJ\,m^{-3}$.

Historically, domestic ethanol to gasoline price ratio has varied according to the vagaries of politics. Therefore, we shall consider that, for the period up to 2030, the proportion between anhydrous and hydrated ethanol production in Brazil, in general, and Goiás State will remain the same as the national average observed between 2008 and 2015, namely: 36.7% anhydrous and 63.3% hydrated [25]. Thus, an average ethanol LHV = 21.72 $GJ\,m^{-3}$ has been employed in the following calculations. Since most governmental scenarios are expressed in energy terms, a weighed LHV value is necessary to derive the projected ethanol volume.

Goiás produced 4.72 hm^3 of 1G ethanol (102.5 PJ) in 2015, of which 2.97 hm^3 were exported to other states, i.e. 64.48 PJ, while consuming 1.75 hm^3, i.e. 38.01 PJ, showing an exporter profile [19,92]. The following scenarios were considered to analyse the impacts of different ethanol policies promoting sugarcane expansion towards the Brazilian Cerrado. Additionally, the higher ethanol supply scenario from EPE was applied aiming to determine the worst-case scenario in terms of environmental impacts in the region. Since the state of Goiás does not produce any gasoline, we have considered four different scenarios in order to estimate the gradual gasoline substitution for ethanol, i.e. 0%; 25%; 50% and; 100% of estimated future gasoline demand in the state.

3.3.1. Scenario 1 - Meeting ethanol demand by 2030

Considering the higher supply scenario of 54 hm^3 of ethanol [30], Goiás should produce 7.56 hm^3 of ethanol to meet 2030 demand, assuming the state keeps its 14% share of Brazil's installed capacity throughout the period. Since Goiás produced 4.72 hm^3 of 1G ethanol in 2015, sugarcane crops should provide an additional 2.84 hm^3 (61.68 PJ) to meet the required 7.56 hm^3 by 2030. This future demand might be met in two different ways:

a) By cutting ethanol exports to other states and;
b) By maintaining the exports to other states, while adding the future 2.84 hm^3 of ethanol demand, totalling 7.56 hm^3 (164.2 PJ)

3.3.2. Scenario 2 – Substituting Goiás State's gasoline consumption

According to [92] and [101], gasoline accounted for 45% of oil products demand in Goiás' transport sector in 2015, equal to 1.47 hm^3 of fuel (47.39 PJ). As stated by Ref. [30], domestic gasoline demand in the period 2015–2030 will increase at a constant annual rate of 0.8%. If Goiás gasoline demand grows at the same rate, this will result in 53.41 PJ in 2030.

By converting this gasoline demand, i.e. 53.41 PJ, into an ethanol energy equivalent, the state of Goiás should produce 2.46 hm^3 of ethanol to replace all projected 2030 gasoline demand in the state. This scenario analyses the impacts of gasoline substitution for ethanol, performed in four different ways:

a) By substituting all Goiás' future gasoline demand but not meeting either ethanol exports to other states or future demand for ethanol;
b) By meeting the exports required from other states and substituting 50% of gasoline for ethanol, but not meeting ethanol future demands;
c) By maintaining the exports required from other states and meeting ethanol demand projected for 2030 and displacing 25% of gasoline with ethanol and;
d) By maintaining the exports required from other states, meeting ethanol demand projected for 2030 and replacing all gasoline demand with ethanol.

A summary of the scenarios is shown in Table 3. Of course, additional scenarios can easily be examined using the same methodology. Additionally, estimates were based only on the 1G sugarcane ethanol production due its technological maturity, while second-generation (2G) ethanol (which is made from the conversion of lignocellulose, i.e. bagasse, leaves, etc., into fermentable sugars) is not commercially competitive in the country due to high production costs and technological constraints. EPE estimates consider only few 2G ethanol plants in Brazil by 2030 [30,102] and the water and land footprint (mainly) from 1G ethanol production are much higher than 2G ethanol, justifying more pessimistic scenarios regarding the use of natural resources by 1G ethanol on determining environmental impacts from sugarcane expansion in the state of Goiás.

4. Results

Based on Brazilian government data, soybean crops have occupied

Table 3
Ethanol production scenarios considering Goiás' internal demand, exports to other states, meeting 2030 demand and different levels of gasoline substitution for ethanol.

Scenarios	Internal ethanol demand *(hm³)*[a]	Ethanol exports *(hm³)*[a]	Meeting future internal demand *(hm³)*[b]	Gasoline substitution levels *(hm³)*[c]	Total ethanol production *(hm³)*	Total ethanol production *(PJ)*	% of current production (2015)
1a	1.75	0	2.84	0	4.59	99.69	97%
1b	1.75	2.97	2.84	0	7.56	164.20	160%
2a	1.75	0	0	2.46 (100%)	4.21	91.44	89%
2b	1.75	2.97	0	1.23 (50%)	5.95	129.22	126%
2c	1.75	2.97	2.84	0.62 (25%)	8.18	177.66	173%
2d	1.75	2.97	2.84	2.46 (100%)	10.02	217.63	212%

[a] Source: [92].

[b] Estimated from Ref. [30].

[c] Estimated from Ref. [101].

44% of the total agricultural area in Goiás in 2008, i.e. 49,280 km^2, followed by corn (18%) and sugarcane (8.5%). Livestock represented the main activity regarding land use in the region, accounting for 155,230 km^2, 76% of total agricultural area. Industry (600 km^2) and the power sector (2800 km^2) footprint were far less representative. Overall, we estimated that the agricultural sector accounted for 80% of water use in 2008 (3720 hm^3), followed by the power sector (15%–700 hm^3), industry (4%) and human supply (1%).

Regarding GHG as mass of CO_{2eq}, the agricultural sector has also dominated the emissions in the state for the same period, accounting for 80%, i.e. 41.67 Tg, followed by the transport sector with 11%, i.e. 5.92 Tg. Industrial processes have accounted for the remaining 9%, i.e. 4.69 Tg. Thermoelectric power plant emissions were insignificant and they have represented all the emissions from the power sector, since hydropower reservoir emissions were not considered for lack of a universal accounting methodology. It is an important fact when considering the 81% share of hydropower generation in the state.

By simulating the Goiás' extended IO table, we estimated the use of energy, water and land, as well as GHG emissions, job creation and GDP changing according to changes in future ethanol demand (Table 4), following the aforementioned scenarios.

To meet the 2030 estimated ethanol demand, Goiás should produce an additional 61.68 PJ. According to *scenario 1a*, it could be met by simply cutting ethanol exports to other states, causing no additional environmental impacts to the Paranaíba basin. On the other hand, other states would have to increase their production to meet about 95% of the 64.48 PJ currently exported by Goiás. Since most of the remaining suitable areas for ethanol production are in the Cerrado, this demand would likely be met by Mato Grosso do Sul state. Therefore, the environmental impacts from sugarcane crop expansion would just be transferred from one state to another, located in the same water-stressed region.

Similarly, estimates of *scenario 2a* consider substitution of all the 2030 gasoline demand in Goiás, equivalent to 53.41 PJ. Again, there is no need for additional ethanol production since the exports to other states might be cut back. Just by reducing ethanol exports in 83%, Goiás State could displace all its 2030 estimated gasoline consumption. Since there are no refineries in Goiás, it imports all its gasoline, mainly from nearby states. Also, the gradual gasoline replacement with ethanol might be politically interesting for Goiás' economic and environmental agendas.

Some highlights are presented below based on the four remaining scenarios (Table 4):

- Scenario 1b: 60% increase over 2015 production, i.e. additional 61.68 PJ, to satisfy both current (102.5 PJ) and future ethanol demand, totalling 164.20 PJ

About 54.5 hm^3 of water and 2815 km^2 of land would be necessary. According to [103], the required land to meet future ethanol demand accounts for 2.4% of natural vegetation cover loss in the Cerrado biome, from 2000 to 2010. All energy sources and industrial processes would require an additional 80.1 PJ of energy, emitting 0.691 Tg as mass of CO_{2eq}, an 14.5% and 1.3% of increase, respectively. About 23,700 jobs would be created, i.e. 0.8% increase over current level, and GDP estimates show an 0.87% increase, i.e. 177 M$, in response to changes in ethanol demand, impacting mostly the biofuels (53%), agricultural (1.4%), transport (0.55%) and chemical products sectors (0.33%).

- Scenario 2b: 26% increase over 2015 production, i.e. additional 26.71 PJ, to substitute 50% of 2030 estimated gasoline consumption but not meeting future internal ethanol demand

This scenario shows the lower additional ethanol requirement and, therefore, lower impacts on state's energy, environmental and socioeconomic systems. It would demand less than 50% of *scenario 1b* requirements in terms of water (23.6 hm^3), land (1220 km^2), energy (34.72 PJ), GHG emissions (0.299 Tg as mass of CO_{2eq}), jobs (10,300) and GDP (76.5% M$). Direct and indirect impacts of changes in final demand would increase the value added mainly in biofuels (23%), agricultural (0.6%), transport (0.24%) and power sectors (0.14%).

- Scenario 2c: 73% increase over 2015 production, i.e. additional 75.16 PJ, to meet future ethanol demand and substitute 25% of 2030 estimated gasoline consumption in Goiás

The only difference between *scenarios 1b* and *2c* is the 25% of gasoline substitution for ethanol. Therefore, the difference between estimates of both scenarios would represent the impacts of this level of gasoline substitution in the state, namely, additional 11.8 hm^3 of water, 610 km^2 of land, 17.4 PJ of energy, 0.149 Tg of GHG as mass of CO_{2eq}, 5100 additional jobs and finally, 37.7 M$ of increase in GDP regarding *scenario 1b*. The total requirements for *scenario 2c* can be verified in Table 4. As one can expect, the biofuels sector would have its value added increased by 64%, while agricultural (1.7%), transport (0.67%), chemical products (0.4%) and power sectors (0.39%) would show lower indirect impacts.

- Scenario 2d: 112% increase over 2015 production, i.e. additional 115.16 PJ, to meet future ethanol demand and substitute 100% of 2030 estimated gasoline consumption in Goiás

Regarding this major change in the state's ethanol supply chain, GDP would increase 1.62%, (to 20,720 M$) accounting for an additional 329.4 M$ due to changes only in final demand for ethanol. To reach the new final demand requirement, it would be necessary an additional 101.7 hm^3 of water and 5250 km^2 of land, an increase of

Table 4
Summary of the estimates for water energy and land uses, as well as GHG emissions, employment and GDP changes for each ethanol prospective scenario.

Scenarios	Additional ethanol (PJ)	Change Over 2015 (%)	Environmental[a]								Social[a]		Economic[a]	
			Water (hm^3)	Change (%)	Land (km^2)	Change (%)	Energy (PJ)	Change (%)	GHG[b] (in Tg)	Change (%)	Jobs (Thousands)	Change (%)	GDP (M$)	Change (%)
1a	–	-	-	-	-	-	-	-	-	-	-	-	-	-
1b	61.68	60	54.5	1.2	2815	1.3	80.1	14.5	0.691	1.3	23.7	0.8	177	0.87
2a	–	-	-	-	-	-	-	-	-	-	-	-	-	-
2b	26.71	26	23.6	0.5	1220	0.6	34.72	6.8	0.299	0.57	10.3	0.35	76.5	0.38
2c	75.16	73	66.3	1.4	3425	1.6	97.5	17	0.840	1.6	28.8	0.96	214.7	1.05
2d	115.13	112	101.7	2.1	5250	2.5	149.5	24	1.289	2.4	44.2	1.5	329.4	1.62

[a] Note: Additional requirements regarding 2008 Goiás' IO structure.
[b] As mass of CO_{2eq}.

2.1% and 2.5%, respectively. Also, overall energy supply would increase 24% to 622.15 PJ, while GHG emissions as mass of CO_{2eq} would go up 2.4%, to about 53.72 Tg. Employment would increase by 1.5%, accounting for 44,200 new jobs, 49% in the agricultural sector, due to increased demand for ethanol. Besides the biofuel sector (98%), the main impacted sectors in terms of value added would be agricultural (2.56%), transport (1%), chemical products (0.61%), power sector (0.59%) and metallurgy (0.28%). On the other hand, overall, 99% and 80% of land and water use change would occur in the agricultural sector, respectively. The land use change estimated from future ethanol demands would account for 4.6% of natural vegetation cover loss in the Cerrado (equivalent to 2-fold the area of Luxembourg), when considered the 2000–2010 period [103].

Some general remarks can be made based on the results presented above:

- To every 1% change in final demand for ethanol, the total energy requirement will change by 0.28%, water demand will change by 0.019%, land-use by 0.023%, GHG emissions by 0.022%, job creation by 0.013% and finally, GDP will change by 0.014%.
- The assumptions made in *scenarios 1b* and *2c* seem to be the most realistic when considering policy goals, since these scenarios target meeting both current and future ethanol demand, as well as ethanol exports to other states. However, the potential ethanol supply does not necessarily mean that this production level is feasible or desirable. It will also depend on the impacts on different variables, such as land prices, production costs, externalities costs, required investment in production capacity and infra-structure.
- Respectively, *Scenarios 1b, 2c* and *2d* represent 15%, 18% and 28% of the Ministry of Agriculture's – MAPA forecasts for the whole country, i.e. an expansion of 19,000 km^2 of sugarcane crops in the country by 2026 [96]. Considering only MAPA's projections for the Centre-West region by 2026 (8000 km^2), *scenarios 1b, 2c* and *2d* would respectively account for 35%, 43% and 66% of total area projected for the entire region but produced only in Goiás State.
- The land use estimated in *scenarios 1b* and *2c* account for 30% and 35% of the 2015 sugarcane crop area in Goiás, and for 2.6% and 3.2% in Brazil, respectively. Since sugarcane crops have been historically replacing old pasture lands, there are still plenty of areas available to their expansion in the state.
- Even in the worst-case scenario (*2d*), the additional water requirements due to changes in ethanol demand ($3.2\,m^3\,s^{-1}$; equivalent to 1.5% of 2010 total water consumption in the Paranaíba basin [32,99]) would cause little impact to its availability in the basin [32]. However, it is fundamental to observe at which basin location the sugarcane expansion would occur, focusing on minimizing conflicts over this resource.
- *Scenarios 2c* and *2d* would require a total energy demand of 570.1 PJ and 622 PJ, respectively, an additional 28% and 40% regarding 2015 Goiás' internal energy supply [92]. Note that changes in ethanol demand would change the overall energy demand in Goiás' economy, which is directly and indirectly used by interindustry sectors to produce the inputs required for meeting that new ethanol demand.

5. Discussion

Although the more realistic scenarios for sugarcane expansion in Goiás require up to 35% increase in crop area growth compared to 2015 level, they would likely not impact land use in the region significantly, given the availability of suitable pasturelands for sugarcane crops expansion. This is a very relevant point regarding GHG emissions, since sugarcane crops store (much) more biomass than natural grasses. In Brazil, pastures comprise roughly a quarter of Brazil's territory, three times the land used in agriculture. On the other hand, Brazil's federal agricultural research agency, EMBRAPA [104], points that 60% of pastures in the Cerrado biome are degraded due to faulty management. Cattle is still mostly raised free range, inefficiently from a land use standpoint; therefore, there is considerable densification potential, freeing up land for food crops being demanded throughout the world.

According to FAO [105], in order to feed a larger, more urban and richer population, world food production must increase by 70% till 2050. On the other hand, UNEP [106] stated that worldwide, yield increases of cereals and primary crops in general have been slowing down since the 1960s. Yield growth for cereals is expected to drop from an average of 1.96% per annum for the period 1980–2000 to 1.01% in 2000–2050, with even slower growth rates for developed countries.

Fischer and Shah [107] calculated the potentially available good land in current grassland/woodland ecosystems for several food crops and concluded that Brazil had more land available for rain-fed maize, soybean, sugarcane and cassava than any other country in the world. Thus, Brazil's importance in meeting future global food and biofuel demand cannot be overstated.

The issue of food crop displacement due to biofuel competition has been raised by UNEP [108], concluding that LUC is the main cause of GHG emissions of biofuels in general. LUC is a complex process caused by the interaction of natural and social systems at different temporal and spatial scales. It can induce GHG emissions due to oxidation of soil organic carbon and due to burning or decomposition of above-ground biomass.

Biofuel crops account for about 4% of global agricultural production area [109]. Therefore, the magnitude of GHG emissions due to LUC from global biofuel production is small compared to the total LUC-related emissions, i.e. agricultural land expansion for food, feed, fibre, cattle ranching, fuel wood and timber (loggings), and expansion of infrastructure generates the greater part of LUC emissions.

The additional water demand from the increasing sugarcane production would not likely impact significantly the region, given the high-water availability in most of the Paranaíba basin, especially in the western section. However, the National Water Agency [99] pointed out some conflict areas regarding multiple water uses especially caused by agricultural demands. Overall, water resources availability in the basin are considered as unthreatened [32,110], but as cropland continues to expand at the expense of Cerrado vegetation, it could affect the rainfall regime that supports both natural vegetation and agricultural production [111]. From a broader standpoint, the Cerrado feeds 8 of the 12 hydrographic regions of Brazil and because 80% of country's electricity comes from hydropower plants, conservation of the biome is also critical for Brazil's energy security [112].

Although most of the basin is suitable for growing sugarcane, this crop's expansion would greatly rely on supplementary irrigation when analysed through climate scenarios considering local changes on temperature, evapotranspiration and air humidity [110]. Also, it is noteworthy mentioning the relatively low water impacts from irrigated sugarcane in the region due to the so-called salvage irrigation, which corresponds to vinasse application. However, the National Water Agency [29] states that the water used in irrigated sugarcane in Brazil is relatively unknown, raising concerns over the use of this resource.

Goiás economy would be slightly impacted in terms of economic growth and social welfare in response to changes in final ethanol demand. Still, a positive correlation between GDP growth and the employment level was observed. As expected, the biofuels sector shows major changes in terms of value added, followed by the agricultural sector for all scenarios.

As pointed out by some authors [52,54,56,60,65], our findings may also be useful to theoretical and empirical research on specifying economic and environmental effects of policies with the use of extended and hybrid IO models. However, note that the deterministic nature of the technical coefficients - which are constant and reflect the economic structure in the base year - does not capture the fact that livestock and sugarcane production expand towards less and less appropriate areas in terms of soil quality, water availability, land slope, etc. That is, the variation of the first unit of final demand has the same impact of the nth unit in IO models, underestimating the real impacts. Additionally, some estimates may be biased due to some inter-relationships among sectors being different in 2030, when compared to the baseline year. Nevertheless, it is important to recognize any initiative focusing on introducing environmental and energy aspects into the conventional national accounts, despite its limitations.

Overall, Brazil suffers from a general lack of integrated federal land and water management, and environmental policy is similarly fragmented [113]. Sustainable management of resources imply actions at various scales and, therefore, national management requires resource-use planning policies considering biomass use and its social, environmental and economic impacts through an integrated standpoint.

Although the nexus literature identifies policy barriers and options for overcoming them, it is based on a technical-administrative view that is a little distant from the reality of decision-making processes. Conflicting objectives may rise from negotiation between varying interests, represented by stakeholders with unequal power and, therefore, nexus analysis must look beyond policy objectives and analyse the principles they are built on [114]. Thus, connecting the nexus to decision-making processes also requires rethinking the boundaries of the nexus analysis, sharing principles which can guide decision-making towards policy coherence and, viewing policy coherence as a continuous process of changing values and perception rather than as an outcome [114].

5.1. Work limitations

Because the Brazilian government does not produce a statistical information system that combines conventional national accounts and environmental accounts, part of the data required to carry out the analyses herein were estimated from different sources and based on a set of assumptions. Thus, an uncertainty must be considered for anyone intending to use the results found herein to perform further analysis. However, all the assumptions applied to cover the lack of data availability were performed through scientific fundamentals focusing on justifying and limiting that uncertainty. On the other hand, it is important to recognize the issues and limitations on introducing environmental and energy aspects into the conventional national accounts.

It should be mentioned that estimates on water use were performed from applying water use coefficients at the bulk production in the country for the base year. Thus, some units of industrial production in the National Accounts System are incompatible to some water use coefficients, preventing precise estimates in these cases. However, industrial processes were less important in terms of water use in the Goiás economy. Also, there were difficulties in estimating water use by the power sector, mainly through estimates from reservoirs evapotranspiration, even though the country's best available data has been employed [65–67].

Regarding livestock production, there are no official data precisely covering the sector's land use in terms of area; the most recent available data is the 2006 Agricultural Census. Most government data are related to the quantity and types of animals and they are poorly related to the area required for raising them. On the other hand, there are several smaller and frequently non-governmental and research initiatives aiming to map the livestock land use in Brazil, to better address this issue in the country [see 75].

The estimated GHG emissions from the Goiás' extended IO model was conducted according to the sectors' emissions published by SEEG [95] but land-use change GHG emissions were excluded from the analysis (overall, "estimates of global ILUC are highly uncertain, unobservable, unverifiable, and dependent on assumed policy, economic contexts, and inputs used in the modelling" [115]). On the other hand, since DLUC is not a significant source of GHG emissions in the Brazilian ethanol life cycle assessment [116], the estimates may be slightly biased [95,116]. In addition, 70% of GHG emissions from the agricultural sector in Goiás comes from livestock production, when land-use change GHG emissions are not accounted [95].

Therefore, further improvements to extended IO models applied to the Brazilian ethanol case can include more accurate (and local) data and coefficients related to water and land uses by economic sectors, as well as including LUC GHG emissions from the agricultural sector. Finally, we strongly suggest analyses considering the use of dynamic IO models, as well as general equilibrium models applied to Brazilian ethanol system.

6. Conclusions

Overall, hybrid IO models coupled with WEF nexus approach are useful in specifying integrated impacts of biofuel policies and they can be applied to other energy commodities, economic sectors and regions in order to collectively address economic, social, environmental and energy goals. In this context, our results suggest that decision makers must keep pushing 1G ethanol expansion in Goiás, since it has no major negative impacts on local environment. However, the competition with food crops for producing in Brazilian suitable areas must be identified and analysed by further studies, considering variations of both land and agricultural commodities' prices. Also, the Brazilian Cerrado has been under increasing anthropic pressure since many years, but LUC in the biome have been largely overlooked (also requiring specific policies). Thus, understanding recent LUC patterns and visualizing a sustainable land use pathway in Goiás might become even more strategic to local and national political agendas. Considering the share of Goiás in the national ethanol production, expanding 1G ethanol in the region would contribute to Brazilian NDCs at the UNFCCC, i.e. to achieve 45% share of renewable energy in the national energy matrix, with 43% of GHG emissions reduction by 2030. Finally, it is important to restrict sugarcane expansion to areas with water constraints, especially in the water management units located in the central section of the Paranaíba basin.

Also, since there are no refineries in Goiás, the government should encourage ethanol substitution for gasoline in order to reduce its import from nearby states. Policies should promote replacing 25% of gasoline consumption in the state aiming to push both GDP and job creation, since water and land use would be slightly impacted when compared to no gasoline replacement. Therefore, given the central role of the state in the governance of both the biofuels market and the impacts of its production, Brazilian public agencies (e.g. MAPA, MME, ANA, EPE, ANP, etc.) should develop policies to manage the nexus of energy, water, food and GHG emissions, according to local conditions and by using integrated tools to assist the decision-making process. In this sense, this work presents an approach which may be used by decision makers and planners to support and overcome some issues identified in the traditional policy-making process, often carried out in isolation by disconnected institutions.

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Appendix A. Supplementary data

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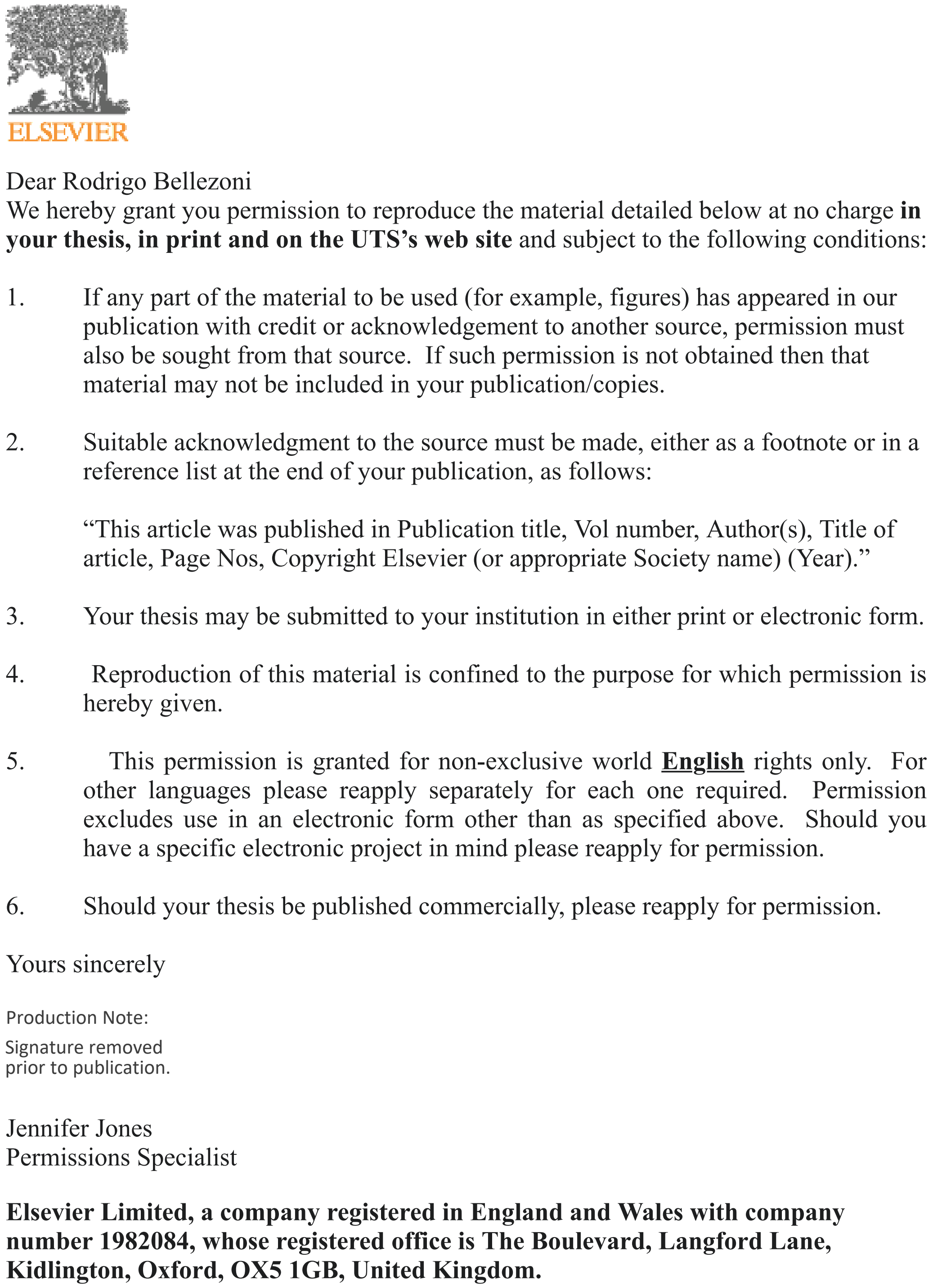

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Authors' Contributions

Mr. Rodrigo A. Bellezoni and Dr. Amaro O. Pereira Jr. conceived of the presented idea. Mr. Rodrigo A. Bellezoni, Dr. Amaro O. Pereira Jr. and Dr. Deepak Sharma developed the theory and Mr. Rodrigo A. Bellezoni performed the analytic calculations and the numerical simulations. Mr. Rodrigo A. Bellezoni, Dr. Amaro O. Pereira Jr. and Dr. Deepak Sharma designed the model. Mr. Rodrigo A. Bellezoni developed the computational framework and analysed the data. Dr. Amaro O. Pereira Jr. and Dr. Deepak Sharma verified the analytical methods and the correctness of the model. Dr. Alberto A. Villela encouraged Mr. Rodrigo A. Bellezoni to investigate land use change and GHG emissions from sugarcane ethanol expansion in the study area and helped to analyse these issues and to review the manuscript. Dr. Amaro O. Pereira Jr. and Deepak Sharma supervised the findings of this work. Mr. Rodrigo A. Bellezoni wrote the paper with support mainly from Dr. Alberto A. Villela, along with inputs from all authors. Dr. Deepak Sharma helped supervise the project and suggested the development of future studies (price change analysis and other economic aspects, included in this thesis). Mr. Rodrigo A. Bellezoni is the corresponding author of this publication and he was the author in charge of addressing reviewers' questions and recommendations, with an important support from Dr. Alberto A. Villela. All authors provided critical feedback and helped to shape the research, analyses and the manuscript.

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