University of São Paulo
"Luiz de Queiroz" College of Agriculture

Biomass to energy: mass and exergy assessment of carbon mitigation and triple bottom line assessment

João Paulo Soto Veiga

Thesis presented to obtain the degree of Doctor in Science.
Area: Agricultural Systems Engineering

Piracicaba
2016

João Paulo Soto Veiga
Agronomist

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
Prof. Dr. **THIAGO LIBÓRIO ROMANELLI**

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To my family, Ilda Soto Veiga, Tobias Leão Veiga, José Soto Veiga, Daniela Trufi Veiga and Cecília Trufi Veiga. Who always loved, supported, incentivized me and encouraged to study, seeing in knowledge and education their great and true value.

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EPÍGRAPH

“Learn from yesterday,
live for today,
look to tomorrow,
rest this afternoon.”

Charles M. Schulz, Charlie Brown's Little Book of Wisdom

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RESUMO

Biomassa para energia: avaliação de massa e exergia para mitigação de carbono e avaliação de sustentabilidade

A energia à qual o planeta é exposto é fixada organicamente via fotossíntese e estocado na forma de combustíveis fósseis, atualmente, as maiores fontes energéticas da humanidade. Desde que Arrhenius concluiu que emissões de CO_2 decorrentes de combustíveis fósseis, poderiam levar a um aquecimento do clima, até os dias atuais, estudos buscam formas de reduzir os impactos antrópicos de forma a atenuar possíveis problemas climáticos. Os esforços para a redução de emissões de CO_2 e outros gases de efeito estufa (GEE) têm como obstáculo uma população mundial crescente, que demanda cada vez mais energia para transporte, eletricidade e calor. Dentre as possibilidades de uso de fontes renováveis de energia, a biomassa é uma que se destaca em alguns países, como no caso do uso de etanol de cana-de-açúcar no Brasil. O uso de biomassa para a produção de combustíveis auxilia na redução da pressão para o uso de mais combustíveis fósseis e fixa organicamente o carbono emitido, contribuindo duplamente para a mitigação de problemas com mudanças climáticas e aquecimento global. O presente trabalho analisa os ciclos de carbono em biocombustível, correlacionando-os com sua energia útil (exergia) valorando a equivalência em área para a produção da exergia equivalente de combustíveis fósseis através de uma nova metodologia de avaliação de mitigação. Foram utilizados trabalhos existentes de análise de ciclo de vida em cana-de-açúcar e eucalipto para obtenção dos dados de inventário e fluxos de carbono e energia. Realizaram-se cálculos de exergia disponível ao usuário final com diferentes rotas de produção de biocombustível, abrangendo tecnologias atuais e em desenvolvimento. Na avaliação exergética, reduzir a humidade da palha da cana de 50% a 30% aumentou a exergia disponível em 13,32 GJ ha^{-1}, 0,67 GJ ha^{-1} para cada 1% de redução na humidade. No caso do eucalipto para combustão, reduzindo-se a umidade de 20% a 15% houve um aumento de 7,52 GJ ha^{-1}, 1,50 GJ ha^{-1} para cada 1% de umidade. Em média, cada Mg de biomassa produzida aumentou 3,02 GJ em cenários de cana de açúcar e 5,93 GJ em cenários de eucalipto. Este conceito traz uma nova perspectiva na mitigação de carbono, avaliando-o por sua funcionalidade. Também foram estudadas as implicações do uso de biocombustíveis em aspectos ambientais, sociais e econômicos em uma análise híbrida de ciclo de vida e insumo-produto (ACV-IP) evidenciando diferenças entre ocupação do uso de solo e duas maneiras de produção de cana-de-açúcar. A ACV-IP demonstrou que, em áreas de mudança do uso do solo de pastagem para cana de açúcar, o consumo de energia aumenta em 3,7 vezes, o emprego é reduzido em 5,4 vezes, e as emissões de GEE são reduzidas à apenas 2% das emissões originais para cada unidade de R$ de alteração na demanda final. A maior parte do emprego é gerado pelo setor da cadeia de suprimentos de produção de cana. A cana produzida pelas usinas origina mais empregos diretos do que a cana produzida por fornecedores agrícolas. Fornecedores usam menos energia e emitem menos GEE do que a produção de cana por usinas.

Palavras-chave: Sustentabilidade; Gases do efeito estufa; Mudanças climáticas; Biocombustíveis; Fluxo de carbono

ABSTRACT

Biomass to energy: mass and exergy assessment of carbon mitigation and triple bottom line assessment

Earth is exposed to an amount of energy that is fixed organically via photosynthesis and stored as fossil fuels, which are currently the major energy sources of humanity. Since Arrhenius concluded that carbon dioxide emissions from fossil fuels could lead to a climate warming, studies have sought ways to reduce human contribution on the environment to mitigate possible negative impacts on climate. The increasing world population is an obstacle for the efforts to reduce CO_2 emissions and other greenhouse gases (GHG), because it demands more energy for transportation, electricity and heating. Among several renewable energy sources, biomass for fuels stands out, such as sugarcane ethanol in Brazil. Using biomass for fuels may help reducing the pressure on fossil fuels, besides, fixing organic carbon already emitted, contributing to mitigate problems of climate change and global warming. Thus, this study aims to analyse carbon cycles of mitigating emissions from fossil fuels with biofuel based on useful energy (exergy) content to determine the equivalent area required. Previous studies of life cycle assessment in sugarcane and eucalyptus were used to obtain carbon- and energy-flow data. These data were applied to estimate the available exergy to the final user through different routes of biofuel production, including current and evolving technologies. Exergy assessment demonstrated that on average, each Mg of biomass produced, led to a change of 3.02 GJ on sugarcane scenarios and 5.93 GJ on eucalyptus scenarios. Reducing sugarcane straw moisture from 50% to 30% increased the exergy output in 13.32 GJ ha^{-1}, an increase of 0.67 GJ ha^{-1} for each 1% of moisture reduce. Eucalyptus to firewood, reducing moisture from 20% to 15% had an increase of 7.52 GJ ha^{-1} in the exergy output, representing 1.50 GJ ha^{-1} of increase for each 1%. This kind of assessment brings a new point of view in carbon mitigation, looking for its functionality. Biofuel use implications in environmental, social and economic aspects were also studied through a hybrid input-output life cycle assessment (IO-LCA) showing differences between the occupation of land use and two different ways of sugarcane production. The IO-LCA showed, in areas of land use change from pasture to sugarcane, energy consumption is increased by 3.7 times, employment is reduced by 5.4 times, and GHG emissions are reduced to only 2% of original emissions for each unit of R$ of final demand changed Most of the employment is generated by the sugarcane supply chain sector. Comparing sugarcane produced by the mills, it originates more direct full time jobs and probably in a more formal job market than sugarcane produced by farm suppliers. Farm suppliers use less energy and release less GHG than mills sugarcane production.

Keywords: Sustainability; Greenhouse gases; Climate change; Biofuels; Carbon flow

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1. INTRODUCTION

The first chapter of this study explains about the basic matters addressed on the two subsequent chapters, expounding the basic science and parameters involved in the analyses.

Initially, carbon flows are explained, their implications on climate and their correlation with energy use, as well as the exergy definition, which will be used to assess the carbon flow on the efforts to mitigate issues caused by climate change and global warming by biofuels. After, it is described the Input-Output and Life Cycle assessments and how they can be hybridized to proceed a more complete analysis.

In the end of this chapter, the general objective of this study was stated and the specific objective of each chapter was described.

1.1 Carbon flows and stocks

Previously to anthropogenic interference, the carbon balance between atmosphere, lithosphere and oceans were closer to zero. Carbon dioxide is withdrawn from the atmosphere, not through chemical reactions, but through huge fluxes into the land or oceans, with an atmospheric lifetime of several years (from 5 to 200 years). Carbon dioxide emissions have increased comparing to preindustrial standards; this is due to anthropogenic actions, basically from fossil fuel combustion and deforestation or other land use changes processes (MAHOWALD, 2012).

The dominant form of carbon in the atmosphere is carbon dioxide – CO_2, which is chemically inactive, but important as it strongly influence the atmosphere radiative properties (CIAIS et al., 2013; MAHOWALD, 2012). Natural and anthropogenic CO_2 stocks and flows are showed on Figure 1.1, where it is possible to view a simplified global carbon cycle and where is possible to identify ‘fast’ reservoir turnovers (carbon in the atmosphere, the ocean, surface ocean sediments and on land in vegetation, soils and freshwaters) and the slow reservoir turnovers, consisting on the huge carbon stores in rocks and sediments (CIAIS et al., 2013).

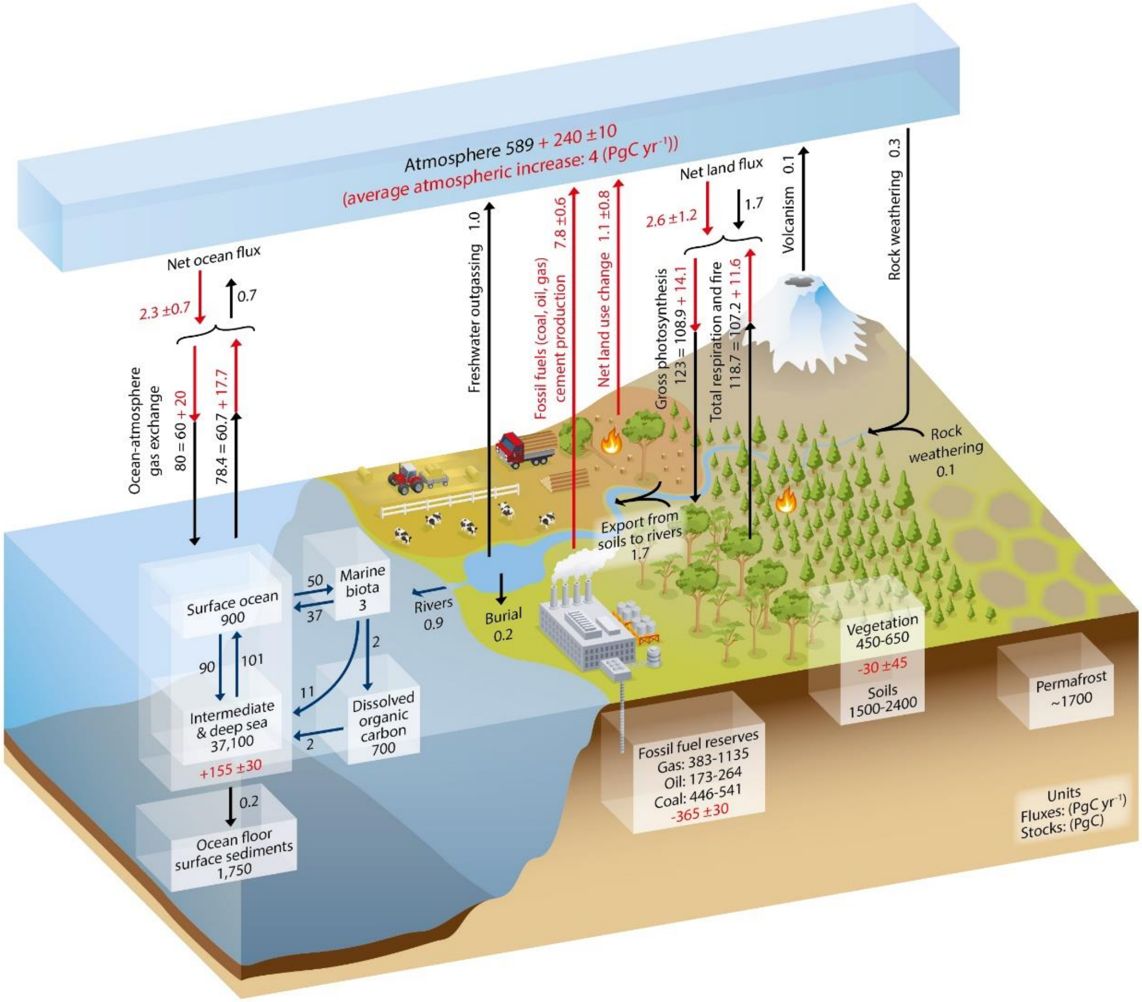

Figure 1.1 - Simplified schematic of the global carbon cycle, stocks in PgC and flows in PgC year^{-1} (1 PgC = 10^{15} gC). Black numbers and arrows indicate reservoir mass and exchange fluxes estimated for the time prior to the Industrial Era, about 1750, red arrows and numbers indicate annual anthropogenic fluxes averaged over the 2000–2009 time period (CIAIS et al., 2013)

Energy and carbon can be intrinsically related and are converted from one carrier to another as carbon changes its chemical form and accumulate energy to be transformed again in its most stable form (CO_2) after be burning to release energy (SASSOON, 2012).

1.2 Emissions, Greenhouse effect and climate changes

Most of the World energy consumption (and thus exergy destruction, explained in section 1.4) comes from fossil fuels, continually emitting more CO_2 in the atmosphere. To track changes of CO_2 in the atmosphere due to fossil fuel burning emissions, since 1958, there is a continuous monitoring in Mauna Loa – Hawaii, indicating a constant increase of CO_2

concentration, mainly caused because fossil fuels use and deforestation (SCHELLNHUBER et al., 2012).

CO_2 in atmosphere is fundamental in photosynthesis sustaining life in the planet. It also acts absorbing the long wave radiation emitted by earth, blocking impeding the system cooling, called the greenhouse effect (ALLEN, 1980), which, occurring moderately, is essential for life.

From the relationship between CO_2 concentration and the retention of energy in the atmosphere as heat, it is expected the average global temperature rises with higher emissions of CO_2. As assessed by Cook (2013), although still criticized by some researchers, it is pretty much consensus that the observed increase of CO_2 concentration, its consequent climate changes and the rise of global temperatures are induced by anthropogenic activity linked with greenhouse gases (GHG) emissions (COOK et al., 2013; ORESKES, 2004).

Increases in the global average temperature about 4 ºC may cause waves of extreme heat, elevation of the oceans level, the acidification of the oceans and, mainly, risks in the food production chain (SCHELLNHUBER et al., 2012). In 2100, at the current average emission trend, the temperature increase must be between 3.7 °C to 4.8 °C higher than the Industrial Revolution (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE - IPCC, 2014).

In 2011, the estimated anthropogenic carbon emitted was 9,470 Tg[1] in whole World. Brazil contributed with 115 Tg of carbon (1.22% of the total). Globally, the increase of carbon between 2009 and 2011 was about 8.4% while in Brazil the increase was 15.6% (ANDRES; BODEN; MARLAND, 2015) as showed in Figure 1.4.

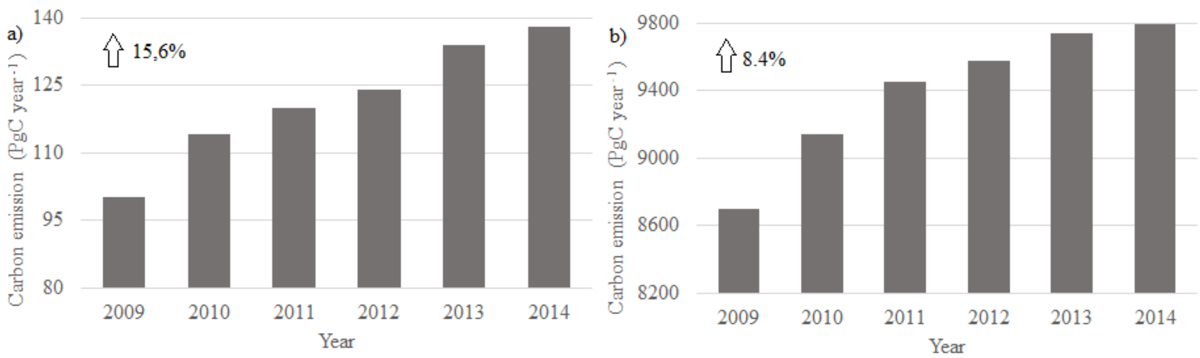

Figure 1.2 - Variation on carbon emissions by year: a) Brazil and b) Worldwide

Besides being causing most of anthropogenic GHG (mainly CO_2, CH_4 and N_2O), another issue of fossil fuel is the fact they emit hazardous gases such as carbon monoxide (CO),

[1] Tg – teragrams (10^{12} grams or 10^6 t)

hydrocarbons (HC), particulate matter (PM), nitrogen oxides (NO_x) and sulphur oxides (SO_x) (CARVALHO, 2011; DALL'OSTO et al., 2010; MALIK et al., 2014), all of these air pollutants have acute and chronic effects on human health, affecting a number of different systems and organs, causing many diseases, reduced life expectancy and premature mortality (KAMPA; CASTANAS, 2008).

Even with several reports and researches warning about the damages in environment and society deriving from GHG increase, in 2011, the main three anthropogenic gases, CO_2, CH_4 and N_2O reached new peaks in the atmosphere with concentrations 140%, 259% and 120% higher from the values observed previously the Industrial Revolution, before 1750 (WORLD METEOROLOGICAL ORGANIZATION/GLOBAL ATMOSPHERE WATCH WMO/GAW, 2012).

To ease and make comparisons possible the gases emitted, all of them are measured as an equivalent of how much CO_2 must be released to reach the same global warming potential, it is called the CO_2 equivalent (CO_2-eq), considering the mass of the emitted gas times a factor to correct its global warming potential.

Worldwide, between 1970 and 2004, the highest growth on GHG emissions was verified in the electricity production and transport, while industry, household and services stood stable. Specifically, energy sector contributes with 26% of GHG emitted, industries with 19%, land use (LU) and land use change (LUC) 17%, agriculture 14%, transport 13%, households 8%, services 8% and garbage and sewage 3%. All these values must be considered as an indicative due to the uncertainties they present (IPCC, 2014).

Among the GHG gases, CO_2 from fossil fuels is the main one, responsible for 57% of the total emissions, deforestation releases 17%, CH_4 contribute with 14%, N_2O with 8% and other sources of CO_2 and fluorinated gases with 4% (IPCC, 2014).

Brazil has a different emission matrix from the rest of the Wold, concentrating emissions of CO_{2eq} in LU and LUC with 35% (majority in the Amazon region), fossil fuels with 30% (majority to transportation), agriculture, cattle and dairy 27% (most from enteric fermentation), industries 6% and residues 3% (SISTEMA DE ESTIMATIVA DE EMISSÃO DE GASES DE EFEITO ESTUFA/OBSERVATÓRIO DO CLIMA – SEEG/OC, 2014).

1.3 Overview of energy use

Humankind history is associated with the progressive development of energy sources and constant changes on how they are used. From the energy daily consumed as food to keep us alive, such as firewood to cook and warm, the use of animal in basic functions such as soil tillage, pulling goods or transport, to the first improved steam machine invention by Matthew Boulton and James Watt at the beginning of the Industrial Revolution and, lately, with the use of many kinds of energy sources for a wide variety human activities (GOLDEMBERG, 1998).

At this scenario, oil became the preponderant source of energy helping to greatly increase food production and improving life quality through economic growth. Energy consumption is strongly correlated with life quality, countries with a consumption of 42 GJ per capita, generally, has the human development index (HDI) higher than 0.8 (GOLDEMBERG, 1998).

In 2011, worldwide energy demand was, approximately, 547 EJ[2] and it is expected to increase between 32 or 43% until 2035, depending on the energetic and economic policies adopted. The main sources of energy were: Oil (31%); Coal (29%); Bioenergy (10%); Nuclear (5%); Hydro (2%); Other renewables (1%), (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT/INTERNATIONAL ENERGY AGENCY - OECD/IEA, 2014).

It is evident that the globally main energy source is fossil fuels (oil and coal totalling 60% of energy use), being a considerable dependency on non-renewable energy sources. Energy renewability is considered as any form of energy that is replenished by natural processes or produced at a rate that equals or exceeds its rate of use (IPCC, 2011). On this understanding, fossil fuels are a non-renewable source of energy, since their production rate is lower than their consumption (ROMANELLI; MILAN, 2010).

Brazil presents a distinguished composition on his energy matrix, since 46% of its total primary energy production (10.81 EJ), are produced by renewable sources, prioritizing the production of hydropower electricity (1.40 EJ), sugarcane products such as ethanol and bagasse (2.06 EJ) and wood to energy (1.03 EJ) (EMPRESA DE PESQUISA ENERGÉTICA - EPE, 2015).

In Table 1.1, it is shown the amount of fossil energy is used in Brazil in seven productive sectors, in which it is possible to notice the amount of energy it is possible to be replaced by renewable sources and decarbonize economy.

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[2] EJ – exajoules (10^{18} joules)

Table 1.1 - Use of fossil energy per economic sector in Brazil in 2014 (EPE, 2015)

	Oil derivatives	Natural gas	Coal	Total
		PJ[3]		
Energy sector	243.43	264.03	7.85	515.31
Residential	273.74	12.98	0.00	286.71
Commercial	19.73	7.49	0.00	27.22
Public	11.39	1.67	0.00	13.06
Agricultural	260.01	0.00	0.00	260.01
Transports	2.995.34	66.74	0.00	3.062.08
Industrial	536.98	406.47	547.67	1.491.13
Total	9.297.87	1.547.42	1.111.04	11.956.33

1.4 Exergy

Exergy is defined as the maximum theoretical work possible to be obtained from a system and the environment around him, as the system strikes in balance with the environment (MORAN; SHAPIRO, 2008). Thus, it presents the quality of the energy, as the system produces useful work until no more work can be produced, when the global system (system and environment) reaches the dead state.

Unlike energy, exergy is not conserved, it is destroyed, proportionally to the entropy generated by the processes' irreversibility, so efforts to reduce exergy destruction, present a less impactful way to perform the process that is being analysed (ROSEN; DINCER, 2001).

Therefore, when we address about reduction and scarcity of resources we cannot speak about matter or energy because these physical quantities can not be generated or consumed, as explained by the First Law of Thermodynamics, only transformed (exception in nuclear reactions) thus the reduction of physical usefulness of energy, which is measured by exergy, is consumed in the processes and, over time, become scarce (GONG; WALL, 2001) as ilustrated in Figure 1.2.

[3] PJ – petajoules (10^{15} joules)

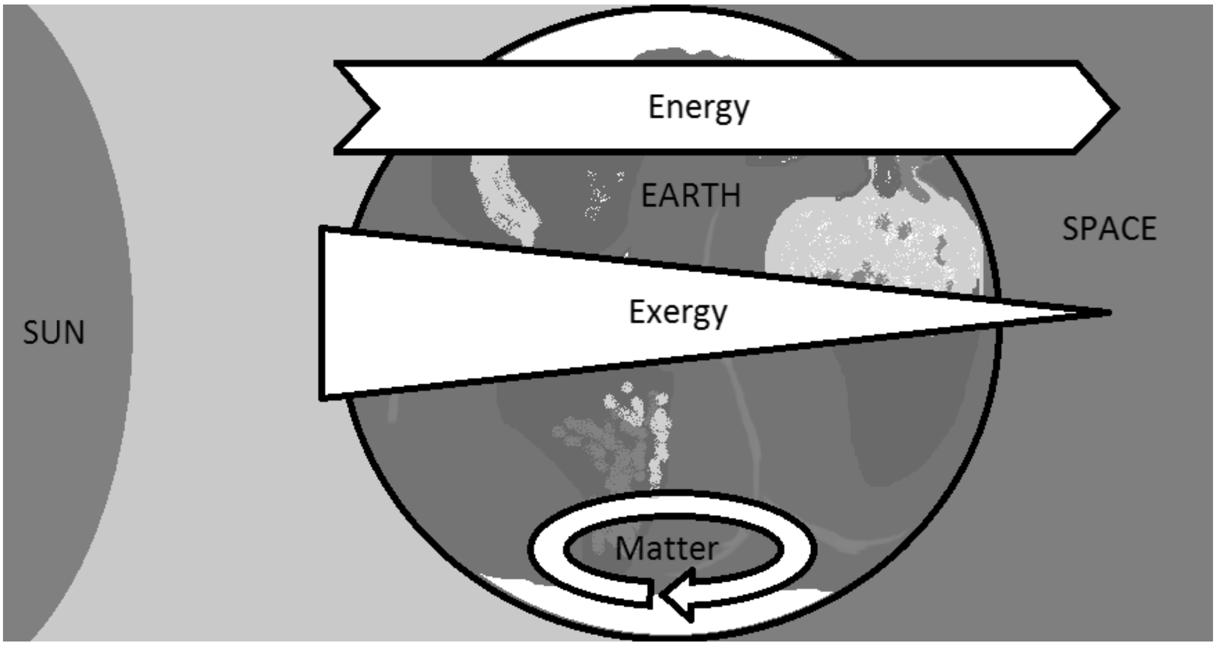

Figure 1.3 - Energy, Exergy and Matter flows (adapted from GONG; WALL, 2001)

In terms of sustainability, it is better to use exergy rather than energy, as it is possible to value the energy available and measure the energetic increase of wastes discharged into the environment. This kind of assessment is possible because exergy determination implies in the combined use of First and Second Laws of Thermodynamics, quantifying entropy generation and exergy destruction, showing, in specific systems assessments, inefficiencies of energy conversions in processes and the reduction of energy utility (OLIVEIRA, 2013).

Exergy flows from prime sources like nuclear (fusion and fission), the thermal energy of the Earth's, gravity, and the Sun. The exergy flows from the Sun accumulates through photosynthesis in a wide variety of secondary reservoirs in the Earth. These second reservoirs can be classified as renewable, such as biomass or deployable, depending on the rate it is replenished (HERMANN, 2006; SASSOON, 2012). Figure 1.3 describes the exergy flow from primary to secondary reservoirs, how it is accumulated and its destruction by natural or anthropogenic causes.

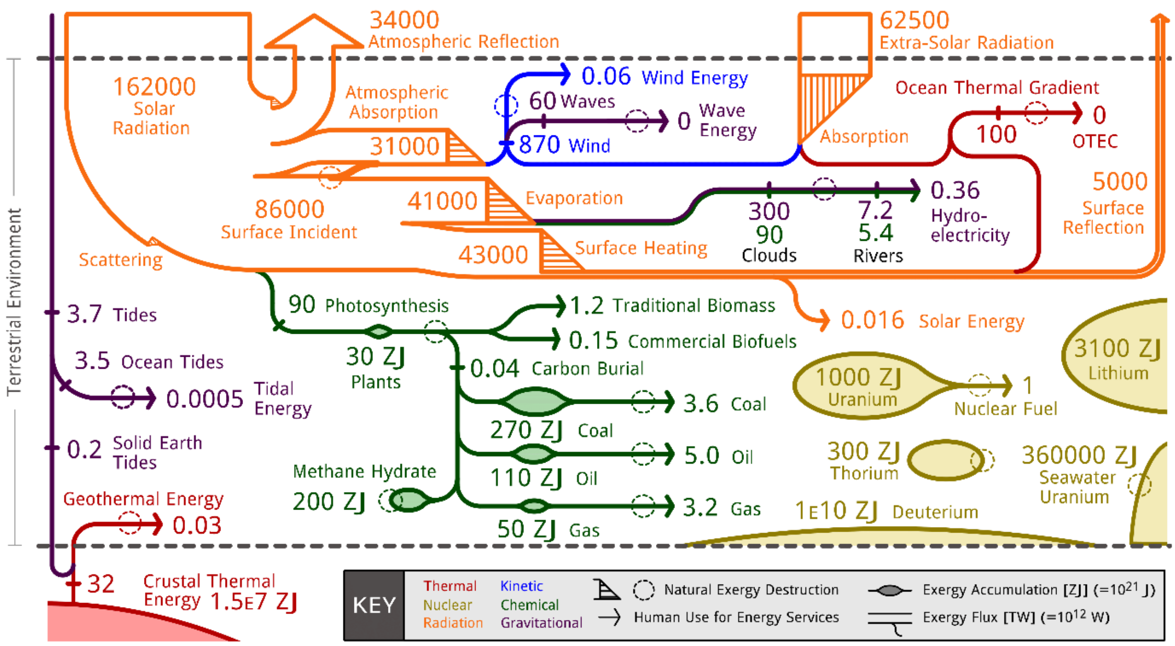

Figure 1.4 - Global reservoirs, flux, and anthropogenic destruction of exergy (HERMANN, 2006)

1.5 CO_2 mitigation by biomass

Mitigation measures must be adopted to reduce impacts of anthropic emissions of GHG in climatic conditions, as well as damage and impairment caused to humankind by global warming (WORLD METEOROLOGICAL ORGANIZATION/GLOBAL ATMOSPHERE WATCH – WMO/GAW, 2012).

One of the possibilities for CO_{2eq} mitigation is its fixation in the soil in the form of organic carbon by captured by plants (MACHADO, 2005). It is estimated that, the soil capacity to store organic carbon is about four times bigger than the plant biomass and three times bigger than the atmosphere's capacity to store CO_2 (BERNOUX et al., 2001; ESWARAN; BERG; REICH, 1993).

Forests are recognized as an important form of carbon sequestration from atmosphere (IPCC, 2001, 2014). Estimates indicate that, globally, forests stock is about 283 Pg[4] of carbon, only in the aerial biomass (HIGA et al., 2012). In this case, biomass refers to dry matter incorporated in the aerial part of vegetal individuals of determined area (BROWN, 1996), if we consider leaf litter and roots as being approximately 30% of the biomass of the aerial part (HARIDASAN, 2000), it is possible to estimate 80 Pg of carbon more to this estimative, varying according to the biome.

[4] Pg – petagrams (10^{15} grams or 10^{9} t)

After planting and harvesting a determined crop, part of the produced biomass, is not economically used and is left in field, forming a layer of organic matter that can help controlling invasive plants (HASSUANI; LEAL; MACEDO, 2005). Residues removal can cause losses in productivity of the next crop planted (WILHELM et al., 2004) due to the depletion of nutrients and greater exposure to humidity loss of the soil superficial layer. However, in case there is too much residue produced, part of that material can be used as fuel, reducing the need for utilizing fossil fuel, and so, avoiding CO_2 emissions.

Carbon in the organic form, as residues of agricultural crops, besides fix and mitigate carbon, can be useful in several ways to the soil and to the croplands, diminishing loss of soil for superficial runoff and in laminar erosion in conditions of covered soil (GRIGG; FOUSS; SOUTHWICK, 2005; LAL, 2009).

1.6 Biofuels

In some countries, biofuels have been considered as a way to develop renewable, sustainable and cost effective energy source, with less emission and less natural resources depletion as well as a way to reduce the dependency on fossil fuel reducing imports of oil and coal from producers countries, avoiding uncertainties in international oil market (MALIK et al., 2014; SINGH; OLSEN; PANT, 2013; NIGAM; SINGH, 2011).

Estimation of the world total energy consumption show increases by 41% until 2035, demanding an increase of about 6.4% per year. It is expected this increase will, majority, come from renewable sources, expanding from 2% to 7% the share of renewable fuels in the world energy consumption and representing 3% of liquid fuels (BRITISH PETROLEUM - BP, 2014).

Most of the paths to convert biomass to energy are well known and usually are by a process of combustion (like firewood to cook), bio-chemical transformation (carbohydrates to ethanol) or mechanical extraction with esterification to produce biodiesel (MCKENDRY, 2002). Other conversion process, as gasification or second generation of ethanol, requires more complex technologies, operating with modern biomasses (GOLDEMBERG, 2009).

Biomass production to obtain biofuel can help to offset CO_2 in the atmosphere either by absorbing CO_2 and fixing it in organic carbon (photosynthesis) or by reducing its emission replacing fossil fuels. However, to quantify the carbon offset by biofuels it must be considered the GHG (mainly N_2O and CH_4) released in agricultural practices and the CO_2 emitted by the LUC (ADLER; GROSSO; PARTON, 2007).

As soil has great amounts of organic carbon, it is essential to consider the previously use of soil. The common sense is consider the removal of a native forest to implement the crop, emitting large amount of CO_2 due to the decay of the organic carbon (mineralization through the decomposition of the organic matter), but if the crop is established in a depleted soil, it is possible, trough cultivation management, like non-tillage, to improve the organic carbon in the soil, helping to fix carbon form the atmosphere (WEST; POST, 2002).

Fossil fuels and land use change (LUC), mainly from natural forests to crop lands, are the main two sources of GHG emissions (Intergovernmental Panel on Climate Change, 2013) and both are correlated with mankind necessities of energy, in the form of food, heat, power, work or transport, tightly linked with mankind, demonstrating the intrinsic relation between fossil fuels and land use to GHG emissions, flows and stocks (Section 1.1).

Bioenergy has a large mitigation potential, but it is necessary to consider aspects such as the sustainability of agricultural practices, the efficiency of bioenergy systems (CHUM et al., 2011) and, crucially, on a trustworthy land-use assessment (SMITH et al., 2014).

Climate change, agriculture, food demand and land use are intrinsic subjects and must be deeply analysed due to them importance. As agriculture is a major user of the land and together with forestry, and other land use (AFOLU) plays a main role for food security and sustainable development, causing considerable high changes on natural CO_2 flows (SMITH et al., 2014).

Accounting both, the direct and indirect LUC (ILUC), effects of biofuels development is essential to improve the environmental assessment, ILUC occurs when new cropland areas for bioenergy feedstock induces a change in land use on other region, shifting the original land use to an alternative area in order to maintain the same production level of food/feed crops (AOUN; GABRIELLE; GAGNEPAIN, 2015).

Higher crop yields and the energy efficiency of biofuels can reduce the pressure on land and therefore the indirect effects associated with LUC and ILUC, also genetic improvement could improve yields, reduce the use of inputs (AOUN; GABRIELLE; GAGNEPAIN, 2015) as well as the use of crops residues like corncob, corn stove or sugarcane trash.

However, despite political agreements, programs for energy efficiency, renewable fuels development and numerous studies regarding environmental issues due to use of fossil fuels, developed and emerging countries keep increasing oil consumption as the main power source to economic growth, leading to higher greenhouse gases (GHG) emissions and depletion of fossil fuel reserves (CAPELLÁN-PÉREZ et al., 2014).

1.7 Input-Output analysis

Originally, Leontief's Input-Output (IO) model (Leontief 1936) referred to the economic flow among productive sectors and has been used in many studies to describe values exchanged between sectors in an economic region, it also can be applied to physical units produced, such as energy or units of production (e.g. mass of sugarcane or units of cars) and, since the late 1960's, it has been extended to environmental pollution assessment aimed not only to the industry in question, but also to its contribution to the economic relations with other sectors (MILLER; BLAIR, 2009).

IO analysis is a methodology broadly applied to economic and structural analyses research; it is also used to assess macro-economic impacts of specific sectors in the economy. The methodology also enables evaluate impacts of new economic activities on a regional or national economy, by using IO tables (MARTÍNEZ et al., 2013).

IO tables are generally constructed from observed economic data for a specific geographic region (nation, state, county, etc.). One is concerned with the activity of a group of industries that both produce goods (outputs) and consume goods from other industries (inputs) in the process of producing each industry’s own output, IO tables, so represent annual monetary flows of goods and services among different sectors in the economy (MILLER; BLAIR, 2009).

Although studies demonstrate the benefits of biofuels (SEABRA et al., 2011; TILMAN et al., 2009) earlier life cycle assessment (LCA) studies do not take into account all the supply-chain impacts, this kind of inaccuracy can be overcome by using input-output (IO) analysis in a hybrid LCA providing an overview of the whole process (MALIK et al., 2015).

A multi-region input-output (MRIO) can describe internal influences of distinct scenarios among economic sectors of a country, its use showed good results to assess socio-economic aspects at the Northeast Brazilian sugarcane industry (MARTÍNEZ et al., 2013). Since the 1990’s, globalization has made international market grow rapidly and, as a result, international trading has become important over time, at this aspect, a MRIO table turns up as a way to investigate international trade (KANEMOTO; MURRAY, 2013).

Generally, impacts are considered isolated, but studies presenting more than one impact usually consider only one aspect of sustainability like environmental, social or economic, using the economic flows to determine material flows.

On the other hand, the MRIO assessment enables a broader approach including direct and indirect aspects of social, environmental and economic traits in only one assessment for all these issues, as an assessment called triple bottom line (TBL), connecting them with economic influences of different scenarios in the MRIO matrix of a region.

1.8 Life Cycle Assessment as tool for impacts and sustainability

Ways to evaluate impacts of anthropogenic actions on the environment have been proposed vis-a-vis the increasing concern as for to the capacity of the planet Earth support regarding the population, consumption of natural resources and residue disposal. Thus, the thought of planet sustainability appears in the 1970's with the question of which are the limits for the population growth (MEADOWS et al., 1972).

An important issue in sustainability is the quantity of carbon emitted, mainly by fossil fuels to generate electricity, heat or as liquid fuel to transport, due to increasing concerns about possible impacts global warming might cause, if the GHG concentration increases (as described in the item 2.2), negatively affecting the society and human health. Thereby, to verify the gas emissions, energy consumption or other aspects that might be brought and after a standardization of these tools that the LCA was established, which quantifies from the extraction of feedstock (cradle) up to its discard in a sanitary landfill (grave) evaluating, therefore, all phases of its life, making use of tools and techniques bound to help environmental management and, long term, sustainable development (JENSEN et al., 1998).

LCA of biofuels demand a great number of variables evaluation and must consider local and climatic factors that vary among studies, as well as it demands further analysis of indirect effects of the use of bioenergy, like land use changes which makes the LCA standardization currently impractical to biofuels assessment (CHERUBINI; STRØMMAN, 2011), allowing to make a consistent LCA from production and utilization of biofuels.

Also, an important point to defined is the methodology to determinate the system boundaries, functional unit, system of reference and land use change. Specifying if your assessment is from well to tank, from tank to wheel and from well to wheel as possible boundaries to stablish a biofuel LCA (GNANSOUNOU et al., 2009).

As the technique spread, several LCA studies concluded differently after studying the same biofuels due to different factors evaluated, as the boundaries applied, time of data collection, considered energy matrix, among other critical factors, proving the necessity of LCA methodology standardization (COLTRO, 2007). The first document directed to standardize LCA methodology was the SETAC Guidelines for Life Cycle Assessment – a Code of Practice (SOCIETY OF ENVIRONMENTAL TOXICOLOGY AND CHEMISTRY - SETAC, 1993), guiding the international normalization works of International Organisation for Standardization (ISO), and lately the regulation series ISO 14040 relative to LCA.

LCA studies are extremely data intensive activities, and results reliability are heavily based on the quality of information upon which the study is based (VIGON; JENSEN, 1995), thus, assessing data quality utilized in the life cycle inventory (LCI) is vital in LCA consistency of results (BAKST et al., 1995).

Results obtained can be showed in different ways, depending on how is the approach desired, a very common kind of result is to expose the environmental intervention, such as CO_2 emission and its consequently concentration enhancing in the atmosphere, and the direct impacts in the environment, like: radiative forcing, global warming, rise of sea level, among other possible impacts. This kind of result quantifies the environmental impacts, commonly, called midpoints of a cause-effect chain (GUINÉE, 2002; JENSEN et al., 1998; TUKKER, 2000). Another way to present the results is correlate the environmental impacts with human health, number of death people, loss of biodiversity, ecosystem well-being, resources depletion, among many possible others (TUKKER, 2000).

Even with the limitation of simplifying some aspects to achieve a detailed and broad scope of analysis the complete life cycle of one determined product, LCA can play a useful role in public and private environmental management in relation to products and process, helping decision makers to choose a more appropriate alternative comparing between usual and new products and prototypes, providing information for decision support (GUINÉE, 2002).

1.9 Hybrid Life Cycle Assessment

Hybrid life cycle assessment involves coupling detailed process data, with environmental, social or economic information and combine them with economic input-output data. This coupling allows us to harness the strengths of both methods – process analysis is specific and detailed, however it is affected by so-called truncation errors that are caused by the selection of a finite system boundary (LENZEN, 2000).

Input-output analysis, in contrast, includes all upstream supply chains, hence is considered complete. However, the sectors in an input-output table contain aggregated data. Consequently, combining the strengths of both methods in a hybrid approach offers completeness and specificity (SUH; NAKAMURA, 2007; SUH, 2004; SUH et al., 2004).

Hybrid LCA has become a well-established technique for quantifying the environmental, social and economic impacts of an economic activity. More recently, an augmentation approach has been suggested for hybridising process data with input-output data (MALIK et al., 2014).

1.10 General objective

The general objective of this study is assess biofuels, studying their flows correlating their use with environmental (GHG and primary energy consumption), social (employment) and economic aspects (imports and economic stimulus), looking for, not only the amounts of GHG mitigated, but assessing the function of these CO_2 and their impacts in a sustainable point of view.

The first specific objective of this study is to assess the biofuel production under a qualitative energy approach to the energy function of carbon mitigated that, biofuels have, assessing mass and energy flows involved on its production. It was measured, not only the required area to mitigate the mass of carbon released by fossil fuels, but it was proposed a new policy methodology to compute the area to replace the useful energy (exergy) released by fossil fuels that emitted GHG (Chapter 2).

Furthermore, the second specific objective was to evaluate direct and indirect impacts of biofuel production, on a multiregional hybrid LCA performing a TBL of environmental, social and economic impacts of biofuel production, and compare these indicators with cattle and other live animals sector (Chapter 3).

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2 CARBON OFFSET BY BIOFUELS COMPARING MASS AND EXERGY FLOWS

Abstract

Biofuels are a key option on the path to economy decarbonisation, in order to reduce climate changes, avoiding problems of extreme climate events and great losses of food and feed production. This study proposes a new policy regarding the measurement of carbon offset by biofuels by adding the concept of exergy on carbon sequestration and the size of the area required to provide the same amount of exergy of fossil fuels, providing equivalent energy in the matrix. Based on previous studies of sugarcane and eucalyptus carbon flows, both crops were considered in five distinct scenarios of biofuel production, approaching a broad technological range for bioenergy production. This study used previous studies on biofuels carbon life cycle inventories (LCI) of sugarcane and eucalyptus to estimate the carbon flow, and correlate it with the exergy available in the biofuel produced. Five scenarios of sugarcane and five scenarios of eucalyptus are used to current old and future paths to produce biofuels and compared with four commercial fuels, diesel, gasoline pure and gasoline blended with 18% and 25% of ethanol. In all cases, sugarcane presented smaller specific exergy, 59% in average, than eucalyptus, but 45% higher exergy output, in average, due to its greater yield. A more intuitive way to increase exergy availability on sugarcane and eucalyptus crops is increasing their yields. However, areas that already present high yield, can focus in reduce the moisture of solid fuels, such as wood and straw, increasing exergy available. Biofuels can reduce pressure on fossil fuels use and have a beneficial effect on CO_2 sequestration, helping to reduce global warming problems, as well as other environmental friendly effects.

Keywords: Bioenergy; Mitigation; Ethanol; Bio-oil; Decarbonisation; Renewable

2.1 Introduction

CO_2, CH_4, N_2O are the main components of greenhouse gases (GHG) emissions and, consequently, climate changes and global warming. It is expected that these effects trigger ozone layer depletion, droughts, reduction of fertile soils, biodiversity loss, freshwater depletion, inducing several consequences for the sustainability of ecological systems, food production, economic activities and human health, threatening food security around the World (LEVY; PATZ, 2015; MCMICHAEL, 2001; MCMICHAEL et al., 2003; WHEELER; VON BRAUN, 2013).

To avoid or to reduce negative environmental impacts, some countries are changing their production structure to a decarbonised system, adopting low-carbon energy sources. Despite the climate change, the subject is not an urgent topic in the USA, it has already proposed a reduction of CO_2 emissions, besides an increasing number of states has adopted energy policy portfolios or packages and a cap-and-trade system is likely to be adopted (CARLEY, 2011; LESTER; HART, 2012; PALTSEV et al., 2007). On the other hand, Europe Union already has a strong policy regarding decarbonisation (DUPONT; OBERTHÜR, 2015; FULTON et al., 2015; TASIOS et al., 2013).

China, whose economic growth has increased in average by 11% per year from 2006-2014 (THE WORD BANK, 2016), is also starting a plan to mitigate and cut GHG emissions, reducing both problems, climate change and air pollution (TENG; JOTZO, 2014). Brazil is one of the countries that are taking great effort to develop renewable energy (MCCRONE et al., 2012) and have already strong plans to reduce emissions (BRASIL, 2016).

Biofuels appear as a key alternative to decarbonisation in all these examples, and it is expected that liquid biofuels will reach around 4% of global road transport fuel demand with a growth of 2.3 times of its use from 2007 to 2020 (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT/INTERNATIONAL ENERGY AGENCY, 2014). Among this scenario, ethanol is one of the most promising options (ROSILLO-CALLE; WALTER, 2006).

Current gasoline and diesel consumption in Brazil in the year of 2014 was 33,429,000 m^3 and 58,885,000 m^3 respectively (EMPRESA DE PESQUISA ENERGÉTICA - EPE, 2015), producing a total of 94,269,780 Mg CO_2 by gasoline and 172,533,050 Mg CO_2 by diesel and totalling 266,802,830 Mg CO_2 of emissions just from these fossil fuels. This amount represents 1.18 EJ by gasoline and 2.36 EJ by diesel of fossil fuel exergy consumed in the year of 2014.

In Brazil, ethanol blended in gasoline is mandatory since 1975 and has had a new impulse on its market since 2003 due to the adoption of flex-fuel cars (RÜTHER, 2016). Moreover, Brazil is the world major ethanol exporter and the second largest producer, after USA (DU; CARRIQUIRY, 2013).

GHG emissions are measured in global warming potential (GWP). In the GWP measurement, all the potential GHG have their warming potential equalized to an equivalent amount of CO_2 mass, making possible to measure how much CO_2 or CO_2-equivalent (CO_{2}-eq) of other GHG gases are emitted or sequestered (SATHAYE; MEYERS, 1995).

Currently, GHG emissions are assessed as proposed by Krey et al. (2014) and the IPCC (2014) in mass of CO_2-eq, regardless the GHG sources coming from energy production, industrial processes, Agriculture, Forestry and Other Land Use (AFOLU), or other economic sector, focusing on how much it contributes to the global warming but with less importance on its utility. This point of view is necessary to equalize the emissions regarding their global warming potential, but does not consider the function of this GHG in their origins, for instance, most of CH_4 is produced by livestock and N_2O by nitrogen fertiliser and animal manure applications to cropland (MONTENY; BANNINK; CHADWICK, 2006).

Similarly, CO_2 sources have different functions such as the biological CO_2 emitted by land use change (LUC), e.g. when a native area is used to produce food or energy. Energy use (electricity and transportation) presents about 68% of total CO_2 emissions in the USA (not accounting other GHGs). Globally, this predominance of CO_2 emissions regards mostly electricity generation and transportation in all developed countries, while in developing countries emissions from industry and LUC are more intense (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2016).

Considering the energy origin of most CO_2 emitted and the possibility to sequester carbon (C), besides reducing pressure on fossil fuel use (CLIFTON-BROWN; BREUER; JONES, 2007), it is necessary to select a very efficient energy biomass and process to produce biofuel (SAIDUR et al., 2012), aimed at reaching both targets: mitigate CO_2 and replace fossil fuel use.

The exergy concept, also known as available energy, can be applied to CO_2 more appropriately then energy concept. Exergy is based on the second law of thermodynamics and can be defined as the maximum work available in a flow of material or energy when they change from an initial state to the steady state (also called dead state), exchanging heat just with the environment (ROSEN; DINCER, 1999; SZARGUT; MORRIS; STEWARD, 1987).

Like energy, the total exergy of a material can be disassembled into different shares of contribution: Chemical exergy, considering the different chemical composition of a material and the system; Physical exergy, considering the difference of temperature, pressure, volume and the difference of potential (SZARGUT; MORRIS; STEWARD, 1987).

This study aimed to develop a methodology to determine the area required to produce the same amount of useful energy (exergy) with sugarcane and eucalyptus in different paths of energy exploitation, verifying distinct technologies of biofuel production and highlighting the most efficient ones.

2.2 Methodology

This study used previous studies on biofuels carbon life cycle inventories (LCI) of sugarcane (BIZZO et al., 2014; LEAL et al., 2013; MACEDO; LEAL, 2004) and eucalyptus (PROTÁSIO et al., 2013; SANTOS et al., 2012; STAPE et al., 2010) to estimate the carbon flow, and thus, provide a new point of view about GHG mitigation process, focusing on the exergy available on the carbon sequestered.

Figure 2.1 shows a simplified flow of the proposed carbon mitigated pathways, its processes and the boundary considered on this assessment. It comprises from the atmospheric CO_2 sequestration to the final source of energy available to use which can be ethanol for Otto-cycle engines, bio-oil to Diesel-cycle engines or electricity for general use.

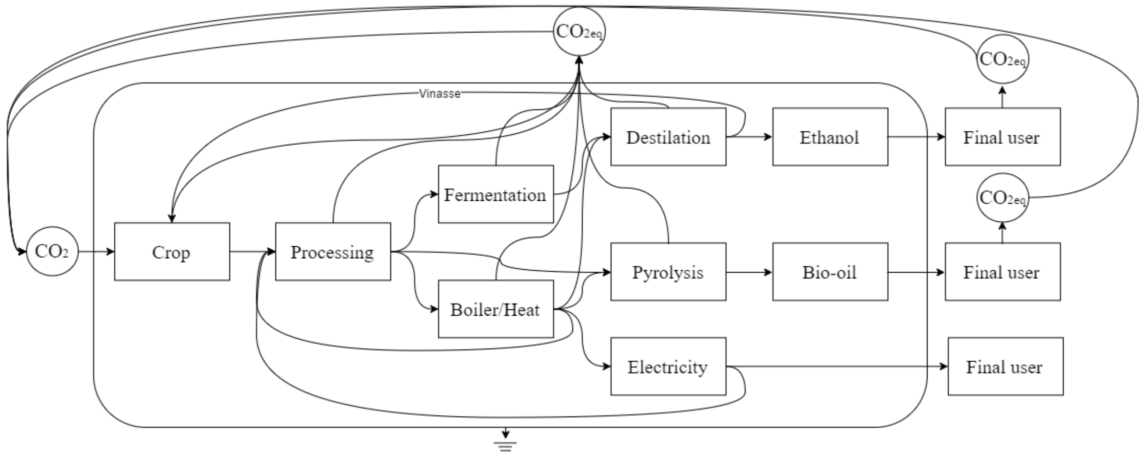

Figure 2.1 - Generic diagram of carbon-energy flow

To determine the energy content of a biofuel, the concept of exergy will be used. Exergy is best suited to evaluate energy process, as it incorporates the second law of thermodynamics which comprises losses and irreversibility of all thermal processes and energy transformations in the process of fuels production and use. The specific exergy of a material is given by the Equation 1 (MORAN; SHAPIRO, 2008).

$$e = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \qquad (1)$$

Wherein: e is specific exergy (kJ kg^{-1}); u is specific internal energy (kJ kg^{-1}); p is pressure (atm); v is volume (m^3); T is temperature (K); V is velocity (m s^{-1}); g is gravity acceleration (m s^{-2}); z is height (m). u_0, v_0 and s_0 are specific properties on the dead state at T_0 and p_0.

The pattern to zero exergy (dead state) is considered as T_0 = 298,15 K (25 °C) e p_0 = 1 atm (101,325 kPa) (ROSEN; DINCER, 1997).

As physical parameters are extrinsic to biofuel use, only the chemical exergy will be considered at this work. The chemical exergy available in a solid fuel is given by Equation 2 and, in a liquid fuel is given by Equation 3 (SZARGUT; MORRIS; STEWARD, 1987), correlating the fuel LHV (low heat value), moisture content, elemental composition and ash content (for calculations of this work it was not considered the ash content due to its low mass fraction).

$$b_{ch} = (C_l + Lz_w)\beta + (b_{ch\,S} - C_S)z_S + b_{ch\,a}z_a + b_{ch\,w}z_w \quad (2)$$

$$b_{ch} = \beta(C_l + Lz_w) + b_{ch\,w}z_w \quad (3)$$

Wherein: b_{ch} is the chemical exergy available in solid fuel; C_l is the lower calorific value of the solid fuel; L is the water vaporization enthalpy, regarded as 2,440 kJ kg^{-1}; z_w is the moisture of the solid fuel; β is the mass ratio between the main components of the fuel (given by Equation 5 to solid fuel and Equation 6 to liquid fuel); $b_{ch\,S}$ is the chemical exergy of sulphur in this solid fuel; C_S is the calorific value of sulphur; z_S is the mass fraction of sulphur present in the solid fuel; $b_{ch\,a}$ is the chemical exergy of ash present in the solid fuel; z_a is the mass fraction of ash present in the solid fuel; $b_{ch\,w}$ is the chemical exergy of the water present in the fuel.

HHV (high heat value) of sugarcane straw and bagasse were considered as 17.7 e 17.1 GJ kg^{-1}, respectively (BIZZO et al., 2014). For eucalyptus it was 19.1 GJ kg^{-1} (QUIRINO et al., 2005).

LHV of these solid fuels were calculated as in equation 3, based on the moisture considered at the time the solid fuel is used.

$$\mathrm{LHV} = [(\mathrm{HHV} - \mathrm{L}(9\mathrm{h} + \mathrm{u})](1 - \mathrm{u}) \quad (4)$$

Wherein: LHV is the fuel low heat value, HHV is the fuel high heat value, h is the fuel hydrogen content; u is the fuel moisture content considered when the fuel is burnt; L is the water vaporization enthalpy, considered as 2,440 kJ kg^{-1}.

The relationship between the compositional elements of the solid and liquid fuel β is given by Equation 5 and 6, respectively (SZARGUT; MORRIS; STEWARD, 1987).

$$\beta = \frac{1.0412+0.2160(z_{H_2}/z_C)-0.2499(z_{O_2}/z_C)[1+0.7884(z_{H_2}/z_C)]+0.0450(z_{N_2}/z_C)}{1-0.3035*(z_{O_2}/z_C)} \quad (5)$$

$$\beta = 1.0374 + 0.0159\frac{H}{C} + 0.0567\frac{O}{C} \quad (6)$$

Wherein: z is a decimal content of the components.

To calculate β, the elemental composition of each biofuel listed in Table 1 was used.

Table 2.1 - Biofuel elemental composition

	Elementary composition (%)				
Biomass	C	H	O	N	S
Bagasse[a]	0.4261	0.0592	0.5090	0.0063	0.0012
Straw[a]	0.4250	0.0602	0.5020	0.0060	0.0024
Eucalyptus[b]	0.4839	0.0629	0.4503	0.0010	0.0020
Charcoal[c]	0.8238	0.0314	0.1243	0.0146	0.0003
Lignin[d]	0.5668	0.0575	0.3475	0.0061	0.0015
Bio-oil[e]	0.4930	0.0620	0.4450	0.0008	0.0000

[a](BIZZO et al., 2014); [b](PROTÁSIO et al., 2013); [c](SOARES et al., 2014); [d](BLUNK; JENKINS, 2000); [e](STANGER et al., 2013)

Subsequently, the chemical exergy available in solid fuel is multiplied by a factor of global efficiency on all cases, bagasse, straw and eucalyptus to electricity. For cogeneration of power plants, it was used a net exergy efficiency of 35% (BOROUMANDJAZI; RISMANCHI; SAIDUR, 2013). As the ethanol yield is the result of a total output, all the efficiency of production is already embedded in the final production.

To determine the exergy content available in 1,000 m³ of commercial fuels it is considered: Densities of 853 kg m^{-3} for diesel oil with emissions of 2.93 kg CO_2 L^{-1}, 747.5 kg m^{-3} for pure gasoline with emissions of 2.82 CO_2 L^{-1} and 789 kg m^{-3} for ethanol (EPE, 2005). Without emission considered, because it is derived from a renewable source as proposed by the European Commission (THE COMMISSION OF THE EUROPEAN COMMUNITIES, 2007). A weighted average of the densities the commercial gasoline blend was used according to the limits required by the Brazilian law (BRASIL, 2014) the addition of anhydrous ethanol must be between 18.0 and 27.5%, 18% was considered as the lowest blend and 25% as the highest as it is indeed used commercially in Brazil.

Chemical exergy values of liquid fuels are 46.984 and 29.471 MJ kg^{-1} for diesel oil and ethanol anhydrous, respectively. As gasoline has different ethanol blends, a value of pure gasoline was used, and the minimum and maximum blends established by law, with 47.386, 44.162 and 42.908 MJ kg^{-1} of gasoline pure, gasoline with 18% of ethanol addition and gasoline with 25% of ethanol addition, respectively, determined according to Szargut, Morris e Steward (1987).

Two possible crops for biofuel were assessed, sugarcane and eucalyptus. A basic scenario with the necessary area to sequester CO_2 by mass was determined considering 169 kg CO_2 Mg^{-1} wet basis (wb) to sugarcane (MACEDO; LEAL, 2004) and 525 kg CO_2 Mg^{-1} (wb) to eucalyptus, considering a content of 16% of C (wb) in the three (SANTOS et al., 2012).

For sugarcane, three ways to produce energy were adopted, the juice extracted with high content of sucrose, bagasse with the usual moisture of its use in a sugarcane mill and straw which is a new source of energy in sugarcane mills in two different moistures (VEIGA et al., 2015).

For eucalyptus, three ways to produce energy were adopted. First burning the wood in a furnace or transforming the wood into charcoal, both are usual ways for this crop as an energy source (PROTÁSIO et al., 2013), second using the entire tree to produce 2nd-generation ethanol (HAMELINCK; HOOIJDONK; FAAIJ, 2005), and third, to produce bio-oil by fast pyrolysis and using it in diesel engines (XIU; SHAHBAZI, 2012).

Possible scenarios reflecting current advanced and future technologies for both crops were considered, summing up 10 scenarios, covering a broad range of possible ways to produce bioenergy through the analysed crops. Table 2.2 summarizes all the crops, how their parts are considered and the purpose of energy considered, ethanol or electricity.

Table 2.2 - Biofuel production scenarios

Scenario	Acronym	Crop	Yield (Mg ha^{-1} year^{-1} wb)	Biomass	Moisture (%)	Purpose
Sugarcane basic	SCb	Sugarcane	85	Juice	*	Ethanol
				Bagasse	50	Electricity
Sugarcane with straw	SCs50	Sugarcane	85	Juice	*	Ethanol
				Bagasse	50	Electricity
				Straw	50	Electricity
Sugarcane with straw	SCs30	Sugarcane	85	Juice	*	Ethanol
				Bagasse	50	Electricity
				Straw	30	Electricity
Sugarcane and bagasse to ethanol	SCe	Sugarcane	85	Juice	*	Ethanol
				Bagasse	*	Ethanol
				Straw	30	Electricity
Sugarcane to ethanol	SCe2	Sugarcane	22	Whole plant	*	Ethanol
Eucalyptus to firewood	Ef20	Eucalyptus	22	Whole tree (firewood)	20	Electricity
Eucalyptus to firewood	Ef15	Eucalyptus	22	Whole tree (firewood)	15	Electricity
Eucalyptus to charcoal	Ec	Eucalyptus	22	Charcoal	6	Electricity
Eucalyptus to ethanol	Ee	Eucalyptus	22	Whole tree	*	Ethanol
				Lignin	20	Electricity
Eucalyptus to bio-oil	Ebo	Eucalyptus	22	Whole tree	*	Bio-oil

* Not considered (wb – wet basis at field conditions)

For sugarcane, the Brazilian average of 85 Mg ha^{-1} (BRASIL, 2013) was used as the basis scenario. To ascertain the influence on yield, two other yields were projected, one with 20 Mg ha^{-1} higher and lower than the base scenario, comprising almost all the range of commercial yields of sugarcane in Brazil for second generation ethanol from the lignocellulosic material, it was used the holocellulose and lignin content of bagasse 59.32% and 22.85% respectively and straw with 65.25% and 20.45% respectively (BIZZO et al., 2014).

For eucalyptus, an yield of 22 Mg ha^{-1}year^{-1} was used, which corresponds to about 46 m^3 ha^{-1} year^{-1} (STAPE et al., 2010), of the production of charcoal with a gravimetric yield of 35% (PEREIRA et al., 2013). Holocellulose and lignin content on eucalyptus was considered as 62.57% and 27.71% respectively (HAMELINCK; HOOIJDONK; FAAIJ, 2005). Different yields were used to observe their influence: a low yield of 15 Mg ha^{-1}year^{-1} was considered as well as a high yield of 38.Mg ha^{-1}year^{-1}.

Ethanol yield from cellulosic material was estimated at 375 g kg^{-1} of holocellulose (CHOVAU; DEGRAUWE; VAN DER BRUGGEN, 2013). On both crops, the lignin material remaining was estimated with 20% of moisture and counted as raw material to burn and produce electricity. Bio-oil yield was calculated as 75% (wet basis) of eucalyptus mass (AMUTIO et al., 2015) and a water content of 25% (BRIDGWATER, 2012).

All the scenarios were compared to assess how much area is necessary to compensate the same amount of exergy of 1,000 m^3 of diesel and gasoline pure (G100) and blended with 18% (G82E18) and 25% (G75E25) of ethanol, as biodiesel blended in Brazilian diesel still incipient it was not considered on or calculations.

In addition, descriptive statistic data is given comparing scenarios with different moistures and yield of the same crop, showing these parameters influence.

The necessary area to produce the same amount of 1,000 m^3 of blended fuels is given by Equation 7.

$$A = \frac{FF_{ex} * 1000}{BF_{ex}} \tag{7}$$

Wherein: A is the crop area necessary to produce the same amount of exergy; FF_{ex} is the blended fuel exergy (GJ m^{-3}); BF_{ex} is the biofuel exergy output (GJ ha^{-1}).

Finally, a relation between CO_2 mass and exergy mitigation showed the difference in the areas to mitigate both, CO_2 and exergy, and how much the crops and the technological parameters and routes of bioenergy production influence in a better exergy yield.

2.3 Results and Discussion

A basic assessment evaluating the area necessary to sequester CO_2 mass emitted by commercial fuels is given in Table 2.3. Even with a lower CO_2 sequestration per mass, as defined on the methodology, sugarcane presents a better result than eucalyptus due to its higher yield per year, requiring less area to mitigate the same amount of CO_2.

Table 2.3 - Emission and necessary crop area to mitigate GHG in mass from 1,000 m^3 of commercial fuels

	Diesel	G100	G82E18	G75E25
Emission (Mg CO_2)	2,930.0	2,820.0	2,312.4	2,115.0
Sugarcane area (ha $year^{-1}$)	173.9	167.4	137.2	125.5
Eucalyptus area (ha $year^{-1}$)	247.1	237.8	195.0	178.4

Exergy content of commercial fuels is shown on Table 2.4 and it presents the necessary amount of exergy available in the biofuel to compensate the same amount of CO_2 emitted. They are the base of comparison for each biofuel scenario.

Table 2.4 - Fossil fuel exergy

Fuel	Exergy content	
	MJ kg^{-1}	GJ m^{-3}
Diesel	46.98	40.08
G100	47.39	35.42
G82E18	44.16	33.34
G75E25	42.91	32.52

For both, sugarcane and eucalyptus scenarios, Table 2.5 indicate chemical exergy and exergy outputs. In all cases, sugarcane presented a smaller chemical exergy than eucalyptus, but the output is higher because of its higher yield.

These results indicate that, with the development of higher density eucalyptus crops with short cycles focused in energy in a commercial scale, there will be a great improvement on the eucalyptus exergy output.

Table 2.5 - Net chemical exergy and Exergy output of main yield

	Scenario	Net chemical exergy	
		MJ kg^{-1}	GJ ha^{-1}
85 Mg ha^{-1} $year^{-1}$	SCb	2.31	196.51
	SCs50	2.80	237.78
	SCs30	2.95	251.10
	SCe	3.34	283.76
	SCe2	3.71	314.99
	Average	3.02	256.83
22 Mg ha^{-1} $year^{-1}$	Ef20	5.66	127.94
	Ef15	5.99	135.46
	Ec	10.22	92.40
	Ee	4.69	106.05
	Ebo	12.30	208.54
	Average	7.77	134.08

Averages and amplitudes are shown on Figure 2.2, in sugarcane the lower exergy output is SCb and the higher SCe2; in eucalyptus the lower exergy is Ec and the higher Ebo. In eucalyptus, the average is close to the lower value, indicating most of the other scenarios do not have a high exergy output, mainly because of low efficiency conversion systems.

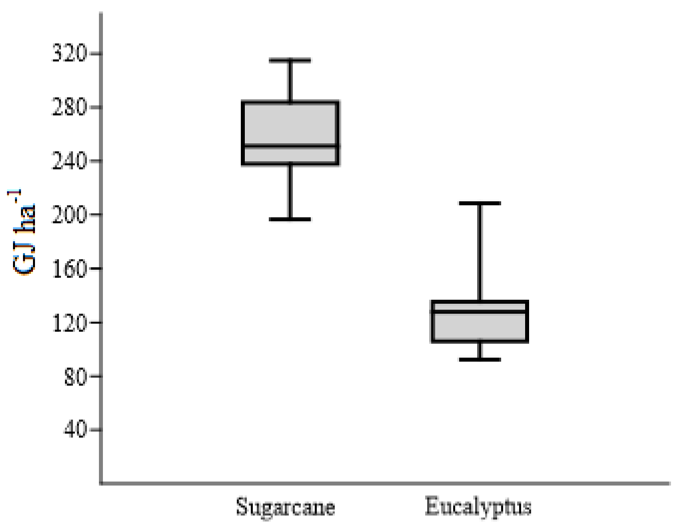

Figure 2.2 - Sugarcane and Eucalyptus exergy output, average and amplitude

For sugarcane scenarios with different moistures, reducing straw moisture from 50% to 30% increased the exergy output in 13.32 GJ ha^{-1}, an increase of 0.67 GJ ha^{-1} for each 1% of moisture reduce.

Similarly, eucalyptus scenarios with different moistures, reducing firewood moisture from 20% to 15% had an increase of 7.52 GJ ha^{-1} in the exergy output, 1.50 GJ ha^{-1} of increase for each 1% of moisture reduced.

As straw represent a third of sugarcane total energy (LEAL et al., 2013), it was expected a smaller improve on exergy output than in the eucalyptus when moisture is reduced, because in the eucalyptus cases all the biomass is used on exergy production.

Table 2.5 also summarizes results with higher and lower yields presented for sugarcane and eucalyptus scenarios. On average, each Mg of biomass produced, leads to a change of 3.02 GJ on sugarcane scenarios and 5.93 GJ in eucalyptus scenarios, which demonstrates higher increments on exergy output in eucalyptus than in sugarcane.

The required area to produce the same exergy of 1,000 m³ commercial fuels is shown in Figure 2.3 and Figure 2.4. In the main scenario of yield for both crops, all sugarcane scenarios present an average of 141.19 ha GJ^{-1} and all eucalyptus scenarios present an average of 284.45 ha GJ^{-1}.

In average, the necessary area to mitigate 1,000m³ of commercial fuels with higher and lower yields in sugarcane scenarios need more 43 ha with a yield of 65 Mg ha^{-1} $year^{-1}$ and less 27 ha with a yield of 105 Mg ha^{-1} $year^{-1}$. Eucalyptus scenarios, also in average, needs more 144 ha with a yield of 22 Mg ha^{-1} $year^{-1}$ and less 115 ha with a yield of 38 Mg ha^{-1} $year^{-1}$.

These results show a decreasing variation on differences with higher yields, it demonstrates that higher incomes on energy, necessary for higher yields, can reduce the efficiency of energy production rather than better results.

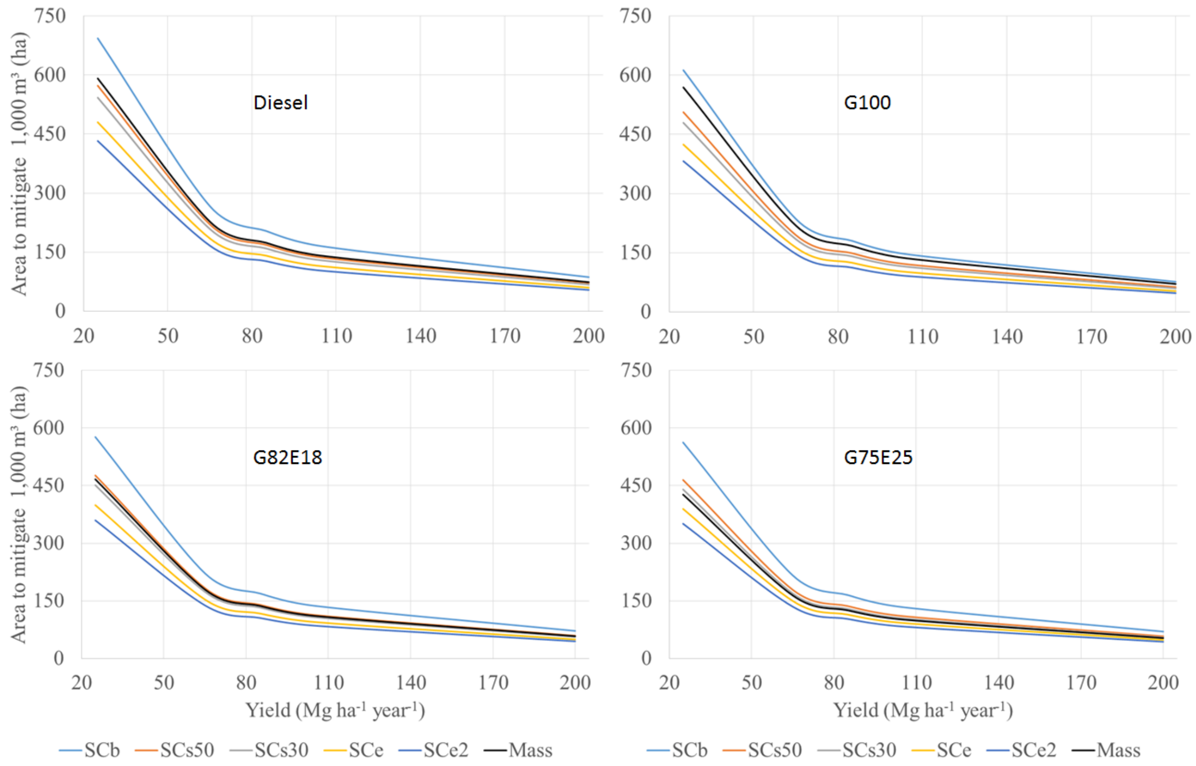

Figure 2.3 - Sugarcane necessary area to mitigate 1,000 m³ of commercial fuels

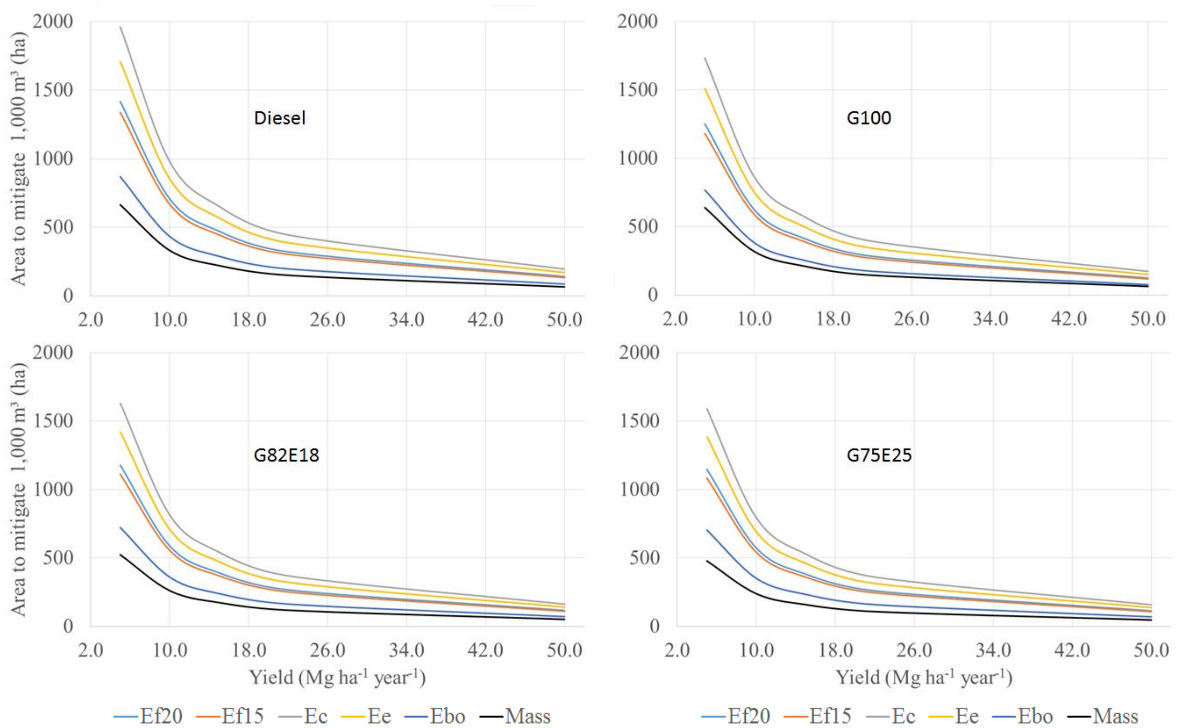

Figure 2.4 - Eucalyptus necessary area to mitigate 1,000 m³ of commercial fuels

Comparing changes in moisture and yield, for each percentage of moisture decreased, there is an increment of 0.6 and 1.5 GJ on average and for each Mg of yield increase, 3.02 and

5.93 GJ on average to sugarcane and eucalyptus, respectively. It demonstrates higher increments on available exergy increasing yield.

The most obvious way to raise exergy availability on sugarcane and eucalyptus crops is increasing their yield. However, areas with high yield require much more investment and energy input to lower increments, at this point focus on moisture could bring better outcomes in the exergy availability then aiming a higher productivity.

The shape of sugarcane and eucalyptus solid fuels pose influence on reducing its moisture. As straw and bagasse already have a large mass-transfer area, eucalyptus must be chiped to accelerate the water losing process. However, larger pieces of wood take more time to reduce moisture but they have better aeration for drying and a lower tendency to absorb rainwater after it is dry (VEIGA et al., 2016). On all conditions, a simple way to reduce moisture is leaving the biomass infield to dry naturally (PARI et al., 2015).

To realize the total amount of area necessary to sequester CO_2 and produce the same exergy content of all fossil fuel consumed in Brazil, Table 2.6 informs the total amount of diesel and gasoline consumed in the year of 2014 (EMPRESA DE PESQUISA ENERGÉTICA - EPE, 2015).

Table 2.6 – Diesel and gasoline consumption, emissions and exergy Brazil in 2014

Fuel	m³	Mg CO_2	10^9 GJ
Diesel	58,885,000	172,533,050	2,36
Gasoline	33,429,000	94,269,780	1,18

In mass terms, to mitigate the amount of CO_2 emitted by gasoline, it is necessary an ethanol dedicated area of 5.6 million ha of sugarcane or 7.95 million ha of eucalyptus. For the amount of CO_2 emitted by diesel, it is necessary 10.24 million ha of sugarcane and 14.55 million ha of eucalyptus.

The area needed to produce the exergy of all gasoline and diesel consumed is presented in Table 2.7. For sugarcane, it is possible to reduce the area in 38% comparing the worst and the best exergy. For eucalyptus there is an even great improvement if comparing Ec and Ebo scenarios, it is possible to reduce 56% of the necessary area to produce all the exergy of fossil fuel.

Table 2.7 - Required area to produce all the exergy of fossil fuels in Brazil

Scenario	Diesel	Gasoline	Total
	10^6 ha		
SCb	12.01	6.02	18.04
SCs50	9.92	4.98	14.91
SCs30	9.40	4.72	14.11
SCe	8.32	4.17	12.49
SCe2	7.50	3.76	11.25
Average	9.43	4.73	14.16
Ef20	18.45	9.26	27.70
Ef15	17.42	8.74	26.16
Ec	25.54	12.81	38.35
Ee	22.25	11.16	33.42
Ebo	11.32	5.68	16.99
Average	18.99	9.53	28.53

The current crop area of sugarcane in Brazil is around 9 million ha in 2016/2017 (COMPANHIA NACIONAL DE ABASTECIMENTO - CONAB, 2016), eucalyptus has around 7 million ha (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE, 2016). On average, it would be necessary an increment of 5 million ha in the current area of sugarcane production and an increment of 21 million ha, in both cases, those whole areas must be dedicated only to energy production.

Although it is difficult to produce all the exergy, it is possible to confirm that biofuels can reduce the pressure on the usage of fossil fuels and also have a beneficial effect of CO_2 sequestration, helping to mitigate climate change and global warming (SMITH et al., 2014), as well as having other environmental friendly effects, considering biofuels usually present S content avoiding emissions of SO_x, particulate matter and problems with acid rain for its combustion (VEIGA et al., 2016).

2.4 Conclusions

The adopted approach is most appropriate in cases of C mitigation studies for biofuels, dealing with the real utility of carbon on fossil fuels in a way to not just remove CO_2 from the atmosphere but also reduce demand on transport fossil fuels energy. Exploring further a crop area, utilizing 2nd generation ethanol or bio-oil technologies, it is possible to produce biofuel from lignocellulosic material and food (e.g. corn grains for food and corncob and straw for biofuel), aiding to reduce the dispute of biofuels and food on land use.

Though exergy assessment is more precise to describe exergy flows, in future works it is also possible to use the available energy content utilizing the LHV as a proxy to exergy flows, facilitating a quick assessment.

In the same manner this work assessed C on its practical use, other ways of mitigation can be counted not only by C mass but also develop alternatives to introduce C utility in the system such as the amount of C in the soil when biochar or mulching is used to sequester C or biodiversity in cases of mitigation projects with natural or planted forests. Using, therefore, not only the C amount sequestered but also its importance on the global carbon cycle with the mitigation method employed.

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3 TRIPLE-BOTTOM-LINE ASSESSMENT OF SÃO PAULO SUGARCANE PRODUCTION BASED ON A BRAZILIAN MULTI-REGIONAL INPUT-OUTPUT MATRIX

Abstract

Sugarcane to biofuels is a reality on the path to economy decarbonisation in Brazil, helping to mitigate global climate changes and reducing pressure on fossil fuel demand. To assess the sustainability performance of sugarcane biofuel production in Brazil, we utilise an extended multi-region input-output (MRIO) matrix to determine the multipliers of carbon emissions, primary energy use, labour, imports and economic stimulus and their relationship to the Brazilian economic system. Furthermore, we perform a hybrid input-output (IO) life cycle assessment to analyse the triple bottom line (TBL) aspects of sugarcane production in the state of São Paulo. It was assessed differences between sugarcane and pasture land use and between two distinct sugarcane production systems: Owners where the mill purchases or rents the area and employs its own labourers and machinery, and Suppliers where sugarcane is produced and sold by farmers to the mill. In areas where pasture to cattle is replaced by sugarcane, energy consumption is increased by a factor of 3.7, employment is reduced by a factor of 5.4 and GHG emissions are reduced to only 2% for each R$ of final demand changed. Suppliers and Owner sugarcane producers have similar results: the total amount of imports in both cases is almost the same. The Owner case results in more direct full time jobs and probably in a more formal job market. Most of the employment is generated in the supply chain sector on both cases. Suppliers case uses less energy and results in less GHG emissions than Owner sugarcane production.

Keywords: Sustainability; Life cycle assessment; Biofuels; Land use change; Input-output

3.1 Introduction

Worldwide, growing concern about climate change and its implications for agriculture, food supply, energy security and the environment has led to a search for alternative energy sources. Biofuels are an approach that some countries have considered in order to develop renewable, sustainable and cost-effective energy sources, with lower emissions and reduced depletion of natural resources (MALIK et al., 2014; SINGH; OLSEN; PANT, 2013).

In addition to anthropogenic greenhouse gases (GHG), mainly CO_2, CH_4 and N_2O, fossil fuel combustion generates hazardous gases such as carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), nitrogen oxides (NO_x) and sulphur oxides (SO_x) (CARVALHO, 2011; IPCC, 2007; MALIK; LENZEN; GESCHKE, 2015).

Estimations of the world total energy consumption indicate an increase of around 41% by 2035, demanding an energy production increase of 6.4% per year. It is expected that this increase will mostly come from renewable sources, expanding their share of global energy consumption from about 2% to 7%, and representing 3% of liquid fuels (BRITISH PETROLEUM, 2014).

In this context of increasing energy use, despite political agreements, programs for energy efficiency and numerous studies regarding the environmental problems of fossil fuel consumption in developed and emerging countries, the use of fossil fuels such as oil, coal and natural gas continues to increase, being the main source for economic growth. This results in higher GHG emissions and further depletion of fossil fuel reserves (CAPELLÁN-PÉREZ et al., 2014).

To reduce the dependence of economies on fossil fuel, and thus reduce problems arising from its use, it is necessary to gradually change to renewable energy sources, such as biofuels, wind or solar energy. Reducing fossil fuel consumption can also reduce oil and coal imports by countries that do not produce them, avoiding uncertainties in the international oil market (NIGAM; SINGH, 2011) and reducing economic dependency.

Most of the paths used to convert biomass to energy are well known and are usually processes of combustion (such as firewood in boilers), biochemical transformation (carbohydrates to ethanol) or mechanical extraction with esterification to produce biodiesel (MCKENDRY, 2002). Other conversion processes, such as gasification or second-generation ethanol, require more complex technologies (GOLDEMBERG, 2009).

Biofuels can be categorised as first, second or third generation, according to the feedstock used. First generation liquid biofuels are produced by fermentation of carbohydrates (e.g. sucrose from sugarcane or starch from corn). Second generation biofuels use lignocellulosic material from any agricultural crop (e.g. bagasse from sugarcane processing, corncobs, eucalyptus residues or forests dedicated to energy production). In the third generation microalgae are used as the raw material (NIGAM; SINGH, 2011).

In Brazil, first-generation ethanol from sugarcane has been the major biofuel, developed since the 1970s, when the *Proalcool* program began, and expanded more recently in the 2000s, when the flex-fuelled cars that reached the marketplace promoted its increased development, Despite other crops could be used to energy as castor beans, soybean, palm (VEIGA et al., 2015) or cassava (VEIGA et al., 2016). To provide raw material for this expansion, some regions increased their sugarcane cropping area by up to 21% in only one year, from 2007 to 2008. In central-southern Brazil, traditionally the main region of sugarcane production, the crop area has grown at a rate of 7% per year (INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS - INPE, 2015).

Also in Brazil, the increase in ethanol utilisation as fuel since the 1970s has brought positive impacts to the environment. Ethanol has been added to gasoline, substituting for lead as a gasoline anti-knock additive, and consequently, reducing the lead concentration in metropolitan regions, as well as decreasing sulphur emissions since sulphur is not present in the ethanol (COELHO et al., 2006). When ethanol is used as a fuel without admixture, noxious emissions are eliminated and GHG emissions from fossil fuels are also mitigated as a result of carbon absorption by the sugarcane crop and only a low volume of diesel is used in its production (GOLDEMBERG; COELHO; GUARDABASSI, 2008).

São Paulo state has shown beneficial socio-economic and environmental impacts associated with the expansion of the sugarcane sector. Comparing the use of ethanol from the sugarcane crop and gasoline as fuel, GHG emissions can vary from -165% to +2%, mainly depending on the soil management. However, given the diverse conditions of ethanol production and management, general inferences cannot be made and each case must be assessed individually with greater accuracy of GHG emission measurement (WALTER et al., 2011).

On the other hand, considering the energy index (ODUM, 1996) in addition to carbon and energy balances, there are issues with large-scale production of ethanol from sugarcane. High consumption of natural resources and environmental impacts has turned ethanol, as it is actually produced, into a non-renewable fuel (PEREIRA; ORTEGA, 2010).

In economic terms, the sugarcane industry produces not only ethanol, but also sugar and occasionally electricity. It contributes around US$ 43 billion to the gross domestic product (GDP) representing around 2% of Brazilian GDP in 2013. However, if all the other sectors involved in sugarcane production, industrial activities and the wholesale, distribution and retail network of products derived from sugarcane, this value can reach US$ 108 billion, accounting for more than 60% of sugarcane sector total value (NEVES; TROMBIN, 2014).

Although some sugarcane mills in Brazil have faced recession, and have shut down due to a crisis since the 2008–2009 agricultural season, the sector is still expanding into new regions, such as Goias and Mato Grosso do Sul states. São Paulo state still remains the largest producer in Brazil, however (SCARPARE; LEAL; VICTORIA, 2015).

The establishment of sugarcane mills in new areas has had a huge impact on their economies. For example, in Quirinopolis, a municipality of Goias state, growth in formal jobs, average wages, GDP and several industries at a rate higher than the national average (NEVES; TROMBIN, 2014) demonstrates the considerable impact on regional economies when a sugarcane mill is established in a municipality.

This expansion to new areas mostly occupies abandoned or extensive pastureland or temporary croplands, rather than deforested areas (WALTER et al., 2011). However, land use change (LUC) and especially indirect land use change (ILUC) can compromise the potential GHG mitigation from ethanol production (LAPOLA et al., 2010). Ferreira Filho and Horridge

(2014) estimate that each new hectare of sugarcane requires, on average, 0.14 ha of deforestation due to sugarcane indirectly influence on cattle production areas.

Although many studies have shown benefits from biofuels (SEABRA et al., 2011; TILMAN et al., 2009), early life cycle assessment (LCA) studies did not take into account all of the supply chain impacts. This uncertainty can be overcome by including input-output (IO) analysis in the hybrid LCA to provide an overview of the whole process (MALIK; LENZEN; GESCHKE, 2015).

Due to the expansion of sugarcane industries, decision makers need to analyse its possible impacts on society, the environment and the economy regarding these aspects. Several efforts have been made to analyse it considering different factors, e.g. the number of jobs added to the region, carbon emissions, nitrogen contamination, and regional GDP improvement among other aspects.

Previous studies on the expansion of sugarcane production have usually analysed its carbon balance especially due to LUC, its impact on food prices given the use of croplands to produce biofuels instead of food, and its social impacts in changing the kind of human labour applied as the traditional sugarcane industry changes from manual to mechanised harvesters (EGESKOG et al., 2014; FERREIRA FILHO; HORRIDGE, 2014; GUILHOTO et al., 2002; MARTÍNEZ et al., 2013; NASSAR et al., 2008; PACCA; MOREIRA, 2009; SPAROVEK et al., 2009; ZILBERMAN et al., 2012).

Originally, Leontief's IO model in the year of 1936 (LEONTIEF, 1936), referred to the economic flow among productive sectors and it has been used in many studies to describe values exchanged between sectors in an economic region. It can also be applied to functional physical units of output, such as energy or units of production (e.g. tons of sugarcane or units of cars), and since the late 1960s its use has been extended to environmental pollution assessments aimed not only at the industry in question but also at its contribution to economic relations with other sectors (MILLER; BLAIR, 2009).

A multi-region input-output (MRIO) analysis can describe the interaction of distinct scenarios among economic sectors of a country. Such an analysis showed good results in the assessment of socio-economic aspects of the northeast Brazilian sugarcane industry, as described by Martínez et al. (2013). Since the 1990s, globalisation has caused the international market to grow quickly and, as a result, international trading has become more important over time. In this respect, an MRIO table can be used as a tool to investigate international trade (KANEMOTO; MURRAY, 2013).

Studies presenting more than one kind of impact class, usually consider only one aspect of sustainability such as environmental, social or economic. On the other hand, MRIO assessment enables a broader approach, also called triple bottom line (TBL), which includes direct and indirect aspects of social, environmental and economic traits, in a single assessment for all of the issues. Connecting social and environmental traits with economic influences of different scenarios in the MRIO matrix of a region thus provides a broader assessment.

An extensive assessment of the sugarcane industry in traditional areas of sugarcane production can provide meaningful information about policies for promoting the development of biofuel production from sugarcane in Brazil.

Looking for a broad understanding of the TBL indicators, a correlation among the assessed multipliers is showed for São Paulo state and Brazil, presenting which are related with imports, economic stimulus (defined as the sum of the supply of goods and services by all industries in the economy describing the indirect turnover of an industry or producer, indicating the stimulus created by it on the whole economy (WIEDMANN; LENZEN; BARRETT, 2009)) , employment, primary energy consumption and GHG emission. Studies that had correlations among multipliers can highlight important tendencies among the variables, such as the inverse relationship between energy and labour multipliers (LENZEN, 2001) and the inverse relationship between labour and GHG emissions (LENZEN; DEY, 2002) or correlations between social and environmental multipliers (LENZEN; SCHAEFFER, 2004).

These data show the possibility of reducing energy consumption and decreasing GHG emissions and the depletion of natural resources by using policies that promote labour-intensive and value-added commodities production, thus demonstrating the value of the type of correlation assessment.

Our study offers an expanded viewpoint on the same theme, including information concerning government allowance plans for potential future expansion areas and the kind of production that should be encouraged, based on environmental, social and economic aspects.

We aim to create an extended MRIO matrix to determine the multipliers of each sector given a broad view about carbon emissions, energy, labour, imports and economic stimulus and their relationship to the Brazilian economic system. These, in turn, are used as the basis to perform a hybrid IO assessment to analyse the triple bottom line (TBL) aspects of sugarcane production in the state of São Paulo, a traditional region of sugarcane production in Brazil.

Differences in the multipliers of sugarcane and cattle and other live animals will be analysed, as most of the sugarcane expansion is taking the place of former pasture areas (SPAROVEK et al., 2009).

A comparison between two different sugarcane production systems is also presented. One in areas owned by a sugarcane mill and other by farmers, indicating the different impacts caused by each one.

3.2 Methods

3.2.1 Hybrid life cycle assessment

Hybrid life cycle assessment approaches combine input-output data (see Section 3.2.2) with detailed data on production systems (See Section 3.3.3). Coupling allows one to harness the strengths of both methods — process analysis is specific and detailed, however it is affected by the so-called truncation errors that are caused by the selection of a finite system boundary (LENZEN, 2000). In contrast, input-output analysis includes all upstream supply chains; hence it is considered complete. Conversely, the sectors in an input-output table contain aggregated data. Consequently, combining the strengths of both methods in a hybrid approach offers completeness and specificity (SUH; NAKAMURA, 2007; SUH, 2004; SUH et al., 2004). Hybrid LCA has become a well-established technique for quantifying the environmental, social and economic impacts of an economic activity. More recently, an augmentation approach has been suggested for hybridising process data with input-output data (MALIK et al., 2014). A schematic of this approach is shown in Figure 3.1 — see also (MALIK et al., 2015; MORAN et al., 2014; RODRÍGUEZ-ALLOZA et al., 2015) for examples of case studies that have employed this approach.

Essentially, this approach offers a way to introduce new sectors into an economy. Thus, an existing input-output model is augmented with additional rows and columns containing data for the new sectors, disaggregated from the original sectors that comprise the new sector. In this study, we augment an MRIO model of Brazil (see Section 3.3.3) with two additional sectors — “Owner Sugarcane” and “Sugarcane Suppliers” (See Section 3.3.6). Our MRIO model contains detailed input-output data for 27 regions of Brazil. We introduce the new sectors into the São Paulo region of the MRIO table because this region is the most important sugarcane producing state in Brazil with 51.3% of a total of 9.06 million hectares harvested in the crop year of 2015–2016 (CONAB, 2016).

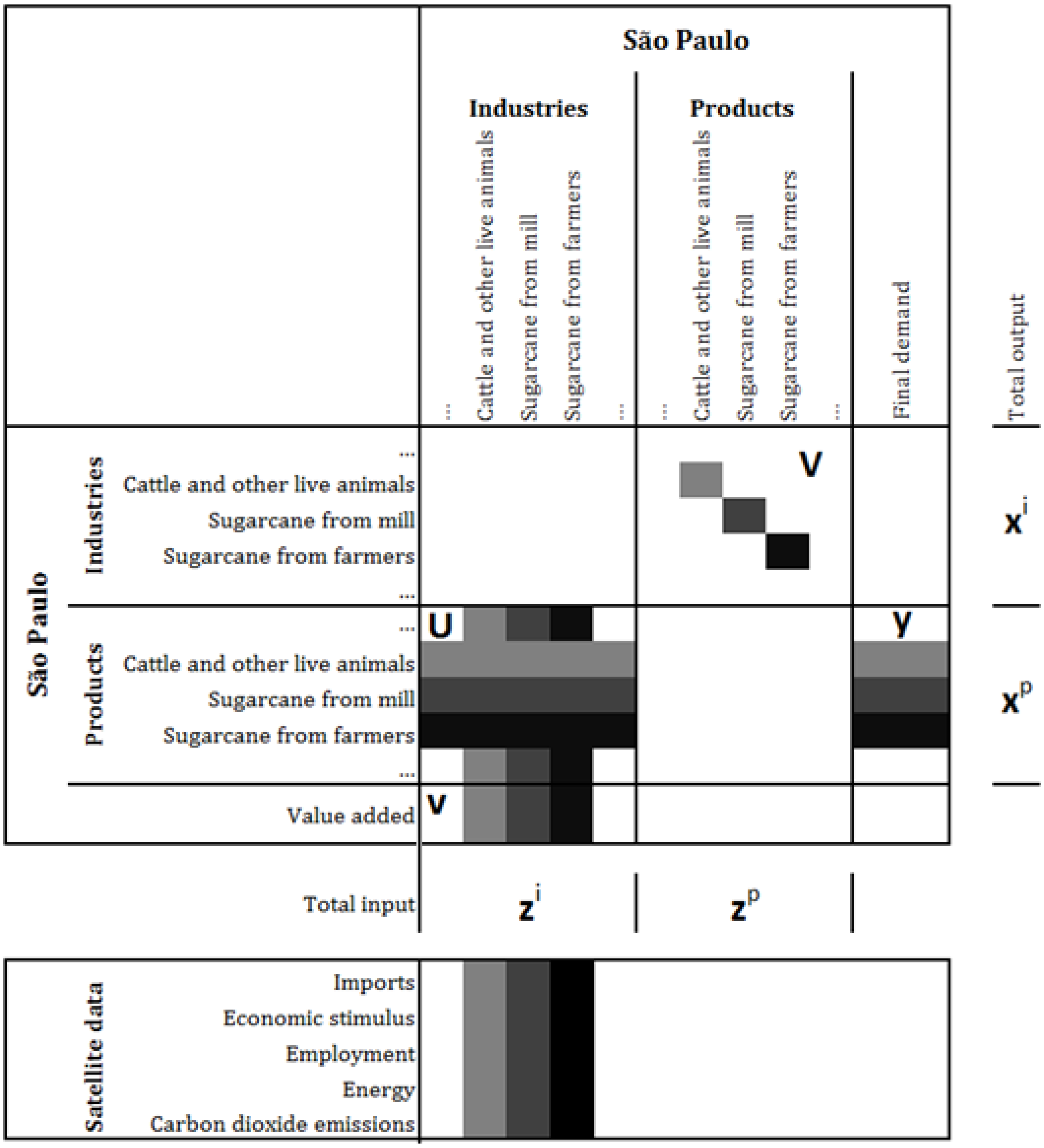

Figure 3.1 - Hybrid sugarcane data with Brazilian MRIO data arranged in a basic supply-use structure based on Lenzen; Rueda-Cantuche (2012) methodology

More specifically, the MRIO table is arranged in a supply-use format (EUROSTAT EUROPEAN COMISSION - EEC, 2008; LENZEN; RUEDA-CANTUCHE, 2012). The use (**U**) matrix harbours the input recipes for the two case studies — these input recipes represent the monetary amount of inputs obtained from other sectors of the economy; the supply table (**V**) contains data on the total production of sugarcane from the "mill" and the "farmers"; the value-added (**v**) matrix shows the primary inputs required for the production of sugarcane in the two case studies; and the final demand (**y**) matrix shows the final demand for sugarcane. Data location is shown as shaded rows and columns. The vertical coloured columns in the use matrix represent the production recipes, whereas the rows represent the sales structures for the two sectors. In addition to monetary data, the matrix also contains data on physical account indicators, such as energy, employment and greenhouse gas emissions (see (MALIK; LENZEN; GESCHKE, 2015) for a detailed explanation of the hybridisation process).

3.2.2 Input-output calculations

Input-output analysis is a macroeconomic technique that describes the complex interdependencies between the different sectors of an economy. It was formulated by Leontief in the 1930s (LEONTIEF, 1966, 1936). An introduction to the basic input-output model is presented elsewhere (DIXON, 1996; MILLER; BLAIR, 2009). In the early 1970s, Leontief and Ford proposed the extension of the monetary input-output framework to account for physical data. These data are crucial for undertaking footprint assessments (LEONTIEF, 1970).

Essentially, the theory of input-output analysis relies on a set of linear equations. In particular, the famous input-output equation can be written as $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, where $\mathbf{x}$ is the total output of an economy, $\mathbf{I}$ is an identity matrix, $\mathbf{A}$ is the direct coefficients matrix that describes the proportion of inputs needed for the production of a unit of output, and $\mathbf{y}$ is the matrix of final demand. In this study, we analysed five types of physical account data — imports, economic stimulus, employment, energy and greenhouse gas emissions. Let $\mathbf{Q}$ be a so-called satellite block containing the employment data for the economy. Then, the matrix $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$ describes the direct intensity q_i for an industry i, and the matrix $\mathbf{m} = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}$describes the total intensity m_i for an industry i. $(\mathbf{I} - \mathbf{A})^{-1}$ is also known as the Leontief inverse. The input-output equations can be further manipulated, as described in (FORAN et al., 2005) to decompose the total impacts according to upstream layers of production, as follows:

$$\mathbf{Q}^* = \mathbf{q}\#\mathbf{L}\mathbf{y}^* = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}^* = \mathbf{q}\#\mathbf{y}^* + \mathbf{q}\#\mathbf{A}\mathbf{y}^* + \mathbf{q}\#\mathbf{A}^2\mathbf{y}^* + \mathbf{q}\#\mathbf{A}^3\mathbf{y}^* + \cdots + \mathbf{q}\#\mathbf{A}^n\mathbf{y}^*, \quad (1)$$

where the impacts are broken down according to various upstream layers of production: direct impacts $\mathbf{q}\#\mathbf{y}^*$; impacts from suppliers in layer 1 ($\mathbf{q}\#\mathbf{A}\mathbf{y}^*$); impacts from suppliers in layer 2 ($\mathbf{q}\#\mathbf{A}^2\mathbf{y}^*$); layer 3($\mathbf{q}\#\mathbf{A}^3\mathbf{y}^*$); and so on up to layer n ($\mathbf{q}\#\mathbf{A}^n\mathbf{y}^*$). In this study, the results for R$ 1 million worth of final demand are used to calculate the multipliers.

3.2.3 MRIO tables and satellite data for Brazil

The core matrix used in this work were built by Ferreira Filho and Horridge (2014), based on the Brazilian I-O table for the year 2005 (Instituto Brasileiro de Geografia e Estatística

- IBGE, 2005a), based on product technology. The regional disaggregation was performed with the use of additional data from the Annual Survey of Industry, the Annual Survey of Services, Municipal Agricultural Research, the National Survey by Household Sampling, and the Consumer Expenditure Survey (Instituto Brasileiro de Geografia e Estatística - IBGE, 2005b).

The studied sugarcane production systems are based on the Programa de Educação Continuada em Economia e Gestão de Empresas - PECEGE (2012) study, which assessed the costs of sugarcane production. The traditional region of sugarcane production in Brazil (mainly São Paulo state) was analysed. Two different systems of sugarcane production were studied: sugarcane produced by the mill itself, called Owner sugarcane and sugarcane bought from farmers around the mill, called Suppliers in this study. The regions assessed are shown in Table 3.1 and Figure 3.1 shows a map of each region in Brazil.

Table 3.1 - Names of the assessed regions and their acronyms

Region	Acronym	Region	Acronym
Rondonia	RO	Sergipe	SE
Acre	AC	Bahia	BA
Amazonas	AM	Minas Gerais	MG
Roraima	RR	Espirito Santo	ES
Para	PA	Rio de Janeiro	RJ
Amapa	AP	Sao Paulo	SP
Tocantins	TO	Parana	PR
Maranhão	MA	Santa Catarina	SC
Piaui	PI	Rio Grande do Sul	RS
Ceara	CE	Mato Grosso do Sul	MS
Rio Grande do Norte	RN	Mato Grosso	MT
Paraiba	PB	Goias	GO
Pernambuco	PE	Distrito Federal	DF
Alagoas	AL		

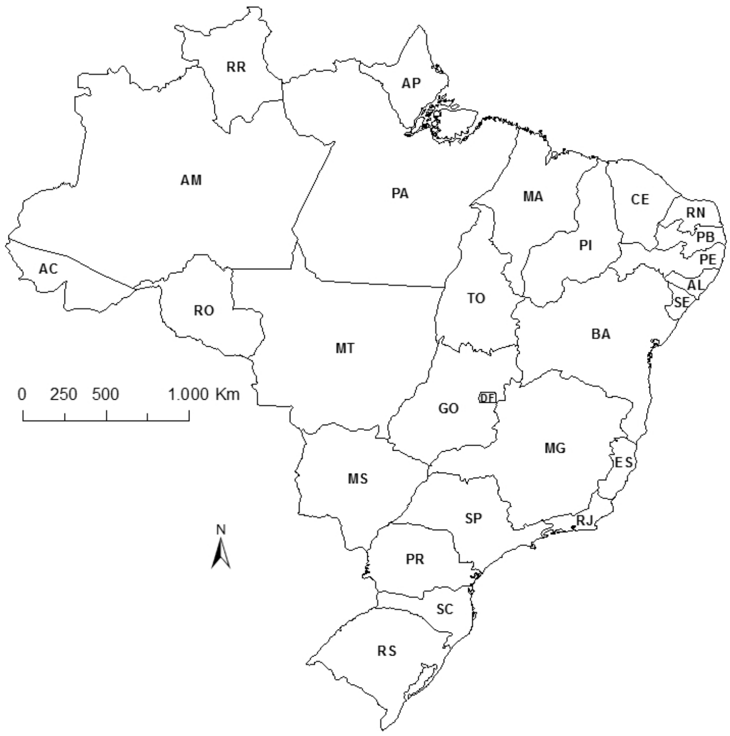

Figure 3.2 - Map of Brazil showing the assessed regions

Primary energy was estimated using Brazilian energy balance data from the base year of 2014 (EMPRESA DE PESQUISA ENERGÉTICA, 2015); GHG emissions were estimated from the data obtained by Sistema de Estimativa de Emissão de Gases de Efeito Estufa/Observatório do Clima (2014) for the year 2013 for each region in Brazil; imports and economic stimulus and employment were already contained in the MRIO table used.

All these satellite data are, originally, presented in different sectors than those used in the IO matrix due to its own particularities and purposes. Thus, it is necessary to rearrange them among the 108 sectors and 27 regions used in this study. To input data in the matrices described in Figure 3.1, all the data were disaggregated using the value added (**v**) from the IO matrix as a weighting factor, in order to resize the original data sectors for the industries sectors used in our IO matrix. The process of rearrangement is described in Lenzen (2011).

3.2.4 Exploratory analysis

Calculation of the coefficient of correlation for the pairs of multipliers was performed to explore the data set and ascertain whether or not some degree of relationship exists between them. This kind of assessment is widely used, being a useful tool that can provide valuable information for making inferences about the topic discussed (BOSLAUGH; WATTERS, 2008).

To perform a correlation test among the satellite data, all 108 sectors were considered as pairs of the variables assessed. Moreover, the multipliers of the two satellites were compared, to determine if there was significant correlation, positive or negative, between the satellite pairs.

The results obtained can guide government policy in promoting environmental friendly resource and energy saving activities through value-added and labour-intensive use as described in Section 3.2.1 (LENZEN; DEY, 2002; LENZEN; SCHAEFFER, 2004; LENZEN, 2001).

3.2.5 Land use change comparison

The expansion of sugarcane areas is mainly taking place in pastures and reducing cattle-raising areas (SPAROVEK et al., 2009). Given this significant land use change, a comparison between cattle and other livestock sectors was performed, comparing their multipliers to forecast their behaviour in areas where the land use changes from cattle to sugarcane. This kind of assessment can be used to encourage or constrain the expansion of sugarcane in some areas, depending on the chosen priorities.

3.2.6 Sugarcane production systems and land use change

There are two main systems of sugarcane production in Brazil. In the first model, the mill purchases or rents the area and employs its own labourers and machinery. This method is called Owner sugarcane and accounted for about 60% of the sugarcane produced in Brazil in 2012 (BRASIL, 2013). In the other method, sugarcane is produced by farmers, herein called Suppliers, whose farms are located around the mills. This production method is characterised by a wide range of farm size and technology.

The amount of sugarcane produced by the mill or purchased from Suppliers differs depending on the mill. Consequently, the decision of which mill to use, and whether Owner sugarcane or Suppliers sugarcane is used is based on economic and management aspects. Furthermore, the MRIO analysis made it possible to assess environmental and social issues along with the economic analysis.

Although the two cases are very similar, this study highlights important differences between Owner and Supplier sugarcane production, and stimulating one or other options may be advantageous depending on the area chosen for development, for example resulting in increased employment or reduced GHG emissions.

3.3 Results

We used a Brazilian national multi-regional input-output (MRIO) table with 27 regions, and 108 sectors and enlarged it with the two analysed sectors, ethanol produced with sugarcane from the mills and ethanol produced with Supplier sugarcane. It was possible to perform an investigation into all sectors and analyse both cases for their direct and indirect impacts on economic, social and environmental issues, providing a broad view of this important Brazilian economic sector.

Given its use of a Brazilian MRIO table to assess environmental, social and economic aspects of the Brazilian sugarcane industry, this study innovates in the TBL assessment for a nationally important sector. In 2013 this sector provided almost 40% in volume of all liquid combustibles for cars using the Otto cycle in Brazil, at a growth rate of 19% relative to the previous year (AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS - ANP, 2014), considering hydrous ethanol used as plain fuel and anhydrous ethanol mixed with gasoline.

The direct and total impacts of sugarcane production were successfully evaluated in five aspects by performing a sugarcane sector TBL assessment, showing influence of the sugarcane sector on the supply chain, and on the supply chain of the supply chain and so on. In decomposed layers of the supply chain, the behaviour of five satellites data indicated all of the impacts throughout all 108 sectors of the Brazilian economy, of both systems of sugarcane production.

3.3.1 Coefficients of correlation

Considering direct impacts on São Paulo state there is a positive correlation between economic stimulus and imports; employment has a weak positive correlation with GHG and a moderate inverse correlation with economic stimulus. A positive correlation between employment and GHG and an inverse correlation between employment and economic stimulus are also observed in the whole country correlation (Table 3.2).

The total impacts on the region of São Paulo (Table 3.3), economic stimulus has a weak significant correlation with imports and a moderate correlation with energy final consumption and GHG emissions, both positive. Employment has a weak negative correlation with energy and a moderate positive correlation with GHG.

Table 3.2 - Correlations of direct impacts on the region of São Paulo

	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00				
Energy	-0.03	1.00			
GHG	-0.05	-0.01	1.00		
Employment	-0.09	-0.13	0.28*	1.00	
Econ. Stimulus	0.27*	0.09	-0.06	-0.45*	1.00

*****Correlations are significant at 95% of confidence level

Table 3.3 - Correlations of total impacts on the region of São Paulo

	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00				
Energy	0.01	1.00			
GHG	-0.04	-0.03	1.00		
Employment	-0.06	-0.24*	0.59*	1.00	
Econ. Stimulus	0.26*	0.30*	0.41*	0.02	1.00

*****Correlations are significant at 95% of confidence level

Considering direct and total impacts on Brazil, (Table 3.4 and Table 3.5), the relationship between employment and economic stimulus in both direct and total impacts was expected and reflects the fact that a sector with high wages and salaries has less important intermediate inputs.

All the other regional correlations (Appendix) replicate the same behaviour, with a moderate or strong negative correlation between employment and economic stimulus.

Considering the direct impacts, there is a weak positive correlation between employment and GHG emissions and, in the total impact correlations, there is a positive correlation between economic stimulus and employment and a moderate positive correlation between employment and GHG showing almost the same behaviour in both direct and total impacts.

It might be expected that energy and GHG gases should have a strong positive correlation as demonstrated by Lenzen and Schaeffer (2004), but in this case the results are quite different. The Brazilian energy matrix has a strong base in renewable sources, which account for 43.5% of all primary energy, with ethanol and hydroelectricity as the main sources (EMPRESA DE PESQUISA ENERGÉTICA, 2015). Both are important sources of energy, reducing the correlation between the total primary energy consumed and GHG emitted.

In this study, we use the sum of all GHG emitted in Brazil, including other significant greenhouse gases such as CH_4 and N_2O arising from essential economic sectors in Brazil (such as agriculture, cattle farming and LUC) in addition to CO_2, weakening the previously observed strong correlation.

The main difference between the study by Lenzen and Schaeffer (2014) and ours is that the former study correlated only CO_2 emissions and considered energy consumption separated from electricity consumption. In the current study CO_2 emissions were examined in relation to the total GHG emissions (measured as CO_{2eq}.) and the entire total primary energy consumed, and in this assessment, no correlation was found between these two variables in any of the analyses.

Table 3.4 - Correlation of direct impacts on Brazil as a whole

	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00				
Energy	-0.03	1.00			
GHG	-0.02	0.03	1.00		
Employment	-0.09	-0.01	0.21*	1.00	
Econ. Stimulus	0.17	-0.04	-0.06	-0.51*	1.00

*Correlation is significant at 95% of confidence level

Table 3.5 - Correlation of total impacts on Brazil as a whole

	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1,00				
Energy	0.02	1.00			
GHG	-0.04	0.05	1.00		
Employment	-0.08	-0.20	0.32*	1.00	
Econ. Stimulus	0.19	0.30*	0.02	-0.22*	1.00

*Correlation is significant at 95% of confidence level

From these correlations, we estimate that by increasing production of commodities with high impact on economic stimulus, there is a tendency to increase energy consumption and decrease employment. This is an assertion that supports the previous cited studies and was defined by Karunaratne (1981) as “energy in the broadest sense is a substitute for labour”.

The positive correlation between employment and GHG emissions is due to a growing economy, so it is necessary to formulate policies to encourage more jobs while still meeting the goals of climate policy through improvements in technology to avoid GHG emissions increase.

3.3.2 Land use change comparisons

Comparisons of sugar cane produced either by Owners or Suppliers with cattle and other livestock (Table 3.6 and Figure 3.3) showed similar results, and for this reason only the Owner result is presented (both graphs are shown in the Appendix).

Among the analysed multipliers in areas where pasture is replaced with sugarcane, imports more than double, probably because more fertilisers and pesticides are used on sugarcane crops and the majority of the products used are imported.

Energy consumption is increased by a factor of 4.7 and 2.7 (Owner and Suppliers, respectively) after land use is converted to sugarcane. Much of this high energy consumption is in sugarcane milling and juice extraction, in preparation for fermentation and ethanol distillation. Although most of the energy comes from sugarcane bagasse, there is wide scope for reducing the amount of energy needed to operate turbines in the mills, thus improving the system efficiency and allowing better use of the self-generated energy by selling the surplus (BIZZO et al., 2014).

Employment is reduced by a factor of between 4.5 and 6.3, mainly because of mechanised crop production in the sugarcane sector, diminishing the number of employees, but usually resulting in better conditions than manual rural labour for the remaining employees. Economic stimulus is similar in both cases, with a small positive result in the Owner case and a somewhat less positive result in the Suppliers case.

GHG emissions are the only case that clearly shows a better result compared with the cattle and other livestock sector, emitting only 2% per Brazilian real (R$) on final demand. This great difference is the result of a low carbon system of production in sugarcane and because cattle emit a great amount of CH_4 from enteric fermentation, and is also connected to deforestation. Two of the three largest sources of GHG emissions in Brazil are enteric fermentation and land use change, totalling 47% of all Brazilian emissions of CO_2eq (SISTEMA DE ESTIMATIVA DE EMISSÃO DE GASES DE EFEITO ESTUFA/OBSERVATÓRIO DO CLIMA, 2014).

Table 3.6 - Comparison of the total impacts of the Owner and Supplier case studies with the cattle and other livestock sector. All data have been normalised in terms of quantity per currency of final demand

	Imports (R$)	Economic stimulus (R$)	Employment (FTE-min.)	Energy (kJ)	GHG (g)
Owner case study	0.19	1.25	2.65	23	216
Suppliers case study	0.16	1.03	1.90	13	182
Cattle & other livestock	0.07	1.17	12.04	5.03	11,976
Owner ratio	2.71	0.94	4.55	4.57	0.02
Suppliers ratio	2.35	1.14	6.34	2.76	0.02

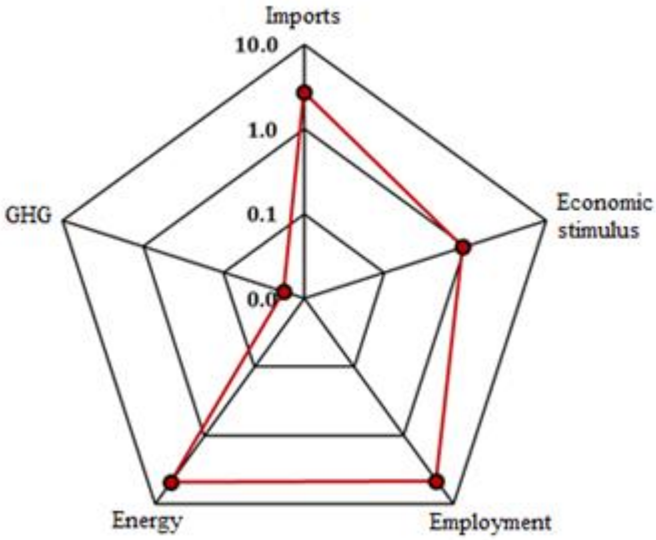

Figure 3.3 - Spider diagram based on Table 3.6. The scale is logarithmic. The line that forms the polygon on the centre (n=1) signifies the cattle and other live animals sector. The position of the red line inside n = 1 represents a better performance than the cattle and other livestock sector, whereas a position outside n = 1 is worse than the cattle and other livestock sector. The case shown is for Owner produced sugarcane

3.3.3 Sugarcane Owners and Suppliers

Decomposition assessment (Figure 3.4) allows a detailed analysis of how each assessed satellite is influenced by sugarcane production and demonstrates which layer of the sugarcane industry the supply chain influences impact the most. Again, as in Figure 3.3, only the Owner sugarcane is shown as both systems have very similar results and both are shown in the Appendix for comparison.

Figure 3.4 shows that total primary energy and economic stimulus exert most of their impacts directly. The first layer is the most important contributor to imports, employment and

GHG emissions, demonstrating that the first supply-chain layer is the most significant sector to consider in these three satellites when aiming to increase employment or concentrate efforts to diminish GHG emissions, reduce imports, and make the whole production chain sustainable.

Most of the total energy is consumed directly which demonstrates that energy efficiency in the sugarcane sector must be considered in order to further improve the ratio of ethanol energy produced in relation with the energy demand. In addition, the largest effect on economic stimulus is due to direct impacts, showing the great influence the sugarcane sector has on the other sectors of its supply chain, stimulating the economy around the mills.

As estimated by Martínez et al. (2013), most employment is generated in the first layer of the supply chain. The employment is generated in many other sectors that furnish fertilisers, pesticides, machinery and parts and provide many other services, such as the maintenance and replacement of agricultural and industrial machines throughout the crop year, and these sectors must be considered in planning areas of expansion.

Improvements in production technology in the sectors comprising the first supply-chain layer could diminish the dependence on foreign inputs, which would reduce imports and help improve the regional economy. In order to support this type of development it is necessary to punctually identify this necessity and encourage research into the development of the required technologies thus reducing the dependence on industries in other countries.

Imports in the sugarcane sector are mainly composed of fertilisers, agrochemicals, machinery and equipment (MARTÍNEZ et al., 2013). In Brazil, imported fertilisers make up almost 70% of the total of fertilisers used in the country (ASSOCIAÇÃO NACIONAL PARA DIFUSÃO DE ADUBOS - ANDA, 2015), and imported agrochemicals account for more than 80% of the total agrochemicals applied in Brazil (INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS - IBAMA, 2014). A reduction in these inputs could decrease the dependence of the sugarcane sector on imports and could be attained by environmentally friendly crop production systems.

The minor contribution to GHG from direct emissions improves the results, making it evident that ethanol produced from sugarcane is an environmentally friendly biofuel in many respects, not only in its production but also in the supply chain.

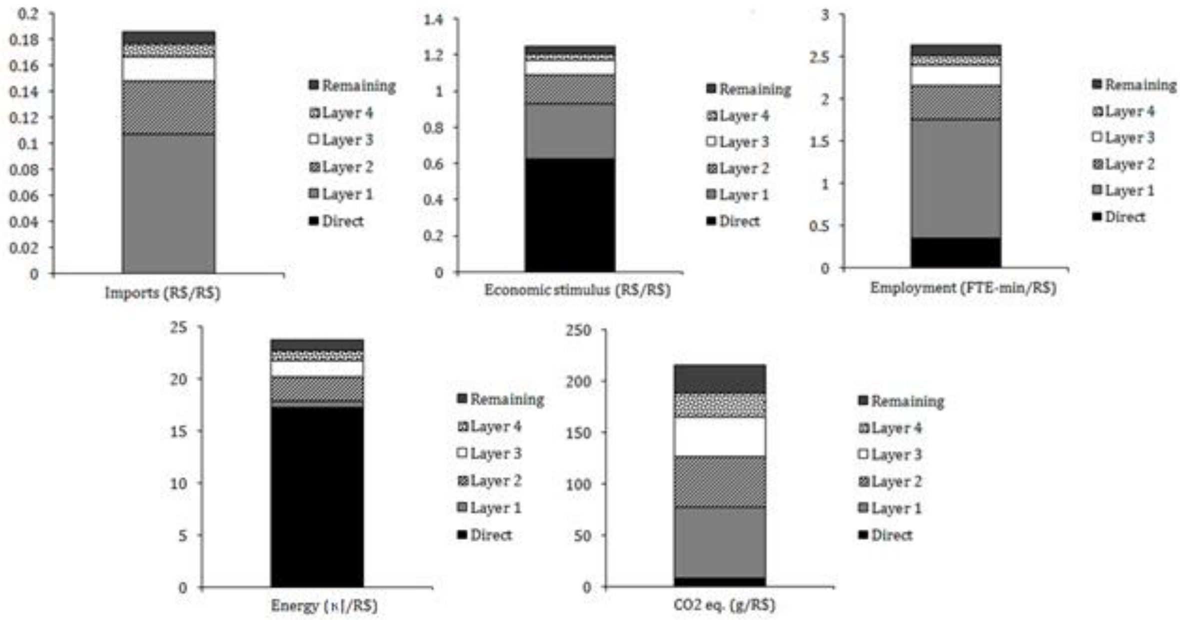

Figure 3.4 - Production layer decomposition TBL bar graphs. The impacts from direct, 1st order, 2nd order, 3rd order, 4th order and remaining order impacts are shown in the shaded regions. The graphs represent the impacts for R$ 1 million worth of final demand. The results shown are for Owner produced sugarcane

Table 3.7 allows the direct comparison of the two systems employed to produce sugarcane and determine which one is more environmentally, socially and economically suitable for the planned development in a sugarcane area.

Due to higher investment in quality and the aim of higher yields from sugarcane fields demanding more investment in fertilisers, pesticides, new machinery and services, all data assessed in the sugarcane produced in the Owner system yielded higher results than the Suppliers group in all five satellites assessed.

Considering the economic point of view, Suppliers produce less than half of imports directly, but given that most imports are in the other layers, the total amount of imports in both cases is almost the same. Economic stimulus is slightly higher in the Owner sugarcane production concerning direct impacts, while both cases demand the growth of their supply chains by similar amounts. In total impacts, Owner production exhibits a slightly larger influence on the other supply chain levels.

Socially, the Owner case originates more direct full time jobs and probably in a more formal job market. This is most likely due to intensive government supervision and efforts of the mills to abide by the labour laws, especially in the region of São Paulo.

As most of the employment is generated in the supply chain sector, the impact of mechanised harvesting means an increase in the number of jobs rather than the expected reduction in the number of people employed as manual harvest is replaced by mechanized harvesters. The reduced number of jobs is compensated and augmented by new jobs in other sectors. Similar results were found by Martínez et al. (2013).

Environmentally, the Suppliers case shows better results, using less energy and releasing less GHG for each Brazilian real (R$) produced, demonstrating that the Supplier model is a more environmentally friendly way to produce sugarcane. Although ethanol from sugarcane is already an environmentally friendly fuel, it is always necessary to seek a more desirable system of production, regarding carbon mitigation and sustainable management practices in all areas.

Table 3.7 - Comparison of the direct and total impacts for the two case studies

	"Owner" case study		"Suppliers" case study	
Indicators	Direct impacts	Total impacts	Direct impacts	Total impacts
Imports (R$ R$$^{-1}$)	0.00	0.19	0.00	0.16
Economic stimulus (R$ R$$^{-1}$)	0.63	1.25	0.50	1.03
Employment (FTE-min. R$$^{-1}$)	0.40	2.60	0.20	1.90
Energy (kJ R$$^{-1}$)	17.3	23.80	8.10	13.90
GHG (g CO_{2eq} R$$^{-1}$)	9.40	216.8	4.40	182.8

3.4 Conclusion

An augmented MRIO matrix was successfully utilised to perform a TBL assessment in a region where sugarcane is traditionally produced in Brazil, assessing two different scenarios of production — by the sugarcane mills, called Owner sugarcane; and by farmers, called Suppliers sugarcane.

The correlation assessment shows which impacts have positive or negative interactions among imports, economic stimulus, employment, primary energy consumption and GHG emissions in São Paulo region and throughout Brazil.

A comparison of the sugarcane sector with the cattle and other livestock production sector was made, given that many of the new areas of sugarcane are taking place in old and abandoned pasture areas. The results showed the impacts of 1 million worth of final demand of the sugarcane sector for both models of production in terms of employment, economic stimulus, primary energy consumed and GHG released directly and indirectly through the whole supply chain in the Brazilian economy.

Comparing cattle and other livestock with the sugarcane sector in economic terms, sugarcane production depends more on imports and provides almost the same economic stimulus, demonstrating that the impacts on the other sectors are equivalent. The sugarcane sector produces less employment than the cattle and other livestock sectors, but in this paper, the quality or remuneration of the jobs generated is not discussed.

In traditional areas, with the gradual elimination of manual harvest, a decrease in unqualified and informal jobs and an increase in better positions as harvester and machinery operators are expected. Although sugarcane production requires more energy, most of the energy is produced by the mill itself and more efficient plants can sell the surplus energy, improving the mill profits and reducing dependence on thermoelectric plants during drought periods when there is reduced hydroelectric production. Considering GHG emissions, the sugarcane sector has a much better performance than the cattle and other livestock sector. It is expected that this behaviour is improving further because of the Sao Paulo state law 11,241/2002 (LEI Nº 11.241, 2002), which requires the gradual elimination of sugarcane waste burning with a complete end to the practice by the year 2031.

Considering the results of the two systems analysed, Owner and Supplier sugarcane production are similar in comparison with cattle and other live animals. Even with minor differences, Owner sugarcane results in more employment and economic stimulus and Supplier sugarcane demands less imports and shows a better result on the environmental aspects assessed — energy consumption and GHG emissions — presenting an environmentally friendly way to produce sugarcane and, therefore, ethanol. This analysis can indicate where each sugarcane production system has a better match with the expected development in a new sugarcane production region.

This study can be the basis for more detailed research not only concerning the sugarcane sector but also concerning other economic sectors of Brazil, providing important information for government investment plans and their economic, social and environmental impacts.

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4 SUMMARY AND FINAL REMARKS

Biofuels are a strategic option on the pathway to decarbonise Global economies, and despite their minority use today as a global energy source their share is increasing in some countries and it is already a reality in Brazil.

Due to the possibility of mitigating C and providing energy a new methodology was proposed to estimate the carbon sequestered by its energy function, this method showed more appropriate dealing with the real utility of carbon on fossil fuels.

On the results obtained in the Chapter 2, it is important to highlight:

- Sugarcane presented a smaller chemical exergy than eucalyptus, but the output is higher because of its higher yield;
- Reducing sugarcane straw moisture increased the exergy output in 0.67 GJ ha^{-1} for each 1% of moisture reduce. Eucalyptus to firewood had an increase 1.50 GJ ha^{-1} of increase for each 1%;
- On average, each Mg of biomass yield increased, led to a change of 3.02 GJ on sugarcane scenarios and 5.93 GJ on eucalyptus scenarios;
- Higher increments on exergy output can be reached on eucalyptus than in sugarcane;
- It would be necessary an increment of $5x10^6$ ha in the actual area of sugarcane production and an increment of $21x10^6$ ha in the actual area of eucalyptus in order to supply all exergy produced by fossil fuels used in Brazil. On both cases, the whole areas should be dedicated only to biofuel production;
- Other methodologies can be developed and used by different functions of C, like improving soil quality or biodiversity as example.

In the results obtained in the Chapter 3, it is important to highlight:

- In areas where pasture to cattle is replaced by sugarcane, energy consumption is increased by a factor of 3.7, employment is reduced by a factor of 5.4 in average and GHG emissions are reduced to only 2% for each R$ of final demand changed;
- Suppliers and Owner sugarcane producers have similar results when compared with Cattle and other live animals sector;
- Total amount of imports in both cases is almost the same, as most of the imports are concentrated on the first supplier layer, like the industry of fertilizers and pesticides to machinery;
- The Owner case originates more direct full time jobs and probably in a more formal job market;

- Most of the employment is generated in the supply chain sector on both cases. Suppliers case uses less energy and releases less GHG than Owner sugarcane production;
- This study can be the basis for more detailed research, not only concerning the sugarcane sector, but also concerning other economic sectors of Brazil, providing important information for government investment plans and their economic, social and environmental impacts.

5 ACKNOWLEDGEMENTS

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APPENDIX

Table A.1 - Direct satellite correlations by region

(to be continued)

RO					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.15610	-0.15430	**-0.23490**	**0.38760**
Energy	-0.15610	1.00000	0.01310	-0.06130	**-0.22450**
GHG	-0.15430	0.01310	1.00000	**0.59060**	**-0.33200**
Employment	**-0.23490**	-0.06130	**0.59060**	1.00000	**-0.66180**
Econ. Stimulus	**0.38760**	**-0.22450**	**-0.33200**	**-0.66180**	1.00000

AC					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.10450	-0.03010	**-0.23770**	**0.32220**
Energy	-0.10450	1.00000	0.14700	0.00940	**-0.21150**
GHG	-0.03010	0.14700	1.00000	**0.31240**	**-0.21530**
Employment	**-0.23770**	0.00940	**0.31240**	1.00000	**-0.69990**
Econ. Stimulus	**0.32220**	**-0.21150**	**-0.21530**	**-0.69990**	1.00000

AM					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.05130	-0.11140	-0.18900	**0.28180**
Energy	-0.05130	1.00000	-0.05560	-0.09640	-0.11200
GHG	-0.11140	-0.05560	1.00000	**0.58570**	-0.16400
Employment	-0.18900	-0.09640	**0.58570**	1.00000	**-0.47720**
Econ. Stimulus	**0.28180**	-0.11200	-0.16400	**-0.47720**	1.00000

RR					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.10570	0.05220	**-0.23370**	**0.31290**
Energy	-0.10570	1.00000	0.04770	0.01150	**-0.24170**
GHG	0.05220	0.04770	1.00000	**0.36610**	**-0.21550**
Employment	**-0.23370**	0.01150	**0.36610**	1.00000	**-0.71500**
Econ. Stimulus	**0.31290**	**-0.24170**	**-0.21550**	**-0.71500**	1.00000

PA					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.06900	-0.09720	-0.17740	**0.28140**
Energy	-0.06900	1.00000	-0.06710	-0.11050	-0.18050
GHG	-0.09720	-0.06710	1.00000	**0.69500**	**-0.37290**
Employment	-0.17740	-0.11050	**0.69500**	1.00000	**-0.62260**
Econ. Stimulus	**0.28140**	-0.18050	**-0.37290**	**-0.62260**	1.00000

Table A.1 - Direct satellite correlations by region

(continuation)

AP					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.10190	0.07440	-0.18790	**0.24350**
Energy	-0.10190	1.00000	0.08070	0.02620	**-0.22520**
GHG	0.07440	0.08070	1.00000	-0.02300	0.05560
Employment	-0.18790	0.02620	-0.02300	1.00000	**-0.67600**
Econ. Stimulus	**0.24350**	**-0.22520**	0.05560	**-0.67600**	1.00000

TO					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.11410	-0.14000	**-0.21210**	**0.32560**
Energy	-0.11410	1.00000	0.12170	-0.11430	-0.18560
GHG	-0.14000	0.12170	1.00000	**0.50390**	**-0.34630**
Employment	**-0.21210**	-0.11430	**0.50390**	1.00000	**-0.65210**
Econ. Stimulus	**0.32560**	-0.18560	**-0.34630**	**-0.65210**	1.00000

MA					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.05070	-0.06860	-0.11380	0.18000
Energy	-0.05070	1.00000	0.06290	-0.12310	-0.05190
GHG	-0.06860	0.06290	1.00000	**0.66830**	**-0.41900**
Employment	-0.11380	-0.12310	**0.66830**	1.00000	**-0.67120**
Econ. Stimulus	0.18000	-0.05190	**-0.41900**	**-0.67120**	1.00000

PI					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.08860	-0.11700	-0.17900	**0.30730**
Energy	-0.08860	1.00000	**0.44090**	0.15820	**0.21360**
GHG	-0.11700	**0.44090**	1.00000	**0.50730**	0.08130
Employment	-0.17900	0.15820	**0.50730**	1.00000	**-0.31470**
Econ. Stimulus	**0.30730**	**0.21360**	0.08130	**-0.31470**	1.00000

CE					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.09440	-0.12050	-0.18210	**0.30550**
Energy	-0.09440	1.00000	**0.27740**	**-0.20890**	-0.03710
GHG	-0.12050	**0.27740**	1.00000	**0.29010**	**-0.23940**
Employment	-0.18210	**-0.20890**	**0.29010**	1.00000	**-0.54110**
Econ. Stimulus	**0.30550**	-0.03710	**-0.23940**	**-0.54110**	1.00000

Table A.1 - Direct satellite correlations by region

(continuation)

RN					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.07080	-0.09290	**-0.20900**	**0.32010**
Energy	-0.07080	1.00000	0.05030	-0.10460	-0.10210
GHG	-0.09290	0.05030	1.00000	0.07870	-0.13650
Employment	**-0.20900**	-0.10460	0.07870	1.00000	**-0.61570**
Econ. Stimulus	**0.32010**	-0.10210	-0.13650	**-0.61570**	1.00000

PB					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.10460	-0.09400	**-0.21430**	**0.29100**
Energy	-0.10460	1.00000	**0.27780**	-0.16450	-0.02330
GHG	-0.09400	**0.27780**	1.00000	0.12440	**-0.25570**
Employment	**-0.21430**	-0.16450	0.12440	1.00000	**-0.59220**
Econ. Stimulus	**0.29100**	-0.02330	**-0.25570**	**-0.59220**	1.00000

PE					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.04550	0.01550	-0.16560	**0.29390**
Energy	-0.04550	1.00000	0.12270	-0.12020	-0.01110
GHG	0.01550	0.12270	1.00000	0.10310	-0.05070
Employment	-0.16560	-0.12020	0.10310	1.00000	**-0.50950**
Econ. Stimulus	**0.29390**	-0.01110	-0.05070	**-0.50950**	1.00000

AL					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.03310	0.01570	-0.17290	**0.24000**
Energy	-0.03310	1.00000	0.10650	-0.06850	-0.08610
GHG	0.01570	0.10650	1.00000	0.12270	-0.10920
Employment	-0.17290	-0.06850	0.12270	1.00000	**-0.56930**
Econ. Stimulus	**0.24000**	-0.08610	-0.10920	**-0.56930**	1.00000

SE					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.06690	-0.10720	**-0.20960**	**0.30540**
Energy	-0.06690	1.00000	0.05790	-0.10590	-0.10020
GHG	-0.10720	0.05790	1.00000	0.14680	**-0.26480**
Employment	**-0.20960**	-0.10590	0.14680	1.00000	**-0.60900**
Econ. Stimulus	**0.30540**	-0.10020	**-0.26480**	**-0.60900**	1.00000

Table A.1 - Direct satellite correlations by region

(continuation)

	Imports	Energy	GHG	Employment	Econ. Stimulus
BA					
Imports	1.00000	-0.03990	-0.09160	-0.13430	**0.31540**
Energy	-0.03990	1.00000	-0.05580	-0.18290	0.14960
GHG	-0.09160	-0.05580	1.00000	**0.58320**	**-0.30430**
Employment	-0.13430	-0.18290	**0.58320**	1.00000	**-0.54160**
Econ. Stimulus	**0.31540**	0.14960	**-0.30430**	**-0.54160**	1.00000
MG					
Imports	1.00000	-0.03570	-0.04990	-0.08450	**0.26830**
Energy	-0.03570	1.00000	-0.03270	-0.16250	0.09890
GHG	-0.04990	-0.03270	1.00000	**0.43420**	**-0.25650**
Employment	-0.08450	-0.16250	**0.43420**	1.00000	**-0.51540**
Econ. Stimulus	**0.26830**	0.09890	**-0.25650**	**-0.51540**	1.00000
ES					
Imports	1.00000	-0.07720	0.07960	-0.15200	**0.25320**
Energy	-0.07720	1.00000	**0.20170**	-0.15210	-0.03280
GHG	0.07960	**0.20170**	1.00000	-0.06970	0.07080
Employment	-0.15200	-0.15210	-0.06970	1.00000	**-0.65950**
Econ. Stimulus	**0.25320**	-0.03280	0.07080	**-0.65950**	1.00000
RJ					
Imports	1.00000	-0.02640	-0.04610	-0.07610	0.15740
Energy	-0.02640	1.00000	0.08130	-0.08960	-0.10020
GHG	-0.04610	0.08130	1.00000	0.14180	-0.07250
Employment	-0.07610	-0.08960	0.14180	1.00000	**-0.50580**
Econ. Stimulus	0.15740	-0.10020	-0.07250	**-0.50580**	1.00000
SP					
Imports	1.00000	-0.03060	-0.05110	-0.09420	**0.27770**
Energy	-0.03060	1.00000	-0.01300	-0.13180	0.08910
GHG	-0.05110	-0.01300	1.00000	**0.28380**	-0.05580
Employment	-0.09420	-0.13180	**0.28380**	1.00000	**-0.44760**
Econ. Stimulus	**0.27770**	0.08910	-0.05580	**-0.44760**	1.00000
PR					
Imports	1.00000	0.03180	-0.15310	**-0.27330**	**0.35030**
Energy	0.03180	1.00000	0.01020	-0.18090	0.15800
GHG	-0.15310	0.01020	1.00000	**0.32120**	**-0.20690**
Employment	**-0.27330**	-0.18090	**0.32120**	1.00000	**-0.54540**
Econ. Stimulus	**0.35030**	0.15800	**-0.20690**	**-0.54540**	1.00000

Table A.1 - Direct satellite correlations by region

(continuation)

SC					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.09300	**0.25250**	**-0.20480**	**0.34300**
Energy	-0.09300	1.00000	0.08290	-0.12960	-0.07120
GHG	**0.25250**	0.08290	1.00000	-0.06020	**0.23050**
Employment	**-0.20480**	-0.12960	-0.06020	1.00000	**-0.57380**
Econ. Stimulus	**0.34300**	-0.07120	**0.23050**	**-0.57380**	1.00000

RS					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.07390	-0.13290	**-0.20280**	**0.23730**
Energy	-0.07390	1.00000	0.02690	**-0.20670**	0.06700
GHG	-0.13290	0.02690	1.00000	**0.53180**	**-0.26860**
Employment	**-0.20280**	**-0.20670**	**0.53180**	1.00000	**-0.51650**
Econ. Stimulus	**0.23730**	0.06700	**-0.26860**	**-0.51650**	1.00000

MS					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.11140	-0.09620	-0.14750	**0.36980**
Energy	-0.11140	1.00000	0.04120	-0.13740	-0.03530
GHG	-0.09620	0.04120	1.00000	**0.37380**	**-0.27730**
Employment	-0.14750	-0.13740	**0.37380**	1.00000	**-0.60180**
Econ. Stimulus	**0.36980**	-0.03530	**-0.27730**	**-0.60180**	1.00000

MT					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.09880	-0.11700	-0.18390	**0.34000**
Energy	-0.09880	1.00000	-0.04860	-0.12590	-0.04980
GHG	-0.11700	-0.04860	1.00000	**0.60140**	**-0.37050**
Employment	-0.18390	-0.12590	**0.60140**	1.00000	**-0.59350**
Econ. Stimulus	**0.34000**	-0.04980	**-0.37050**	**-0.59350**	1.00000

GO					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.07120	-0.08460	-0.13790	**0.30230**
Energy	-0.07120	1.00000	-0.01730	-0.13360	0.00440
GHG	-0.08460	-0.01730	1.00000	**0.52160**	**-0.36350**
Employment	-0.13790	-0.13360	**0.52160**	1.00000	**-0.57490**
Econ. Stimulus	**0.30230**	0.00440	**-0.36350**	**-0.57490**	1.00000

Table A.1 - Direct satellite correlations by region

(conclusion)

DF					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.08950	0.04300	-0.11900	0.17710
Energy	-0.08950	1.00000	**0.32130**	-0.03110	**-0.22670**
GHG	0.04300	**0.32130**	1.00000	-0.10560	-0.05350
Employment	-0.11900	-0.03110	-0.10560	1.00000	**-0.64570**
Econ. Stimulus	0.17710	**-0.22670**	-0.05350	**-0.64570**	1.00000

Table A.2 - Indirect satellite correlations by region

(to be continued)

RO					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.15160	**-0.23650**	-0.17390	**0.45960**
Energy	0.15160	1.00000	-0.05610	**-0.31830**	**0.50840**
GHG	**-0.23650**	-0.05610	1.00000	**0.65840**	**-0.27750**
Employment	-0.17390	**-0.31830**	**0.65840**	1.00000	**-0.43180**
Econ. Stimulus	**0.45960**	**0.50840**	**-0.27750**	**-0.43180**	1.00000

AC					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.15870	-0.10450	**-0.27030**	**0.40920**
Energy	0.15870	1.00000	0.01960	**-0.32030**	**0.53330**
GHG	-0.10450	0.01960	1.00000	**0.46780**	-0.17530
Employment	**-0.27030**	**-0.32030**	**0.46780**	1.00000	**-0.40000**
Econ. Stimulus	**0.40920**	**0.53330**	-0.17530	**-0.40000**	1.00000

AM					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.10140	-0.15140	-0.11870	**0.34500**
Energy	0.10140	1.00000	-0.06840	-0.18170	**0.20170**
GHG	-0.15140	-0.06840	1.00000	**0.69740**	-0.05270
Employment	-0.11870	-0.18170	**0.69740**	1.00000	-0.12980
Econ. Stimulus	**0.34500**	**0.20170**	-0.05270	-0.12980	1.00000

RR					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	**0.22830**	-0.03910	**-0.27250**	**0.42270**
Energy	**0.22830**	1.00000	0.02960	**-0.34810**	**0.48960**
GHG	-0.03910	0.02960	1.00000	**0.46870**	-0.15920
Employment	**-0.27250**	**-0.34810**	**0.46870**	1.00000	**-0.38780**
Econ. Stimulus	**0.42270**	**0.48960**	-0.15920	**-0.38780**	1.00000

Table A.2 - Indirect satellite correlations by region

(continuation)

PA					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.15200	-0.14910	-0.18950	**0.32080**
Energy	0.15200	1.00000	-0.14870	**-0.31860**	**0.39880**
GHG	-0.14910	-0.14870	1.00000	**0.77310**	**-0.22610**
Employment	-0.18950	**-0.31860**	**0.77310**	1.00000	**-0.31200**
Econ. Stimulus	**0.32080**	**0.39880**	**-0.22610**	**-0.31200**	1.00000

AP					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.15250	0.05540	**-0.23740**	**0.27540**
Energy	0.15250	1.00000	**0.34170**	**-0.27410**	**0.41690**
GHG	0.05540	**0.34170**	1.00000	0.03470	0.04330
Employment	**-0.23740**	**-0.27410**	0.03470	1.00000	**-0.30720**
Econ. Stimulus	**0.27540**	**0.41690**	0.04330	**-0.30720**	1.00000

TO					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.03960	**-0.21190**	-0.17590	**0.39610**
Energy	0.03960	1.00000	0.02850	**-0.33080**	**0.27610**
GHG	**-0.21190**	0.02850	1.00000	**0.57910**	**-0.24830**
Employment	-0.17590	**-0.33080**	**0.57910**	1.00000	**-0.39060**
Econ. Stimulus	**0.39610**	**0.27610**	**-0.24830**	**-0.39060**	1.00000

MA					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.02300	-0.09560	-0.11690	0.17360
Energy	0.02300	1.00000	-0.03570	**-0.31380**	**0.43550**
GHG	-0.09560	-0.03570	1.00000	**0.71610**	**-0.25500**
Employment	-0.11690	**-0.31380**	**0.71610**	1.00000	**-0.32140**
Econ. Stimulus	0.17360	**0.43550**	**-0.25500**	**-0.32140**	1.00000

PI					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.03520	-0.12990	-0.15800	**0.34430**
Energy	-0.03520	1.00000	**0.36740**	0.02550	**0.33880**
GHG	-0.12990	**0.36740**	1.00000	**0.62480**	0.14400
Employment	-0.15800	0.02550	**0.62480**	1.00000	-0.16770
Econ. Stimulus	**0.34430**	**0.33880**	0.14400	-0.16770	1.00000

Table A.2 - Indirect satellite correlations by region

(continuation)

CE					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.03620	-0.12180	-0.07110	**0.32700**
Energy	0.03620	1.00000	0.09640	**-0.27240**	**0.35640**
GHG	-0.12180	0.09640	1.00000	**0.58670**	0.12550
Employment	-0.07110	**-0.27240**	**0.58670**	1.00000	-0.15860
Econ. Stimulus	**0.32700**	**0.35640**	0.12550	-0.15860	1.00000

RN					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.02430	-0.12560	-0.10260	**0.36480**
Energy	-0.02430	1.00000	-0.00370	**-0.28240**	0.14270
GHG	-0.12560	-0.00370	1.00000	**0.30270**	0.04090
Employment	-0.10260	**-0.28240**	**0.30270**	1.00000	**-0.26650**
Econ. Stimulus	**0.36480**	0.14270	0.04090	**-0.26650**	1.00000

PB					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.03220	-0.13780	-0.09650	**0.36000**
Energy	0.03220	1.00000	**0.27680**	**-0.28630**	**0.32150**
GHG	-0.13780	**0.27680**	1.00000	**0.37010**	0.07720
Employment	-0.09650	**-0.28630**	**0.37010**	1.00000	**-0.23190**
Econ. Stimulus	**0.36000**	**0.32150**	0.07720	**-0.23190**	1.00000

PE					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.06170	-0.05080	-0.08100	**0.28660**
Energy	0.06170	1.00000	0.19180	**-0.23320**	**0.35730**
GHG	-0.05080	0.19180	1.00000	**0.53380**	**0.24400**
Employment	-0.08100	**-0.23320**	**0.53380**	1.00000	-0.12470
Econ. Stimulus	**0.28660**	**0.35730**	**0.24400**	-0.12470	1.00000

AL					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.07240	-0.04280	-0.03300	**0.26740**
Energy	0.07240	1.00000	0.18230	**-0.23900**	**0.20490**
GHG	-0.04280	0.18230	1.00000	**0.42270**	0.12510
Employment	-0.03300	**-0.23900**	**0.42270**	1.00000	-0.13910
Econ. Stimulus	**0.26740**	**0.20490**	0.12510	-0.13910	1.00000

Table A.2 - Indirect satellite correlations by region

(continuation)

	SE				
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.02770	-0.14210	-0.08930	**0.33430**
Energy	0.02770	1.00000	-0.00050	**-0.24740**	0.18120
GHG	-0.14210	-0.00050	1.00000	**0.27580**	-0.07340
Employment	-0.08930	**-0.24740**	**0.27580**	1.00000	**-0.27580**
Econ. Stimulus	**0.33430**	0.18120	-0.07340	**-0.27580**	1.00000

	BA				
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.01890	-0.08610	-0.05730	**0.28680**
Energy	-0.01890	1.00000	-0.03930	**-0.28950**	**0.28970**
GHG	-0.08610	-0.03930	1.00000	**0.58920**	0.07720
Employment	-0.05730	**-0.28950**	**0.58920**	1.00000	**-0.22260**
Econ. Stimulus	**0.28680**	**0.28970**	0.07720	**-0.22260**	1.00000

	MG				
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.02020	-0.05690	-0.06260	**0.23440**
Energy	-0.02020	1.00000	-0.05090	**-0.27600**	**0.34470**
GHG	-0.05690	-0.05090	1.00000	**0.61130**	0.12890
Employment	-0.06260	**-0.27600**	**0.61130**	1.00000	**-0.20600**
Econ. Stimulus	**0.23440**	**0.34470**	0.12890	**-0.20600**	1.00000

	ES				
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.10150	0.03630	-0.13570	**0.26940**
Energy	0.10150	1.00000	**0.67990**	**-0.29580**	**0.38740**
GHG	0.03630	**0.67990**	1.00000	0.15750	**0.23640**
Employment	-0.13570	**-0.29580**	0.15750	1.00000	**-0.29350**
Econ. Stimulus	**0.26940**	**0.38740**	**0.23640**	**-0.29350**	1.00000

	RJ				
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	-0.03810	-0.03920	-0.05150	0.14140
Energy	-0.03810	1.00000	-0.03290	**-0.27820**	0.08570
GHG	-0.03920	-0.03290	1.00000	**0.57520**	**0.39120**
Employment	-0.05150	**-0.27820**	**0.57520**	1.00000	0.08340
Econ. Stimulus	0.14140	0.08570	**0.39120**	0.08340	1.00000

Table A.2 - Indirect satellite correlations by region

(continuation)

SP					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.00950	-0.04410	-0.05990	**0.26000**
Energy	0.00950	1.00000	-0.03300	**-0.24150**	**0.30040**
GHG	-0.04410	-0.03300	1.00000	**0.59000**	**0.40790**
Employment	-0.05990	**-0.24150**	**0.59000**	1.00000	0.02510
Econ. Stimulus	**0.26000**	**0.30040**	**0.40790**	0.02510	1.00000

PR					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	**0.32110**	**-0.22760**	**-0.39400**	**0.45960**
Energy	**0.32110**	1.00000	0.00650	**-0.26110**	**0.32640**
GHG	**-0.22760**	0.00650	1.00000	**0.48670**	0.15150
Employment	**-0.39400**	**-0.26110**	**0.48670**	1.00000	**-0.27660**
Econ. Stimulus	**0.45960**	**0.32640**	0.15150	**-0.27660**	1.00000

SC					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	**0.38600**	0.13760	**-0.28220**	**0.48060**
Energy	**0.38600**	1.00000	**0.55210**	**-0.25840**	**0.52770**
GHG	0.13760	**0.55210**	1.00000	**0.24800**	**0.35980**
Employment	**-0.28220**	**-0.25840**	**0.24800**	1.00000	**-0.22670**
Econ. Stimulus	**0.48060**	**0.52770**	**0.35980**	**-0.22670**	1.00000

RS					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	**0.30540**	**-0.21220**	**-0.32620**	**0.36050**
Energy	**0.30540**	1.00000	-0.01480	**-0.26840**	**0.33430**
GHG	**-0.21220**	-0.01480	1.00000	**0.58110**	0.06240
Employment	**-0.32620**	**-0.26840**	**0.58110**	1.00000	-0.19810
Econ. Stimulus	**0.36050**	**0.33430**	0.06240	-0.19810	1.00000

MS					
	Imports	Energy	GHG	Employment	Econ. Stimulus
Imports	1.00000	0.03820	-0.17720	**-0.21670**	**0.45820**
Energy	0.03820	1.00000	0.00640	**-0.30150**	**0.28220**
GHG	-0.17720	0.00640	1.00000	**0.55090**	-0.07140
Employment	**-0.21670**	**-0.30150**	**0.55090**	1.00000	**-0.39390**
Econ. Stimulus	**0.45820**	**0.28220**	-0.07140	**-0.39390**	1.00000

Table A.2 - Indirect satellite correlations by region

(conclusion)

	Imports	Energy	GHG	Employment	Econ. Stimulus
MT					
Imports	1.00000	0.02330	**-0.20440**	-0.12960	**0.41220**
Energy	0.02330	1.00000	-0.07320	**-0.29000**	**0.24460**
GHG	**-0.20440**	-0.07320	1.00000	**0.66180**	**-0.23340**
Employment	-0.12960	**-0.29000**	**0.66180**	1.00000	**-0.39240**
Econ. Stimulus	**0.41220**	**0.24460**	**-0.23340**	**-0.39240**	1.00000
GO					
Imports	1.00000	0.06940	-0.12140	-0.15790	**0.29810**
Energy	0.06940	1.00000	-0.03030	**-0.28740**	**0.28420**
GHG	-0.12140	-0.03030	1.00000	**0.64240**	0.13270
Employment	-0.15790	**-0.28740**	**0.64240**	1.00000	-0.18310
Econ. Stimulus	**0.29810**	**0.28420**	0.13270	-0.18310	1.00000
DF					
Imports	1.00000	0.09740	-0.08100	-0.18220	**0.21620**
Energy	0.09740	1.00000	**0.21430**	**-0.26870**	**0.43810**
GHG	-0.08100	**0.21430**	1.00000	**0.29160**	**0.20700**
Employment	-0.18220	**-0.26870**	**0.29160**	1.00000	**-0.26450**
Econ. Stimulus	**0.21620**	**0.43810**	**0.20700**	**-0.26450**	1.00000

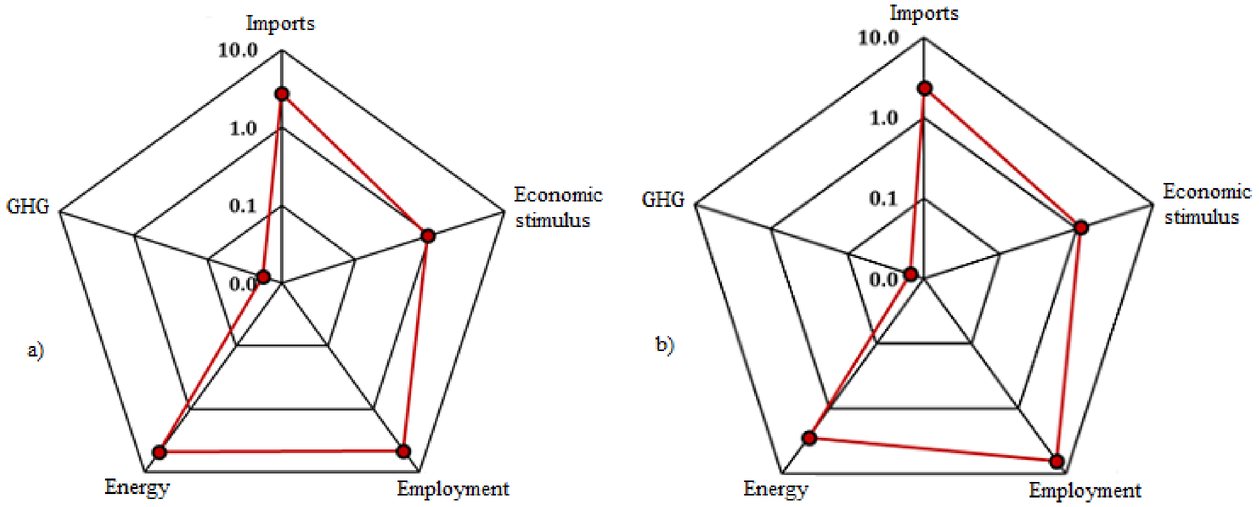

Figure A.1 - Spider diagram based on Table 1. The scale is logarithmic. The line that forms the polygon on the centre (n=1) signifies the benchmark. Position of the red line inside n = 1 represents a better performance than the benchmark sector, whereas positions outside n = 1 are worse than the benchmark a) Owner and b) Suppliers

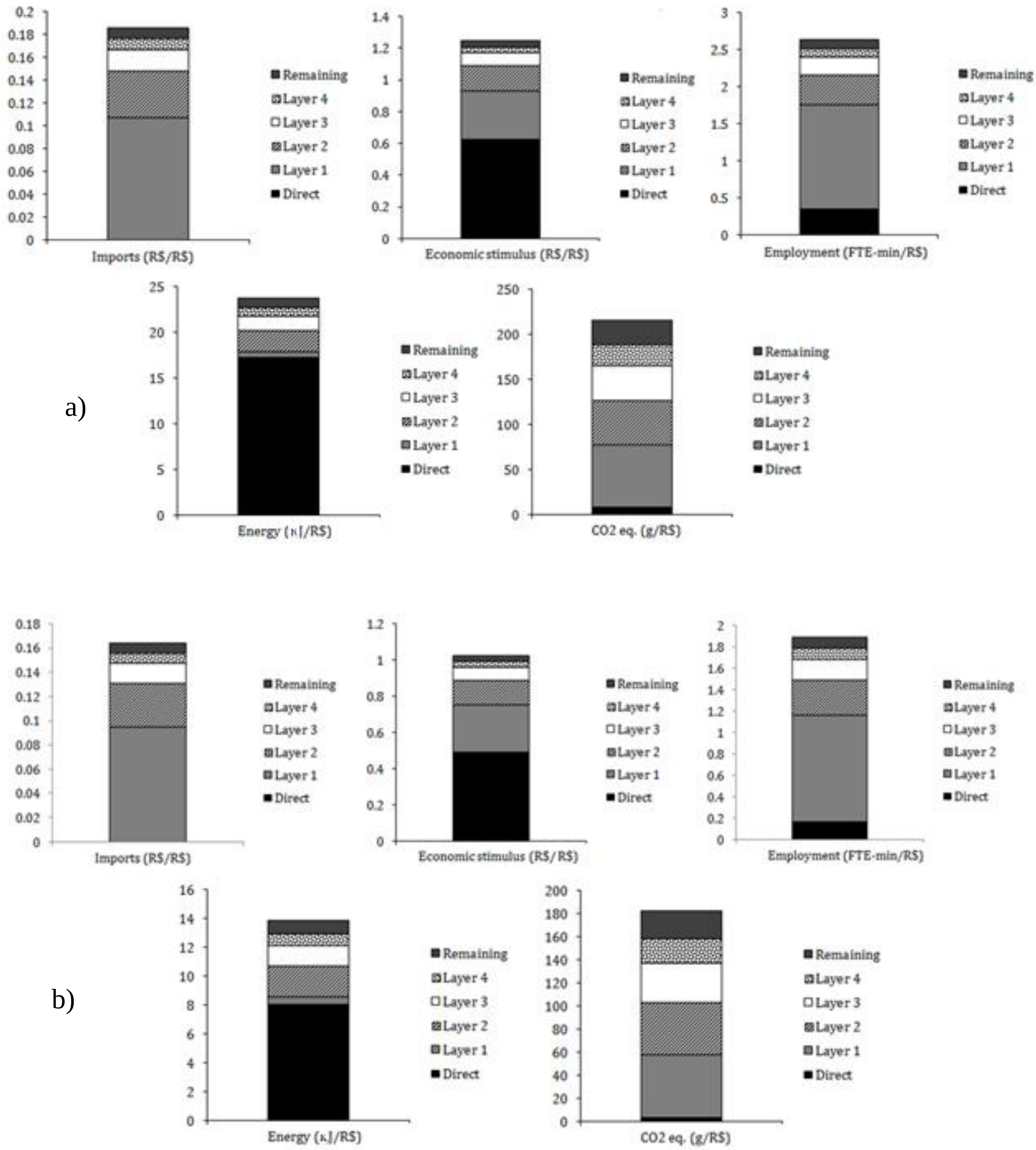

Figure A.2 - Production Layer Decomposition TBL bar graphs. The impacts from direct, 1st order, 2nd order, 3rd order, 4th order and remaining orders are shown in the shaded regions. The graphs represent the impacts for R$ 1 million worth of final demand. a) Owner and b) Suppliers