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Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil

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HIGHLIGHTS

- Optimal location & scale of ethanol plants for expansion in Goiás until 2030.
- Ethanol costs from sugarcane vary between 710 and 752 US$/$m^3$ in 2030.
- For eucalyptus-based ethanol production costs vary between 543 and 560 US$/$m^3$ in 2030.
- System-wide optimization has a marginal impact on overall production costs.
- The overall GHG emission intensity is mainly impacted by former land use.

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ABSTRACT

The expansion of the ethanol industry in Brazil faces two important challenges: to reduce total ethanol production costs and to limit the greenhouse gas (GHG) emission intensity of the ethanol produced. The objective of this study is to economically optimize the scale and location of ethanol production plants given the expected expansion of biomass supply regions. A linear optimization model is utilized to determine the optimal location and scale of sugarcane and eucalyptus industrial processing plants given the projected spatial distribution of the expansion of biomass production in the state of Goiás between 2012 and 2030. Three expansion approaches evaluated the impact on ethanol production costs of expanding an existing industry in one time step (one-step), or multiple time steps (multi-step), or constructing a newly emerging ethanol industry in Goiás (greenfield). In addition, the GHG emission intensity of the optimized ethanol supply chains are calculated. Under the three expansion approaches, the total ethanol production costs of sugarcane ethanol decrease from 894 US$/$m^3$ ethanol in 2015 to 752, 715, and 710 US$/$m^3$ ethanol in 2030 for the multi-step, one step and greenfield expansion respectively. For eucalyptus, ethanol production costs decrease from 635 US$/$m^3$ in 2015 to 560 and 543 US$/$m^3$ in 2030 for the multi-step and one-step approach. A general trend is the use of large scale industrial processing plants, especially towards 2030 due to increased biomass supply. We conclude that a system-wide optimization as a marginal impact on overall production costs. Utilizing all the predefined sugarcane and eucalyptus supply regions up to 2030, the results showed that on average the GHG emission intensity of sugarcane cultivation and processing is −80 kg CO_2/m^3, while eucalyptus GHG emission intensity is 1290 kg CO_2/m^3. This is due to the high proportion of forest land that is expected to be converted to eucalyptus plantations. Future optimization studies may address further economic or GHG emission improvement potential by optimizing the GHG emission intensity or perform a multi-objective optimization procedure.

1. Introduction

The increasing energy demand and the growing awareness of climate change due to fossil fuel related greenhouse gas emissions (GHG) have raised the interest in the use of biomass for energy. As

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Nomenclature

Abbreviations

Bioscope	decision support system using a MILP structure, developed by University Illinois
CPLEX	a GAMS solver designed to solve large, difficult problems with minimal user intervention.
CSP	centralized storage and pre-processing
DSS	decision support system
GAMS	General Algebraic Modelling System
GHG	greenhouse gas
GIS	geographical information system
LP	linear programming
MILP	mixed integer linear programming
SC	supply chain
TC	tonne cane

Indices

i	biomass supply region
k	industrial processing facility location

a result, the global annual biofuel production increased significantly from 153 PJ in 1990 to 1988 PJ in 2012, and is likely to grow even further with increasing biofuel demand [1]. World biofuel production is dominated by ethanol, which originates mainly in the United States of America (USA) and Brazil [2,3]. The large scale production and consumption of bioethanol in Brazil occurred already since the implementation of the Brazilian Alcohol program in 1975 [4]. Due to this experience and know-how, the (mature) industrial processing technology, but also due to the availability of suitable land, Brazil has a large potential to further expand its ethanol production [2,5]. Currently, more than half of the Brazilian sugarcane based first generation ethanol production is located in the Centre South region, especially São Paulo state [6]. However, the sugarcane production in the states of Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais and Paraná has expanded rapidly in recent decade [5,6]. Although currently sugarcane is the biomass feedstock for ethanol production in Brazil, the utilization of new industrial processing technologies using ligno-cellulosic feedstock could enable the use of a wider range of biomass feedstock for ethanol production. Eucalyptus cultivation in combination with novel processing technology holds great promise, especially in regions less suitable for sugarcane cultivation [7,8].

The expansion of the ethanol industry in Brazil faces two important challenges. First, the aim to reduce total ethanol production costs in order to compete with fossil fuels and other biofuels. Second, the objective of limit the GHG emission intensity of ethanol production, as biofuels are intended to reduce anthropogenic GHG emissions by fossil fuel replacement. Currently, sugarcane based ethanol from Brazil has low production costs and achieves high GHG emission reduction compared to fossil fuels, but also compared to other biofuels produced worldwide [9]. Total ethanol production costs of different biomass crops in Brazil are mainly determined by land cost, biomass yield, logistics, conversion efficiency and scale of industrial processing [8]. The total GHG emissions intensity of ethanol production is mainly determined by land-use change (LUC) emissions, pre-harvest burning (common for manual sugarcane harvesting), emissions related to fertilizer application [10,11], and emissions related to biomass feedstock transportation. Furthermore, the ethanol conversion efficiency, and the GHG emission credits for the co-production of surplus electricity are important to determine the GHG intensity of ethanol production [10]. In order to assess the costs and GHG performance of the expansion of the ethanol industry in Brazil, these parameters, which are in many cases spatially highly heterogeneous, should be taken into account.

Strategic biofuel supply chain optimization could be applied to optimize the costs and GHG emissions of potential ethanol production chains in Brazil. A strategic supply chain analysis provides insight into the importance of the different variables in the supply chain design and trade-offs between them, such as the trade-off between transport costs and economy of scale of industrial processing. Numerous studies applied strategic biofuel supply chain optimization procedures to select an optimal bioenergy supply chain design, e.g. [12–19]. More detailed, strategic optimization models have been applied to determine the lowest overall biofuel production cost or GHG emissions of the total system design [20–23].

- The optimization study of Mansuy et al. [19] used fire-affected forestry biomass in two forest management units in Eastern Canada. The analysis was performed on a 10 by 10 km grid cell scale and due to the low availability of affected forestry biomass, only a limited amount of pellet plants were required.
- Samsatli et al. [18] used the United Kingdom as case study region for a hypothetical biomass supply chain optimization for both costs and GHG emissions?. The most important drawbacks are; the limited amount of supply regions (160), the coarse resolution of the supply regions and not considering land demand for other purposes.
- In the study of Pettersson et al. [17], the emerging biofuel industry using forestry biomass integrated with existing wood using industry was modelled. Although the biomass availability in this study was based on the detailed assessment of Lundmark et al. [24], which was later aggregated, the study preselected only 51 potential biofuel production sites for whole of Sweden.
- Cobuloglu and Büyüktahtakın [16] used a multi-objective optimization model to maximize profit of a hypothetical biofuel production facility in Kansas, USA using multiple biomass feedstock. The objective function included both costs and the weighted economic value of several environmental impacts. This study included the expansion of biomass cultivation over other land uses in order to supply the biofuel production facility. The square sourcing area is divided into 440 potential biomass supply regions to supply only one biofuel facility; no other biofuel production facilities are considered.
- The study of Liu et al. [15] determined the total profit, fossil energy input, and GHG emissions of biofuel production pathways in China. The results shows the interlinkage of those three elements. However, the study was limited to 25 model supply regions (provinces), of which only 14 were selected as potential locations for biofuel production.

In general, these strategic supply chain analyses are applied for a hypothetical case, for a small amount of biomass supply regions, or present the biomass supply on a very aggregate level. However, the selection of the location, size and type of industrial processing technology of industrial processing plants is determined by the location of biomass supply, transport and type of processing technology to bioenergy [25]. The optimal location of industrial processing plant(s) may differ when optimizing the location of one industrial plant or optimizing a larger region which includes multiple plants. Such system optimization includes the distribution of biomass between the different industrial plants to find the optimal overall solution. The literature reviews of supply chain