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Research paper

Water-energy-food nexus of sugarcane ethanol production in the state of Goiás, Brazil: An analysis with regional input-output matrix

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ABSTRACT

Concerns about impacts of biomass growth for biofuel production emphasize the importance of planning energy crops expansion considering land, water, food and biodiversity. Brazil is the second largest ethanol producer worldwide and sugarcane is cultivated in many regions, including the Brazilian Cerrado (a Savannah-type biome). This paper analyses the impacts of first-generation sugarcane expansion in the Paranaíba basin (Goiás State), focusing on how future demand for ethanol could affect local resources availability. The study area is a sugarcane expansion frontier in Brazil, thus, the Cerrado biome should be focus of research considering competition for land and water uses. An economic-ecologic Input-Output (IO) framework was applied to develop a water-energy-food (WEF) nexus analysis. The Goiás' IO table was expanded to assess water, energy and land uses, GHG emissions and employment levels through six different ethanol supply scenarios.

Results show that if sugarcane expansion projected to 2030 considers the Goiás' extended IO structure for the year 2008, it should cause little impact on land and water availability in the state, due to both the ample availability of suitable pasturelands for sugarcane expansion as well as water in most of the Paranaíba basin. The WEF nexus analysis is a valuable tool on guiding the sustainable management of natural resources considering water, energy, land use and GHG emissions as goals to the same policy. In particular, the hybrid extended IO-WEF nexus framework is useful to design effective biofuel policies, collectively addressing impacts on environmental, social and economic spheres, in a local or broader context.

1. Introduction

Debates on energy security, oil price variability and the growing global commitment to address climate change have intensified throughout the 21st century, motivating increasing investments in renewable energy resources. Researchers have focused on liquid biofuels, which in Brazil have long contributed to reduce greenhouse gas emissions (GHG) from the transport sector, besides contributing to agricultural development and reducing oil imports dependency.

Biofuel production has attracted the attention of policy makers and the current debate is largely focused on the environmental and socio-economic implications of first-generation (1G) biofuel crops, since they impact food production, water security and biodiversity [1–10].

Concerns about the impacts of biofuel production emphasize the importance of planning the expansion of energy crops considering all the resources involved [11–13]. In this context, a water, energy and food nexus approach (WEF nexus) is currently quite popular in environmental management [14–18], finding fertile ground in policy-making and science. The logic behind the WEF nexus concept is that it shifts attention from a one-sector view to a more integrated one [18].

Brazil is the second largest producer of fuel ethanol worldwide, with a record production of 30.23 hm^3 in 2015 [19]. Considering the country's still wide availability of land for energy crops, Brazilian 1G sugarcane ethanol is a well-known success story of commercial use of biomass for energy purposes, given its low "well-to-wheels" GHG emissions, the crop's very high yield (typical of C4 plants), low water footprint and its low induced deforestation [20–22].

The use of ethanol as an alternative fuel in Brazil expanded after the first oil crisis, with the PROALCOOL Program in 1975. First it was employed as an octane booster to gasoline and later as a complete

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substitute in properly adapted engines. The program has attracted significant investments in agricultural and industrial processes related to 1G ethanol production, stimulating sugarcane growing and the construction of ethanol plants in the country. Additionally, an important domestic ethanol market was consolidated through a huge investment cycle focusing on promoting flex-fuel engines, which gives to consumers the choice of fuelling their car with petrol or ethanol in any proportion, according to their selling prices. Brazilian ethanol can be produced both in autonomous distilleries and in the most common mixed-sugar ethanol plants.

Brazilian 1G ethanol production rose from 10.6 hm^3 in 2000/01 to 17.8 hm^3 in 2006/07, and then to 30.2 hm^3 in 2015/16, with significant increases in agricultural and industrial productivity [19]. In 2016, sugarcane biomass energy accounted for 17.5% of Brazil's internal energy supply, whereas ethanol had a 5.6% share of the final energy consumption [23]. Currently, anhydrous ethanol is employed as an oxygenated additive to gasoline (from 18% to 27% blending). Hydrous ethanol is employed in dedicated engines or in flex-fuel engines (up to E100).

As stated by Brazil's National Agency of Petroleum, Natural Gas and Biofuels – ANP [24], as of February 2017, the country had 384 ethanol mills, producing 334 $dam^3\,d^{-1}$, with sugarcane being the feedstock used in 97% of authorized mills [24]. According to ANP [25], 36.7% of all ethanol produced in the country between 2008 and 2015 was anhydrous ethanol, while the hydrous ethanol share was 63.3%. In the same period, 95% of all ethanol consumed was for energy purposes [25].

Sugarcane is cultivated in many Brazilian states, being the top crop in terms of raw biomass production and third in terms of area, after soybeans and corn. The largest sugarcane-producing area is the Centre-South region, accounting for more than 90% of the country's production [19,26]. Sugarcane is also the most irrigated crop in the country (30% of total), with about 17,000 km^2 [27], and the National Irrigation Policy [28] encourages the expansion of irrigated areas. However, 98% of that is the so-called salvage irrigation, i.e. 20–80 mm $year^{-1}$ irrigation aiming to partially reduce the water stress in the dry season, which corresponds to the application of vinasse in the soil. Vinasse is a potassium-rich ethanol distillation by-product produced in large amounts (about 10 L for each litre of ethanol) and diluted with water recycled from the process (when necessary) [29]. Therefore, despite the significant share of sugarcane in the total irrigated area, it is noteworthy that the water demand by km^2 is much lower than other crops mainly due to low application levels (salvage irrigation) and high water reuse of industrial processes (vinasse application).

The projected increase in ethanol consumption in the transport sector over the next decade (about 54 hm^3) [30] is inducing the expansion of sugarcane production to areas such as the Brazilian Cerrado (a Savannah-type biome, located mainly in the Centre-West region) [31,32]. There has been a rapid growth of sugarcane crop in this region, from about 3700 km^2 in 2000 to about 19,600 km^2 in 2015, a 5-fold increase [19]. Goiás and Mato Grosso do Sul states were the main drivers behind this increase, accounting for 85% of the region's current production [19]. The growing demand for new production sites has led to the exploration of water-stressed areas and it justifies further analysis on the Paranaíba basin, a river basin located in the state of Goiás which has recently raised concerns on water and land resources availability.

Although the country has great potential for expanding sugarcane production, as well as the logistics required for ethanol production and export in large scale [33], sugarcane crops impact the soil and water through erosion, and its irrigation can reduce the water availability to irrigate food crops, meet human consumption, as well as industrial and power generation demands. Water, energy and land are basic resources to any production process, but the intensity by which they are being exploited has led to growing environmental impacts.

Thereby, this paper analyses the impacts of the ongoing 1G sugarcane ethanol production expansion towards the Brazilian Cerrado (specifically to the Paranaíba basin, Goiás State), aiming to understand how the interlinkages between the local economic sectors may influence the availability of resources in the region and how future demand for ethanol could impact local resources availability, based on current Brazilian ethanol policies and targets. The analysis performed herein is based on the WEF nexus approach, which is carried out through Input-Output (IO) model concepts.

Since there is no uniform framework to analyse the issues of WEF nexus [10,15–18,34–39], researchers have been seeking for a suitable method to analyse it. Due to its robustness, the IO model is one of the most widely applied methods in economics. It analyses the interdependence of sectors in an economy, showing how the output of a given sector is an input to another, on a national or regional level [39]. IO models can also be expanded to account for energy and environmental impacts [40,41], by considering a proportion between the sector's output and the corresponding impact levels. Additionally, some IO model interactions of the Brazilian ethanol sector with the national economic system has been applied to analyse the impacts of ethanol and sugar exports [42,43], impacts from adding ethanol plants to system [44], studies on ethanol demand forecasts [45] and socioeconomic analyses from different technological approaches for producing ethanol [46–48]. Since most of these studies have focused on economic aspects of the ethanol sector, they unfortunately could not properly address environmental issues regarding the sector itself and the Brazilian economy.

Conversely, some studies have developed IO analysis considering energy and carbon intensities of different ethanol technological routes [49,50] and by integrating IO models with Life Cycle Analysis (LCA) to appraise economic and GHG emissions of 1G and 2G ethanol production in Brazil [51]. Also, some studies have applied IO models coupled with linear programming approaches for distinct objectives [52,53]. Finally, the use of hybrid IO models with multi-objective linear programming [54–56] focusing on the analysis of the economic-energy-environmental-social spheres coupled with LCA estimates for ethanol production in Brazil was carried out by Carvalho et al. [56]. These authors have concluded that hybrid IO models are useful tools to assess the impacts from changes in the output of economic sectors in ethanol prospective scenarios, highlighting the importance on analysing direct and indirect impacts from technical and political choices [56].

As stated, while IO models have many applications, there has been little investigation considering environmental commodities in hybrid IO models applied to WEF nexus [52,56–60]. However, despite some relevant recent studies considering hybrid IO models focusing on the analysis of environmental impacts of the Brazilian ethanol system [51,54,56], they only consider GHG emissions and one single resource of the WEF nexus, i.e. excluding water and land resources. Indeed, studies on hybrid IO models considering GHG emissions and water, energy and land uses as variables to the same nexus analysis (as explored herein) are rare (see Ref. [60], which have not analysed GDP and employment indicators). In this context, we justify the use of hybrid IO models as a WEF nexus tool aiming to analyse 1G sugarcane ethanol expansion in the Paranaíba basin, located in the Brazilian Cerrado. Additionally, this work overcomes the lack of integrated analysis focusing on water-energy-land resources, as well as GHG emissions and socioeconomic aspects from a river basin/state perspective, i.e. IO model concepts coupled with WEF nexus approach. This hybrid IO-WEF nexus framework was chosen because of its wide potential to assess integrated impacts throughout the economy, besides being a reliable decision-making tool for planning purposes and it can also be applied to other energy commodities and target sectors, as well as economic systems and regions to promote the sustainability of biofuels and policy integration. The WEF nexus approach; IO model concepts; the hybrid IO modelling and data sources are presented in section 2. Section 3 covers Brazilian sugarcane industry status; study site; Brazilian ethanol outlook and policy scenarios. Section 4 presents the results of Goiás State case study, and discussions about the potential impacts of sugarcane