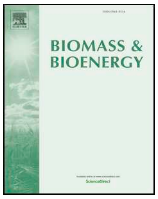
Biomass and Bioenergy 122 (2019) 391–399

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe



Research paper

Bioelectricity potential from ecologically available sugarcane straw in Brazil: A spatially explicit assessment

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ARTICLE INFO

Keywords:
Sugarcane biomass
Electricity
Bioenergy potential
Spatial distribution
São paulo state

ABSTRACT

The electricity mix of Brazil is for 80% composed by renewable sources, of which the majority is supplied by hydropower. However, as the domestic energy demand is expected to increase and the abilities to expand hydropower capacity in Brazil are constrained, it is important to increase the contribution of other renewable energy resources. Considering the high theoretical potential and mature conversion technologies, bioelectricity from sugarcane straw could be a promising option. Our study aims to assess the bioelectricity potential from ecologically available sugarcane straw in the state of Sao Paulo (Brazil) at multiple scales for the 2012 crop-year. We use a spatially explicit approach taking into account the spatial distribution of sugarcane fields, the spatial variation of sugarcane yield, the location and the milling data of each mill. We define a business as usual, a moderate and a high scenario on the amount of straw that can be removed given environmental constraints. The bioelectricity potential from ecologically available sugarcane straw is estimated between 18.7 and 45.8 TWh in Sao Paulo, equal to 22–37% of the electricity demand. The results show large geographical differences, with generally higher potentials and shorter collection radiuses for the mills in the traditional sugarcane areas compared to the mills in the expansion areas. We conclude that bioelectricity from sugarcane straw could have a significant contribution to the electricity supply in Brazil. The identification of regions with high potentials for bioelectricity production could support local and regional decision making on bioenergy planning.

1. Introduction

International energy policies have established ambitious targets regarding the use of renewable energy sources for electricity production, e.g. the Renewable Energy Directive (EU-RED) from the European Commission [1] and the Clean Power Plan from the Environmental Protection Agency of United States [2]. Unlike many other countries, Brazil has more than 80% of its electricity mix composed by renewable sources, of which the majority is supplied by hydropower [3]. However, the seasonality of hydropower, as well as the increasing periods of unexpected droughts incurs the insecurity of supply of hydroelectricity [4]. In addition, as the domestic energy demand is expected to increase and the abilities to expand hydropower capacity in Brazil are constrained by socio-environmental concerns [5], it is important to increase the contribution of other renewable energy resources.

In Brazil, the use of sugarcane residues to produce bioelectricity has steadily grown since in the last decade [6]. Currently, bioelectricity from sugarcane bagasse represents 6–8% of the electricity produced in Brazil [7]. However, considering the large sugarcane production, the current bioelectricity produced from sugarcane residues is rather limited [8]. To increase the bioelectricity production, the use of sugarcane straw has been occasionally employed as a supplementary source [9]. The sugarcane straw comprises the leaf part of the sugarcane plant (also composed by stalks and belowground biomass), divided in typically green tops and dry leaves on the side of the plant with moisture levels ranging between 11 and 68% [10,11]. Due to the high nutrient and moisture content, the tops and green leaves are recommended to be left on the field [12]. This could have many agronomic and environmental advantages: nutrient recycling, plant growth, soil carbon accumulation, soil biodiversity, and more water availability due to less soil evapotranspiration [10–15]. However, there is also a great potential of sugarcane straw for bioenergy purposes due to the high energy content,

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https://doi.org/10.1016/j.biombioe.2019.02.001
Received 30 March 2018; Received in revised form 31 January 2019; Accepted 4 February 2019

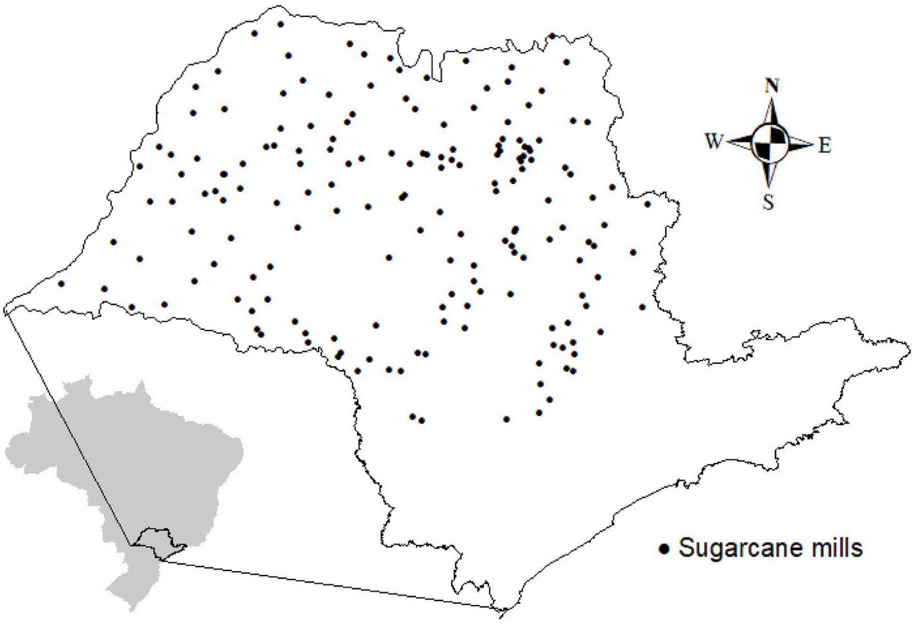

Fig. 1. Location of the 174 operating sugarcane mills in São Paulo (Brazil) in the 2012 crop-year.

efficient conversion technologies and the large theoretical availability [11,16,17]. Therefore, it is important to understand how much sugarcane straw could be available for bioelectricity purposes given that part of the straw is needed to meet the agronomic and environmental requirements [10,18].

The main studies quantifying the potential of sugarcane residues (bagasse and straw) for bioelectricity purposes in Brazil, generally rely on aggregated data sources at different geographical coverages. The Decadal Energy Plan (PDE) [17] has projected scenarios for the development in bioelectricity production from sugarcane residues in Brazil. For a business-as-usual scenario considering a conservative conversion efficiency, a technical potential of 63 TWh is projected for 2026. In 2009, UNICA (Brazilian Sugarcane Industry Association) and COGEN (Cogeneration Industry Association) using 20% *w/w* of straw to sugarcane ratio (SSR) and a straw removal rate of 70%, estimated the potential of bioelectricity from sugarcane straw at 33.2 TWh for the state of São Paulo in 10 years' time [19]. For the 2014 crop-year, Trombeta et al. [20] quantified the bioelectricity potential for a diversified group of sugarcane mills across the country. The results were aggregated at sub-state level and showed an overall bioelectricity potential of 47 TWh for the Brazilian central-south region.

Although these studies provide information on the potentials of bioelectricity from sugarcane straw, they lack field reality as the information on the biomass availability is derived from macroeconomic projections or aggregated data sources. Therefore, the spatial variability of sugarcane straw variability at field level is neglected. This hampers local decision-making, as it remains unclear where and how much sugarcane straw are available and for which mills it would be promising to increase their bioelectricity production. To minimize the uncertainties in estimating the bioelectricity potentials from sugarcane straw, a spatially explicit assessment on straw availability for bioenergy production is required [21,22]. Such bottom-up assessment is relevant for policy makers to comprehend and explore the bioenergy potential in a given region.

The objective of our study is to assess the bioelectricity potential from ecologically available sugarcane straw in Brazil at field, mill and state level, taking into account the spatial variation in sugarcane yield and the milling information of each mill. We select the state of São Paulo as case study because of the large representation of the state in the sugarcane market (i.e. more than 50% of the national sugarcane production in 2012, i.e. 329×10^6 Mg) [23] and the advanced technological stage of the main mill groups [24]. In addition, since the 2002 state law on phasing out the burning of sugarcane fields before harvest, São Paulo has been leading the research on the applications on sugarcane straw [25]. Among the Brazilian states, São Paulo is by far the largest electricity consumer, using about 30% of the electricity produced in Brazil [26]. Also, São Paulo is an electricity importer from other Brazilian regions, such as state of Paraná and North Region, where important hydroelectricity plants are located [26]. For these reasons, both the need and opportunity to develop other renewable energy sources (such as bioelectricity from straw combustion) are very prominent in the state of São Paulo. We assess the potential for the 2012 crop-year (sugarcane planted in 2011 and harvested in 2012) for two reasons. First, the high-quality was freely available for the 2012 crop-year [27,28]. Secondly, the sugarcane industry faced multiple crises [29] in the following 2013 and 2014 crop-years, which have led to a massive shutdown of the mills in that period. Consequently, the data for these crop-years are assumed not to be representative. The spatial modeling method employed in this study can be replicated in other case studies both in Brazil and other bioenergy-producing countries.

2. Methods

To quantify the bioelectricity potential from ecologically available sugarcane straw in São Paulo for the 2012 crop-year, we first assess the spatial variability of sugarcane by combining spatial datasets of sugarcane fields and remote sensing time-series data on sugarcane yield. Based on the SSR and scenarios on the amount of straw that needs to remain on the field for environmental reasons, the ecological availability of sugarcane straw for bioelectricity purposes is calculated. Then, the potential collection radius for each of the 174 mills in the state of São Paulo is determined (see Fig. 1) and a typical power plant to operate with sugarcane straw is assumed to estimate the bioelectricity potential from sugarcane straw for each mill in São Paulo state.

2.1. Spatial variation in sugarcane yield

To assess the spatial variation in sugarcane yield in the state of São Paulo, we use the 2012 crop-year state level sugarcane mask from the Canasat project [27]. The Canasat project annually monitored the cultivation of sugarcane in the central-south region of Brazil. The spatial data of Canasat has been widely employed for assessments of the

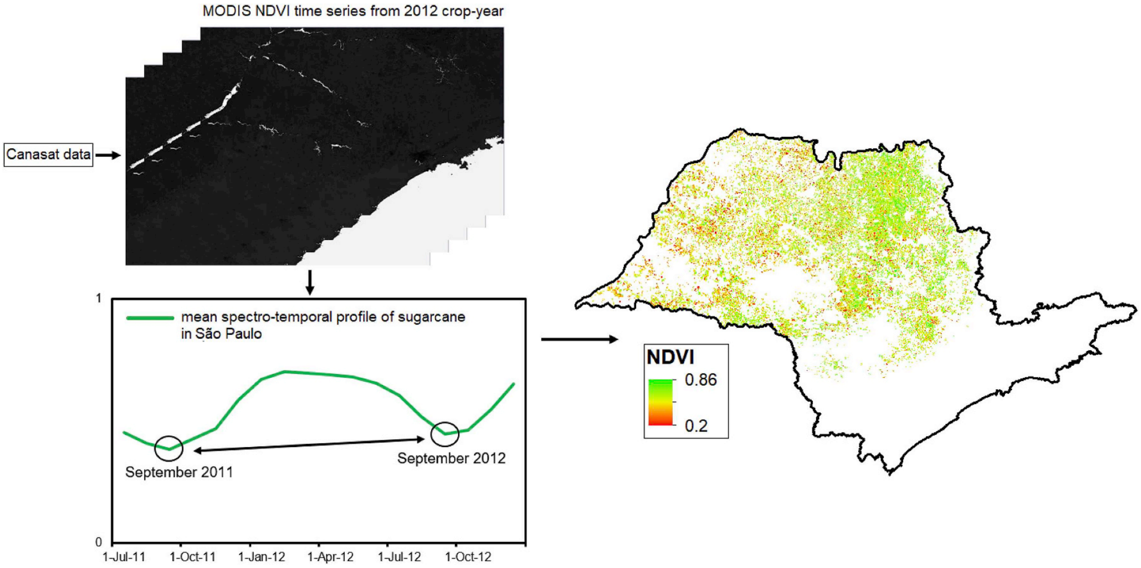

Fig. 2. Extraction of the NDVI time series (i.e. 2012 crop-year composite bands) from September 2011 to September 2012 clipped with CANSAT sugarcane mask.

sugarcane sector in Brazil because of its high spatial accuracy [30,31]. However, it provides only information on where sugar cane is cultivated and not on the spatial variation in sugarcane yield. To cover this issue, we use the vegetation index - a spectral ratio from remote sensing data used for vegetation assessment - from Normalized Difference Vegetation Index (i.e. NDVI from MOD13Q1 product) [28,32].

The NDVI is often used in studies for crop yield estimations by virtue of the high correlation with the greenness phase of crops [33]. For our study, we generate the spatially explicit annual mean NDVI value for the 2012 crop-year (i.e. calculated based on 23 images from September 2011 to September 2012, at 16 days interval and a pixel size of 250 m) (Fig. 2). The mean NDVI data is clipped with the CANASAT sugarcane mask, with mean NDVI values ranging from 0.2 to 0.86 in the 959,891 pixels (Fig. 2). These mean NDVI values are rescaled to sugarcane yield levels based on the average sugarcane yield annually reported by IBGE (i.e. Min.: 20.8 Mg ha^{-1}; Max.: 112.1 Mg ha^{-1} [34].

2.2. Ecological availability of sugarcane straw

Ecological potential assessments of bioenergy considers the ecological availability of a given resource under the current technology capability while preserving the local ecosystems [21,35]. To calculate the ecological availability of sugarcane straw for bioelectricity purposes, the SSR and the straw removal constraints are considered. The first is defined as the total amount of straw on the standing plant, consisting of tops, green and dry leaves [10]. In this study, the state average of 14% *w/w* is used to quantify the maximum amount of sugarcane straw available (i.e. the theoretical potential) [25].

Regarding the straw removal constraints, there are many uncertainties about the amount of straw that needs to be left on the field for environmental and agronomic purposes [13,36]. Thus far, no quantitative assessment for sugarcane straw mulching levels at a regional level was carried out. Ideally, from the bioenergy producer perspective, the sugarcane straw supplier seeks to recover the maximum amount of straw available in a given area instead of moving to another location because of high costs of switching sites. On the other hand, with higher amount of straw recovered, higher nutrient (i.e. fertilizers) application is required in the forthcoming sugarcane cycle to compensate the organic and mineral compounds removed with the straw [37]. Additionally, sugarcane straw needs to be left on the field to maintain soil organic matter levels, protect the soil from erosion, preserve micro and macro-fauna and improve the soil structure and soil moisture content [10,12,25]. Therefore, it is highly recommended that a given minimum amount of sugarcane straw has to be maintained on the field depending on the local agro-ecological conditions (e.g. meteorological, soil properties and crop features and management) in order to continuously provide the local ecosystem services [13].

According to Hassuani et al. [25], 7.5 Mg ha^{-1} of straw (dry basis) should be left on the field for controlling weed and pests. Similarly, Nunes et al. [13] suggested that 7 Mg ha^{-1} of straw is the minimum required for assuring environmental and agronomic benefits. Based on these reference values, we define a Business as Usual (BAU) scenario of 7.5 Mg ha^{-1} of straw that has to be maintained on the field. Progressively, we also define the Moderate and High scenarios with straw mulching levels of 5.4 Mg ha^{-1} and 3.2 Mg ha^{-1}, respectively. These average numbers are retrieved from Cardoso [18] for a typical sugarcane yield level (i.e. 82.1 Mg ha^{-1}) and were established assuming technical and environmental/agronomic constraints for straw removal. Then, the ecological availability of sugarcane straw for the three scenarios is calculated for every pixel using equation (1).

$$SA_p = Y_p \times SSR - SM \tag{1}$$

SA_p	Straw availability in pixel *p*	$Mg.ha^{-1}$
Y_p	Sugarcane yield in pixel *p*	$Mg.ha^{-1}$
SSR	Straw to sugarcane ratio	%
SM	Straw mulching levels on dry basis	$Mg.ha^{-1}$

2.3. Bioelectricity potential from sugarcane straw at mill level

To assess the bioelectricity potential at the mill level, we assume that the mills only collect the sugarcane straw from the fields in their sugarcane collection area. The collection radius of each mill is set in accordance to the milling data of the 174 mills for the 2012 crop-year. The milling data is acquired through the Brazilian Sugar and Ethanol Guide [38], which covers the milling data of most of the 174 operating mills in the 2012 crop-year. The missing milling values are filled by approaching the remaining mills directly. Based on the crushing capacity of each mill in 2012, the radius for each mill is defined by combining the spatial distribution of the sugarcane mills (Fig. 1) containing the respective milling data, and the spatial distribution of sugarcane. The radius is defined by the circular area of which the cumulative sum of the sugarcane yield equals the amount of sugarcane crushed in 2012 crop-year (Fig. 3). In this calculation, no losses during the harvesting

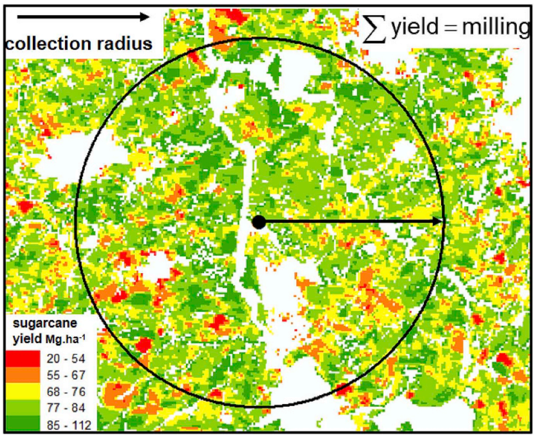

Fig. 3. Schematic representation of the biomass collection radius calculation: from the mill location, a circular selection is employed where the cumulative sum of the pixels containing sugarcane yield values should match the milling data.

and transportation operations are accounted for. We assume that the straw available in the collection area of the sugarcane mill (i.e. ecologically available) is used in the mill to produce bioelectricity (i.e. electricity generating capacity).

To convert the amount of sugarcane straw available into bioelectricity (equation (2)), we assume a Lower Heating Value (LHV) of straw of 13.3 MJ kg^{-1} on wet basis (i.e. 15% moisture content), based on Seabra et al. [39]. The 15% moisture content can be reached naturally when the straw remains on the field for a drying period of 10–15 days after sugarcane harvest [40]. The baling system recovery route is usually deployed to recover the straw available on the field. This route is rated as a promising option for straw recovery due to the high energetic quality of the straw delivered at the mill [41]. Moreover, no straw losses in both on-farm and transportation operations is assumed (i.e. the amount of straw recovered on the field is the same as that feeds the boiler).

$$El = \sum \frac{SA_{pm} \times 13.3 \times Eff_m}{3.6} \tag{2}$$

El	Bioelectricity potential	KWh
SA	Straw availability in pixel *p* in mil *m*	kg
13.3	Lower Heating Value (15% moisture content)	MJ kg^{-1}
Eff_m	Conversion efficiency in mill *m*	%
3.6	Megajoule to kilowatt conversion	MJ KWh^{-1}

For the bioelectricity system, we consider a power plant adjacent to the sugarcane mill exclusively to produce exportable bioelectricity from sugarcane straw (Fig. 4). This additional power plant comprises Rankine system with high pressure and temperature boilers (65 bar/480 °C), Condensing Extraction Steam Turbines (CEST) [42], and does not supply the internal energy demands of the sugarcane mill. This is typical power plant found in modern sugarcane mills designed to produce large bioelectricity surpluses [20,43]. The bioelectricity surpluses sourced from bagasse in the cogeneration system of the sugarcane mill are not estimated for not being the target of our study.

To calculate the variation of electrical conversion efficiency in the adjacent plants, we adapt a realistic range of electrical efficiency varying from 20% to 35% as function of the electricity generating capacity of the power plant (see Fig. 5). This is based on the empirical relationship between electrical conversion efficiency and electricity generating capacity of biomass CHP plants determined by Cutz et al. [44], and a review of studies concerning bioelectricity systems in Brazilian sugarcane mills [45–47].

2.3.1. Sensitivity analysis

To assess the impact of uncertainties in key input variables on the bioelectricity potential from ecologically available sugarcane straw, a sensitivity analysis is performed. The three key parameters selected are: moisture content of sugarcane straw, the SSR and the electrical conversion efficiency. Apart from the straw removal rate, these parameters are expected to have a large effect on the bioelectricity production. The straw moisture content is varied between 40% moisture (i.e. 9.3 MJ kg) and dry basis (i.e. 15.6 MJ kg) [18,25]. The SSR is varied from 11 to 17%, based on Hassuani et al. [25]. To the electrical conversion efficiency range of 20–35%, a small absolute variation of ± 5% (i.e. 15–30% and 25–40%) is primarily applied in accordance to the reality of the sugarcane power plants [46]. In this parameter, we also assess the sensitivity of the bioelectricity potential for fixed efficiencies values of 20% and 35% applied in all the adjacent power plants.

3. Results

The bioelectricity potential from the ecologically available sugarcane straw are based on the spatial explicitly assessment of ecological availability of sugarcane straw and the capacity of the 174 operating sugarcane mills in 2012 crop-year.

Based on sugarcane yield levels and 14% of SSR, the theoretical potential of sugarcane straw in the state of São Paulo is estimated at 58.9×10^6 Mg (i.e. the total amount of sugarcane straw production on the fields). Considering the 3 scenarios on straw mulching levels, the ecological availability of sugarcane straw is 16.7×10^6 Mg (BAU), 28.3×10^6 Mg (Moderate) and 40×10^6 Mg (High) (Fig. 6). Accounting all the fields (i.e. pixels of the spatial data), the straw removal rate ranges from 0 to 82%, with averages of 31% (BAU), 51% (Moderate) and 72% (High) (Fig. 7).

At mill level, the collection radius ranges from 2.3 to 30.4 km and the ecological availability of sugarcane straw in the Moderate scenario at mill level ranges from 5.7 to 632.5×10^3 Mg (see Fig. 8). The distance-supply plot on the right-hand graph of Fig. 8 shows that the collection radius is not necessarily a function of the amount of sugarcane processed. Due to the spatial distribution of sugarcane fields and their respective yield levels, some mills need to go for long distances to meet their ecological potential of sugarcane straw. The mills that require long collection areas are mostly located in sugarcane expansion areas in the West of São Paulo, where the sugarcane fields are more sparsely distributed. Moreover, the ongoing sugarcane expansion in that area mainly occurs on less fertile sandy soils. Consequently, the yield levels tend to be lower compared to traditional optimal agronomic areas (e.g. fertile clayey soils) in the Northeast of São Paulo [48,49]. Conversely, sugarcane mills with large ecological availability of sugarcane straw (e.g. > 200×10^3 Mg) essentially occur in the north eastern part of the state due to the high density of sugarcane fields and the high agro-ecological suitability.

To highlight the differences in the ecological availability of sugarcane straw and the collection radius of the mills, we select the mill with the highest sugarcane straw availability (mill A) and the one that has the longest radius (mill B) (Fig. 8). Mills A and B are typical mills from different regions (approx. 430 km from each other) and we compare them based on the Moderate scenario (i.e. 5.4 Mg ha^{-1} straw mulching) (Fig. 9). Only 13% of the area within the straw collection area of Mill B is represented by sugarcane fields, whereas the collection area of mill A has a much higher sugarcane density of 75%. The density of sugarcane fields has large effect on agricultural operations and consequently in straw recovery logistics. Each field from mill A could provide on average 6.5 Mg ha^{-1} of sugarcane straw (straw removal rate: 50%), whereas mill B 5.2 Mg ha^{-1} (straw removal rate: 44%). For 273 ha of sugarcane fields within the collection radius of mill A, no

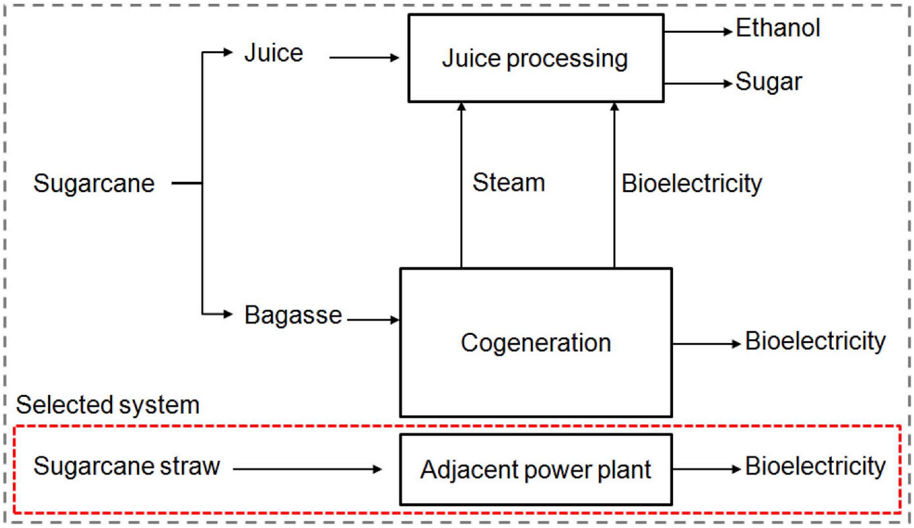

Fig. 4. Conceptual framework of the sugarcane mill. The selected system, i.e. adjacent power plant (red dashed line box) has its process design and technical parameters described in Seabra et al. [39,42]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

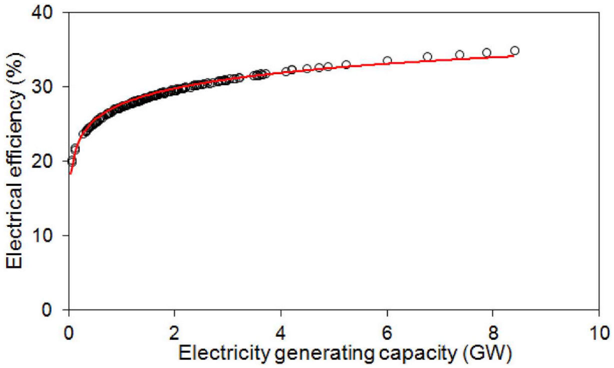

Fig. 5. Assumed relationship between the electrical efficiency and electricity generating capacity of the power plant adjacent to the sugarcane mills. Based on Cutz et al. [44].

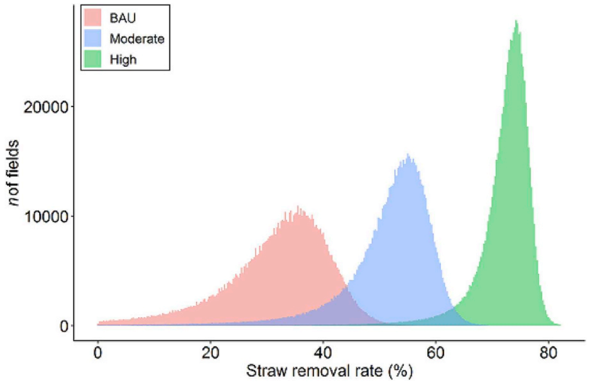

Fig. 7. The straw removal rate (in % of sugarcane straw theoretically available on the field) for approximately 900,000 sugarcane fields (5.6 Mha) in São Paulo for the BAU, Moderate and High scenarios.

straw can be recovered, while in the collection area of mill B this applies to 402 ha (black areas in Fig. 9). Given that vast amount of land operated by the sugarcane mills, the number unavailable fields presented in the Moderate scenario are negligible, accounting for less than 1% in both mills. The absence of sugarcane straw is due to sugarcane reforming areas or last ratooning cycles (i.e. lowest yield levels throughout the 6 years of sugarcane cycle).

The bioelectricity production per mill ranges between 2.5 and 508.2 GWh in the BAU scenario, 4.2–817 GWh in the Moderate scenario, and 5.9–1144 GWh in the High scenario. In Fig. 10, the histograms indicate the distribution of the sugarcane mills according to their bioelectricity potential from ecologically available sugarcane straw in each scenario. For BAU and Moderate scenarios, the majority of sugarcane mills have a production of bioelectricity up to 200 GWh (light green bars), which represents 89% (BAU) and 66% (Moderate) of the total number of mills. Differently, the majority of mills (53%) in the High scenario have the potential to supply more than 200 GWh. Beyond that, there are sugarcane mills in the Moderate and High scenarios could potentially supply more than 500 GWh of bioelectricity (light blue bars), which is currently comparable to a medium size fossil-based power plants in Brazil [50]. The total bioelectricity potential from ecologically available sugarcane straw of the 174 mills in São Paulo is estimated at nearly 45.8 TWh in the High scenario, which is approximately six times higher than the bagasse-based bioelectricity surplus produced in 2012 (7.2 TWh) in the state of São Paulo and more than the double of the current surpluses (21.4 TWh) in Brazil [24,51]. In the Moderate and BAU scenarios, the bioelectricity potential from

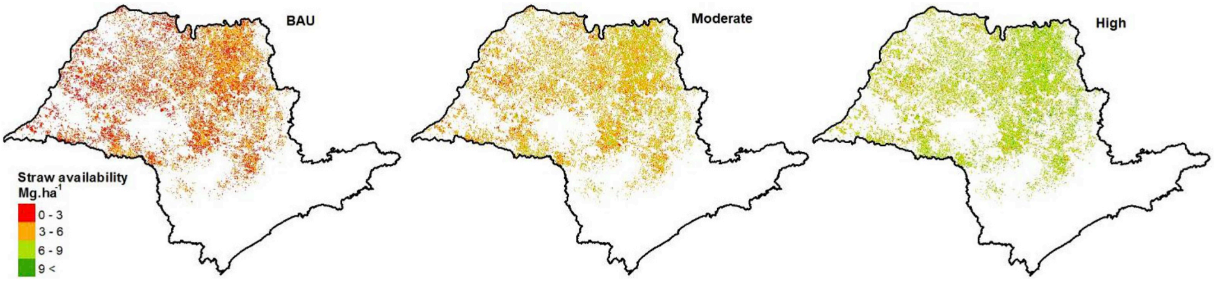

Fig. 6. The spatial distribution of sugarcane straw availability per hectare in the BAU, Moderate and High scenarios.

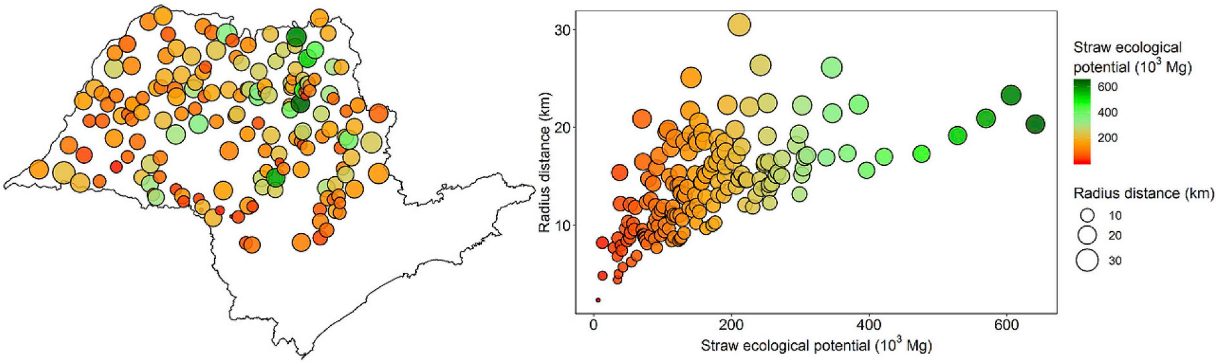

Fig. 8. Ecologically available sugarcane straw in the Moderate scenario aggregated at mill level in relation to the straw collection radius.

ecologically available sugarcane straw respectively reduces to 31.8 TWh and 18.7 TWh.

In the sensitivity analysis, no significant change is verified as all the parameters present a similar linear behavior for the variation applied (Fig. 11). The most prominent difference is the steeper decrease of the bioelectricity potential as the moisture content increase in the Moderate and High scenarios, whereas in the BAU scenario the variation is minor. This happens because most of the bioelectricity in the BAU scenario is sourced from mills with homogeneous high-yield fields. The parameter that presents the highest variation (5.6 TWh - 59.9 TWh) in the bioelectricity production among the scenarios is the SSR (straw-sugarcane ratio). The other parameters, straw moisture content and the electrical conversion efficiency are characterized by similar impact on the bioelectricity variation (13.1 TWh - 53.7 TWh and 15.6 TWh - 53.3 TWh, respectively). The latter is also assessed by using the maximum (35%) and minimum (20%) electrical efficiencies fixed for all the mills, showing similar bioelectricity potential range between 12.3 TWh and 52.7 TWh among the scenarios.

4. Discussion

4.1. Results

The ecological availability of sugarcane straw in 2012 crop-year ranges from 16.7 × 10^6 Mg in the BAU scenario to 40 × 10^6 Mg in the High scenario. At field level, we show that the amount of straw recovered varies from 0 to 14.8 Mg ha^{-1}, representing a removal rate of 0–82%. Low amounts of straw per hectare may not be economically advantageous as it compromises the straw recovery costs of sugarcane straw depending on the recovery route employed [37].

Currently, the average of exportable bioelectricity per Mg of sugarcane (i.e. electricity yield) in Brazil is 32.1 KWh.Mg^{-1} [51]. In our scenarios, the range of electricity yield (i.e. KWh per Mg of sugarcane) is estimated between 46 KWh.Mg^{-1} and 120 KWh.Mg^{-1}. Moreover, our results present that in 2012 crop-year, the mills could have produced 45.8 TWh of bioelectricity from sugarcane straw in the High scenario. This is between 40% and 60% of the fossil-based (e.g. coal, natural gas) electricity currently produced in Brazil [52], while the energy demand required for mobilizing the sugarcane straw [53] is below 5% of the bioelectricity production for all scenarios. Compared to the High scenario, the potentials in the BAU (18.7 TWh) and the Moderate (31.8 TWh) scenarios are considerably lower. These numbers, however, would still meaningfully contribute to the annual electricity supply at state level (i.e. ranging from 22% to 37% of the current electricity supplied in São Paulo) [54]. As shown in the sensitivity analysis, the bioelectricity potential from ecologically available sugarcane straw has a larger variation (5.6 TWh - 59.9 TWh) due to uncertainties in the SSR, which highly depends on the sugarcane cultivar, ratooning cycle and meteorological effects [25]. Other parameters, such as straw moisture content and conversion efficiency are also assessed, presenting lower variations between 13 TWh and 53 TWh. Nonetheless, the impact of the uncertainty of these parameters should be constantly considered in alternative bioenergy systems and in different potential assessments (e.g. techno-economic).

The results also show regional differences of mills located in traditional and expansion areas of sugarcane production. Unlike the mills in the traditional sugarcane areas (e.g. Northeast of São Paulo), which has a high agro-ecological suitability for sugarcane cultivation, the typical

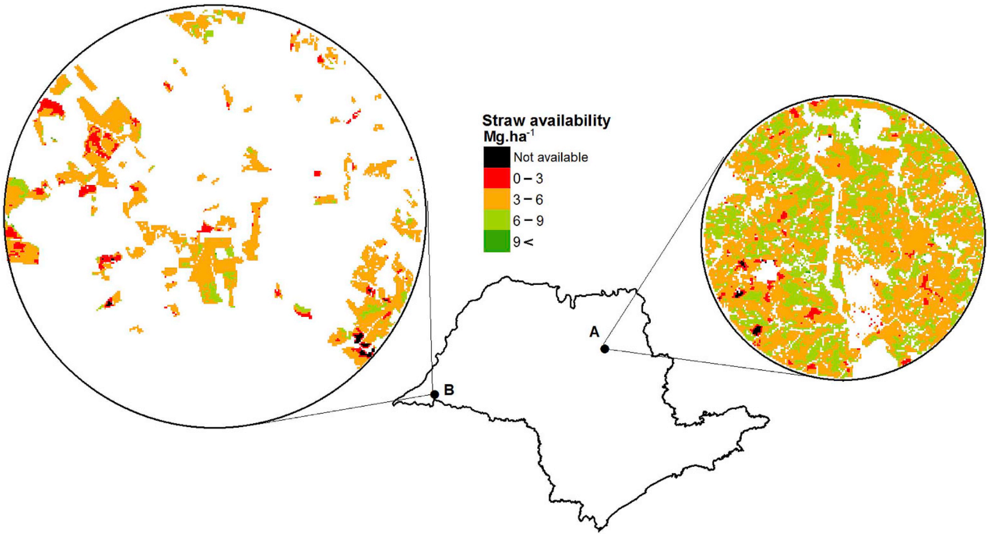

Fig. 9. Spatial distribution of the ecological availability sugarcane straw of mill A (Ribeirão Preto region) and B (Presidente Prudente region) within their collection radius. This comparison elucidates the differences between sugarcane systems of typical mills in the northeast (traditional areas) and west (expansion areas) of São Paulo.

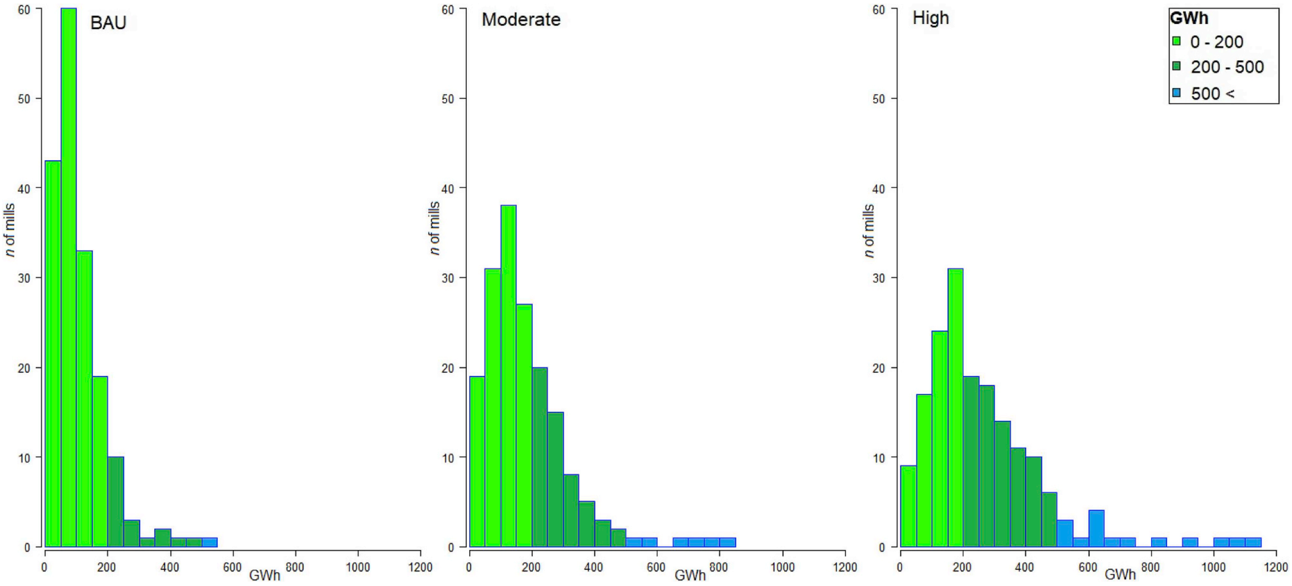

Fig. 10. Bioelectricity production of the sugarcane mills of 2012 crop-year for BAU, Moderate and High scenario on ecological availability of straw.

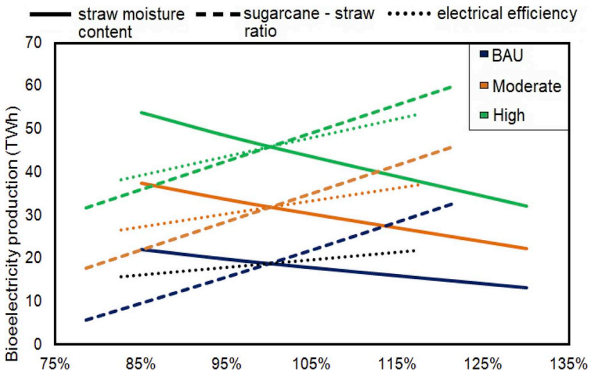

Fig. 11. Sensitivity analysis of the bioelectricity potential from ecologically available sugarcane straw in the BAU, Moderate and High scenario. In the vertical axis, the sensitivity of bioelectricity potential can be analyzed. In the horizontal axis, the relative variation of the key parameters is shown: straw moisture content (85%–130%); straw-sugarcane ratio (79%–121%); electrical conversion efficiency (83%–117%).

mills located in expansion regions are hindered by a lower level of straw availability per hectare and a lower density of sugarcane fields. With new sugarcane mills, it is expected that the sugarcane density and thereby sugarcane straw availability will increase in the expansion areas in the coming years [55]. The expansion areas in the state of São Paulo are also characterized by the high presence of sandy soils, which is a constraint for straw removal as it is likely to have high water infiltration inducing agronomic and environmental issues [48]. Alternatively, the presence of other land uses (e.g. eucalyptus plantation and annual crops) could serve as a supplementary source of agricultural residues, which could alleviate the seasonal availability of sugarcane straw. The use of alternatives sources for bioelectricity production is already a reality in Brazil

Apart from these underlying geographical differences, the real production of bioelectricity surpluses in 2012 in typical mills from these regions does not fully represents the results of the ecological availability of sugarcane straw for bioelectricity production. Based on the 2012 cogeneration ranking [38], the top ten bioelectricity producer mills from traditional areas have presented similar bioelectricity surpluses as the best cases from the expansion areas. Despite the similar contribution, the mills with the highest capacities of the state, normally located in traditional areas, have a significant internal demand for bagasse to thermal energy for producing sugar and 1G ethanol. As verified by Trombeta [20], typical mills from traditional areas still have cogeneration systems only designed to operate with bagasse at lower efficiency rates, reducing the bioelectricity surpluses. Differently, the prominent mills located in expansion areas are normally brownfields and greenfields built in the last decade [56]. As a downside, the amount of less suitable areas available in expansion areas hampers the production of sugar-based core-products. Consequently, the internal demand for bagasse tends to be lower, contributing to envision a business model focused on bioelectricity surpluses (e.g. new boilers, straw usage). This strategy has recently resulted in higher revenues compared to mills in traditional areas [57].

4.2. Methods and recommendations for future studies

In the spatial modeling, we consider that each mill was supplied by the nearest sugarcane fields within the established collection radius. This approach can be very realistic for isolated mills in regions with low competition for sugarcane areas, whereas it can be much less realistic for clusters of mills in traditional sugarcane regions of the state. In fact, the clusters of mills are competing for the same sugarcane areas, and therefore may have to source from more distant sugarcane fields, which may have underestimated the collection radius. Specifically, a spatial optimization exercise matching the sugarcane supply pixels with the mills' capacity seeking to minimize the collection distances should be addressed as a continuation of this study to provide a more realistic spatial distribution of the fields to each mill [58,59]. Broadly, future studies on bioenergy potentials should prospect and incorporate spatially explicit information to precisely assess the characteristics of local contextual factors and their potential impact on plant capacity. More than understanding the geographical differences, spatially explicit assessments ultimately contribute for a more precise estimation of the bioenergy potentials.

To assess the ecological availability of sugarcane straw for bioelectricity production, we assume only straw mulching levels as environmental criterion to maintain local environmental services. This is a decisive indicator as it largely affects the bioenergy system from the agronomic (e.g. fertilizer application, weed control) [25] and environmental perspective (e.g. organic carbon maintenance and erosion control) [14,60,61]. To improve our study, agro-ecological variables (e.g. soil, meteorological and topographic data) should be considered to modeling the straw mulching required at field level, rather than the assumed fixed mandatory mulching levels as used in our study. It should be also noted that other environmental constraints can play an important role in limiting the potential and have to be considered in further studies. As example, the assessment of carbon [62] and water [63] footprint throughout the bioelectricity from sugarcane straw supply chain. From the market perspective, there may be a strong increase in non-agronomic competitive uses for sugarcane straw in the future, namely 2nd generation ethanol [64]. Thus, the supply of low cost alternative residues either available within (e.g. bagasse, lignin) or outside (e.g. wood chips) the mill is of great importance to maintain bioelectricity surpluses [65,66].

To the extent of our knowledge, no sugarcane mill power plant is currently operating exclusively with sugarcane straw. The sugarcane straw is normally mixed with bagasse at similar sizes to reduce the damages in the boiler caused by chemical compounds available in the straw (e.g. potassium and chlorine) [10,11]. Other key assumption taken refer to the baling system recovery route, which is seen as an efficient recovery route for bioenergy purposes due to low moisture content of the straw delivered at the plant [41]. However, the straw baled could contain high content of mineral impurities depending on the fraction of straw recovered (i.e. chances are higher as the baler machine gets close to the soil). Therefore, if great quantity of undesirable mineral compounds is burn along with the straw in the boilers, this could also lead to damages in the boiler [11].

The bioelectricity from sugarcane straw requires efficient power plants to minimize the technical challenges. These power plants have been gradually introduced in the main sugarcane mills in the last years to generate great bioelectricity surpluses and also to receive sugarcane straw. In this study, we assume a relationship between the capacity of the plant and the electrical efficiency [44]. This is not necessarily true when comes to bioelectricity business in Brazilian sugarcane mills. In general, the adoption of high efficient boilers has been triggered by recent built modern sugarcane mills with medium capacity that conceive bioelectricity as a core business model such as ethanol and sugar. Based on that, it is highly recommended that future studies explore the transition of sugarcane mills to the bioelectricity venture taking into account historical, geographical and local contextual factors. This could better describe the electrical efficiency of the plants in sugarcane mills and consequently the bioelectricity potential at mill level.

5. Conclusion

Using spatially explicit data on 2012 crop-year, we assess that the sugarcane mills from state of São Paulo (Brazil) have a large ecological availability of sugarcane straw for bioelectricity production. Based on the scenarios analyzed (BAU, Moderate and High), the sugarcane mills have an ecological availability of sugarcane straw ranging from 16.7×10^6 Mg to 40×10^6 Mg. The areas with large potential of sugarcane straw are located in the Northeast region of São Paulo with the presence of very suitable fields for straw recovery. With an electric conversion efficiency ranging from 20% to 35% across the mills, the total bioelectricity potential from ecologically available sugarcane straw in São Paulo ranges between 18.7 TWh and 45.8 TWh, and at mill level the potential varies from 4 GWh to 1140 GWh in the scenarios.

The comprehension of the spatially explicit ecological availability of sugarcane straw for bioelectricity production at mill level may support policy makers in decentralizing energy policies at local scale. In parallel, we assess that yield levels and distances for straw supply have high spatial variability over the sugarcane mills of the state. Therefore, our study could be used as platform to assess the location effect on the sustainability of bioelectricity from sugarcane straw supply chain. This could provide reliable results on bioelectricity potentials at local and regional levels supporting different bioenergy stakeholders.

Acknowledgments

The study has been co-funded by a scholarship from the Coordination of Improvement of Higher Education (CAPES/Brazil), and Be Basic Flagship 9.1 project ‘Identifying, Quantifying and Qualifying Sustainability for the Biobased Economy’.

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