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An anticipatory life cycle assessment of the use of biochar from sugarcane residues as a greenhouse gas removal technology

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ABSTRACT

Greenhouse gas removal technologies are needed to reach the targets of the UNFCCC Paris Agreement. Among existing technologies, the use of biochar is considered promising, particularly biochar derived from the large quantities of sugarcane residues available in South America and elsewhere. However, the net greenhouse gas removal potential of sugarcane biochar has not been assessed hitherto. We use a scenario-based anticipatory life cycle assessment to investigate the emissions associated with a change from the combustion of sugarcane residues in a combined heat and power plant to the pyrolysis of these residues for biochar production and field application in São Paulo State, Brazil. We define scenarios based on different mean marginal electricity production and biochar production share. The results indicate that emissions from covering the electricity deficit generated by partial combustion of biomass during biochar production is the main emitting process. Overall, the processes associated with biochar production lower the net greenhouse gas benefits of the biochar by around 25%. Our analysis suggests that allocating 100% of the available sugarcane residues to biochar production could sequester 6.3 ± 0.5 t CO_2eq ha^{-1} yr^{-1} of sugarcane in São Paulo State. Scaled up to the entire State, the practice could lead to the removal of 23% of the total amount of GHGs emitted by the State in 2016.

1. Introduction

A global decrease of greenhouse gas (GHG) emissions of around 6% yearly is needed to reach the targets of the UNFCC Paris Agreement and limit global temperature increases to well below 2 °C above pre-industrial levels (IPCC, 2018). Numerous greenhouse gas removal (GGR) technologies have been proposed to achieve this (Haszeldine et al., 2018; Nemet et al., 2018; Smith et al., 2013; Woolf et al., 2010). One of the promising technologies is based on biochar, the carbon-rich material produced in thermochemical conversion of biomass under restricted oxygen supply (IPCC, 2019; Schmidt et al., 2018). Sugarcane (*Saccharum officinarum* L.) cultivated for ethanol as well as human consumption is one of the largest sources of residual biomass globally, with 1.9 Gt of fresh sugarcane harvested in 2018 (FAO, 2019). It is grown in more than 90 countries, but most current production is in Brazil (Cardoso et al., 2019). Within Brazil, 55% of sugarcane is produced in the São Paulo State on more than 5.7 Mha (Theodor Rudorff, 2014). Sugarcane cultivation generates large quantities of residues, particularly with the increasingly widespread practise of "green harvesting" – mechanical harvest of cane without prior burning of leaves (Romero et al., 2007).

The purpose of the current study is to refine a previous scoping of biochar GGR for sugarcane in São Paulo State (Lefebvre et al., 2020) using life cycle assessment (LCA) to allow more accurate and transparent analysis of the full carbon burden (Goglio et al., 2020). Published LCAs for biochar GGR have been site- and system-specific (Matuštík et al., 2020) and cannot be extended to the assessment of the high potential sugarcane system. In this study, we i) adjust the carbon (C) sequestration potential of sugarcane residue biochar for emissions associated with biochar production and use, and ii) compare the typical sugarcane processing chain (baseline) with a modified one in which biochar production from sugarcane bagasse and/or straw is integrated. The global

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warming potential of the alternate processes provides more accurate net greenhouse gas removal figures and, for the first time, a anticipatory LCA (Wender et al., 2014) for biochar production and use in a high potential GGR system.

2. Method

2.1. Sequestration potential of sugarcane residue biochar in São Paulo

Our recent study assessed the carbon sequestration potential of transforming sugarcane production in São Paulo to include biochar (Lefebvre et al., 2020). Available residues (dry basis) included 10.4 t ha^{-1} yr^{-1} of bagasse processing residues and 2.9 t ha^{-1} yr^{-1} of recovered straw (considering that 7 t ha^{-1} yr^{-1} of straw is reserved for optimal soil protection and agronomic sustainability (Silva et al., 2019)). If 100% of these residues are used for biochar production, we calculated that conventional slow pyrolysis would produce up to 4.2 t of biochar (tBC), Lefebvre et al. (2020). Applied back to the field, we predicted this biochar would increase soil C stocks by 2.35 ± 0.4 t C ha^{-1} yr^{-1}; the uncertainty represents the diversity of soil type and climate of the study area (Lefebvre et al., 2020).

2.2. Objectives and system boundary

This study applies LCA methodology to assess the difference in net GHG emissions (as carbon dioxide equivalents; CO_2eq) between use of available sugarcane residues in providing power (CHP combustion plant) versus producing biochar (in a slow pyrolysis plant) (Fig. 1). This screening LCA does not take account of emissions associated with processes present in both baseline and biochar scenarios (e.g., emissions arising in common field operations or the emissions associated with sugarcane processing), where the emissions can be considered equivalent. This screening LCA uses 100-year global warming potentials (GWP) as prescribed in the IPCC Fifth Assessment Report (AR5) (IPCC, 2014). The functional units applied in our LCA are (i) per hectare of sugarcane crop for São Paulo state, and (ii) per tonne of CO_2eq sequestered.

2.3. Software, database & data processing

SimaPro 9 database (EcoInvent 3.6) were used to assess the emission factors of processes and fuels (PRé Consultants: Life Cycle consultancy and software solutions, 2019). The IPCC 2013 GWP 100a V1.03 method was used to assess the SimaPro processes' carbon footprint (Myhre et al., 2013). Publicly available data were used when processes could not be found in the databases, when they better represented the process under study, or to provide a range of values used for the uncertainty analysis. The data and emission factors (EF) used in this study are available in the Supplementary Information (Section 3). R software version (3.5.1) (Core Team, 2018) was used to compute the life cycle impact assessment and the uncertainty analysis. The R package ggplot2 (Wickham, 2016) was used to produce the figures.

2.4. Scenario description

Biochar contains a large proportion of the energy content of the original biomass (Bergman et al., 2015), so pyrolysis logically produces less electricity than combustion in CHP. Our data collection found that, on average, the electricity generated by the CHP plant delivers 950 kWh t^{-1} residue (electric) but only 114 kWh t^{-1} residue for pyrolysis (see Supplementary Information – Section 3). As a result, Brazil will need to

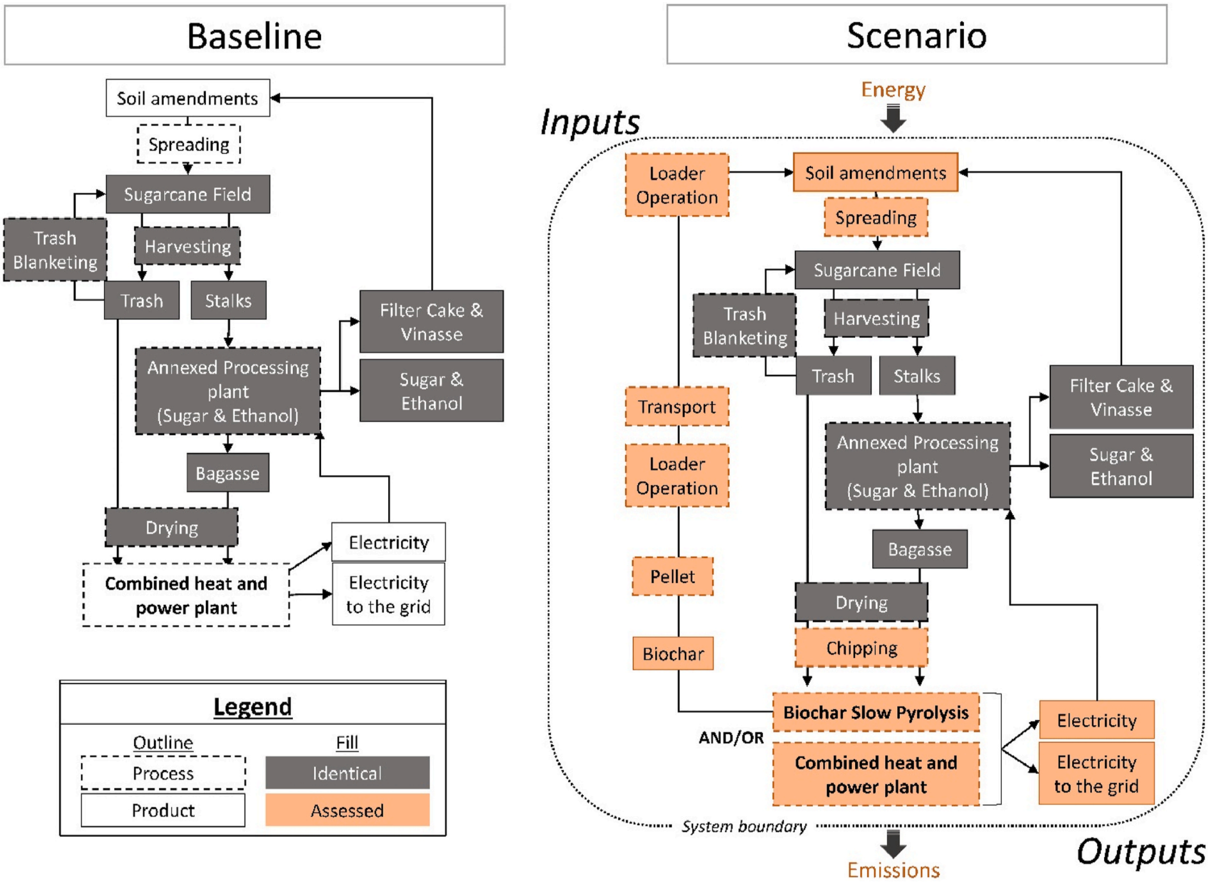

Fig. 1. Comparison between the baseline system and the assessed scenario. The orange box represents the process or products susceptible to change from the baseline to the biochar producing scenario and, hence, are assessed for their carbon footprint.

cover the resulting deficit using other electricity sources that would require additional infrastructure. The national energy mix will consequently change by the increased input into the grid from the marginal supply, and hence lead to a new carbon footprint per unit of electricity produced nationwide. Therefore, the LCA of biochar also needs to encompass (i) the carbon footprint of the required additional infrastructure to allow for the production of this energy deficit, and (ii) the carbon footprint of the updated country energy mix to cover this electricity deficit.

2.4.1. Updating the national energy mix

To update the Brazilian energy mix we first approximated the additional energy needed at national scale, considering a change from CHP to BC production. The associated electricity deficit is 150 kWh from the residues associated with one ton of harvested sugarcane. Sugarcane yields on average 74 t ha^{-1} (CONAB, 2018). In Brazil, there are 10,189, 208 ha dedicated to sugarcane production (FAO, 2019). Therefore, supposing that available residues from all sugarcane field are used in a CHP, the national electricity deficit of changing from CHP to BC would be 113 TWh.

Table 1 shows the national electricity mix (in TWh) with their respective EF. By allocating the 113.2 TWh to the generation appropriate to the scenario (see section 2.4.2), as well as by adjusting the electrical output produced by the combustion of sugarcane biomass ("Biomass (Sugarcane)") to 0 – now used for biochar production, we can define a new GWP (in $kgCO_2eq\ kWh^{-1}$) for the updated country energy mix (Table 2).

2.4.2. Consequential electricity scenarios

The different scenarios of this anticipatory LCA are based on assumptions of the marginal energy supply of the country. The marginal energy production technology is the technology most likely to respond to changing demand (Lund et al., 2010). Among the energy sources in Brazil, natural gas (NG – Scenario 1), wind (Scenario 2), and a mixture of both (75% NG, 25% wind – Scenario 3) were selected as being the most probable marginal energy in a near future (de Oliveira Noronha et al., 2019; Diógenes et al., 2019; EPE, 2017; Khatiwada et al., 2016; Panorama Offshore, 2018; Santos et al., 2017; Seabra et al., 2011). An additional energy mix scenario (Scenario 4) was based on the recent work from Vandepaer et al. (2019) who, among other things, used consequential life cycle inventories to project the marginal electricity mix of Brazil for the year 2040 (Vandepaer et al., 2019). Complete description of the scenarios is available in the Supplementary Information – Section 1. Table 2 reports the updated national energy mixes and emissions factors for the scenarios assessed.

2.4.3. Biochar scenarios

In addition to the marginal energy scenarios, we set up three subscenarios where 100%, 50%, and 25% of the maximum biochar production potential is reached. The 50% biochar production sub-scenario considers that respectively 0% and 60% of the available straw and bagasse, are allocated to biochar production while the 25% biochar production sub-scenario considers that respectively 0% and 30% of the available straw and bagasse are allocated to biochar production. The residual biomass in the 50% and 25% sub-scenario is considered to be utilised in CHP.

Table 1
Brazilian energy mix in 2016 and predicted for 2021 (Barros et al., 2018) and emission factors (EF) (Wernet et al., 2016).

	2016	2021	EF
Unit	TWh	TWh	$kgCO_2eq\ kWh^{-1}$
Hydro	380	517	0.072
Wind	33	75	0.015
Solar	0	11	0.077
Biomass (Sugarcane)	38	51	0.029
Biomass (other)	11	15	0.057
Nuclear	16	15	0.011
Natural Gas	45	20	0.555
Hard Coal	16	10	1.223
Oil	38	34	0.725
TOTAL	579	749	/

2.5. System description

2.5.1. Baseline

In the baseline system, it was assumed that the sugarcane processing plant is an annexed plant producing ethanol, sugar and electricity. This type of processing plant is the most widespread in SP (Cardoso et al., 2019). The available residues are burned in a 65-bar pressure boiler with an efficiency of 88%. The electricity is produced by a CHP generator with condensing-extraction turbines (Cardoso et al., 2019). The residual heat produced by the CHP (or pyrolyzer) was not considered in this analysis because there is function for surplus heat. The facility processes 3 Mt sugarcane during 190 days of operation per season (Cardoso et al., 2019).

2.5.1.1. Sugarcane mills' surplus electricity. Sugarcane processing in Brazil use various technologies (Pippo and Luengo, 2013). The amount of electricity exported from the mills to the grid varies accordingly. Low technology facilities import electricity from the grid (Pippo and Luengo, 2013). The average electricity demand of a sugarcane processing site is around 30 kWh t^{-1} of harvested cane (Birru et al., 2019; Cardoso et al., 2019; Klein et al., 2018; Pippo and Luengo, 2013; Seabra and Macedo, 2011). In our assessment we assume that all facilities in São Paulo are 'modern' or 'state of the art' mills and export electricity to the grid. Based on the processing size of our baseline scenario in São Paulo (3 Mt sugarcane processed per season) (Cardoso et al., 2019), with an average yield of 74 t ha^{-1} (CONAB, 2018) and the sugarcane area of 5,768,172 ha (Theodor Rudorff, 2014), the state should have 143 processing sites. This number is consistent with the official number of 160 sites (Conab, 2019), meaning that our case study reflects the average situation for São Paulo state. Taking into account the cane yield and the available sugarcane residues and assuming that the available straw is combusted along with the bagasse, our representative site would generate about 170 kWh t^{-1} of harvested sugarcane, use 30 kWh internally and export about 140 kWh to the grid (Alves et al., 2015; Birru et al., 2019; Cardoso et al., 2019; Dias et al., 2011; Klein et al., 2018; Olivério and Ferreira, 2010; Sampaio et al., 2019; Seabra and Macedo, 2011).

2.5.2. Biochar producing system

Our scenarios consider biochar to be produced by a conventional industrial slow pyrolyzer at around 550 °C. Slow pyrolysis was selected because it favours biochar over other products when compared to other pyrolysis options (Basu, 2010). In our scenarios the bio-oil is not collected but rather combusted in the gas phase (Basu, 2010; Gabra et al., 2001). This approach has been reported in previous studies (Azzi et al., 2019; Park et al., 2014; Roy and Dias, 2017; Wang et al., 2014). The gas released during pyrolysis is used to generate electricity (de Oliveira Vilela et al., 2014; Oldfield et al., 2018; Quirk et al., 2012; You et al., 2017). In addition to the biochar plant, the biochar producing system also includes grinding of the biomass, the production of biochar pellets, and their transportation and application on the field. Description of each process is available in the Supplementary Information – Section 2.

2.6. Additional effect of biochar application

2.6.1. Reduced nitrous oxide emissions from soils

Quirk et al. (2012) evaluated the effect of biochar from either sugarcane bagasse or sugarcane straw on the emission of nitrous oxide from

Table 2

Summary table of the electricity mixes and emission factors considered for each scenario.

	Unit	Baseline (Barros et al., 2018)	Scenario 1 (NG)	Scenario 2 (Wind)	Scenario 3 (NG [75%] & Wind [25%])	Scenario 4 (Vandepaer et al., 2019)
Year	/	2021	2021	2021	2021	2040
Hydro	%	69	63.8	63.8	63.8	17.3
Wind	%	10	9.3	23.2	12.7	4.92
Solar	%	1.5	1.4	1.4	1.4	64.24
Sugarcane biomass	%	6.8	0.0	0.0	0.0	1.66[b]
Other biomass	%	2	1.9	1.9	1.9	
Nuclear	%	2	16.4	1.9	1.9	1.3
Natural gas	%	2.7	1.2	2.5	12.9	10
Hard coal	%	1.3	4.2	1.2	1.2	0
Oil	%	4.5	4.2	4.2	4.2	0.01
Updated GWP	$kgCO_2eq\ kWh^{-1}$	/	0.187	0.111	0.168	/
High to medium voltage [a]	$kgCO_2eq\ kWh^{-1}$	/	0.008	0.005	0.008	/
Infrastructure	$kgCO_2eq\ kWh^{-1}$	/	0.001	0.009	0.003	/
Total GWP	$kgCO_2eq\ kWh^{-1}$	0.153	0.196	0.125	0.178	0.136

[a] Transformation from high to medium voltage based on losses reported by the Ecoinvent 3.6 database (Severinghaus, 2019; Wernet et al., 2016).

[b] Vandepaer et al. (2019) does not differentiate between sugarcane and other biomass in his electricity mix.

soil under sugarcane land in Australia. They reported that "*In the fertilised soil bagasse biochar significantly reduced [by 14.3%] N_2O emissions compared to both control and straw biochar amended soils*" (Quirk et al., 2012). The emission factor of nitrous oxide is 0.7% of applied N in São Paulo state under sugarcane cultivation when 5 tonnes of straw ha^{-1} are removed (Gonzaga et al., 2019). This agrees with the range offered by Filoso et al. (2015), and the control treatment of Quirk et al. (2012). The IPCC Tier 1 guidelines (IPCC, 2006) for direct and indirect N_2O emissions from organic fertilizer (vinasse, filter cake, straw blanket) are 1.22% of their N content. Combining the yearly addition of N containing amendments (i.e. urea, vinasse, filter cake, residue blanket) using the N_2O emissions factor from Gonzaga et al. (2019) for the urea and from the IPCC for the rest, the emissions reaches 1.46 kg N_2O ha^{-1} yr^{-1}, or 388 kg CO_2eq ha^{-1} yr^{-1} (Hallegatte et al., 2016). The findings of Quirk et al. (2012) are in the lower range reported by Abbruzzini et al. (2017) for sugarcane in São Paulo state and agree with the figure used in Thers et al. (2019) study using an application of 1 tBC ha^{-1} on oilseed rape in Denmark.

2.6.2. *Biochar induced fertilizer reduction*

We considered biochar to increase the nitrogen use efficiency by 11% (Liu et al., 2018) and phosphorus use efficiency by 10% (Borges et al., 2020), independently of the biochar application rate simulated. In addition, we accounted for the liming potential of biochar according to Quirk et al. (2012). Fertilizer and lime inputs were reduced based on the increased nutrient use efficiency and liming potential of biochar (Supplementary Information – Section 3).

2.6.3. *Accounting for the pyrolysis plant construction material*

Yang et al. (2016) provide a list of the materials and energy needed to build a pyrolysis plant. Their study accounts for the emissions associated with the workshop and office construction, the emissions to build the equipment (shredding, drying, and pyrolysis system), and the electricity required for the auxiliary systems and domestic consumption. The carbon footprint of the pyrolysis plant and its maintenance reaches 117 kg CO_2eq tBC^{-1} (using the 2021 Brazilian electricity emission factor (Barros et al., 2018)). Roberts et al. (2010) also reports the amount of material for a pyrolysis plant working at 80% full capacity with a lifetime of 20 yr, processing 10 t h^{-1} of biomass, including onsite storage of the biomass. Assuming 200 days of production, at 7 h day^{-1}, and the averaged 32.5% sugarcane residue BC yield (i.e., 31.3% for bagasse and 33.6% for straw, Supplementary Material, Section 3), the carbon footprint of constructing the pyrolysis plant reaches 133 kg CO_2eq tBC^{-1}.

2.6.4. *Non - CO_2 GHG emissions*

Data on pyrolysis emissions are scarce, especially considering the post combustion of the syngas for energy production (Azzi et al., 2019; Pennise et al., 2001) and the plant scale considered in this study. We assumed that the industrial pyrolysis plant modelled here releases few to none non-CO_2 GHG emissions. Considering the scale of the simulated plant, if GHG are released from the facility, the emissions would be under strict state regulations. We assume these regulations to be similar to the emission regulations of a CHP plant. Since our scenarios substitute CHP for pyrolysis, in its entirety or in part depending on the scenarios, we assumed that emissions from the pyrolysis plant (if any) would be equivalent to the emissions of a CHP and hence cancel each other.

2.7. *Uncertainty analysis*

The uncertainty analysis was conducted using the range of values obtained through the literature search. A statistical distribution was applied to each range of values from where a random selection of 10,000 values were made for the Monte Carlo simulations. The simulations were made in R software (3.5.1) (Core Team, 2018). The distributions applied were: emission factors and electricity productions/demands– pert, transport distance– uniform, diesel use – lognormal. Additional information on the uncertainty analysis can be found in the Supplementary Material – Section 4.

3. Results

Fig. 2 shows the contribution analysis of our LCA using NG as the marginal energy and considering 100% of the available residues for BC production. This result shows that the biochar soil application accounts for the majority of its sequestration potential while the reduced nitrous oxide emission from the soil, the electricity production during pyrolysis

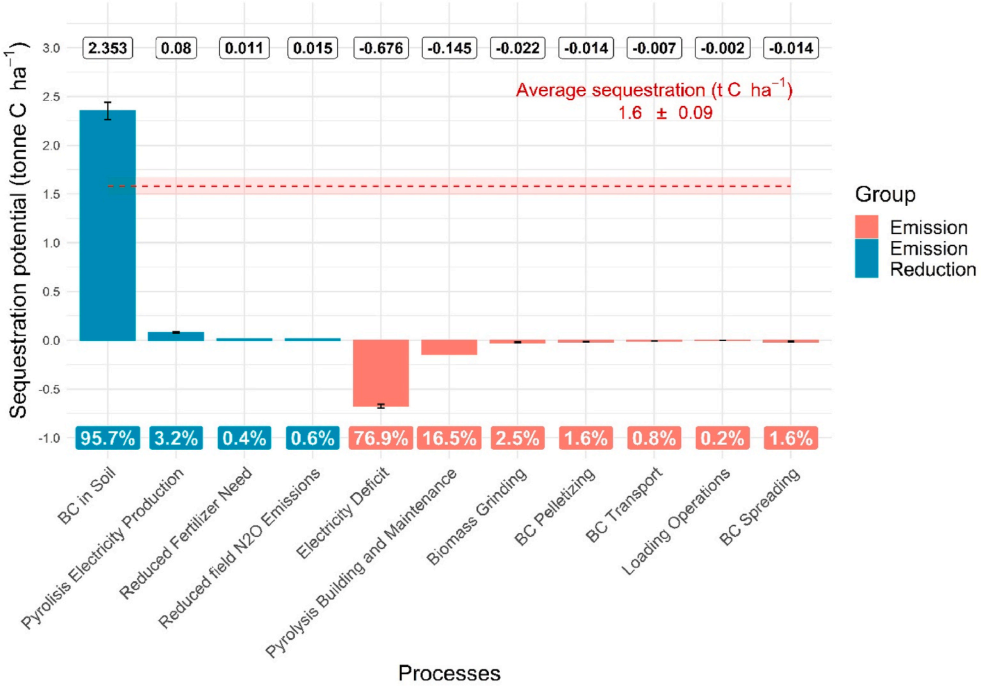

Fig. 2. Contribution analysis considering NG as marginal energy and 100% allocation of available sugarcane residues to BC production. The upper outlined numbers report the exact figures in t C ha^{-1} for each process. The under outlined numbers report the share of each process within each group (emission or emission reduction). The ribbon and error bars are ±1 SD. The dotted line represents the net sequestration value.

and the reduced fertilizer need due to biochar application accounts for less than 5%. On the emissions side, covering the electricity deficit is responsible for most of the emissions associated with the practice, while grinding the biomass, pelletizing, transporting, loading, and spreading the biochar accounts for less than 10% of the total emissions of the practice. These observations remain valid regardless of the scenario assessed. The contribution analyses for each of the scenarios are available in the Supplementary Material – Section 5.

Fig. 3 shows the combined results for all the marginal energy mixes and the three sub-scenarios (biochar production share) assessed. On average, production of 100%, 50% and 25% of the maximum biochar production potential can sequester a net of 6.3 ± 0.5, 3.6 ± 0.3 and 1.8 ± 0.3 t CO_2eq ha^{-1} (mean ± SD), respectively. In addition, these results show that the carbon sequestration of the practice increases as the EF of the marginal electricity mix decreases.

Fig. 4 shows the remaining fraction of the carbon sequestration

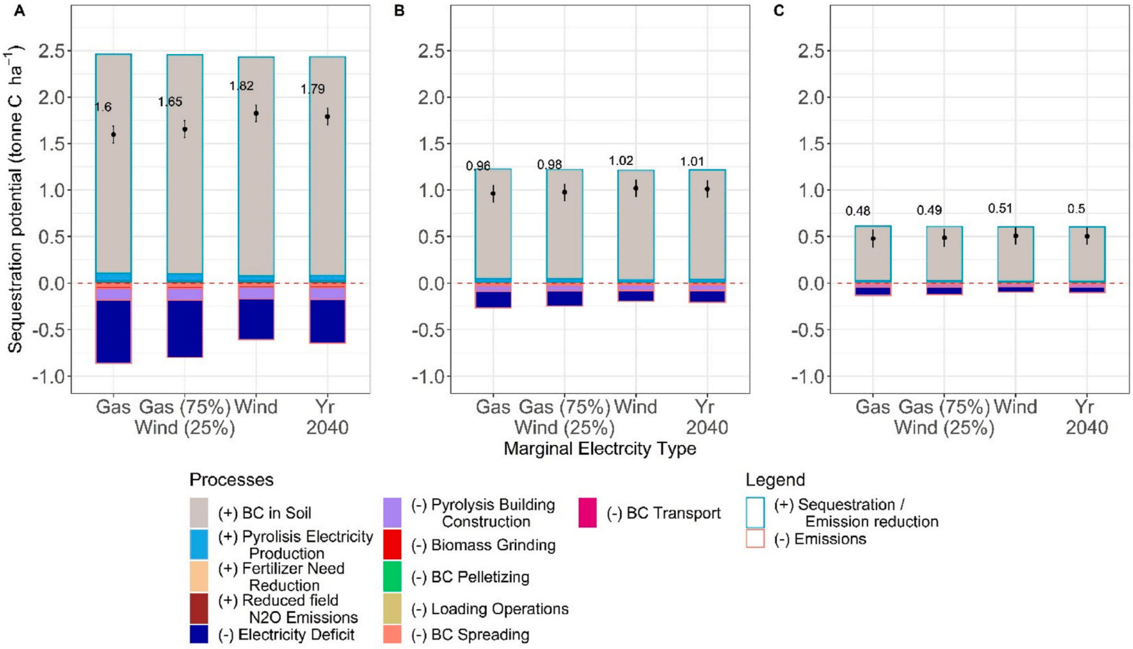

Fig. 3. Combined results of all scenarios. Section A, B and C represent the production of 100%, 50% and 25% of the maximum biochar production. The remaining residues in section B and C are treated in a CHP similarly to the baseline. The black dots and labels are the net sequestration with associated error bars representing ±1 SD.

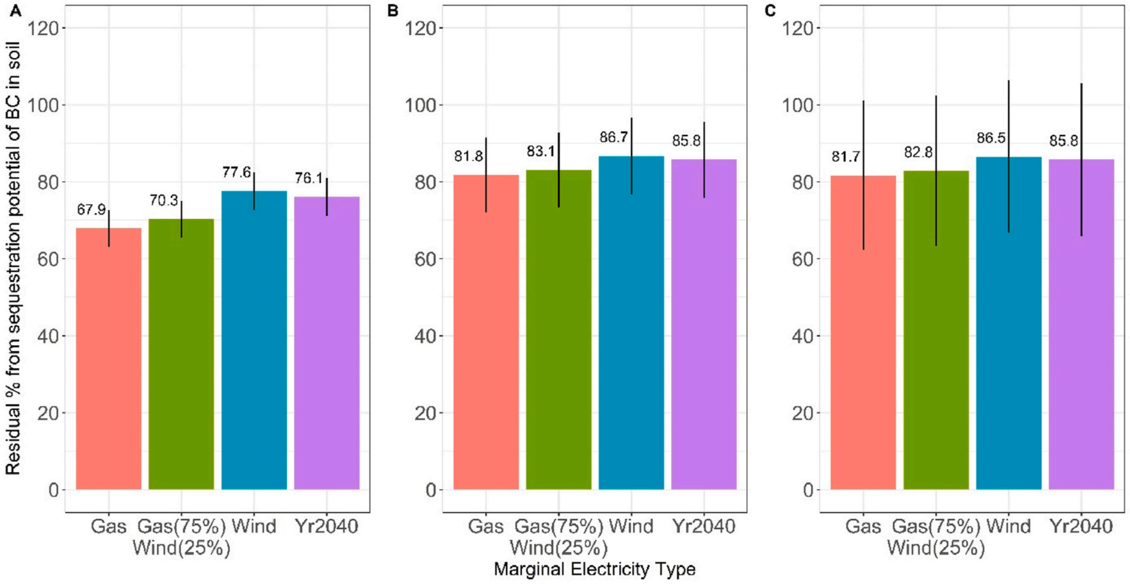

Fig. 4. Biochar soil carbon sequestration efficiency: the remaining carbon capture potential of biochar in soils of after accounting for all the processes, in percent. Section A, B and C represent the production of 100%, 50% and 25% of the maximum biochar production. The remaining residues in section B and C are treated in a CHP similarly to the baseline. The error bars are ±1 SD.

potential of one tonne of biochar once we have accounted for the all the additional processes (biochar soil carbon sequestration efficiency). This value is calculated by comparing the actual carbon sequestration potential of biochar addition once accounting for all the processes included in this LCA with the original carbon sequestration potential of biochar alone (i.e., 2.35 t C ha^{-1}, Section 2.1). It shows that allocating part of the residues to the CHP plant (section B & C – Fig. 4) increases the biochar soil carbon sequestration efficiency (residual sequestration potential of BC in soil after subtracting the emissions).

4. Discussion

4.1. Biochar carbon sequestration

Considering the averaged value of all marginal electricity mixes and BC production share, our LCA suggests that each tonne of BC that might be produced from sugarcane residues in São Paulo and applied back to fields should sequester 1.64 ± 0.11 t CO_2eq tBC^{-1}. Comparisons with other biochar systems is complicated, because their abatement potentials are highly site- and scenario-specific (Matuštík et al., 2020). Our estimate is lower than that from the LCA of Rajabi Hamedani et al. (2019) for willow wood biochar on Belgian willow plantation (~2 t CO_2eq tBC^{-1}) and slightly higher than that of Thers et al. (2019) for biochar from Danish oilseed rape (~1.44 t CO_2eq tBC^{-1}). Peters et al. (2015) explored the potential carbon benefit of producing and applying biochar produced from chipped poplar wood on Spanish poplar plantation, where the heat produced during pyrolysis was used as substitute for natural gas, with direct burning of the woodchip for heat as the reference scenario. They calculated a carbon abatement potential for their biochar scenario that is more than twice our average result (~3.9 t CO_2eq tBC^{-1}). Brassard et al. (2018) found on average a carbon sequestration potential of almost half that using switchgrass as feedstock and applying the biochar to Canadian wheat (~2.3 t CO_2eq tBC^{-1}). Our results reflect our choice of biochar produced at around 550 °C. This could change with factors including soil management, the biomass streams utilised, how biochar is integrated into the cropping system, and the national electricity mix.

On average, allocating 100% of the available residues to biochar production led to emissions of 0.30 ± 0.07 t CO_2eq per t CO_2eq sequestered. This is reduced to 0.19 ± 0.05 and 0.19 ± 0.05 t CO_2eq per t CO_2eq sequestered when 50% and 25% of the maximum potential biochar production is reached (see Supplementary Material, Section 5 for complete data). This is roughly twice the 0.135 t CO_2eq emitted per t CO_2eq sequestered for carbonation and four times the 0.075 t CO_2eq emitted per t CO_2eq sequestered for enhanced weathering of basalt rock in São Paulo State (Lefebvre et al., 2019). Applied to the whole State, allocating 100% of the sugarcane residues to biochar production could lead to the sequestration of 36 Mt CO_2eq yr^{-1} or 23% of the 159 Mt CO_2eq emitted by the State in 2016 (SEEG, 2016). Producing 50% and 25% of the maximum biochar production potential could lead to the sequestration of 21 and 10 Mt CO_2eq yr^{-1}, respectively.

4.2. The marginal electricity mix

Determining the impact of energy use is a key component of LCA (Vélez-Henao and Garcia-Mazo, 2019). Our results show that the “greener” the energy mix of Brazil, the greater is the carbon sequestration benefit arising from biochar deployment. However, predicting future demand for electricity and the future energy mix in the face of increasing demand is highly uncertain (Vandepaer et al., 2019).

Hydropower is currently the main source of electrical power in Brazil. Some argue that as the number of potential new dam sites is limited, hydropower’s share of the mix will not substantially increase (Dale et al., 2013; Leal et al., 2019). Others see 70 GW of untapped potential installed by 2035 (IEA, 2013), centred in the Amazon. Hydro projects require planning and consultation, and risk damage to local communities, biodiversity and the wider environment, potentially hampering their development (IEA, 2013; Santos et al., 2017). In addition, massive investment would be required in the transmission grid from the Amazon region to the southeast region where electricity consumption is greatest. In our scenarios, the electricity used to offset transition from biomass combustion to partial combustion for biochar has a major impact on the results, accounting for at least 50% of emissions across all scenarios assessed. If the anticipated increase in renewable energy in the Brazil energy mix (de Oliveira Noronha et al., 2019; EPE, 2017) was realised, this would slightly alter our results. Nevertheless, as the EF of Brazilian electricity decreases, the net carbon sequestration potential of biochar will increase. Conversely, as the EF of electricity increases, the carbon sequestration decreases. Therefore, sugarcane producing countries mainly relying on coal for their electricity production will benefit less or even emit more CO_2eq from such practice than countries with greener energy mixes. Under Brazilian conditions, the net zero carbon sequestration benefit of the practice is reached when the emission factor of electricity reaches 0.687 kg CO2eq kWh^{-1}; e.g., with an energy mix of 12% coal and 88% natural gas. Finally, seasonal and daily variations of energy supply and demand also need to be taken into account. We expect the wind powered scenario to require a greater installed capacity to cover the electricity deficit than the more versatile NG scenario. However, this difference is likely to be small.

4.3. Selecting the residue

The following section explores the results of our analysis if only the available bagasse or straw is used to produce biochar while the other residue is combusted in the CHP. For instance, the allocation of all the available straw (i.e., 2.85 t dry matter ha^{-1}) to biochar production and the combustion of the bagasse (i.e., 10.4 t dry matter ha^{-1}) in a CHP leads to an average (including all electricity mixes scenarios - Table 2) net sequestration potential of 0.57 t CO_2eq ha^{-1} (or 0.199 t CO_2eq t of straw $residue^{-1}$) and a biochar soil carbon sequestration efficiency of 41%. Conversely, allocating all the available bagasse to biochar production and incinerating the available straw in a CHP leads to an average net sequestration potential of 6.11 t CO_2eq ha^{-1} (or 0.590 t CO_2eq t of bagasse $residue^{-1}$) and a biochar soil carbon sequestration efficiency of 84%. Although sugarcane straw and bagasse have an equivalent low heating value (15.25 MJ kg^{-1} and 15.13 MJ kg^{-1} dry weigh, respectively), processing the bagasse requires drying it from 50% moisture content by weight, lowering the overall energy production; whereas the straw usually has a moisture content of 15% by weight when collected from the field (Dias et al., 2011). Data collection on the energy production of straw and bagasse support this observation as sugarcane straw produces slightly more electricity when treated in a CHP than bagasse (Supplementary Information – Section 3). In addition, bagasse biochar has a higher carbon content than straw biochar (i.e. 1 kg of bagasse or straw produces 0.20 kg BC-C and 0.14 kg BC-C, respectively; Cross and Sohi, 2013; Quirk et al., 2012), leading to a lower loss of carbon sequestration potential. Further investigations of the properties of sugarcane bagasse and straw biochar when produced in the modelled pyrolyzer, as well as on the electricity production of both biomass types, are needed before these findings can be generalized. In addition, the combustion of straw can be problematic if used in combination with some gas turbines without proper filtration systems, because straw's high silica content can lead to corrosion of the turbine blade and abrasion of the tubing while its high chlorides content can create fouling in the boilers (Alves et al., 2015; Anukam et al., 2016; Gabra et al., 2001; Olivério and Ferreira, 2010). These observations show that the physicochemical properties of the biomass should be taken into account when selecting the most appropriate processing method either to minimize the production of elements reducing the overall efficacy of turbines and/or boilers, or to maximise biochar carbon content production by selecting a carbon rich feedstock.

4.4. Additional effects

Decreased albedo induced by biochar application to crop fields (Williamson, 2016; Zhang et al., 2018) is thought to reduce its carbon abatement potential by up to 20% (at application rate of 30 tBC ha^{-1}) (Meyer et al., 2012), as a result of increased soil temperature promoting oxidation of other soil carbon pools (EASAC, 2018). We did not account for such effect in this study because sugarcane is a perennial and fast growing species (Scarpare et al., 2016) covering the soil rapidly, thereby reducing the effect on albedo.

Likewise, although there is evidence of positive effects of BC on yield (Ye et al., 2020), this study does not adjust sugarcane yield following biochar application. Yield response to biochar depends biochar characteristics, soil and crop type, co-amendment and other factors (Ye et al., 2020). We know of no published field studies on the effects of sugarcane biochar on sugarcane yield in São Paulo. Doses of 5 t ha^{-1} and 10 t ha^{-1} biochar from sugarcane straw had no impact on sugarcane yield in Indonesia (Hariyono et al., 2020).

Recent and future innovations in biomass pyrolysis could increase the LCA benefits of a biochar scenario; for example, alkali metal (K and Na) additions have been shown to increase biochar yield by around 15% as well as increasing the stability of biochar carbon in soil (Mašek et al., 2019). Integration of biochar with fertiliser management has potential for synergistic effects on carbon abatement. Recent laboratory and glasshouse studies have shown the potential to integrate K and P into biochar as an effective compound product. Treatment of sugarcane-straw biochar with KOH followed by neutralisation with H_3PO_4 increased the P content of the biochar and led to higher sugarcane yield and P use efficiency (Borges et al., 2020).

5. Conclusions

Changing the processing chain for sugarcane residues from the current typical CHP system to a system based on slow pyrolysis with biochar production could provide net carbon abatement of 6.3 ± 0.5 t CO_2eq ha^{-1} or 1.64 ± 0.11 t CO_2eq t $biochar^{-1}$, taking into account the emissions associated with set up and running. The gain arises mainly from the C stored as biochar in the soil; losses are mostly due to the electricity deficit caused by the partial combustion of biomass during pyrolysis. Applied to São Paulo State, transformation of the available sugarcane residue to biochar could lead to the sequestration of 36 Mt CO_2eq yr^{-1} or 23% of the State's GHG emissions in 2016.

Data availability

All data generated or analysed during this study are included in the published article and Supplementary information.

CRediT authorship contribution statement

David Lefebvre: Conceptualization, Methodology, Software, Writing – original draft. **Adrian Williams:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Guy J.D. Kirk:** Conceptualization, Supervision, Validation, Writing – review & editing. **Jeroen Meersmans:** Validation, Software, Writing – review & editing. **Saran Sohi:** Resources, Validation, Writing – review & editing. **Pietro Goglio:** Resources, Validation, Writing – review & editing. **Pete Smith:** Funding acquisition, Project administration, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127764.

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