


# Mapping the environmental and techno-economic potential of biojet fuel production from biomass residues in Brazil

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**Abstract:** This study assesses the environmental potential of crop residues and the techno-economic potential of biojet fuel (BJF) production in Brazil. Different production routes are evaluated from two types of biomass residues (sugarcane straw and eucalyptus harvest residue), and four different technological pathways (alcohol to jet, Fischer–Tropsch, hydrothermal liquefaction and pyrolysis). The environmental potential of biomass residues is determined utilizing spatio-temporal projections of land-use change in Brazil and by explicitly modeling the erosion risk and the soil organic carbon (SOC) balance spatially. The assessment of the techno-economic potential of BJF production from the environmental potential of sugarcane straw (SCS) and eucalyptus harvest residues (EHRs) considers the BJF total costs, which result from a summation of biomass residue recovery costs, BJF conversion costs, and BJF transportation costs. These BJF total costs are compared with the range of fossil jet fuel prices at Brazilian airports to quantify the techno-economic potential. The environmental potential of biomass residues varies from 70 Mt in 2015 to 102 Mt in 2030, with SCS being highly constrained by SOC, whereas EHRs are more constrained by the high erosion risk. These quantities can generate a techno-economic BJF potential ranging from 0.45 EJ in 2015 (46 US\$/GJ – 65 US\$/GJ) to 0.67 EJ in 2030 (19 US\$/GJ – 65 US\$/GJ). In 2030, several BJF production routes can be competitive with fossil jet fuel prices. The northeast and southeast regions have the highest potential, especially in 2030. © 2020 The Authors. *Biofuels, Bioproducts, and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Key words: crop residues; straw; aviation biofuels; GIS; bioenergy potential; sugarcane; eucalyptus; erosion; soil organic carbon

## Introduction

Aviation biofuel (hereafter called biojet fuel – BJF) is foreseen as an emerging bioenergy supply chain, which could require large amounts of biomass resources in the coming years.<sup>1</sup> Although, globally, BJF production is currently in an early development stage, many dedicated initiatives and policy statements have already suggested the conditions for biomass utilization for this purpose. For example, the International Civil Aviation Organization (ICAO) has indicated that biomass crops for BJF should not compete with food crops.<sup>2</sup> The Sustainable Aviation Fuel Users Group (SAFUG) emphasized the importance of using biomass sources without compromising water availability or biodiversity.<sup>3</sup>

Historically, conventional so-called first-generation biofuels, for example sugarcane ethanol and soybean biodiesel, thrived in Brazil because of low production costs, land availability and suitability, and government incentives.<sup>4,5</sup> However, there are major sustainability concerns related to the use of (food) crops for BJF production (e.g. deforestation and food insecurity).<sup>6,7</sup> Recently, second-generation biofuels from lignocellulosic biomass residues have gained momentum in Brazil, as they can avoid competition for suitable land and related potential negative effects.<sup>8</sup> Previous studies have indicated that the Brazilian agricultural sector produces 1.6–4 EJ/year of biomass residues that can be recovered from the field for non-agronomic applications (e.g. bioenergy and animal feed).<sup>9,10</sup> However, the removal of biomass residues for bioenergy use could have major agronomic and environmental implications (e.g. impacts on soil organic carbon, soil erosion, and nutrient availability).<sup>11</sup> Hence, many studies have been conducted to quantify the amount of biomass residues that can be recovered without compromising cropping.<sup>12–15</sup>

Sustainable residue removal rates strongly depend on a series of agronomic and environmental variables (e.g. soil, climate, and terrain), which present high spatial and temporal variability.<sup>11,12,16</sup> Many studies have quantified the biomass residue potential considering spatial variation in environmental constraints.<sup>10,17–24</sup> At a global level, Daioglou *et al.*<sup>17</sup> projected ecological potential from crop and forestry residues of 70–100 EJ/year by applying fixed removal rates to account for environmental constraints. Monforti *et al.*<sup>19</sup> estimated a potential of 2.3 EJ/year of biomass residues in Europe considering soil organic carbon (SOC) conservation

as a constraint for crop-residue removal. Muth *et al.*<sup>25</sup> quantified the potential of biomass residues at county level in the USA, using soil-erosion risk as a constraint. Portugal-Pereira *et al.*<sup>26</sup> mapped the ecological and economic potential of agricultural residues for bioelectricity production in Brazil. At country level, other studies have also assessed the environmental potential of biomass residues.<sup>22,27,28</sup> Of all these studies, a more limited number<sup>19,21,29,30</sup> have used a bottom-up approach to model the environmental constraints spatially to estimate the biomass residue removal rate at field level. All of these studies contributed, to differing extents, to an understanding of how the spatial heterogeneity in agro-ecological conditions affect the environmental potential of biomass residues for bioenergy. However, these assessments do not link the spatial variability of biomass residues potential for estimating biomass and bioenergy supply chain costs.

Several studies have assessed the techno-economic performance of BJF production from biomass residues.<sup>31–33</sup> In Brazil, studies have addressed the (aggregated) spatial distribution of biomass residues to quantify the techno-economic potential and costs of BJF supply chains.<sup>34,35</sup> However, these studies do not account for the spatially explicit variation in biomass residue availability as they do not consider the spatial heterogeneity of biomass yields and sustainable removal rates. Nevertheless, biomass yields and removal rates strongly affect biomass potential and costs, and therefore the techno-economic potential of BJF.<sup>36</sup> Thus far, no study has included the implications of environmental constraints in quantifying the potential and cost of biomass residues, and the techno-economic potential of BJF production spatially and temporally explicitly. The outcomes from a techno-economic assessment of BJF supply chains considering the environmental constraints and resulting spatial variability of biomass residues are therefore highly relevant to the broader bioenergy community and, more specifically, to the BJF industry stakeholders in Brazil.

The objective of this study is to assess the spatio-temporal environmental and techno-economic potential of BJF production from biomass residues in Brazil. This study is a follow up on the work on the techno-economic potential of BJF from energy crops conducted by Cervi *et al.*<sup>37</sup> Unlike that study, in the current work we explicitly assess the environmental potential of biomass residues spatially, as the yield and the environmental constraints for residue removal depend on various spatially heterogeneous agro-ecological conditions. The environmental and techno-

economic potential is quantified for baseline (2015) and near future (2030) scenarios, to account for the effect of land use change on biomass residue potential, and for the effect of expected technological improvements on the techno-economic potential of BJF supply chains (hereafter called BJF production routes).

## Selected residues

The potential of biomass residues for bioenergy depends on several parameters, such as the type of crop, crop area, crop yield, residue-to-crop ratio, residue removal rate, and non-agronomic competitive uses.<sup>38,39</sup> In this study, two types of biomass residues are considered: sugarcane straw and eucalyptus harvest residues. These biomass residues are selected because of the large production of sugarcane and eucalyptus in Brazil, the potential large availability of their residues, the availability of data, and also because they have been identified as promising bioenergy resources in previous studies.<sup>10,40–42</sup> Key characteristics of the selected biomass residues and their current status in Brazil are described below and in Table 1.

### Sugarcane straw

The sugarcane ratoon cycle usually requires 5 to 6 years. In sugarcane systems, the sugarcane straw (SCS) is left on the field after the mechanical harvest. This brings many agronomic and environmental advantages such as increasing soil organic carbon, recycling of nutrients, and controlling soil erosion.<sup>12,16</sup> However, SCS is composed of lignocellulosic material with high calorific value, which has strong potential in the bioenergy industry.<sup>45</sup> Currently, in some modern sugarcane mills, SCS is marginally used for producing bioelectricity and / or 2G ethanol production.<sup>8,46</sup>

Assuming an average straw-to-sugarcane ratio of 14%,<sup>47</sup> 105 Mt of SCS was theoretically available in Brazil in 2015.<sup>43</sup> This potential is mainly found in the southeast and center-west regions of Brazil (see supplementary material 1 for Brazilian macro-region divisions). However, some of the available straw should be left in the field to preserve soil quality. Some studies have explored the maximum amount of sugarcane

straw that can be removed without impeding soil quality in Brazil, but all of them are site specific.<sup>13,48</sup>

### Eucalyptus harvest residues

Eucalyptus plantations are found in the south and southeast regions of Brazil, around the main pulp and paper facilities. Eucalyptus plantations generally have a 21-year cycle, with harvests after every 7 years. Usually, wood management operations (e.g. debarking) are executed on the field to facilitate wood transportation, and also for silvicultural reasons (e.g. residues acting as a soil amendment).<sup>49</sup> These operations result in the availability of eucalyptus harvest residues (EHRs), which could amount to around 15% of the cumulative wood yield (average of 270 t of wood per hectare after seven cultivation years).<sup>50</sup> However, these residues also play an important role in maintaining soil quality. Very few studies have explored the environmental effect of EHR removal.<sup>51</sup>

### Production routes

Four technological pathways for drop-in BJF are included in the assessment of the techno-economic potential of BJF from biomass residues: Pyrolysis (PYR), hydrothermal liquefaction (HTL), Fischer–Tropsch (FT), and alcohol to jet (ATJ). These technologies are chosen because of their current fuel and technology readiness level (FRL and TRL) (see the studies by de Jong *et al.* and E4tech<sup>52,53</sup> for further information on the technology status), their positive techno-economic performance in previous studies, and cost data availability.<sup>33,54</sup>

Pyrolysis and HTL have not yet been certified by ASTM (the American Society of Testing Materials) for commercial BJF production. These technologies convert biomass directly to liquid fuels through thermo-chemical reactions (see Gollakota *et al.* and Wang and Tao<sup>55,56</sup> for a detailed description of these pathways). Currently, the companies Steeper Energy and Licella (HTL), and UOP (PYR) are developing these pathways for BJF production at pilot scale.<sup>57,58</sup> Moreover, both technologies have shown promising techno-economic results in the study of de Jong *et al.*<sup>33</sup> Fischer–Tropsch is also a thermo-chemical pathway, which is relatively mature and is already used

**Table 1. General information about sugarcane straw and eucalyptus harvest residues in Brazil.**

Biomass	National production in 2015 (Mt)	Current average yield (t/ha/year)	Residue type	Residues to crop ratio (%)	Sources
Sugarcane	750	80	Sugarcane Straw	14	16,43
Eucalyptus	130	30	Harvest residues (e.g. Barks, branches)	15	10,44

in the conversion of fossil resources into liquid fuels.<sup>59</sup> In the bioenergy case, lignocellulosic biomass is converted to synthetic gas and then into hydrocarbons through FT reactions.<sup>60</sup> This technology received ASTM acceptance in 2009 with permission for 50% blend with conventional jet fuel.<sup>61</sup> The ATJ biochemical pathway produces BJF from alcohols (e.g. ethanol, butanol, and methanol). Recently, ASTM approved an increase from 30% to 50% drop-in of ATJ in conventional jet fuel 112. The companies Gevo and Lanzatech are currently leading the ATJ development.<sup>33,112,113</sup> If more plants are commissioned in the coming years, the readiness level is likely to increase.

In this study, the BJF production routes are combinations of the biomass residues and the BJF technologies. In total, eight production routes are assessed (four from SCS and four from EHR) – see Fig. 1.

## Methods

The assessment of the environmental and techno-economic potential of BJF from biomass residues is divided into two main components: the spatially explicit modeling of the environmental potential of biomass residues and the techno-economic assessment of BJF from these biomass residues (Fig. 2).

The environmental potential of biomass residues is part of the theoretical potential (i.e. the total amount of biomass residues produced in the field) and could be removed given environmental constraints.<sup>42,62</sup> In this study, two

environmental criteria are applied for the assessment of the environmental potential of biomass residues: the erosion risk and the SOC balance. Several studies have indicated the importance of water erosion control for eucalyptus and sugarcane residue management to avoid soil losses through runoff.<sup>21,63,64</sup> Potential erosion risk caused by wind is not considered in this study, as it is assumed to be negligible compared with water erosion in the Brazilian arable areas.<sup>65</sup> Maintaining or improving SOC levels is assumed to be crucial as it is generally the main source of organic matter in agricultural soils, which is key for soil productivity.<sup>11,66</sup> In this study, the risk of soil erosion is considered by excluding all (potential) sugarcane and eucalyptus areas for residue removal where the annual soil loss already exceeds the location specific tolerable limits for soil loss. A SOC balance approach is applied to assess the quantity of residue that can be removed without compromising SOC levels. The erosion risk and SOC constraints are combined to assess the spatial distribution of SCS and EHR for two points in time (2015 and 2030); see Eqn 1. In this study, we do not account for the non-agronomic competitive uses for the biomass residues.

The techno-economic potential of BJF from biomass residues refers to the share of the theoretical potential that can be achieved given certain economic constraints.<sup>22</sup> In this study, the production costs of BJF production routes sourced from the environmental potential of SCS and EHR in 2015 and 2030 are assessed. The BJF production costs (expressed in US\$/GJ) include the costs for biomass residue recovery, BJF production (i.e. conversion), and BJF transportation. We

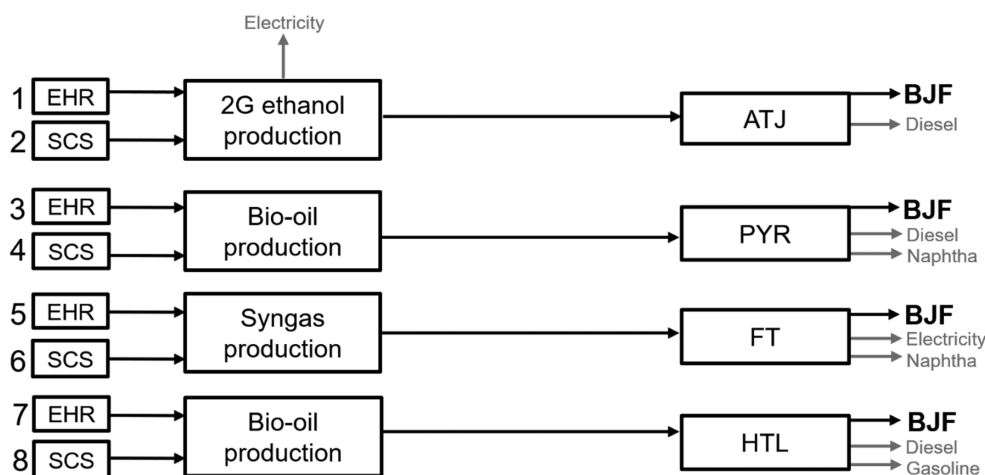


Figure 1. BJF production routes from biomass residues. 1) EHR\_ATJ: BJF from 2G ethanol based on eucalyptus harvest residues via ATJ; 2) SCS\_ATJ: BJF from 2G ethanol based on sugarcane straw via ATJ 3) EHR\_PYR: BJF from eucalyptus harvest residues via PYR; 4) SCS\_PYR: BJF from sugarcane straw via PYR; 5) EHR\_FT: BJF from eucalyptus harvest residues via FT; 6) SCS\_FT: BJF from sugarcane straw via FT; 7) EHR\_HTL: BJF from eucalyptus harvest residues via HTL; 8) SCS\_HTL: BJF from sugarcane straw via HTL.

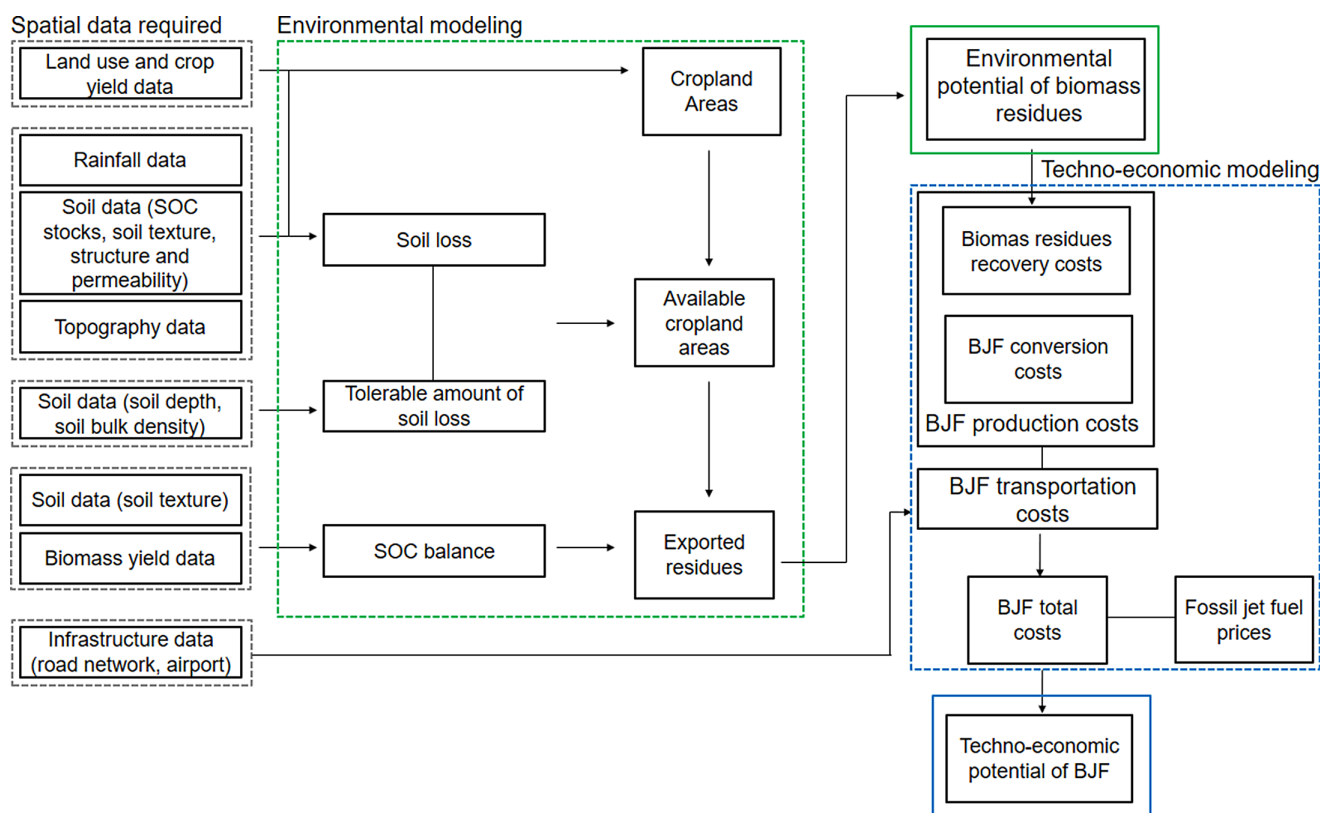


Figure 2. Workflow for estimating the environmental potential of biomass residues (green solid outline box) and techno-economic potential of BJJ from biomass residues (blue solid outline box). The spatial data (dashed gray outline boxes) are used as inputs for both environmental modeling (green dashed outline box) and the techno-economic modeling (blue dashed outline box).

quantify the amount and determine the spatial distribution of BJJ potential from biomass residues that could be produced at costs that are lower than those of the fossil counterpart.

$$EPr_{p,y} = Er_{p,y} \times ER_{p,y} \tag{1}$$

Item	Description	Unit
$EPr_{p,y}$	Environmental potential of biomass residues in pixel $p$ in year $y$	t/ha
$Er_{p,y}$	Residue availability according to SOC balance in pixel $p$ in year $y$	t/ha
$ER_{p,y}$	Erosion risk in pixel $p$ in year $y$	0, 1

### Crop data and yield levels

The assessment of the potential of biomass residues is based on the spatial distribution of sugarcane for SCS and planted forest (i.e. areas occupied by eucalyptus plantations) for EHR sourced from maps of current and future land use in Brazil modeled by Van der Hilst et al.<sup>67</sup> at a 5 × 5 km pixel resolution. These projections of land-use developments in Brazil to 2030 are based on scenario analyses utilizing macro-economic and land-use models – see Van der Hilst

et al.<sup>67</sup> The spatial variation in crop yield levels is calculated by multiplying the spatial variable agro-ecological suitability levels ( $S$ ) by the time-specific maximum attainable yield ( $M$ ) (Eqn 2) in areas of sugarcane and planted forest ( $A$ ). The agro-ecological suitability map for sugarcane is derived from IIASA – GAEZ,<sup>68</sup> and the suitability map for eucalyptus is based on Cervi et al.<sup>37</sup> The data on current maximum attainable yield is derived from national agricultural statistics<sup>43</sup> for sugarcane and from Stape et al.<sup>69</sup> for eucalyptus. Development of sugarcane and eucalyptus yield over time is based on historical trends (i.e. annual increase of 0.8% for sugarcane and 1.4% for eucalyptus, in line with Van der Hilst et al.).<sup>67</sup>

$$Y_{b,p,y} = A_{b,p,y} \times Su_{b,p} \times M_{b,y} \tag{2}$$

Item	Description	Unit
$Y_{b,p,y}$	Yield of biomass $b$ in pixel $p$ in year $y$	t/ha
$A_{b,p,y}$	Area in use for biomass $b$ in pixel $p$ in year $y$	0, 1
$Su_{b,p}$	Agro-ecological suitability for biomass $b$ in pixel $p$	%
$M_{b,y}$	Maximum attainable yield of biomass $b$ in year $y$	t/ha



## Erosion risk constraint for biomass residues recovery

The areas that are in use for sugarcane or eucalyptus in 2015 or 2030, which are already facing erosion risks beyond the spatially explicit tolerable limits for soil loss, are excluded for biomass residue removal. The Revised Universal Soil Loss Equation (RUSLE)<sup>70</sup> (Eqn 5) is employed to calculate the potential annual amount of soil loss (t/ha/year) by water erosion (Table 2). Using the same approach as Muth and Bryden,<sup>29</sup> we compare the annual amount of potential soil loss in a given biomass area to the tolerable limits ( $T$  value) of soil losses (Eqn 3). The tolerable limit of soil loss is defined as the maximum amount that a given soil can lose while maintaining productivity.<sup>74</sup> It is calculated through the multiplication of soil bulk density by the soil depth (Eqn 4), in line with Muth and Bryden.<sup>29</sup> The areas where the potential soil loss are below the tolerable limits are considered available for residue recovery,<sup>1</sup> whereas areas exceeding this limit are considered as ‘no-go’ (0) areas<sup>29</sup> (Eqn 3). In the areas available for biomass residue recovery, we assume 2 t/ha/year of biomass residues are retained on the field for erosion control, in line with Andrews.<sup>75</sup> Table 2 describes the variables used in the RUSLE equation as well as the sources of the spatially explicit data, and

supplementary material 2 describes all the input equations for each RUSLE parameter.

$$ER_{p,y} = \begin{cases} 0, & An_{p,y} > T_p \\ 1, & An_{p,y} \leq T_p \end{cases} \quad (3)$$

Item	Description	Unit
$ER_{p,y}$	Erosion risk in pixel $p$ in year $y$	0, 1
$An_{p,y}$	Annual soil loss in pixel $p$ in year $y$	t/ha
$T_p$	Tolerable soil loss limit in pixel $p$ in year $y$	t/ha

$$T_p = \frac{H_p \times D_p}{1000} \quad (4)$$

Item	Description	Unit
$T_p$	Tolerable soil loss limit in pixel $p$	t/ha
$H_p$	Soil depth in pixel $p$	m
$D_p$	Soil bulk density in pixel $p$	kg m <sup>3</sup>

$$An_{b,p,y} = R_p \times K_p \times L_p \times S_p \times C_{b,p,y} \times P_p \quad (5)$$

**Table 2. Description of RUSLE variables and the spatial datasets used for their calculation.**

RUSLE variable	R	K	L and S	C	P
	Rainfall erosivity*	Soil erodibility**	Slope length and steepness***	Land cover management****	Control practice*****
Unit	MJmm ha <sup>-1</sup> h <sup>-1</sup> y <sup>-1</sup>	t ha h ha <sup>-1</sup> MJ <sup>-1</sup> mm <sup>-1</sup>	Dimensionless	Dimensionless	Dimensionless
Data required	Rainfall	Topsoil texture, topsoil organic carbon (0–30 cm)	Slope and flow accumulation	Land use	Slope
Data source	European Centre for Medium-Range Weather Forecasts (ECWMF)	World soil grids (international soil reference and information Centre - ISRIC) and global soil organic estimates (Joint Research Centre - JRC)	Shuttle radar topographic Mission (SRTM)	Brazilian land use scenarios (PLUC model)	Shuttle radar topographic Mission (SRTM)
Variability	Spatial	Spatial	Spatial	Spatial and temporal	Spatial

\*The R factor refers to the ability of water to detach and transport soil particles.<sup>71</sup> We assume the same erosivity values for 2015 and 2030 to avoid the complexity of climate models to project future rainfall.

\*\*The K factor represent the susceptibility of a given soil to erosion<sup>71</sup>.

\*\*\*The L factor is defined as the horizontal distance from the original point of overland sediment flows to the point where the slope decreases and the sediment deposition begins, or where the runoff flows into a given channel. The S factor represents the influence of slope gradient on erosion<sup>71</sup>.

\*\*\*\*The C factor is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled land.<sup>72</sup> It addresses the cover characteristics of a given land use over the entire year. In agricultural land use, the C factor is very sensitive to variations of crop canopy, type of cultivar, and possible crop rotations throughout the year.<sup>73</sup> For sugarcane and to a lesser extent for eucalyptus, there is a large number of studies seeking to determine the C factor in different cultivation systems and agro-ecological conditions. In this study, we use the average of C factors (sugarcane: 0.17; eucalyptus: 0.08) reported in different studies for sugarcane and eucalyptus in Brazil (see details in supplementary material 2).

\*\*\*\*\*The P factor gives the ratio between the soil loss expected from a certain soil conservation practice to that increasing / decreasing surface slope<sup>71</sup>.

Item	Description	Unit
$An_{p,y}$	Annual soil loss in biomass area $b$ in pixel $p$ in year $y$	t/ha/year
$R_p$	Rainfall erosivity factor in pixel $p$	MJ/mm/ha/h/y
$K_p$	Soil erodibility factor in pixel $p$	t/ha/h/ha/MJ/mm
$L_p$	Slope length factor in pixel $p$	–
$S_p$	Slope steepness factor in pixel $p$	–
$C_{b,p,y}$	Cover management factor in biomass area $b$ in pixel $p$ in year $y$	–
$P_p$	Control practice factor in pixel $p$	–

## Modeling the residue removal rate through SOC balance

To estimate the amount of residue that can be removed for BJB production without decreasing soil organic carbon levels, we quantify the SOC dynamics by adapting the Association of German Agricultural Analytic and Research Institutes (VDLUFA) humus balance tool.<sup>76</sup> This is a simple agronomic spreadsheet model that has been used to assess soil fertility in crop rotation systems in Germany.<sup>77</sup> The model quantifies the humus input and output from crop rotation systems. However, the downside of the VDLUFA humus balance is the use of dimensionless humus values (i.e. humus equivalent units) that are specific for the German context, which limits the application in a broader context.<sup>78</sup> For this reason, we use more general physical organic carbon (OC) values to quantify the SOC dynamics. The use of OC values in humus balance tools has been already applied in a study by Kolbe<sup>79</sup> for different crop types (e.g. roots, tuber, fodder, grasses).

To quantify the impact of biomass management on SOC dynamics, we assess the changes in SOC over the lifetime of sugarcane (6 years) and eucalyptus (21 years), and this is hereafter called the SOC balance. We assess SOC variations after each ratooning / harvesting cycle (i.e. three harvest cycles for eucalyptus and six for sugarcane). The SOC balance quantifies the SOC inputs and outputs to the soil for each harvest cycle within the timeframe (crop lifetime) (see supplementary material 3). The sources of SOC input considered in this study are above and below ground biomass and organic fertilizers, whereas the SOC outputs (i.e. SOC depletion) are due to SCS and EHR removal and below-ground SOC decomposition. These factors are affected by crop management, and by the interaction with agro-ecological factors (e.g. soil texture and biomass yield),<sup>48</sup> which are spatially heterogeneous. As no other study assessed the SOC dynamics in sugarcane and eucalyptus systems in a spatially explicit manner, in this study the SOC dynamics are quantified by upscaling the results found in different site-specific experiments (see the key references in the supplementary material 3) to pixel level. These studies

provide data of SOC increase / decrease in the crop lifetime of the biomass systems assessed under different agro-ecological conditions. Using spatially explicit data on soil texture and biomass yield, the SOC dynamics observed in these site-specific studies are upscale to grid level. The rule of the SOC balance model works with an 'if-else' conditional statement: If the amount of SOC at the end of each harvest cycle is lower than the previous year, all the residue must be left on the field, or else all the residues can be removed. Hence, there are both harvest cycles with all residues being recovered and harvest cycles in which all the residues are kept on the field. After calculating the SOC balance of each harvest cycle over the entire time frame, the average annual amount of removed residues over the timeframe is estimated.

Equation (6) describes the general SOC balance calculation accounting for the SOC inputs and outputs; Eqn (7) shows the model rule (i.e. decision on whether or not recover the residues based on the SOC balance), and Eqn (8) quantifies the biomass residues exported from the field (i.e. environmental potential). For a deeper understanding of the SOC balance, supplementary materials 3 and 4 provide the raw data (e.g., the amount of fertilizer, and the mass of above- and below-ground biomass), all the equations, and a simple demonstration (in a spreadsheet format) of the calculations required in model framework for both biomass systems.

$$OCB_{t,p,y} = BAGC_{t,p,y} + TFe_{t,p,y} + \begin{cases} 0, & t = 0 \\ CO_{t-1,p,y}, & t > 0 \end{cases} \quad (6)$$

Item	Description	Unit
$OCB_{t,p,y}$	Soil organic carbon balance in harvest cycle $t$ in pixel $p$ in year $y$	t C/ha
$BAGC_{t,p,y}$	Below-ground and / or above-ground contribution to OC in harvest cycle $t$ in pixel $p$ in year $y$	t C/ha
$TFe_{t,p,y}$	Total OC from fertilizer applied in harvest cycle $t$ in pixel $p$ in year $y$	t/ha
$CO_{t-1,p,y}$	SOC carried over from previous harvest cycle $t-1$ in pixel $p$ in year $y$	0, t C/ha

$$Dr_{t,p,y} = \begin{cases} 0, & OCB_{t,p,y} < OCB_{t-1,p,y} \\ 1, & OCB_{t,p,y} \geq OCB_{t-1,p,y} \end{cases} \quad (7)$$

Item	Description	Unit
$Dr_{t,p,y}$	Decision on recover (1) or not recover (0) residues in harvest cycle $t$ in pixel $p$ in year $y$	0, 1
$OCB_{t,p,y}$	SOC balance in harvest cycle $t$ in pixel $p$ in year $y$	t C/ha
$OCB_{t-1,p,y}$	SOC balance in previous harvest cycle $t-1$ in pixel $p$ in year $y$	t C/ha

$$TR_{t,p,y} = ER_{t,p,y} \times Dr_{t,p,y} \tag{8}$$

Item	Description	Unit
$TR_{t,p,y}$	Total amount of residues in harvest cycle $t$ pixel $p$ in year $y$	t/ha
$ER_{t,p,y}$	Exported residues in harvest cycle $t$ pixel $p$ in year $y$	t/ha
$Dr_{t,p,y}$	Decision on recover (1) or not recover (0) in harvest cycle $t$ in pixel $p$ in time $y$	0, 1

### Techno-economic potential assessment Biomass residues recovery costs

Biomass residue recovery is assumed to be carried out some time after harvest to allow for natural drying in the field. Sugarcane straw and EHR are assumed to have the same moisture content of 15%, which has also been used in other studies.<sup>42,80,81</sup> For SCS, the baling system is selected as a recovery route.<sup>36</sup> In the baling system, the straw available on the field is windrowed, baled, and loaded onto a truck.<sup>82</sup> For EHR, the chipping system is selected as it is generally employed in both pulpwood and forestry residues harvest,<sup>83</sup> and it has already been tested for EHR in Brazil.<sup>81</sup> The EHR are collected in the field by a forwarder, are chipped and then loaded into a truck container at the roadside. Figure 3 presents the field operations of both residue recovery systems.

The biomass residue recovery costs (US\$/t) are the result of the sum of farm-gate costs and transportation costs. The first is composed of operational costs (e.g. machinery, depreciation, diesel, and labor), and for SCS it also includes a marginal cost for agricultural inputs required to compensate for the nutrient losses of residue removal.<sup>36,82</sup> The farm-gate costs depend on the available biomass residue per hectare (see Eqn (9) and Cervi et al.).<sup>84</sup> For

EHR, the farm-gate costs also depend on yield (Eqn (10)). This relationship is estimated as a function of machinery costs per hour (US\$/h) and machine productivity (t/h)<sup>83</sup> (see supplementary material 5). The transportation costs of biomass residues, including costs of diesel, lubricants, labor, and truck depreciation are fixed at 0.052 US\$/t.km, which is an average for different road types.(i.e. highway, secondary and dirt roads), sourced from Jonker (2017).<sup>85</sup> Like Van der Hilst et al.<sup>99</sup>, the transportation costs are calculated in a geographic information system (GIS) environment by estimating the biomass density within a hypothetical radius, which varies according to the input capacity of the BJF plants (see Table 3), and the spatial availability of biomass residues (Eqn (11)).

$$SCS\_Cf = 71.88 \times EPr^{-0.631} \tag{9}$$

Item	Description	Unit
$SCS\_Cf$	SCS farm-gate cost	US\$/t
$EPr$	Environmental potential of SCS	t/ha

$$EHR\_Cf = 339.47 \times EPr^{-0.869} \tag{10}$$

Item	Description	Unit
$EHR\_Cf$	EHR farm-gate cost	US\$/t
$EPr$	Environmental potential of EHR	t/ha

$$TC_{P,r,p,y} = C_{P,r,y} \times \frac{2}{3} \times I_{py}^{0.5} \times (EPr_{r,p,y} \times Dr_{r,p,y})^{-0.5} \tag{11}$$

Item	Description	Unit
$TC_{P,r,p,y}$	Biomass transportation cost of production route $P$ and biomass residue $r$ in pixel $p$ in year $y$	US\$/t

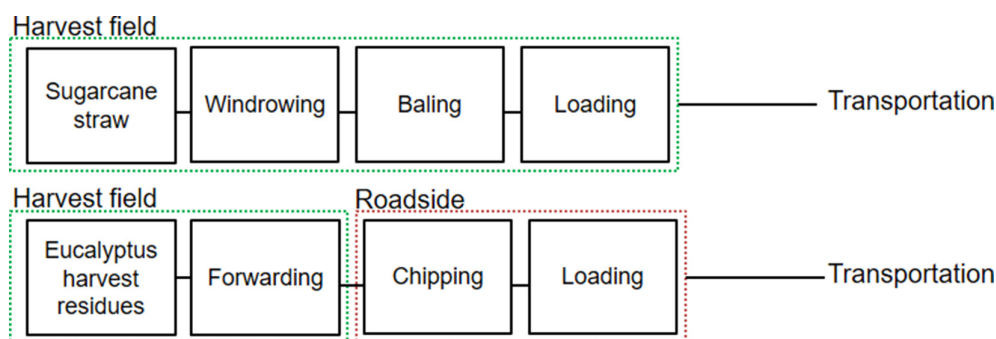


Figure 3. Schematic representation of biomass residue recovery systems. For EHR the system takes place at the harvest area (green box) and also at roadside (brown box). For SCS, the entire system is carried at the harvest area.



**Table 3. Biojet fuel conversion yield, techno-economic characteristics, and input cost data for the BJJ plants.**

Production route (ID)	BJJ input capacity (Mt of biomass) <sup>*</sup>		BJJ conversion yield (t of biomass / t of BJJ) <sup>**</sup>		Cost-growth factor <sup>***</sup>	FCI <sup>****</sup> (US\$/t biomass)		OPEX (US\$/t biomass)		Source	Co-products <sup>*****</sup>
	2015	2030	2015	2030		2015	2030	2015	2030		
SCS_ATJ <sup>*****</sup>	0.72	1.5	0.119	0.152	0.59	1207.7	510.3	279.6	148.3	33,86,87	D, EI
SCS_PYR <sup>*****</sup>	0.6	0.8	0.065	0.065	0.35	3536.2	1229.7	224.8	86.4	33,89	N, D
SCS_FT <sup>*****</sup>	0.6	1	0.151	0.151	0.43	2113.7	875.3	73.4	35.8	33,90	N, EI
SCS_HTL <sup>*****</sup>	0.35	0.8	0.15	0.15	0.38	2764.7	899.3	268.9	96.3	91	D, G
EHR_ATJ <sup>*****</sup>	0.72	1.5	0.119	0.152	0.59	1207.7	510.3	279.6	148.3	33,86,87	D, EI
EHR_PYR <sup>*****</sup>	0.6	0.8	0.065	0.065	0.37	3536.2	1229.7	224.8	86.4	33,89	N, D
EHR_FT <sup>*****</sup>	0.6	1	0.151	0.151	0.47	2113.7	875.3	73.4	35.8	33,90	N, EI
EHR_HTL <sup>*****</sup>	0.35	0.8	0.15	0.15	0.4	2764.7	899.3	268.9	96.3	91	D, G

<sup>\*</sup>The input capacities of the BJJ plant are considered to be equal for both types of biomass residue.  
<sup>\*\*</sup>For the BJJ conversion yield, we assume a constant maximum BJJ distillation/upgrading verified in the literature for both 2015 and 2030. In ATJ production routes, there is a slight change over time due to improvements in the upstream processes of 2G ethanol production<sup>86</sup>.  
<sup>\*\*\*</sup>The cost growth factors are sourced from de Jong et al.,<sup>33</sup> which set the six main variables of the RAND method (*pctnew*, *impurities*, *complexity*, *inclusiveness*, *commercialization status* and *project definition*) based on an extensive survey of the BJJ market worldwide in 2015. In this study, we change the *impurities* variable from 4 to the maximum 5 level in all SCS based BJJ pioneer plants due to higher impurity level of SCS,<sup>45</sup> except the downstream ATJ plant, which is fed by ethanol from the upstream 2G plant. The cost growth factor of the 2G plant is set at 0.53, based on Kazi et al.<sup>92</sup> As the ATJ technology has been commercialized aviation biofuels since 2016,<sup>93</sup> we also change the commercialization status from 0.06361 to 0.04011. See supplementary material 6.  
<sup>\*\*\*\*</sup>A scale factor of 0.7 is used to adjust the FCI to the scale of the BJJ plant. The original FCI data is updated to 2015 values by using the Brazilian inflation index (IGP-DI).  
<sup>\*\*\*\*\*</sup>Co-products from the BJJ plant: D – diesel; N – naphtha; EI – electricity; G – gasoline. The electricity in ATJ plants is supplied by the power plant from the 2G ethanol plant, which uses unfermented materials (lignin) to feed the boiler.<sup>94</sup> In the FT plants, the electricity is sourced from off-gases<sup>88</sup>.  
<sup>\*\*\*\*\*</sup>The input capacity and progress development over time are aligned with the study of Cervi et al.<sup>37</sup> In their study, despite using eucalyptus pulpwood as feedstock in thermochemical routes, we apply the same scale to allow for a fair BJJ production cost comparison. Moreover, no distinction in biomass residues pre-treatment is assumed between 2G from EHR and 2G from SCS. The main downstream processes in ATJ plants are dehydration, oligomerization, and hydrogenation (i.e. off-site hydrogen supply).  
<sup>\*\*\*\*\*</sup>The 2015 scales for the thermochemical routes (PYR, FT, and HTL) are based on other studies.<sup>89-91,95</sup> By 2030, HTL and PYR achieve the maximum scale of 800 kt/year input projected by Jong et al.<sup>96</sup>; whereas FT is expected to process 1 Mt/year of dry biomass according to the projections developed by E4tech<sup>53</sup>.  
<sup>\*\*\*\*\*</sup>Main downstream processes: crude bio-oil production and upgrading. The hydrogen is produced on-site through steam reform<sup>88</sup>.  
<sup>\*\*\*\*\*</sup>Main downstream processes: syngas production, gas cleaning, upgrading and separation. In this design, the hydrogen is produced on-site with a hydrocracker recovery plant<sup>88</sup>.  
<sup>\*\*\*\*\*</sup>Main downstream processes: biocrude production, and upgrading. The hydrogen is produced on-site through steam reform<sup>33</sup>.

Item	Description	Unit
$C_{P,r,y}$	Unit biomass transportation cost of production route $P$ and biomass residue $r$ in year $y$	US\$/tkm
$I_{Py}$	Input capacity of production route $P$ in year $y$	t
$EPr_{r,p,y}$	Environmental potential of biomass residues $r$ in pixel $p$ in year $y$	t/ha
$D_{r,p,y}$	Density of biomass residues $r$ within the radius in pixel $p$ in year $y$	%

## BJF production costs

In line with the studies of Jong *et al.*<sup>33</sup> and Cervi *et al.*,<sup>37</sup> the techno-economic potential of BJF production is assessed for a greenfield BJF plant in two development stages, a pioneer plant and an  $n$ th plant. For 2015, a pioneer plant is assumed, and its production costs are largely affected by the techno-economic risks of building the ‘first of kind’ BJF plant.<sup>33,95</sup> These risks are addressed by the cost growth factor based on the RAND method,<sup>97</sup> which accounts for the technological risks and the associated potential cost increase because of unforeseen problems when starting up a first of a kind BJF plant.<sup>33</sup> It is applied as denominator for estimating the fixed capital investment (FCI) and the operating expenditures (OPEX) of BJF pioneer plants in 2015, and for almost all BJF production routes it is sourced from Jong *et al.*<sup>33</sup> (Table 3). In this study, however, despite both EHR and SCS represent lignocellulosic feedstock, it has to be considered that the use of SCS for BJF has more technical constraints due to impurities (e.g. dust) and high ash and chlorine content, which can lead to high degradation, mainly in thermochemical technologies.<sup>35,53</sup> To address these constraints, the cost growth factor of SCS based pioneer plants has been adjusted (see the cost growth factor in Table 3). For the  $n$ th plant in 2030, the expected development of the technological pathways at commercial scale is taken into account. Table 3 describes the techno-economic characteristics of the BJF production routes for 2015 and 2030 and all input data (further details can be found in supplementary material 6).

To calculate the BJF production costs at the plant gate of each production route  $P$  in year  $y$ , the discounted annual biomass residues recovery costs (BC), FCI ( $I$ ), annual operational – OPEX – costs ( $M$ ) and annual revenues ( $Rev$ ) from non-hydrocarbon co-products (e.g. electricity) are accounted for over the plant lifetime ( $t$ ). The BJF production costs at plant gate are determined by dividing all the discounted costs and revenues by the discounted mass of hydrocarbon outputs (e.g. BJF, diesel, naphtha) as they present similar mass density<sup>98</sup> – that is, mass allocation.

$$BJFC_{Py} = \frac{\sum_{t=1}^n (I_{Py} + M_{Py} + BC_{Py} - Rev_{Py}) \times (1+r)^{-t}}{\sum_{t=1}^n Output_{Py} \times (1+r)^{-t}} \quad (12)$$

Item	Description	Unit
$BJFC_{Py}$	BJF costs of production route $P$ in year $y$	US\$/t
$I_{Py}$	FCI of production route $P$ in year $y$	US\$
$M_{Py}$	OPEX of production route $P$ in year $y$	US\$
$BC_{Py}$	Biomass costs of production route $P$ in year $y$	US\$
$Rev_{Py}$	Non-hydrocarbon revenues of production route $P$ in year $y$	US\$
$Output_{Py}$	Hydrocarbon outputs of production route $P$ in year $y$	t
$t$	Years	Year
$r$	Discount rate	%

The total BJF production costs (hereafter called BJF total costs) are calculated by summing the BJF production costs at the plant gate (i.e. Eqn 12) and the BJF transportation costs. The latter are calculated by using the spatial distribution of the airports in Brazil, and the current (2015) and planned (2030) highways (see Cervi *et al.*).<sup>37</sup> We assume that the BJF is transported by trucks to the nearest airport (see supplementary material 7). The distances are estimated in a GIS environment and multiplied by the unit BJF transportation costs per road type expressed in tonne-kilometers – that is 0.054 US\$/tkm for primary roads (i.e. inter-regional paved roads) and 0.22 US\$/tkm for secondary roads (i.e. paved roads in poor conditions).<sup>54,99</sup>

## Techno-economic potential of BJF

The techno-economic potential of BJF from biomass residues is defined as the amount of BJF that can be produced at a cost below the Brazilian fossil jet fuel prices. For each grid cell, the minimum BJF production costs (min. BJF costs) across the production routes are determined for 2015 and 2030. The same approach was used in Cervi *et al.*<sup>37</sup> for assessing the techno-economic potential of BJF from energy crops. First, we compare the min. BJF costs from biomass residues with the range of current fossil jet fuel prices at Brazilian airports (19–65 US\$/GJ)<sup>100</sup> to quantify the range of the techno-economic potential. The fossil jet fuel price data includes additional components (e.g. profits, income and state taxes) that are not accounted for in the BJF cost calculation due to high uncertainty and limited data availability. Second, BJF production costs from all production routes are assessed to identify alternative options competitive with fossil jet fuel prices. Finally, we quantify the regional techno-economic

potential (i.e. macro-regional level) of each production route by comparing the BJF production costs of each pixel with the fossil jet fuel price of the nearest airport.

## Sensitivity analysis

We develop a sensitivity analysis to account for the uncertainty in the potential and the costs of BJF production from biomass residues. As this study is divided into two main components (i.e. the environmental potential of biomass residues and the techno-economic potential of BJF from biomass residues), we assess the uncertainty of key parameters in each of these components. For the environmental modeling, we assumed biomass yield developments towards 2030 based on historical yield developments. However, yield developments are uncertain and may not follow the historical yield growth rate, as it can be affected by climate, land quality, management factors, and technology development.<sup>22</sup> As an example, in the last decade, the sugarcane yield has been stalled due to soil compaction caused by mechanical harvesting and a lack of better management practices in the sugarcane fields.<sup>101</sup> To account for this, we include the conservative assumption of stagnant yield levels (at the level of 2015) in this sensitivity analysis.

For the techno-economic assessment, we originally applied the cost growth factor to address the technological progress of BJF production routes between 2015 to 2030. However, in the past two decades little progress has been made in reducing capital costs, especially in the thermochemical pathways.<sup>60</sup> In this sensitivity analysis, therefore, we also account for a more conservative assumption regarding technological progress, assuming no difference in BJF technology deployment between 2015 and 2030. Hence, it is assumed that the BJF plants in 2030 are also pioneer plants (instead of *n*th plants).

## Results

### Environmental potential of biomass residues

The environmental potential of biomass residues is estimated at approximately 70 Mt/year (0.9 EJ/year) in 2015 and 102 Mt/year (1.4 EJ/year) in 2030. The SCS accounts for 62% (43 Mt/year) of the biomass residues potential in 2015 and for 70% (71 Mt/year) in 2030. The increase in SCS availability towards 2030 is aligned with the projected overall increase in sugarcane production of 63%. Hence, the expansion of sugarcane areas mostly takes place in areas with similar agro-ecological suitability, with comparable risk of erosion and / or SOC depletion. The EHR potential increases by 17%, from 26 Mt/year in 2015 to 31 Mt/year in 2030. This exceeds

the projected increase in eucalyptus production (13%) in this time period. The expansion of eucalyptus areas in Brazil is expected to take place around the current eucalyptus areas, and therefore in similar conditions.

The increase in the SCS supply over time is largely related to the expansion of sugarcane areas in the center-west of Brazil – see Fig. 4, which shows the spatial distribution of the environmental potential of SCS in 2015 and 2030. The areas with high SCS availability are concentrated in a few central-southern states (i.e. mainly São Paulo and Goiás), whereas the areas with moderate to low availability (<6 t/ha/year) are scattered in the center-south and in the northeast. For EHR, the areas with low residue availability (<3 t/ha/year) are widely distributed from the northeast coast to the border of Amazon regions, while areas with high residue availability (>5 t/ha/year) are clustered in the extreme south and at the border of the states of Bahia and Minas Gerais.

For both 2015 and 2030, the erosion risk reduces the theoretical potential of SCS (i.e. 85 Mt/year in 2015 and 141 Mt/year in 2030) by 30%, whereas the theoretical potential of EHR (i.e. 41 Mt/year - 48 Mt/year of SCS) is reduced by 35% (Fig. 5). This means the expansion areas face a similar erosion risk as current sugarcane and eucalyptus production areas. Nonetheless, it is clear that an important share of the EHR potential is limited by erosion risk in both 2015 and 2030. Furthermore, the theoretical potential of SCS is decreased by 18% (in 2015) and 21% (in 2030) because of the SOC balance constraint, which is negatively affected by the expansion of sugarcane on sandy soils. For EHR, in both 2015 and 2030, the theoretical potential is reduced by less than 1% because of the SOC balance constraint. This is mainly due to the recurrent annual input of SOC from litterfall, which positively impacts SOC dynamics. For SCS, therefore, the two environmental constraints have an approximately similar impact on the SCS potential, with a significant reduction from the SOC constraint, whereas the EHR potential is mostly constraint by erosion risk.

### Techno-economic potential of BJF from biomass residues

#### Biomass residues recovery costs

The majority of the environmental potential of SCS and EHR is available at 30 US\$/t to 100 US\$/t of biomass residue total recovery costs (Fig. 6 – left-hand side). Regardless of the type of biomass residue and the time horizon, very little is supplied beyond 100 US\$/t (Fig. 6 – left hand side). For SCS, 40 Mt (2015) and 60 Mt (2030) is available below 50 US\$/t, whereas the EHR shows a smaller variation as it accounts for 10 Mt (2015) and 7 Mt (2030). Figure 6 (right

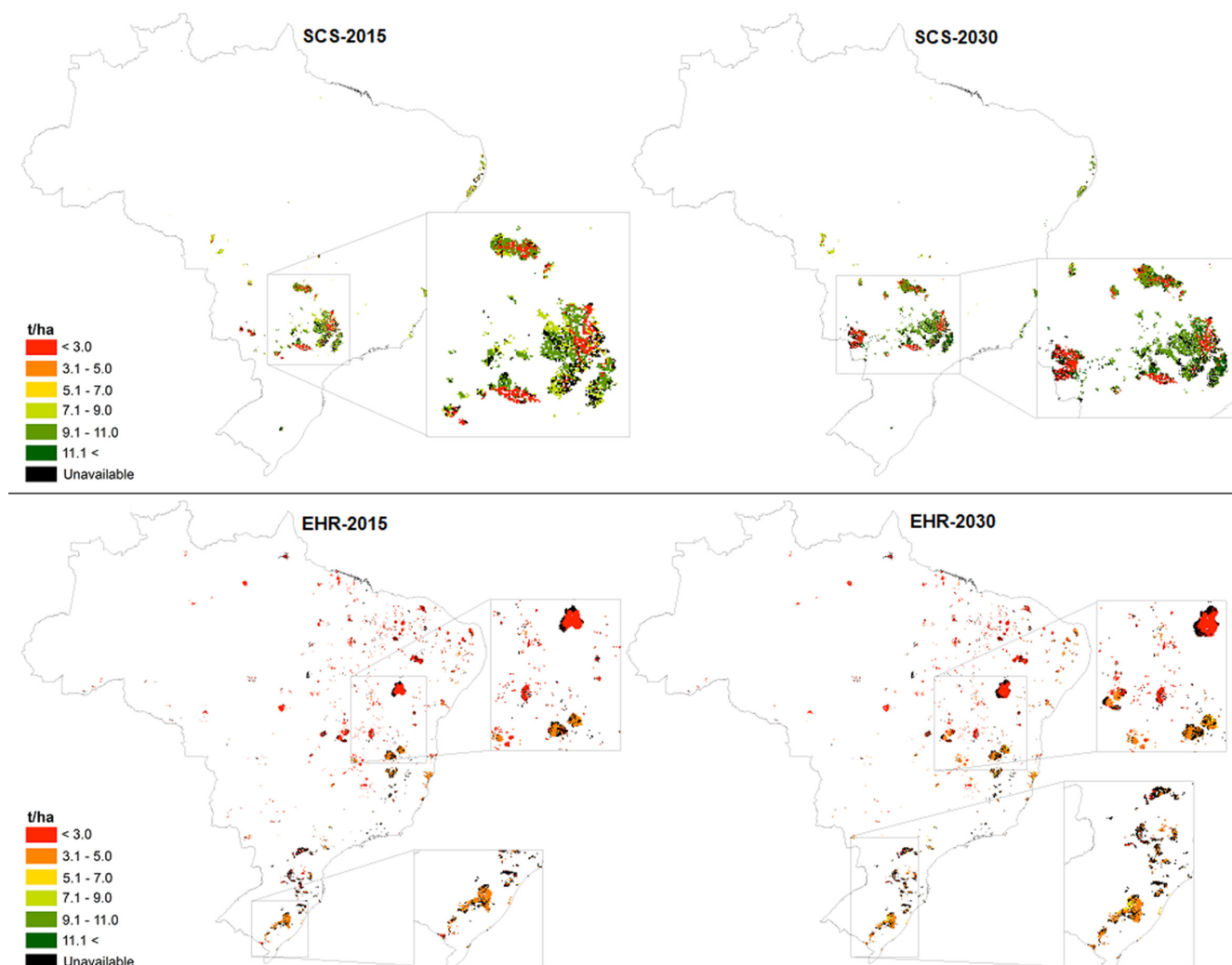


Figure 4. Spatial distribution of the environmental potential (removal rate – T/ha) of SCS and EHR in Brazil in 2015 and 2030.

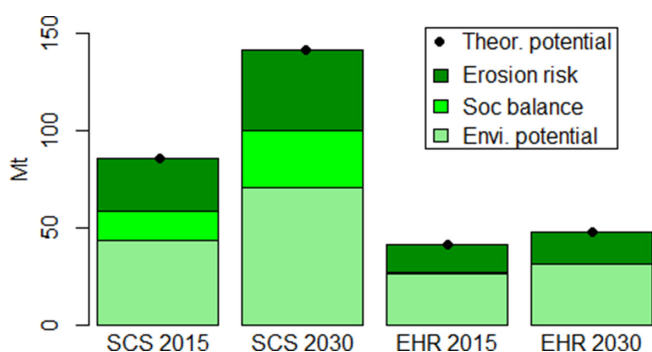


Figure 5. The effect of environmental constraints (erosion risk and SOC balance) on the environmental potential of SCS and EHR in 2015 and 2030.

hand side) displays the cost-breakdown of biomass residues. On average, the farm-gate costs of SCS are slightly higher than EHR due to the complexity of the baling system and,

to a lesser extent, the fertilizer cost related to nutrient compensation. In 2015, farm-gate cost comprises about 40% (EHR) – 60% (SCS) of biomass residues recovery costs (Fig. 6 – right hand side). By 2030, the biomass residues transportation costs increase considerably due to a larger radius required to recover a higher amount of biomass residues used as input in the BJJ plant. There is also increasing expansion of both sugarcane and eucalyptus to areas with poorer agro-ecological conditions, thereby affecting the transportation distances even more. The transportation costs are even more relevant for EHR, as it encompasses 60% (in 2015, 66% in 2030) of the total residue recovery costs, due to the relatively large service areas of logging operations. These results correspond to the ATJ production routes, which are the plants with the largest input capacity. In the remaining production routes, biomass residue transportation costs are slightly lower.



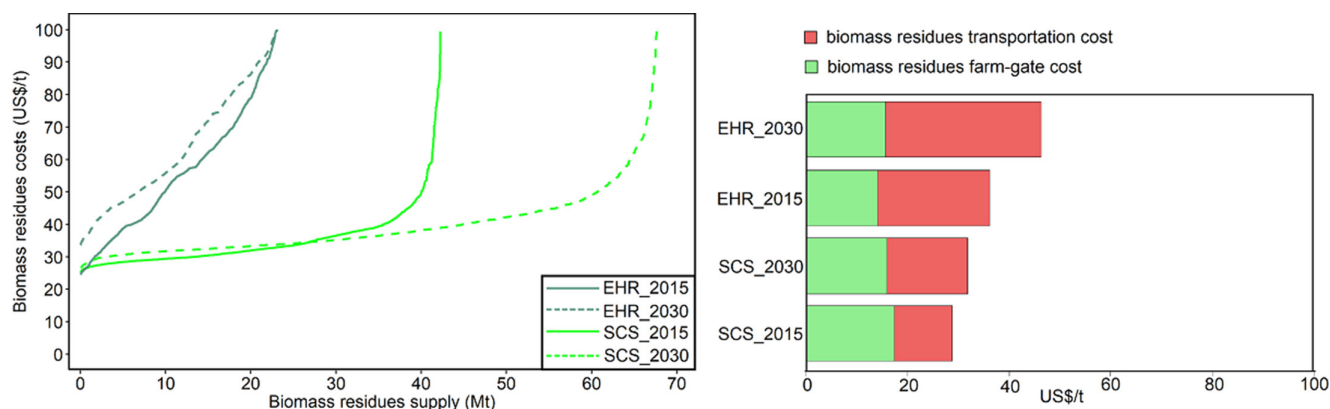


Figure 6. On the left-hand side: Biomass residues cost supply curves for SCS and EHR in 2015 and 2030. On the right-hand side: Biomass residue recovery cost breakdown with the share of the farm-gate and transportation costs for SCS and EHR.

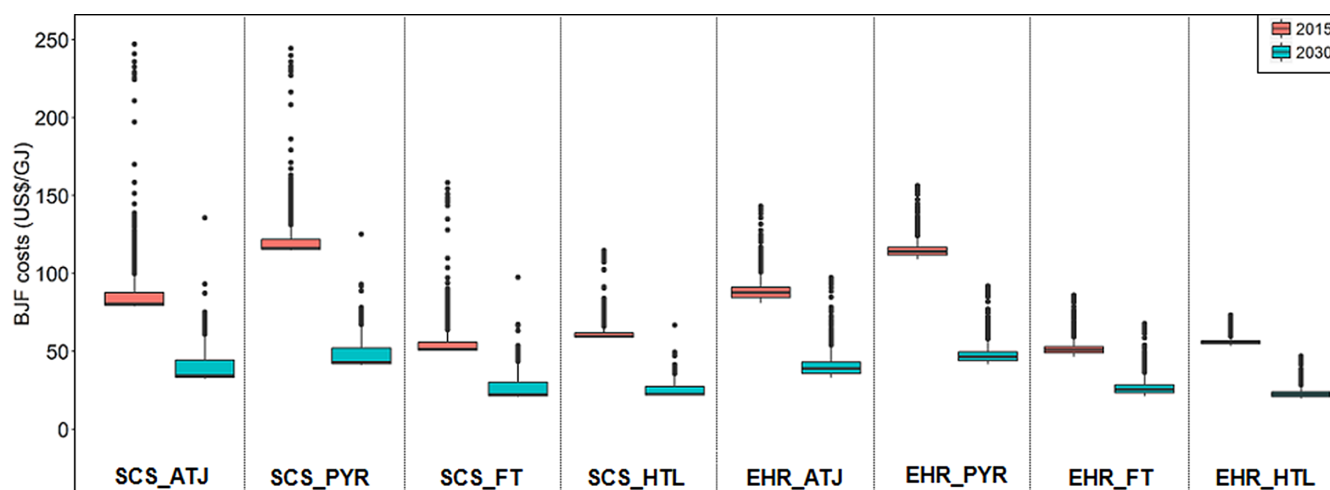


Figure 7. Boxplots displaying the BJF production costs variability of each production route in 2015 and 2030. Note that there is a high number of outliers at the higher end, which indicates the presence of areas with very high biomass residue recovery costs (i.e. very low biomass residue availability). For SCS-based production routes, the boxplot median is very close to the lower limit, which indicates large number of areas with high and homogeneous levels of SCS availability.

## BJF production costs

The BJF production costs present a spatial variability range between 46.5 US\$/GJ and 247 US\$/GJ in 2015 and between 19.6 US\$/GJ and 135 US\$/GJ in 2030 (Fig. 7). The BJF production routes based on SCS have a higher spatial variability than EHR, which is caused by the presence of areas with very high SCS recovery costs (Fig. 7). These SCS areas often require high mulching levels to maintain SOC levels, resulting in a low availability of SCS for recovery. On average, the production costs of BJF, based on SCS, are slightly lower than BJF from EHR. This is mainly caused by lower biomass residue recovery cost. The BJF production

routes with the lowest average costs in 2015, are those from FT technology (SCS\_FT and EHR\_FT), which currently has the second best TRL, and also high conversion yields. In 2030, the average BJF production costs are reduced by half because of the lower cost of the *n*th plant compared the to pioneer plant. The HTL production routes stand out with the lowest production costs due to high conversion yields and the projected sharp decrease in the capital intensity towards 2030. The PYR-based production routes are characterized by the highest production cost reduction, due to the high projected technological development of their *n*th plants.

In Fig. 8, we detail the BFJ cost breakdown for each production route. For 2015, the biomass cost component



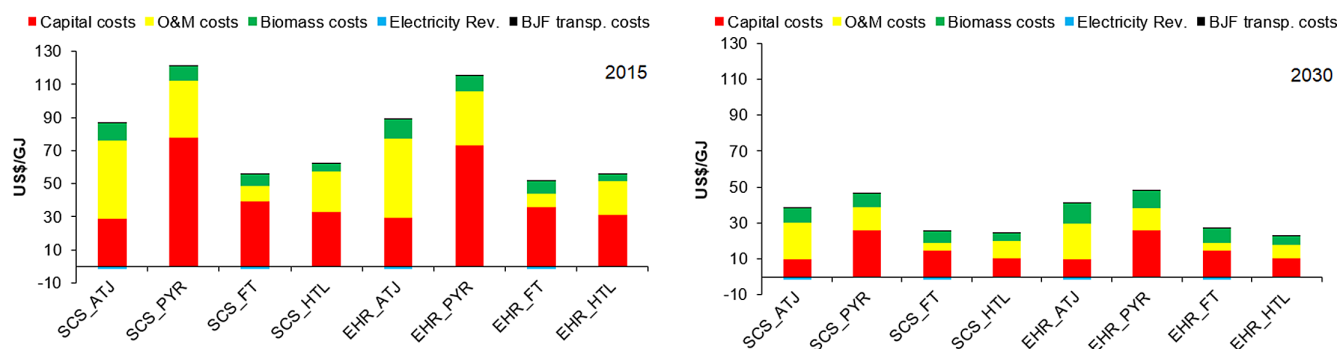


Figure 8. Average BJJ production cost breakdown showing the contribution of biomass, capital, operational, and BJJ transportation costs to the BJJ production costs of each routes in 2015 and 2030.

has a low contribution to the overall BJJ production cost. Because of the high capital demanding technologies (e.g. HTL, FT and PYR), the biomass costs are often low compared to the conversion costs. The share of biomass residues costs increases towards 2030, mainly due to a strong reduction in the capital costs, and only to a marginal extent to the increase in biomass residues costs in some locations. The operational cost contribution is significantly high in ATJ plants due to the 2G ethanol production needed, and also in the PYR plants due to high utility requirements (e.g. natural gas). Moreover, the electricity revenues in the ATJ and FT plants only marginally (1–3%) reduce BJJ production costs. Finally, as expected, the BJJ transportation cost contributes very little to the total BJJ production costs. The areas of biomass residues supply are often close to the main highways and the main Brazilian airports. The BJJ transportation costs of SCS-based routes remain constant over time around 0.1 US\$/GJ and vary between 0.32 US\$/GJ and 0.26 US\$/GJ for EHR-based routes in 2015 and 2030.

## Techno-economic potential assessment

The techno-economic potential of BJJ is defined as the volume of BJJ that can be produced from SCS and EHR at a cost lower than fossil jet fuel prices. For each pixel with SCS or EHR availability, the lowest (min.) cost BJJ production route is selected. The techno-economic potential of BJJ from SCS and EHR is composed by SCS\_FT, EHR\_FT, SCS\_HTL, and EHR\_HTL production routes with a BJJ supply ranging from 0.45 EJ/year in 2015 to 0.67 EJ/year in 2030. These quantities are delivered with min. BJJ total costs below the maximum fossil jet fuel price of 65 US\$/GJ at Brazilian airports. The BJJ cost-supply curve of the techno-economic potential highlights the significant difference between the BJJ total costs in 2015 and in 2030 (left hand side of Fig. 9). In 2015, the min. BJJ total costs vary spatially between 46

US\$/GJ and 65 US\$/GJ. The BJJ potential consists mainly of SCS\_FT and EHR\_FT production routes, with a small contribution from SCS\_HTL (right hand side of Fig. 9). Compared with the current fossil jet fuel prices, the techno-economic potential of BJJ from biomass residues in 2015 is in between the average and maximum jet fuel prices in Brazil (Fig. 9). In 2030, the min. BJJ total costs range from 19 US\$/GJ to 49 US\$/GJ, which indicates that BJJ from crop residues could reach costs comparable with the fossil jet fuel prices of the largest airports in Brazil (e.g. Sao Paulo, Rio de Janeiro, Brasilia). The SCS\_FT production route remains dominant in the techno-economic potential of 2030. However, SCS\_HTL and EHR\_HTL show a substantial increase compared to 2015, which shows the large projected technologic improvements in HTL technology in the coming decade.

In the sensitivity analysis, the results show that assumptions regarding yield and technology improvements have a significant effect on the BJJ total costs and on the techno-economic potential in 2030. Assuming a BJJ pioneer plant in 2030 (instead of BJJ *n*th plant), the minimum BJJ total costs are in line with the BJJ total cost in 2015 (sensitivity tech. in Fig. 9) until a supply of 0.4 EJ. The increase of biomass recovery cost towards 2030 is marginal mainly for SCS, with no large effect on the minimum BJJ total costs. In this scenario, the techno-economic potential of BJJ in 2030 is the same as the original assessment. Hence, when considering the availability of biomass resources and the maximum fossil jet fuel price in Brazil as a cutoff for determining the techno-economic potential, the deployment of hypothetical BJJ pioneer plants in 2030 may not represent a lower BJJ supply, even though the costs of production in pioneer plants is a factor of two higher than in *n*th plants. In the other sensitivity assessment (yield), in which we assume no biomass yield increase towards 2030, the BJJ total costs vary between 19 US\$/GJ and 57 US\$/GJ in 2030 (sensitivity yield – Fig. 9). This is in line with the cost range for 2030, assuming a

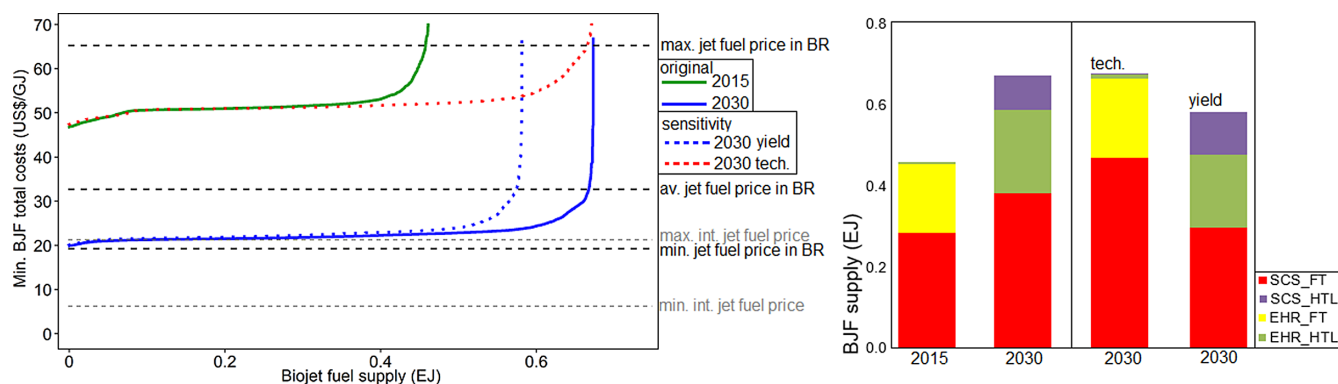


Figure 9. On the left-hand graph, the solid lines show cost supply curves of the techno-economic potential of BJJ from biomass residues in 2015 and 2030, and the dashed lines show the sensitivity scenarios (tech. and yield). The dashed gray lines show the range of the international jet fuel price at the refinery (US Gulf Coast kerosene jet fuel spot price).<sup>102</sup> The dashed black lines represent the range of jet fuel prices commercialized in the Brazilian airports.<sup>100</sup> They are used to measure the techno-economic potential of BJJ from biomass residues. On the right-hand graph, the stack bars show the BJJ production routes that contribute to techno-economic potential.

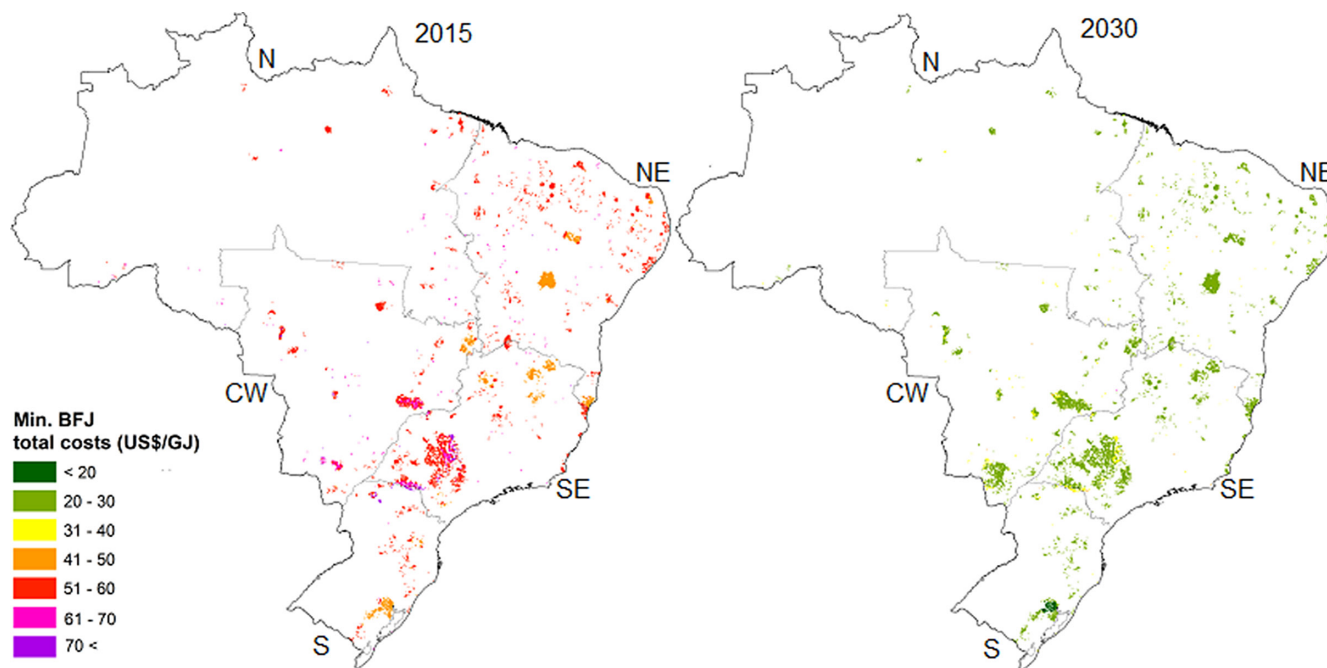


Figure 10. Spatial distribution of the min. BJJ costs from biomass residues in 2015 and 2030 in the Brazilian macro-regions. N: north; NE: northeast; SE: southeast; CW: Center-west; S: south.

biomass yield increase, due to the very small effect of biomass residue costs on the BJJ total costs for the production routes that contribute to the techno-economic potential. However, assuming no yield increase towards 2030, decreases the techno-economic BJJ potential by 0.1 EJ, as less BJJ is produced.

Figure 10 shows the spatial distribution of the techno-economic BJJ potential with the min. BJJ total costs for 2015

and 2030. For 2015, it is relatively easy to detect the most promising regions to produce the cheapest BJJ ranging from 40 to 50 US\$/GJ (shades of orange) in the south and a few areas in the state of Bahia (i.e. northeast region), which are characterized by high EHR availability. The majority of SCS-based production routes are produced at higher costs in the southeast of Brazil due to the current technical challenges of converting SCS into BJJ. In 2030, however, it is projected that

almost all areas where EHR or SCS are available will produce BJF between 20 and 30 US\$/GJ.

In Fig. 11, we plot the cost supply curves for all the BJF production routes that present BJF total costs below the maximum fossil jet fuel price in Brazil (65 US\$/GJ) at least in one location. Most of these BJF production routes do not contribute to the techno-economic potential (i.e. these production routes do not present the lowest BJF production cost at any location), which is only formed by the HTL and FT-based production routes (see Fig. 9). However, it should be noted that other production routes also present a very good performance either in producing BJF total lower than the fossil prices (e.g. SCS\_HTL in 2015) or with a high possibility of BJF supply (e.g. EHR\_ATJ and SCS\_ATJ in 2030). At several locations, many production routes could produce BJF below the fossil jet fuel price.

Figure 12 shows, for every macro-region, which production route could produce BJF below the fossil jet fuel price at the nearest airport. It should be noted that fossil jet fuel prices vary across airports within the macro-regions. We assess that only EHR\_PYR is not able to supply BJF production costs

below the fossil jet fuel prices, whereas the remaining seven production routes could achieve production costs below this threshold in various regions. In particular, the center-west and southeast regions present a high diversity of production routes that can produce up to 0.35 EJ/year of BJF at costs below the fossil jet fuel prices.

## Discussion and conclusions

### Environmental potential of biomass residues for BJF production

The environmental potential of biomass residues is projected at 43.3 Mt/year in 2015 and 70.8 Mt/year in 2030 for SCS, and 26.4 Mt/year and 30.9 Mt/year for EHR. The increase in the environmental potential over time is primarily a result of the crop yield development and the expansion of eucalyptus and sugarcane areas. The majority of the SCS potential is found in the southeast and center-west regions, due to presence of the sugarcane ethanol industry. Potential areas for SCS on the northeast coast are also available. This already has a

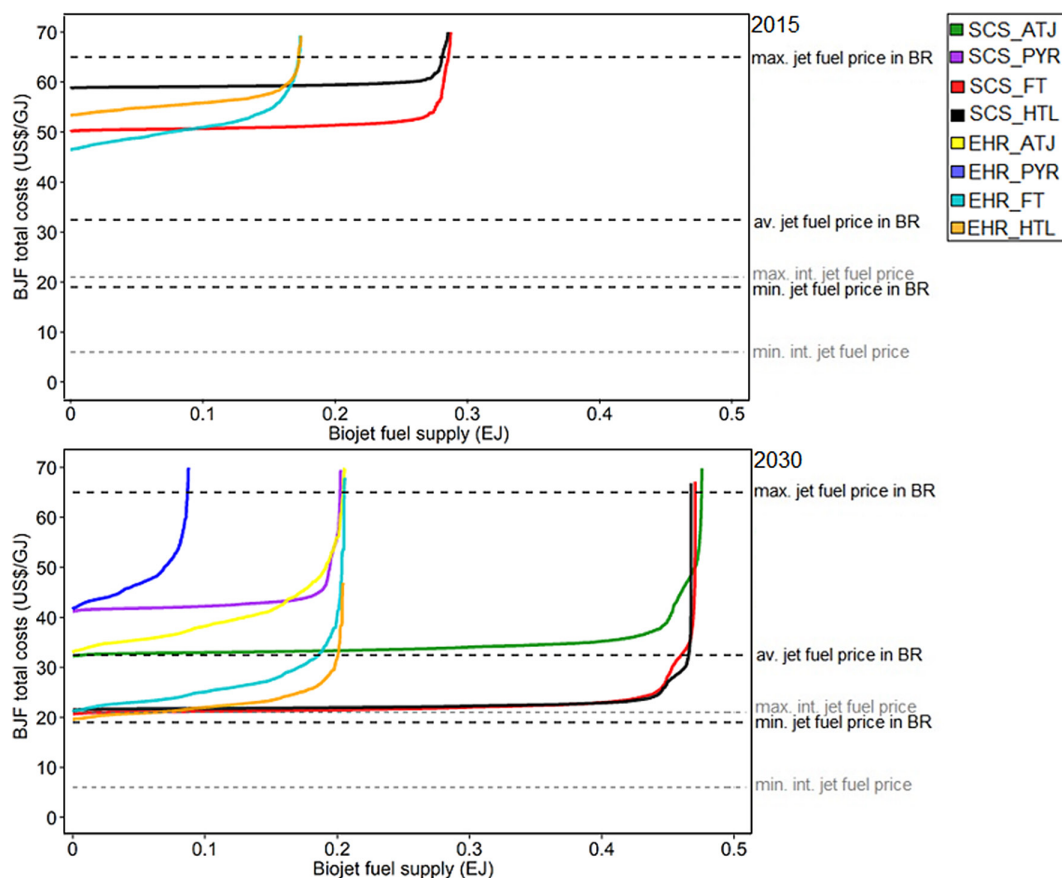


Figure 11. BJF cost-supply curves of all the production routes assessed in 2015 and 2030.

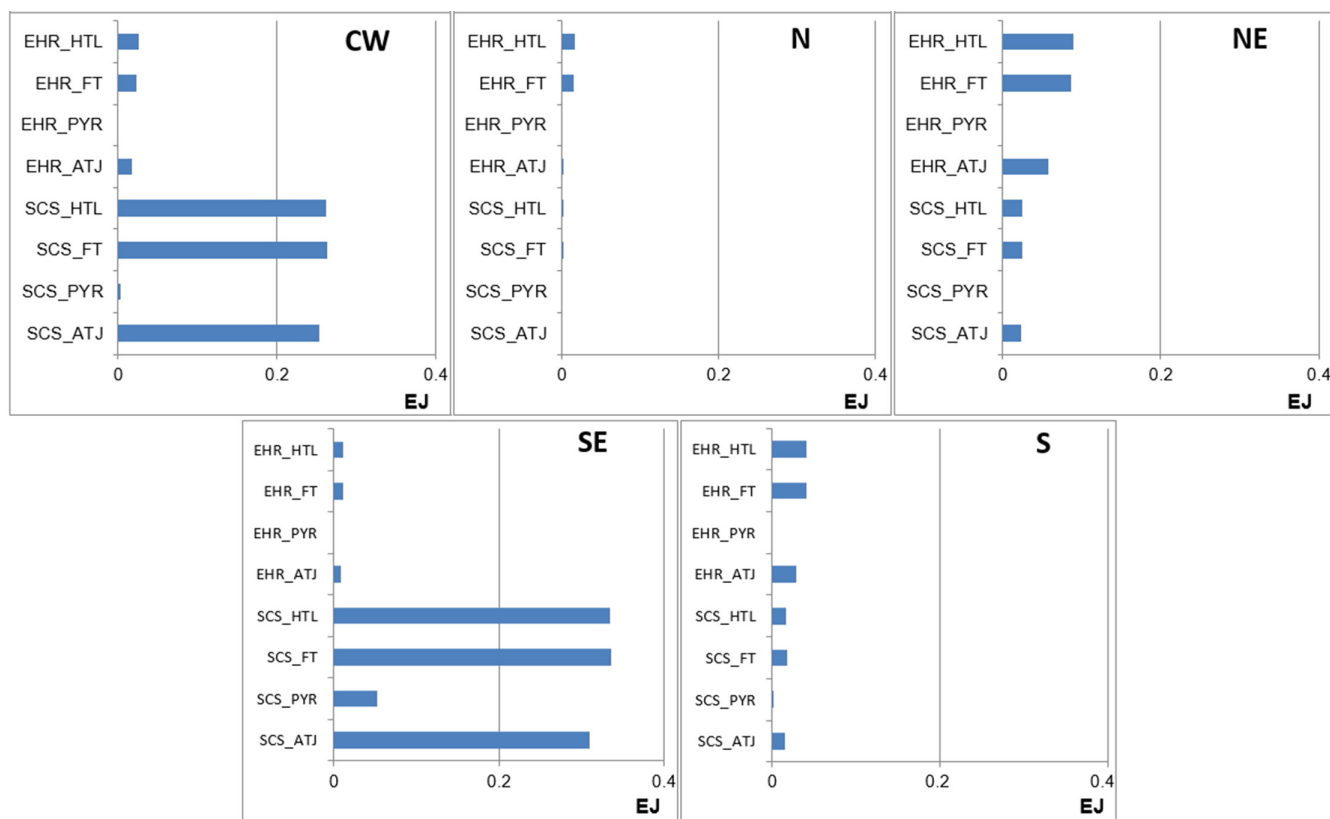


Figure 12. Techno-economic potential of BJT from biomass residues from each production routes in 2030 at Brazilian macro-regional level (i.e. south - S, southeast - SE, northeast - NE, north - N and center-west - CW). Note that the potentials provided for each macro-region partly overlap (i.e. available biomass residues could reach BJT total cost below fossil yet fuel prices via several production routes), and should therefore not be summed.

2G ethanol plant based on SCS in Alagoas state (Granbio SA).<sup>103</sup> For EHR, the south and northeast regions present the strongest environmental potential in some specific states (Paraná and south of Bahia). The results also show that SOC is a major constraint affecting the environmental potential of SCS, mainly in the expansion areas (west of São Paulo and center-west region). In general, we find that the SOC balance tool can easily be applied in sugarcane systems and it is easily combined with spatial datasets (i.e. soil and crop-yield data). However, the reliability of the results needs to be further improved by calibrating the model on in-depth field data of specific case studies at local level. For long-term projections on SOC dynamics, more detailed simulations are needed (e.g. making use of biogeochemical models) – especially for eucalyptus – and additional environmental factors should be included (e.g. climate data).<sup>114,115</sup> The environmental potential of EHR is more constrained by the erosion risk (spatially heterogeneous), as the litterfall from eucalyptus trees positively affects the SOC balance. This high risk of erosion in eucalyptus can be critical if eucalyptus

monoculture expands over marginal lands (e.g. degraded pasturelands) in the coming years. Implementing agroforestry systems instead of monoculture eucalyptus plantations could potentially mitigate these problems and may offer higher changes for EHR recovery.<sup>104</sup> The reliability of our results on soil loss can be increased by including more spatial detailed data (e.g. slope, soil), long term projections on e.g. the effect of climate change on rainfall erosivity), as well as local, more detailed studies in different agro-ecological conditions to calibrate the soil-loss estimations.

Previous studies estimated the potential supply of SCS in Brazil ranging from 42.77 Mt/year in the 2010s<sup>10</sup> to 135.6 Mt/year in the 2020s.<sup>105,106</sup> These estimations are primarily based on projections of sugarcane production, combined with a fixed countrywide SCS removal rate to address the soil and agronomic constraints. In our study we developed a more refined approach as the annual removal rate varies for each grid cell and over time, driven by the SOC balance calculation. However, competitive uses and practical restrictions (e.g. crop features and treatments, density of the fields, transportation

distance), which may affect the SCS that can be mobilized for BJF, are not considered in this study. For EHR, only Roozen<sup>10</sup> has quantified the environmental potential in the Brazilian center-south regions from 6 Mt/year (in 2012) to 11 Mt/year (in 2030), applying a fixed removal rate of 52%. The limited number of studies on EHR potential in Brazil can be explained by the still very limited use of these residues in the pulp and paper industry but also due to the current lack of integration of this industry with bioenergy supply chains. However, there is a large EHR potential, which is the theoretical potential of a single harvested field at around 45 t/ha of EHR. Currently, some sugarcane mills use EHR as a supplementary resource for bioelectricity production in periods of high demand (with high bioelectricity market prices).<sup>107</sup> Given this, we expect that the potential application of biomass residues in the BJF industry is likely to be based mainly on SCS and supplemented with EHR.

In this study, we only focused on SCS and EHR. However, considering that Brazil is one of the leading agricultural producers in the world, other agricultural residues could also have large potentials. The majority of the environmental impacts of producing bioenergy from biomass residues are related to agricultural management and recovery operations. In this study, SOC and erosion risk related to biomass residue removal is considered. However, other environmental impacts (such as greenhouse gas emissions, impact on water availability, and biodiversity) and impacts related to the rest of the supply chain (i.e. transport, conversion, distribution and use) should also be quantified for a holistic view of the environmental potential of BJF from residues. The spatio-temporal approach demonstrated in this study is an important step in that direction.

## Techno-economic potential of BJF from biomass residues

The techno-economic potential of BJF from biomass residues is significantly higher in 2030 (0.67 EJ/year for a range of min. BJF total costs between 19 US\$/GJ and 66 US\$/GJ) than in 2015 (0.45 EJ/year for a much higher range of min. BJF total costs between 46 US\$/GJ and 114 US\$/GJ). In Cervi *et al.*,<sup>37</sup> part of the techno-economic potential sourced from eucalyptus wood-based FT and HTL greenfield plants in Brazil achieved min. BJF total costs of 47–64 US\$/GJ for FT in 2015, and 20–102 US\$/GJ for HTL in 2030. Using wheat straw from Europe as feedstock in BJF technologies, de Jong *et al.*<sup>33</sup> found a range of min. BJF selling prices between 32–88 US\$/GJ in BJF *n*th plants, with HTL leading the lower costs, whereas ATJ resulted in the highest costs. However, Klein *et al.* have shown that FT and ATJ from SCS could reach minimum selling prices (at plant gate) between 10–19 US\$/

GJ if BJF production is integrated with existing biorefineries in Brazil.<sup>108</sup> Different co-production scenarios can therefore also be explored further spatially.

Currently, the demand for fossil jet fuel in Brazil is close to 0.26 EJ/year<sup>109</sup> with jet fuel prices between 19 US\$/GJ and 65 US\$/GJ, with an average of 32 US\$/GJ.<sup>100</sup> Based on our results, it is unlikely that the BJF from residues can compete with fossil jet fuel in the most demanding regions in 2015 (or in 2030 in absence of technological learning as demonstrated in the sensitivity analysis) due to the low fossil jet fuel price. However, due to the large extent of the country and the current lack of infrastructure for fuel distribution to remote areas in the center-west and north of Brazil (see Carvalho *et al.*<sup>34</sup> for analyzing the location of refineries and airports in Brazil), niches for the development of competitive BJF from biomass residues may exist and should also be explored in more specific case studies. For the current wide implementation of BJF from biomass residues, more incentives (e.g. lower interest rates, carbon saving credits), other strategies to lower production costs (e.g. lowering the residue supply cost, integration with existing biorefineries), and the development of BJF technologies are needed to increase the competitiveness of BJF. In addition, the assumption of blending BJF with fossil jet fuel in the airports may not be the best economic choice for all the regions, as the potential integration of BJF plants with near oil refineries may lead to other techno-economic benefits (e.g. supply of utilities, co-product handling). Therefore, regional contextual factors should be addressed as an extension of our study.

For 2030, all production routes are assessed as *n*th plants. This is based on the premise that these technologies will mature over the next decade, largely due to them also being deployed outside Brazil. The results show that under these assumptions, the BJF from biomass residues becomes much more competitive, with production costs very close to the minimum Brazilian fossil jet fuel price. Apart from the increase in HTL technology potential, we also see alternative BJF production routes having competitive BJF costs in the southeast and center-west regions, where biomass residues are available. For 2030, it is projected that the Brazilian fossil jet fuel demand increases to almost 0.4 EJ,<sup>110</sup> whereas global demand is projected to increase to 15 EJ.<sup>111</sup> By that time, we expect that – depending on policy incentives and other factors – some of the projected BJF techno-economic potential of 0.8 EJ may be supplied. Meanwhile, efforts are needed to enable the realization of the techno-economic potential, thereby optimizing the BJF plants' location and scale, and increasing overall infrastructure development of fuel distribution hubs, supply of utilities (e.g. electricity, hydrogen, yeasts), and human resources.



## References

- Cortez LAB, *Roadmap for Sustainable Aviation Biofuels for Brazil: A Flightpath to Aviation Biofuels in Brazil*, 2nd edn. Blucher, Blucher, São Paulo, p. 272 (2014) p.
- ICAO. ICAO Environmental Report 2013 [Internet]. ICAO Environmental Report 2013. Montreal; 2013. Available: <http://www.icao.int/environmental-protection/Pages/EnvReport13.aspx>
- SAFUG. Our commitment to sustainable options [Internet]. Sustainable Aviation Fuel Users Group. 2018. Available: <http://www.safug.org/safug-pledge/>
- Coelho ST, Goldemberg J, Lucon O and Guardabassi P, Brazilian sugarcane ethanol: lessons learned. *Energy Sustain Dev* **10**(2):26–39 (2006).
- De Oliveira FC and Coelho ST, History, evolution, and environmental impact of biodiesel in Brazil: a review. *Renew Sustain Energy Rev* **75**:168–179 (2017).
- Cantarella H, Nassar AM, Cortez LAB and Baldassin R, Potential feedstock for renewable aviation fuel in Brazil. *Environ Dev* **15**:52–63 (2015).
- Moraes MAFD, Nassar AM, Moura P, Leal RLV and Cortez LAB, Jet biofuels in Brazil: sustainability challenges. *Renew Sustain Energy Rev* **40**:716–726 (2014).
- Dias MOS, Lima DR and Mariano AP, Techno-economic analysis of cogeneration of heat and electricity and second-generation ethanol production from sugarcane, in *Advances in Sugarcane Biorefinery: Technologies, Commercialization, Policy Issues and Paradigm Shift for Bioethanol and by-Products*, 1st edn, ed. by MHL S and Chandel A. Amsterdam: Elsevier, pp. 197–212 (2017).
- EPE. Inventário Energético de Resíduos Rurais [Internet]. EPE, Recursos tecnológicos. 2014. Available: <http://www.epe.gov.br/mercado/Documents/Série Estudos de Energia/DEA 15-14 - Inventário Energético de Resíduos Rurais.pdf>
- Roozen A. Availability of sustainable lignocellulosic biomass residues in Brazil for export to the EU. 2015;(November 2014).
- Cherubin MR, Oliveira DM d S, Feigl BJ, Pimentel LG, Lisboa IP, Gmach MR et al., Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: a review. *Sci Agric [Internet]* **75**(3):255–272 (2018). Available: [http://www.scielo.br/scielo.php?script=sci\\_arttext&pid=S0103-90162018000300255&Ing=en&tIng=en](http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0103-90162018000300255&Ing=en&tIng=en) [15 February 2018].
- Carvalho JLN, Nogueiro RC, Menandro LMS, Bordonal R d O, Borges CD, Cantarella H et al., Agronomic and environmental implications of sugarcane straw removal: a major review. *Glob Chang Biol* **1**:1–16 (2016).
- Bordonal R d O, Menandro LMS, Barbosa LC, Lal R, Milori DMBP, Kolln OT et al., Sugarcane yield and soil carbon response to straw removal in south-Central Brazil. *Geoderma* **328**(May):79–90 (2018). Available: <http://linkinghub.elsevier.com/retrieve/pii/S001670611732044X>.
- Cantarella H, Cerri CEP, Carvalho JLN and Magalhaes PSG, How much sugarcane trash should be left on the soil? *Large Sci Agric* **70**(5):1–2 (2013).
- Mouratiadou I, Stella T, Gaiser T, Wicke B, Nendel C, Ewert F et al., Sustainable intensification of crop residue exploitation for bioenergy: opportunities and challenges. *GCB Bioenergy* **2019**:71–89 (2019).
- Leal MRLV, Galdos MV, Scarpore FV, Seabra JE a, Walter A and Oliveira COF, Sugarcane straw availability, quality, recovery and energy use: a literature review. *Biomass and Bioenergy [Internet]* **53**:11–19 (2013). Available: <http://linkinghub.elsevier.com/retrieve/pii/S0961953413001396>.
- Daioglou V, Stehfest E, Wicke B, Faaij A and van Vuuren DP, Projections of the availability and cost of residues from agriculture and forestry. *GCB Bioenergy* **8**(2):456–470 (2016).
- Monforti F, Bódis K, Scarlat N and Dallemard JF, The possible contribution of agricultural crop residues to renewable energy targets in Europe: a spatially explicit study. *Renew Sustain Energy Rev* **19**:666–677 (2013). Available: [http://ac.els-cdn.com/S1364032112006740/1-s2.0-S1364032112006740-main.pdf?\\_tid=323d27d6-42d6-11e6-b902-00000aab0f26&acdnt=1467740021\\_56e675c0654981ef5b25dde0fe411d02](http://ac.els-cdn.com/S1364032112006740/1-s2.0-S1364032112006740-main.pdf?_tid=323d27d6-42d6-11e6-b902-00000aab0f26&acdnt=1467740021_56e675c0654981ef5b25dde0fe411d02).
- Monforti F, Lugato E, Motola V, Bodis K, Scarlat N and Dallemard JF, Optimal energy use of agricultural crop residues preserving soil organic carbon stocks in Europe. *Renew Sustain Energy Rev* **44**:519–529 (2015).
- Muth DJ, Bryden KM and Nelson RG, Sustainable agricultural residue removal for bioenergy: a spatially comprehensive US national assessment. *Appl Energy* **102**:403–417 (2013).
- Mateos E, Edeso JM and Ormaetxea L, Soil erosion and forests biomass as energy resource in the basin of the Oka river in Biscay. *North Spain Forests* **8**(7):1–20 (2017).
- Batidzirai B, Valk M, Wicke B, Junginger M, Daioglou V, Euler W et al., Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: illustrated for South Africa. *Biomass Bioenergy* **92**:106–129 (2016). Available: <https://doi.org/10.1016/j.biombioe.2016.06.010>.
- Haase M, Rösch C and Ketzer D, GIS-based assessment of sustainable crop residue potentials in European regions. *Biomass Bioenergy* **86**:156–171 (2016).
- Scarlat N, Fahl F, Lugato E and Dallemard JF, Biomass and bioenergy integrated and spatially explicit assessment of sustainable crop residues potential in Europe. *Biomass and Bioenergy* **122**:257–269 (2019).
- Muth DJ, McCorkle DS, Koch JB and Bryden KM, Modeling sustainable agricultural residue removal at the subfield scale. *Agron J* **104**(4):970–981 (2012).
- Portugal-Pereira J, Soria R, Rathmann R, Schaeffer R and Szklo A, Agricultural and agro-industrial residues-to-energy: techno-economic and environmental assessment in Brazil. *Biomass Bioenergy* **81**:521–533 (2015).
- Nelson RG, Walsh M, Sheehan JJ and Graham R, Methodology for estimating removable quantities of agricultural residues for bioenergy and bioproduct use. *Appl Biochem Biotechnol* **113**:013–026 (2004). Available: <http://link.springer.com/10.1385/ABAB:113-1-3:013>.
- Lin T, Xu J, Shen X, Jiang H, Zhong R, Wu S et al., A spatiotemporal assessment of field residues of rice, maize, and wheat at provincial and county levels in China. *GCB Bioenergy* **11**(10):1–13 (2019).
- Muth DJ and Bryden KM, An integrated model for assessment of sustainable agricultural residue removal limits for bioenergy systems. *Environ Model Softw* **39**:50–69 (2013).
- Thiffault E, Barrette J, Paré D, Titus BD, Keys K, Morris DM et al., Developing and validating indicators of site suitability for forest harvesting residue removal. *Ecol Indic* **43**:1–18 (2014).
- Alves CM, Valk M, de Jong S, Bonomi A, van der Wielen L and Solange M, Techno-economic assessment of biorefinery technologies for aviation biofuels supply chains in Brazil. *Biofuels Bioprod Biorefin* **11**(1):778–800 (2016).
- Bittner A, Tyner WE and Zhao X, Field to flight: a techno-economic analysis of the corn Stover to aviation biofuels supply chain. *Biofuels Bioprod Biorefin* **9**:201–210 (2015).

33. de Jong S, Hoefnagels R, Faaij A, Slade R, Mawhood R and Junginger M, The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. *Biofuels, Bioprod Biorefining* **9**(6):778–800 (2015).
34. Carvalho F, Szklo A, Program EP, De Tecnologia C, De Janeiro R, Portugal-pereira J et al., Potential for biojet production from different biomass feedstocks and consolidated technological routes: a georeferencing and spatial analysis in Brazil. *Model Anal* **13**(6):1–22 (2019).
35. Tagomori IS, Rochedo PRR and Szklo A, Techno-economic and georeferenced analysis of forestry residues-based Fischer-Tropsch diesel with carbon capture in Brazil. *Biomass Bioenergy* **123**:134–148. Available from (2019). <https://doi.org/10.1016/j.biombioe.2019.02.018>.
36. Cardoso TF, Chagas MF, Rivera EC, Cavalett O, Morais ER, Geraldo VC et al., A vertical integration simplified model for straw recovery as feedstock in sugarcane biorefineries. *Biomass Bioenergy* **81**:216–223 (2015).
37. Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, de Jong S and Van Der HF, Spatial modeling of techno-economic potential of biojet fuel production in Brazil. *GCB Bioenergy* **12**(2):1–22 (2019).
38. Scarlat N, Martinov M and Dallemard J-F, Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use. *Waste Manag* **30**(10):1889–1897 (2010). Available: <http://www.ncbi.nlm.nih.gov/pubmed/20494567>.
39. Milhau A and Fallot A, Assessing the potentials of agricultural residues for energy: what the CDM experience of India tells us about their availability. *Energy Policy* **58**:391–402 (2013).
40. Carvalho F. Evaluation of the Brazilian Potential for Producing Aviation Biofuels through Consolidated Routes. 2017. Available: <http://www.ppe.ufrj.br/ppe/production/tesis/fmcarvalho.pdf>
41. Pincelli ALSM, Moura LF d and Brito JO, Quantification of harvest residues in Eucalyptus grandis and Pinus caribaea var. Hondurensis forests (in Portuguese). *Sci For* **45**(115):519–526 (2017).
42. Cervi W, Augusto R, Lamparelli C, Eugênio J, Seabra A, Junginger M et al., Bioelectricity potential from ecologically available sugarcane straw in Brazil: a spatially explicit assessment. *Biomass Bioenergy* **122**:391–399 (2019).
43. IBGE. Sistema IBGE de Recuperação Automática - SIDRA. 2015.
44. IBÁ. Relatório Anual - 2016. Indústria Brasileira de Árvores. 2016.
45. Menandro LMS, Cantarella H, Franco HCJ, Kölln OT, Pimenta MTB, Sanches GM et al., Comprehensive assessment of sugarcane straw: implications for biomass and bioenergy production. *Biofuels Bioprod Biorefin* **11**:488–504 (2017).
46. Junqueira TL, Chagas MF, Gouveia VLR, Rezende MCAF, Watanabe MDB, Jesus CDF et al., Techno-economic analysis and climate change impacts of sugarcane biorefineries considering different time horizons. *Biotechnol Biofuels* **10**(1):50 (2017 Dec 14).
47. Hassuani SJ, Leal MRLV, Macedo I de C. Biomass power generation: sugar cane bagasse and trash [internet]. Série Caminhos para a Sustentab. 2005. Available [http://www.sucre-ethique.org/IMG/pdf/CTC\\_energia\\_-\\_biomass\\_1\\_.pdf](http://www.sucre-ethique.org/IMG/pdf/CTC_energia_-_biomass_1_.pdf)
48. Carvalho JLN, Hudiburg TW, Franco HCJ and DeLucia EH, Contribution of above- and belowground bioenergy crop residues to soil carbon. *GCB Bioenergy* **9**(8):1333–1343 (2017).
49. Achat DL, Deleuze C, Landmann G, Pousse N, Ranger J and Augusto L, Quantifying consequences of removing harvesting residues on forest soils and tree growth - a meta-analysis. *For Ecol Manage* **348**:124–141 (2015).
50. Gatto A, de Barros NF, Novais RF, da Silva IR, Leite HG, Leite FP et al., Estoques de carbono no solo e na biomassa em plantações de eucalipto. *Rev Bras Cienc do Solo* **34**(4):1069–1079 (2010).
51. Rocha JHT, Gonçalves JLM, Brandani CB, Ferraz A d V, Franci AF, Marques ERG et al., Forest residue removal decreases soil quality and affects wood productivity even with high rates of fertilizer application. *For Ecol Manage* **430**:188–195 (2018).
52. de Jong S. Green Horizons: On the production costs, climate impact and future supply of renewable jet fuels. Utrecht University; 2018.
53. E4tech. Advanced drop - in biofuels UK production capacity outlook to 2030 Final Report [Internet]. UK Department for Transport. 2017. Available: <https://www.gov.uk/government/publications/advanced-drop-in-biofuels-uk-production-capacity-outlook-to-2030>
54. de Jong S, Hoefnagels R, Wetterlund E, Pettersson K, Faaij A and Junginger M, Cost optimization of biofuel production – the impact of economies of scale, integration, intermodal transport and distributed supply chain configurations. *Appl Energy* **195**:1055–1070 (2017).
55. Gollakota ARK, Kishore N and Gu S, A review on hydrothermal liquefaction of biomass. *Renew Sustain Energy Rev* **81**:1378–1392 (2018).
56. Wang WC and Tao L, Bio-jet fuel conversion technologies. *Renew Sustain Energy Rev* **53**:801–822 (2016).
57. Perkins G, Batalha N, Kumar A, Bhaskar T and Konarova M, Recent advances in liquefaction technologies for production of liquid hydrocarbon fuels from biomass and carbonaceous wastes. *Renew Sustain Energy Rev [Internet]* **115**:109400 (2019).
58. Cortez LAB, Baldassin R and de Almeida E, Energy from sugarcane [internet], in *Sugarcane Biorefinery, Technology and Perspectives*, ed. by Santos F, Rabelo S, de Matos M and Eichler P. Amsterdam: Elsevier Inc., pp. 117–139 (2020).
59. Xie X, Wang M and Han J, Assessment of fuel-cycle energy use and greenhouse gas emissions for Fischer-Tropsch diesel from coal and cellulosic biomass. *Environ Sci Technol* **45**(7):3047–3053 (2011).
60. Tijmensen MJA, Faaij APC and Hamelinck CN, Hardeveld MRM van. Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. *Biomass Bioenergy* **23**:129–152 (2002).
61. IATA. IATA Sustainable Aviation Fuel Roadmap. 2015.
62. Batidzirai B, Smeets EMW and Faaij APC, Harmonising bioenergy resource potentials - methodological lessons from review of state of the art bioenergy potential assessments. *Renew Sustain Energy Rev* **16**(9):6598–6630 (2012).
63. Wichert MCP and Alvares CA, Site preparation, initial growth and soil erosion in Eucalyptus grandis plantations on steep terrain. *Sci For* **46**(117):17–30 (2018).
64. Silva GRV, Souza ZM, Martins Filho MV, Barbosa RS and Souza GS, Soil, water and nutrient losses by Interrill. *R Bras Ci Solo* **36**(1):963–970 (2012).
65. Bertoni J and Lombardi Neto F, *Conservação do solo*, 9th edn. Icone, São Paulo, pp. 1–355 (2014).
66. Liska AJ, Yang H, Milner M, Goddard S, Blanco-Canqui H, Pelton MP et al., Biofuels from crop residue can reduce soil carbon and increase CO2 emissions. *Nat Clim Chang* **4**(5):398–401 (2014).

67. van der Hilst F, Verstegen JA and Woltjer G, Mapping direct and indirect land use changes resulting from biofuel production and the effect of LUC mitigation measures land use change resulting from biofuel production. *GCB Bioenergy* **10**(11):1–54 (2018).
68. Tóth G, Kozłowski B, Prieler S, Wiberg D. Global Agro-ecological Zones User's Guide 2012;74. Available: [http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/GAEZ\\_User\\_Guide.pdf](http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/GAEZ_User_Guide.pdf)
69. Stape JL, Binkley D, Ryan MG, Fonseca S, Loos RA, Takahashi EN *et al.*, The Brazil eucalyptus potential productivity project: influence of water, nutrients and stand uniformity on wood production. *For Ecol Manage* **259**(9):1684–1694 (2010).
70. Renard BKG, Foster GR, Weesies GA and Porter JI, Revised universal soil loss equation (Rusle). *J Soil Water Conserv* **46**(1):30–33 (1991).
71. Teng H, Viscarra Rossel RA, Shi Z, Behrens T, Chappell A and Bui E, Assimilating satellite imagery and visible-near infrared spectroscopy to model and map soil loss by water erosion in Australia. *Environ Model Softw* **77**:156–167 (2016).
72. Wischmeier W and Smith D, Science and education administration United States Department of Agriculture in cooperation with Purdue agricultural Experiment Station. **537** (1978). Available: <https://naldc.nal.usda.gov/download/CAT79706928/PDF>.
73. da Rocha GC, Conservação do solo e cana-de-açúcar: aspectos legais e bibliométricos e uma ferramenta de determinação do Fator C (RUSLE). *Tese* 1–95 (2017).
74. Smith RM and Stamey WL, How to establish erosion tolerances. *Soil Water Conserv* **19**(3):3 (1964).
75. Andrews SS, Crop residue removal for biomass energy production: effects on soils and recommendations. *USDA-Natural Resour Conserv Serv* **7**:1–7 (2006). Available: [http://nitcnrcsbase-www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/nrcs142p2\\_053255.pdf](http://nitcnrcsbase-www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053255.pdf).
76. VDLUFA. Standpunkt Humusbilanzierung: Eine Methode zur Analyse und Bewertung der Humusversorgung von Ackerland. 2014;21.
77. Brock C, Franko U, Oberholzer HR, Kuka K, Leithold G, Kolbe H *et al.*, Humus balancing in Central Europe—concepts, state of the art and further challenges. *J Plant Nutr Soil Sci* **176**(1):3–11 (2013).
78. Wietschel L, Thorenz A and Tuma A, Spatially explicit forecast of feedstock potentials for second generation bioconversion industry from the EU agricultural sector until the year 2030. *J Clean Prod* **209**:1533–1544 (2019).
79. Kolbe H, Site-adjusted organic matter-balance method for use in arable farming systems. *J Plant Nutr Soil Sci* **173**(5):678–691 (2010).
80. Seabra JEA and Macedo IC, Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil. *Energy Policy* **39**(1):421–428 (2011).
81. do Canto JL, Machado CC, Seixas F, Souza AP d and de Mello Sant' Anna C, Evaluation of a wood chipping system for eucalyptus tops for energy (in portuguese). *Rev Árvore* **35**:1327–1334 (2011).
82. Cardoso TF, Cavalett O, Chagas MF, Morais ER, Carvalho JLN, Franco HCJ *et al.*, Technical and economic assessment of trash recovery in the sugarcane bioenergy production system. *Sci Agric* **70**(5):353–360 (2013).
83. Lundmark R, Athanassiadis D and Wetterlund E, Supply assessment of forest biomass e a bottom-up approach for Sweden. *Biomass Bioenergy* **75**:213–226 (2015).
84. Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M and van der Hilst F, Spatial assessment of the techno-economic potential of bioelectricity production from sugarcane straw. *Renew Energy* **156**:1313–1324 (2019).
85. Jonker G, *Quantification and Comparison of the Economic and GHG Performance of Biomass Supply Chains*. Utrecht: Utrecht University, (2017).
86. Jonker JGG, van der Hilst F, Junginger HM, Cavalett O, Chagas MF and Faaij APC, Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies. *Appl Energy* **147**:593–610 (2015).
87. Santos CI, Silva CC, Mussatto SI, Osseweijer P, van der Wielen LAM and Posada JA, Integrated 1st and 2nd generation sugarcane bio-refinery for jet fuel production in Brazil: techno-economic and greenhouse gas emissions assessment. *Renew Energy* **129**:733–747 (2017).
88. Diederichs GW, *Techno-Economic Assessment of Processes that Produce Jet Fuel from Plant-Derived Sources* by. Stellenbosch: Stellenbosch University, (2015).
89. Jones S, Meyer P, Snowden-Swan L, Padmaperuma A, Tan E, Dutta A *et al.*, Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels: fast pyrolysis and hydrotreating bio-oil pathway. *Energy [Internet]* **97**:1–97 (2013). Available: [http://www.pnnl.gov/main/publications/external/technical\\_reports/PNNL-23053.pdf%5Cnhttp://www.nrel.gov/docs/fy14osti/61178.pdf](http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23053.pdf%5Cnhttp://www.nrel.gov/docs/fy14osti/61178.pdf).
90. Diederichs GW, Mandegari MA, Farzad S and Görgens JF, Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. *Bioresour Technol* **216**:331–339 (2016).
91. Tzanetis KF, Posada JA and Ramirez A, Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: the impact of reaction conditions on production costs and GHG emissions performance. *Renew Energy* **113**:1388–1398 (2017).
92. Kazi FK, Fortman J and Anex R, Techno-economic analysis of biochemical scenarios for production of cellulosic ethanol. *Natl Renew Energy Lab* **102**:1–102 (2010).
93. Yao G, Staples MD, Malina R and Tyner WE, Stochastic techno-economic analysis of alcohol-to-jet fuel production. *Biotechnol Biofuels* **10**(1):18 (2017). Available: <http://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-017-0702-7>.
94. Jonker JGG, Junginger HM, Verstegen JA, Lin T, Rodriguez LF, Ting KC *et al.*, Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil. *Appl Energy [Internet]* **173**:494–510 (2016).
95. Swanson RM, Satrio JA, Brown RC and Hsu DD, Techno-economic analysis of biofuels production based on gasification techno-economic analysis of biofuels production based on gasification Alexandru Platon. *Energy* **89**:S11–S19 (2010) Available: <http://linkinghub.elsevier.com/retrieve/pii/S0016236110003741>.
96. de Jong S, Stralen J Van, Londo M, Hoefnagels R, Junginger M. Renewable jet fuel supply scenarios in the European Union in 2021–2030 in the context of proposed biofuel policy and competing biomass demand running head: the future supply of renewable jet fuel in the EU. 2018.
97. Meroo EW, Phillips KE, Myers CW. Understanding cost growth and performance shortfalls in Pioneer process plants [internet]. Library of congress cataloging in publication data 1981. Available: <https://www.rand.org/content/dam/rand/pubs/reports/2006/R2569.pdf>
98. Stratton RW, Min Wong H and Hileman JI, Life cycle greenhouse gas emissions from alternative. *Jet Fuels*



- 571:1–153 (2010). Available: <http://web.mit.edu/aeroastro/partner/reports/index.html>.
99. Van der Hilst F and Faaij APC, Spatiotemporal cost-supply curves for bioenergy production in Mozambique. *Biofuels, Bioprod Biorefin* 6:405–430 (2012). Available from: <http://onlinelibrary.wiley.com/doi/10.1002/bbb.1332/abstract>.
100. FAB. Logistic centre: Jet fuel prices [Internet]. Brazilian Airforce: Jet fuel prices at the airports. 2018. Available from: <http://www2.fab.mil.br/celog/images/combav/QUEROSENE.xlsx>
101. Bordonal R d O, JLN C, Lal R, de Figueiredo EB, de Oliveira BG and La Scala N, Sustainability of sugarcane production in Brazil. A review. *Agron Sustain Dev* 38(2):1–23 (2018).
102. Index Mundi. U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB, US\$ per gallon [Internet]. Available: <https://www.indexmundi.com/commodities/?commodity=jet-fuel> [30 July 2019]
103. Grassi MCB and Pereira GAG, Energy-cane and RenovaBio: Brazilian vectors to boost the development of biofuels. *Ind Crops Prod* 129:201–205 (2019).
104. Sone JS, de Oliveira PTS, Zamboni PAP, Vieira NOM, Carvalho GA, Macedo MCM *et al.*, Effects of long-term crop-livestock-forestry systems on soil erosion and water infiltration in a Brazilian Cerrado site. *Sustain* 11(19):1–13 (2019).
105. COGEN. Bioeletricidade – Reduzindo Emissões & Agregando Valor ao Sistema Elétrico. 2009.
106. EPE. Plano decenal de expansão de energia 2026. Rio de Janeiro; 2016.
107. Novacana. 4 usinas de cana-de-açúcar vendem energia no Leilão A-5: 6.355 GWh e R\$ 146,3 milhões. novacana.com [Internet]. 2016 May 2; Available: <https://www.novacana.com/n/cogeracao/4-usinas-cana-de-acucar-vendem-energia-leilao-a-5-6-355-gwh-r-146-3-milhoes-020516/>
108. Klein BC, Chagas MF, Junqueira TL, Rezende MCAF, Cardoso T d F, Cavalett O *et al.*, Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. *Appl Energy* [Internet] 209:290–305 (2018). Available: <http://linkinghub.elsevier.com/retrieve/pii/S030626191731499X>.
109. Petrobras. Suprimento de QAV Da Produção e Importação aos Aeroportos [Internet]. 1o Workshop sobre Compras Centralizadas – Centro Logístico da Aeronáutica. 2016. Available: [http://www2.fab.mil.br/celog/images/workshop/WorkShop\\_Petrobras.pdf](http://www2.fab.mil.br/celog/images/workshop/WorkShop_Petrobras.pdf)
110. MME. Modelo RenovaBio: Cenário, Meta, Premissas e Impactos [Internet]. 2017. Available: <http://www.mme.gov.br/documents/10584/74698855/2a+Reunião+Aberta+CRBio++MME.+1+Modelo+Metas+de+Redução+de+Emissões++Cenário+e+Premissas++03-05-2018++Auditorio+MCTIC/fe66806b-a71c-44c6-8c8d-dd8064526e18;jsessionid=92450C84ABC54D461A6BB89C398DFF0A.srv1>
111. IEA. World Energy Outlook 2016 [Internet]. Paris; 2016. Available: [http://www.oecd-ilibrary.org/energy/world-energy-outlook-2016\\_weo-2016-en](http://www.oecd-ilibrary.org/energy/world-energy-outlook-2016_weo-2016-en)
112. PNNL. PNNL technology clears way for ethanol-derived jet fuel [Internet]. PNNL News. 2018. Available: <https://www.pnnl.gov/news/release.aspx?id=4511> [2 February 2019]
113. Mawhood R, Gazis E, de Jong S, Hoefnagels R and Slade R, Production pathways for renewable jet fuel: a review of commercialization status and future prospects. *Biofuels Bioprod Biorefin* 10(4):462–484 (2016).
114. Campbell EE and Paustian K, Current developments in soil organic matter modeling and the expansion of model applications: a review. *Environ Res Lett* 10(12):1–36 (2015).
115. Oliveira DMS, Williams S, Cerri CEP and Paustian K, Predicting soil C changes over sugarcane expansion in Brazil using the DayCent model. *GCB Bioenergy* 9(9):1436–1446 (2017).



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