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Article

AVAILABILITY AND ENVIRONMENTAL PERFORMANCE OF WOOD FOR A SECOND-GENERATION BIOREFINERY

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Abstract: The current Global Climate Change, the 2030 Agenda and the Planetary boundaries have driven new development strategies, such as the circular economy, bioeconomy and biorefineries. In this framework, this study analyzes the potential availability and sustainability of the wood supply chain for a small-scale biorefinery aiming at producing 280–300 L of bioethanol per ton dry biomass, consuming 30,000 t of dry biomass per year harvested in a 50 km radius. This wood production goal was assessed from *Eucalyptus grandis* stands planted for solid wood in northeastern Uruguay. Moreover, to understand the environmental performance of this biomass supply chain, the energy return on investment (EROI), carbon footprint (CF) and potential soil erosion were also assessed. The results showed that the potential wood production would supply an average of 81,800 t of dry mass per year, maintaining the soil erosion below the upper threshold recommended, an EROI of 2.3 and annual CF of 1.22 $kg\ CO_{2-eq}m^{-3}$ (2.6 $g\ CO_{2-eq}MJ^{-1}$). Combined with the environmental performance of the bioethanol biorefinery facility, these results would show acceptable values of sustainability according to EU Directive 2009/28/ec because the bioethanol CF becomes 1.7% of this petrol's CF.

Keywords: *Eucalyptus*; EROI; carbon footprint; soil erosion; bioethanol

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1. Introduction

Population growth and its resource consumption (food, fibers, fuels and minerals) have directly and indirectly developed several environmental impacts on a world scale (e.g., climate change and biodiversity loss). From a public policy viewpoint, objectives and/or strategies have been proposed to solve these problems, through proposals such as sustainable development [1], the Elkington [2] triple bottom line (social, economic and physical-natural) or multidimensional assessments with life cycle assessments (LCAs) [3] approaches that, in general, only allow a relative comparison of development styles or production strategies, without being able to identify sustainability in absolute terms. Conversely, Rockström et al.[4] highlighted the need to work according to natural systems limits because any economic or social arguments that try to overpass these natural limits will always have negative consequences.

Moreover, the global goals of the 2030 Agenda for Sustainable Development aim to avoid overlap or to contradict these goals and new proposals such as the circular economy, reuse economy and bioeconomy (Figure 1), mainly for reduction in raw material consumption, fossil energy and production of waste. In the same direction, bioeconomy proposes a circular economy based on agricultural and forest products and biological wastes, for the production of biobased products, biofuels and bioenergy, sometimes using biorefineries [5–8].

A biorefinery is a facility for the generation of energy (e.g., biofuels) and biobased products (e.g., food, feed, fibers and chemicals) as a result of the combination of several process steps (e.g., mechanical, thermochemical, chemical and biochemical processes), using different raw materials, from both virgin and residual sources [5,9,10]. Thus, biorefineries

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have arisen as a potential solution because they avoid the increase in greenhouse gas (GHG) emissions by the production of biofuels and reduce waste production and consumption of new raw materials. In this way, biorefineries are an industrial strategy with greater economic strength than a traditional chemical industry because this strategy is based on the coproduction of several biobased products.

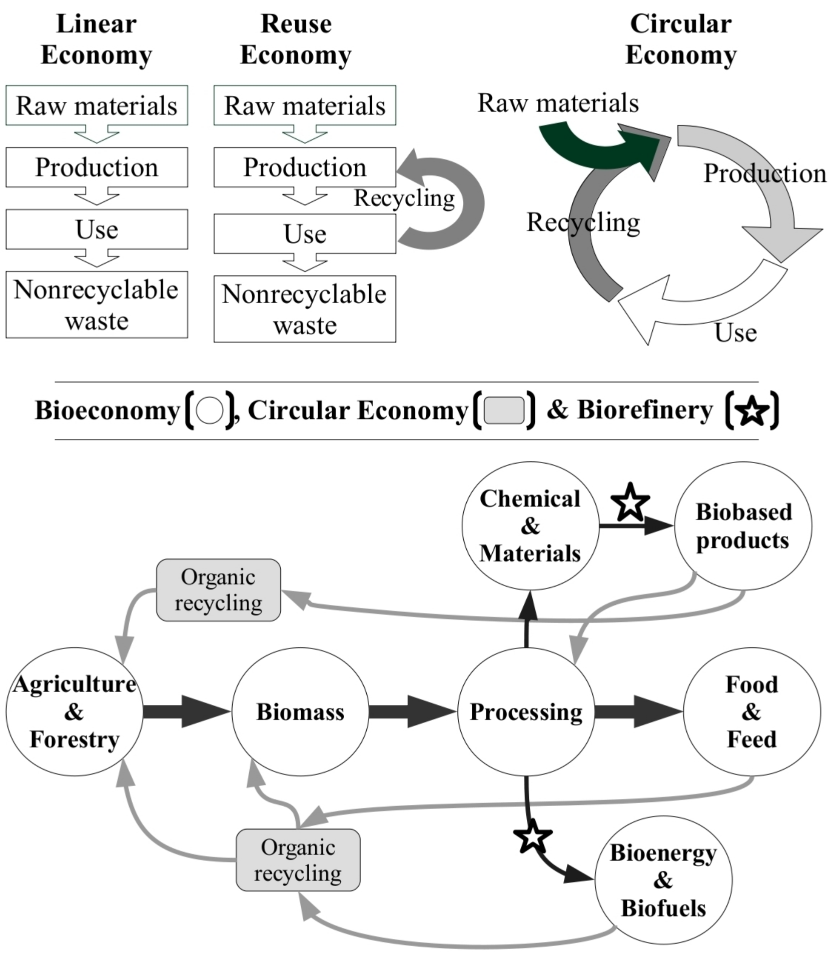

Figure 1. Flux diagrams of a linear economy, reuse economy, circular economy, bioeconomy and the potential position of biorefineries.

Biorefineries as a potential solution imply several assumptions, such as (1) economic and environmental costs lower than a production based on fossil fuels or fresh raw materials, (2) availability of residues from sustainable agricultural productions [11,12] and (3) an energy return on investment (EROI) higher than 2 [13–16]. These assumptions can be false, which is the reason that the EU Directive 2009/28/ec requests a limit on GHG emissions for recognition of a biofuel as such [17]. Moreover, the agriculture/forest residues left on soil can only be harvested in the amount that is not required to maintain the soil organic matter and soil fertility. If these variables are not considered, the harvest of agriculture/forest residues will reduce the soil erosion resistance [18][19], cation exchange capacity and soil fertility [20]. Therefore, before the development of a biorefinery, it is necessary to survey hidden natural subsidies that can be allowed by circumstantial socioeconomic conditions. A good tool for analyzing the productive scenario is to know if the EROI of the whole process is higher than 2.

Countries with a GDP based on the exportation of agricultural products could have the conditions for developing a circular economy based on biorefineries for the development of biobased products. An example could be Uruguay, whose GDP depends largely on the exportation of sulfate chemical wood pulp, frozen bovine meat, soybeans, concentrated milk and rice [21]. Therefore, Uruguay could support a circular economy scheme and a bioecon-

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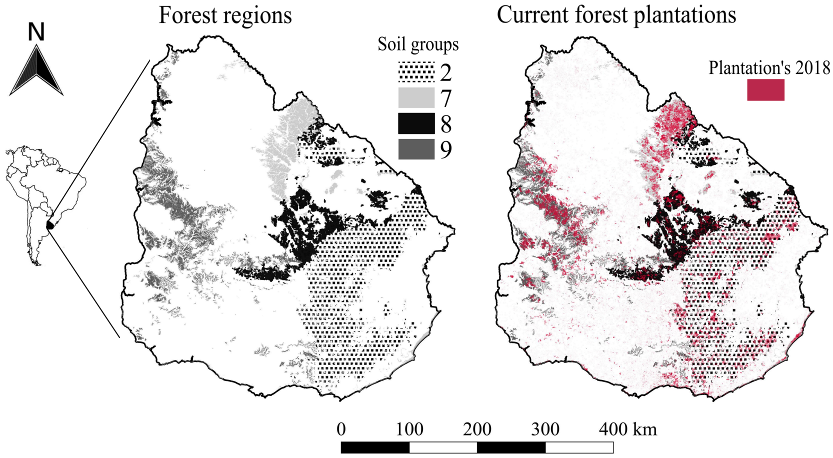

Figure 2. Left map: Regions prioritized for forest plantations (black and grey patterns) according to the National Commission for Agroeconomic Studies of the Land Classification (CONEAT), soils corresponding to groups 2, 7, 8 and 9 have adequate soil fertility for forest plantation. Right map: The current forest plantations (red) reported by the Forestry Directorate (DGF) (Ministry of Cattle, Agriculture, and Fisheries, MGAP) [26].

omy using biorefineries mainly, with harvest residues or wood from forest plantation of solid wood because the biomass production is higher than the minimum amount required (7 $ton\ ha^{-1}\ yr^{-1}$) to maintain the soil organic matter balance [19]; currently, solid wood production is higher than the demand of the national industry or international market; and finally, the use for biofuels or biobased products is a research area under development in this country [22–24].

Forest plantations in Uruguay have achieved good yields with exotic trees (25 $m^3\ ha^{-1}\ yr^{-1}$, *Eucalyptus* spp.; 20 $m^3\ ha^{-1}\ yr^{-1}$ *Pinus* spp.) on soils defined by law (Figure 1) due to their low suitability for food production. Currently, forest plantations cover over one million of the 4,420,000 hectares prioritized by law for forest plantations (Figure 2) [25]. The produced wood has two industrial uses, bleached cellulose pulp and solid wood. The latter industry grows a large proportion of wood that is not processed and remains on the field. In the country's northwest, currently, these solid wood plantations with a turn of 25 years occupy almost 200,000 ha [26] with the genera *Eucalyptus* (*E. grandis* and *E. dunnii*) and *Pinus* (*P. taeda*, *P. elliottii*) at a ratio of 70% and 35%, respectively. An EROI estimation of eight-year *Eucalyptus* wood found a value of 4 (at the farm gate) [27]. It is possible to assume that wood from a 21 years plantation could reach similar values at the farm gate.

This work evaluated two of the aforementioned hypotheses. First, the availability from solid wood forest production to supply 30,000 t dry biomass for a semi-industrial pilot scale (280–300 L of bioethanol per ton of dry biomass; [28]). To test this, the wood production was estimated in a 50 km radius zone in the northeast with a forest growth model of current plantations. Second, the acceptability of environmental performance of this wood supply chain was evaluated; EROI, carbon footprint (CF) and soil erosion were estimated. These analyses assumed that a conservative scenario (e.g., area planted, growth behavior and tree species) will remain constant for the next 25 years.

2. Materials and Methods

2.1. Study region

The Uruguayan northeast region (30° 39′ 14,49″ - 32° 56′ 29,22″ S, 54° 44′ 26.79″ - 56° 41′ 21,23″ W) covers the Departments (political divisions) of Tacuarembó and Rivera. The most extended climax vegetation is perennial pasture, characterized by tall grass in most of the territory [29]. The climate is temperate and humid without a dry season (Cfa) according to the Köppen–Geiger classification [30] and with the highest rainfall in the country (Table 1).

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Table 1: Climate characteristics of the northeast region for the period 1980–2009 [31].

Climatic variable	Mean	Minimum	Maximum
Rainfall (mm)	1400	1200	1600
Temperature (°C)	17.7	12.9	22.6
Accumulated days with frosts	30	20	40
Radiation ($h\ d^{-1}\ yr^{-1}$)	7		
Annual air relative humidity (%)	74	70	78
Potential evapotranspiration ($mm\ month^{-1}$)	1100	1000	1200

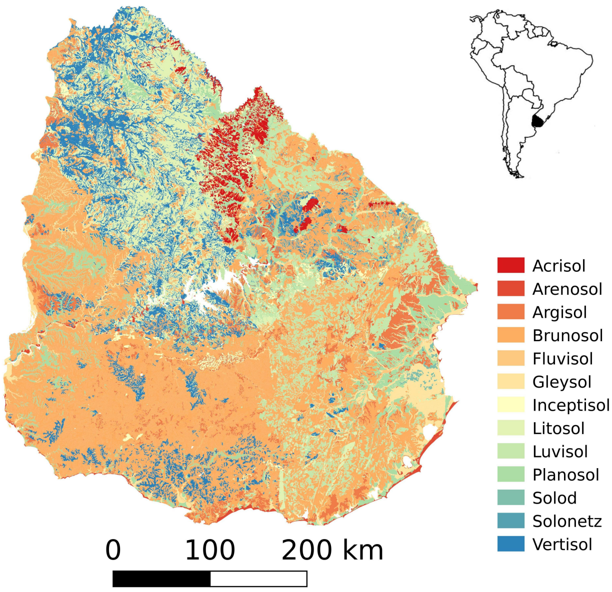

Figure 3. Soil taxonomy map of Uruguay according to Durán and García-Préchac (2007) elaborated by Beretta-Blanco and Carrasco-Letelier [18].

According to the Soil Atlas of Latin America and the Caribbean, the main soils of Uruguay are phaeozems, leptosols, vertisols, acrisols, and luvisols [32], which were redefined at the highest resolution available in Uruguay (Figure 3). The northeast region of the country (30° 11′ - 35° 1′ S, 53° 23′ - 58° 26′ W) covers 176,215 km2 and comprises the Departments of Rivera and Tacuarembó, near the Brazilian border. In this region, most commercial plantations occur on acidic soils, low in base saturation with exchangeable aluminum and significant textural differentiation between superficial and subsuperficial horizons, and deep (up to 1.5 to 3 m). These soils were classified as acrisols and luvisols according to the Uruguayan soil taxonomy [33], the parent material of which are sandstones from the Tacuarembó or Rivera [34,35].

At the national level, plantation management changes according to the final product (i.e., pulp or solid wood). Plantations in the northeastern Departments of Rivera and Tacuarembó comprise the genera *Pinus* and *Eucalyptus*, and occupy more than 200,000 ha [26] (Table 2) that are managed for sawmills and plywood mills.

2.2. Estimation of potential wood supply

Solid wood production of Eucalyptus is the main target of the forest plantations analyzed. The forest plantation considered: (1) a mean harvest rotation age of 11 and 21 years for thinning and clear cut, respectively (Table 3), (2) a minimum log diameter of 19 cm for local sawmill and plant board and (3) the remaining portion of the stems was considered as a potential source of biomass. The potential wood supply was estimated through the four following sequential steps.

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1. The cadastral records of plantation plans recorded by DGF in the region since 1975 were gathered and classified for the species and purpose of interest. This information included the species, plantation date, intended product (solid, pulp, etc.), number of trees per hectare, effective planted area and cadastral number.
2. The information was georeferenced through its corresponding cadastral number within the georeferenced national cadastral records [37] and checked with the geographical information system (GIS) of the National Forest Inventory for years 2010, 2011 and 2014 [38].
3. Based on the plantation date of each record, a commercial thinning at age 11 years and a clear cut at age 21 years were assumed. We assumed that biomass formed at the first thinning was not exported, therefore was not computed. The thinned (second thinning) and harvested areas for each year were multiplied by the estimated amount of dry matter considering: a) a stem portion between 19 and 6 cm diameter only; b) a stem portion smaller than 6 cm plus twigs, branches, leaves, and bark; c) a stem portion smaller than 19 cm plus half of the biomass corresponding to twigs, branches, leaves, and bark; applying dry matter coefficients according to [39].
4. The maximum amount of forest biomass was calculated for a catchment area of 50 km radius. The effective area and medium annual increase (MAI) of forest were considered for the determination of potential wood. The current amount of *Eucalyptus grandis* and its projection for the next 25 years were estimated based on the area projected to be harvested or thinned per year and the amount of dry matter per ha for thinned or harvested plantations according to PROBIO [39] (Table 5). In the framework of potential harvestable biomass, this work analyzed the potential production of different schemes of production (Table 6) of logs with different diameters (>20 cm, 19–6 cm, <6 cm) in a zone of 50 km radius. The GIS information was processed and analyzed with QGIS [41].

2.3. Estimation of soil loss

Estimation of the mean annual soil erosion (A) was performed using the information required by the Universal Soil Loss Equation/Revised Universal Soil Loss Equation (USLE/RUSLE) model (Eq. 1) validated for Uruguay [42–44] In this model, the mean soil loss (A) is expressed in units of $t\ (ha\ yr)^{-1}$ according to Foster et al. [45]:

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where the rainfall erosivity factor (R-factor) is expressed in $(MJ\ mm)(ha\ h\ yr)^{-1}$, the soil erodibility factor (K-factor) is expressed in $(t\ ha\ h)(ha\ MJ\ mm)^{-1}$, L is the slope length factor, S is the slope gradient factor, C is the crop management factor and P is the erosion control practice factor.

The mean annual soil loss was estimated based on a shapefile developed by the intersection of the mapping of CONEAT's soil groups [46,47]. The soil loss was estimated by the product of all the factors in the model (Eq. 1), where each factor of the equation

Table 2: Plantation area (ha) according to the species planted in the region [26].

Forest species	Department		Planted area by forest species
	Rivera	Tacuarembó	
Pinus taeda *Pinus elliotii*	74.107	62.158	180.019
Eucalyptus grandis *Eucalyptus saligna*	45.038	23.441	68.479
Eucalyptus dunnii	1.799	41.355	43.154
Eucalyptus globulus	0	334	149.329

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Table 3: Operations of *Eucalyptus* plantations for sawmills and plywood mills.

Operation	Year	Description
Ant's control	0 to 1.5	2 to 4 times
Soil preparation	0	Plantation rows, minimum slope, subsoil ripping, 1 or 2 offset disk passes, mounding
Plantation	0	800–1200 trees per hectare, manual or mechanized, clones or seeds
Fertilization	0	On the plantation, prescription according to soil characteristics (i.e., 45 g per plant)
Weed controls	0 to 2	Postemergent previous plantation, preemergent on the plantation and postemergent one or two times up to canopy closure
Thinnings	2 to 10	2 to 3 thinnings depending on site quality and company purposes
Prunings	2 to 10	2 to 3 prunings depending on site quality and company purposes up to 6.5 or 9 m
Pre-harvest	16 to 19	Ant's control
Harvest	16 to19	Cut-to-length systems mainly, but full-tree systems can occur depending on topography and density

was incorporated into the GIS as a new information layer according to the description by Carrasco-Letelier and Beretta-Blanco [19].

2.4. Energy return on investment (EROI) and Carbon footprint

The estimation of the EROI and CF was done by building a life cycle inventory (LCI), which did not include human labor as an energy input. Infrastructure, machinery, chemicals, fertilizers, fuels and transportation were included. The subsystems considered by the EROI and the CF were seed production/nursery, field preparation, planting, pruning, harvest and transportation to the biorefinery.

The study considered one cubic meter of harvested wood as a functional unit. The scope considered was cradle-to-gate of a biorefinery located 50 km from the harvest site. All relevant activities and inputs (>1% of the CF) under management control, consumed electrical energy and other supply chains were considered.

Table 4: *Eucalyptus grandis* wood composition expressed in percentage, according to Lima et al. [40].

Residues fraction	Mineral	Lignin	Cellulose	Xylan
Wood	0.4	29.7	49.0	14.8
Bark	10.3	20.6	47.0	11.4
Leaves	4.7	34.3	48.0	8.0

2.4.1. Energy return on investment (EROI)

The EROI was calculated according to Hall et al. [48,49] and Townsend et al. [16] on a spreadsheet for all the subsystems considered in the LCI. The energy of each component and process (engines and machinery, pesticides and fertilizers [95]) were estimated according to their corresponding rates and conversion factors into energy units (MJ). When the primary national data of a particular input or emission was not available, information from literature with similar regional conditions was used [50]. In the worst scenario, when the regional data were not available, international databases were used [51–54].

Table 5: Solid wood production with *Eucalyptus* plantations.

	Planting	Thinnings		Harvest
		1st	2nd	
Age	1	6	11	21
Trees per hectare before thinning	800	665	500	187
Harvested trees ($tree\ ha^{-1}$)		165	250	187
MAI ($m^3\ ha^{-1}\ yr^{-1}$)		24	29	28
Total harvested biomass ($m^3\ ha^{-1}$)		23.3	94.4	583
Logs sawmill ($m^3\ ha^{-1}$) >19 cm		11	65	545
Logs biorefinery ($m^3\ ha^{-1}$) 6-19 cm			29	32
Tips ($m^3\ ha^{-1}$) <6 cm			0.4	6.0

Table 6: Potential feedstocks scenarios using different fractions of trees.

Options	Branches and leaves	Bark	Diameter of logs		
			>20cm	19-6 cm	<6cm
Current scenario	Field	Field	Sawmill and plywood mill	Pulp mill	Field
Alternative scenario I	Field	Field	Sawmill and plywood mill	Pulp mill	Biofuel plant
Alternative scenario II	Field	Field	Sawmill and plywood mill	Biofuel plant	Field
Alternative scenario III	50% of tip biomass removed	Field	Sawmill and plywood mill	Biofuel plant	Field

2.4.2. Carbon footprint(EROI)

LCI was evaluated in a spreadsheet using information from interviews and forest company records. This information was transferred to the OpenLCA software [54] using the AGRYBALYSE database. A temporal scope of 100 years was considered for the global warming potential (GWP) emissions according to the Intergovernmental Panel on Climate Change Fifth Assessment Report [60], with a GWP of 1, 25 and 265 for CO_2, CH_4, and N_2O, respectively. Considered emissions were CO_2 emitted by fossil fuel used [51] because there are no national records of these fuel consumptions. These conversion factors have low variability between countries [52]. The NO_x emissions were not accounted because there is no validated model for them.

3. Results

3.1. Potential wood supply

3.1.1. Geographic distribution and availability

According to forest plans presented to DGF, the effective area occupied by *Eucalyptus grandis* plantations for sawmilling and plywood mills in the northern region is 68,479 ha. Based on this area and using biomass coefficients [39], projections of total biomass production for the region fluctuate between 70,000 and 300,000 t of dry matter per year, with an average of 180,000 t (Figure 4).

Plantation forests managed for sawmills are long-rotation crops, therefore, regional yearly yield variations are likely related to the age of the stands and the number of hectares ready to be harvested or thinned within the year. However, harvests can be delayed or advanced depending on market prices, feedstock needs, etc. The potential feedstock production for the scenarios of Table 6 considering the total area and a 50 km radius buffer zone (centered at 31° 13′ 26.25″ S and 55° 39′ 34.87″ W) is presented in Figure 5. Tips

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Table 7: Energy conversion factors used for EROI estimation

Inputs	Units	$MJunit-1$	Reference	[55]
Fuel	L	38.6	MJ	[55]
Herbicide	L	327	MJ	[56]
Machines	kg	68.9	MJ	[55]
Lubricant	L	38.6	MJ	[55]
Formicide	kg	184.7	MJ	[56]
Electricity	Kwh	3.6	MJ	
Liquied petroleum gas	Kg	30.33	MJ	[57]
Gasoline	L	39.61	MJ	[57]
Glyphosate	Kg	476	MJ	[58]
N-fertilizer	Kg	51.47	MJ	[59]
P-fertilizer	Kg	9.17	MJ	[59]
K-fertilizer	Kg	5.96	MJ	[59]
Ammonium sulfate fertilizer	Kg	1.12	MJ	[57]
Urea	Kg	75.63	MJ	[57]
Insecticide	Kg	325	MJ	[59]
Eucalyptus globulus	Kg	19	MJ	INIA's data

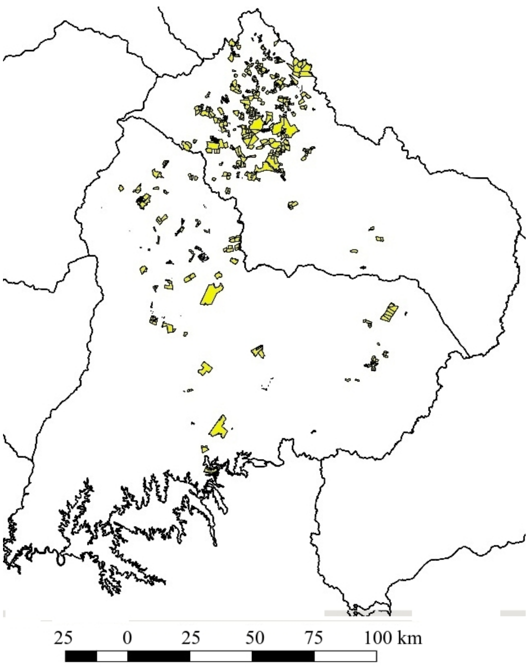

Figure 4. *Eucalyptus grandis* plantations for sawmilling and plywood purposes in Rivera and Tacuarembó (in yellow).

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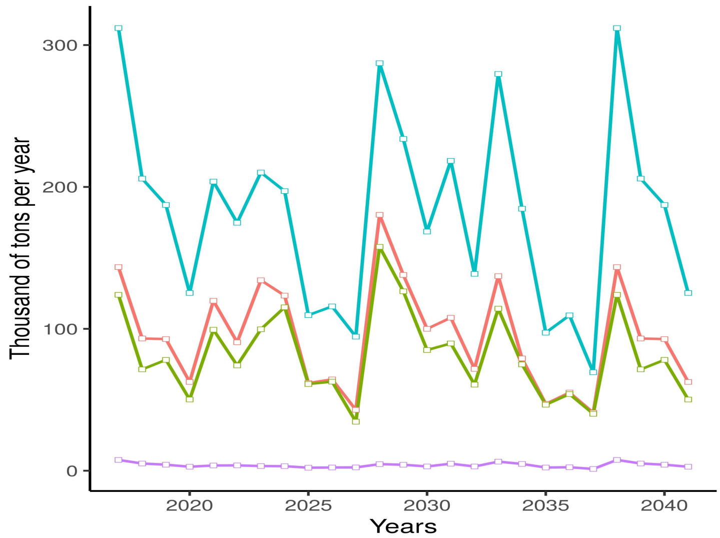

Figure 5. Modeling results of *Eucalyptus grandis* production according to the scenarios described in Table 6. Total residues (cyan); Alternative scenario I, wood and branches below 6 cm in diameter (purple); Alternative scenario II, wood from logs with a diameter between 6 and 19 cm (green); and Alternative scenario III, wood from logs with a diameter less than 19 cm and 50% of harvested branches (orange).

(Alternative scenario I) with a diameter smaller than 6 cm have very low availability (3.9 $t\ yr^{-1}$), whereas logs with a diameter between 6 and 19 cm (Alternative scenario II) showed an annual average yield of 81,800 t air-dry matter (ADM) and a range of 40,000 to 150,000 t ADM. Finally, Alternative scenario III shows an annual average yield of 91,900 t ADM, with a range between 50,000 and 160,000 t ADM.

3.2. Soil erosion by water

In the 50 km radius catchment area, there is 17.8% (104,460 ha) of 586,983 ha of soils (Figure 6C) with an annual erosion higher than the tolerable value (7 $Mg\ ha^{-1}\ yr^{-1}$). This occurs in steep, sandy loam soils [19,36,61]. In this context, in the 73,152 ha of plantations studied (Figure 6D), 7.8% is found on soils with erosion greater than tolerable.

3.3. EROI and CF

Most of the information about inputs, machinery characteristics, lifespans, fuel consumption and others were obtained from interviews with different forest companies (Table A1). When the data were not available, the information was obtained from peer-reviewed publications. In exceptional cases, the information was obtained from non-peer-reviewed literature. Most of the information gap was on tree nurseries; in this case, data contained in Heller et al.[58] were used.

EROI estimation showed that the most important energy consumption was in the processes of harvest, second thinning and plantation, which correspond to 53%, 25% and 13% of the total input energy, respectively. In terms of inputs, agriculture machinery, fuel and pesticides explain 46%, 41% and 11% of energy consumption, respectively. The ratios between energy output and input give a value between 44.5 and 49.1 for EROI; these values divided by the 21 years of plantations become values between 2.12 and 2.34.

The CF results showed a mean value of 1.22 $KgCO_{2-eq}$ per cubic meter of wood per year or 25.8 $KgCO_{2-eq}\ m^{-3}$ for a 21-years old wood (Table 9). The major contributions to this CF outcome were linked to the harvest and second thinning processes at 74% and 9%, respectively. This was mainly caused by fuel consumption and machinery.

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Table 8: Energy inputs and energy output of agro-industrial forestry chain. All values are expressed in $MJ\ ha^{-1}$.

	All biomass	Solid wood	Current scenario	Alternative I	Alternative II	Alternative III
Fuel	58,673	54,903	57,928	57,970	57,928	58,301
Electricity	57	57	57	57	57	57
Pesticides	16,086	16,086	16,086	16,086	16,086	16,086
Fertilizers	1,912	1,912	1,912	1,912	1,912	1,912
Agricultural machinery	63,675	61,592	62,675	62,800	62,675	63,175
Total energy input	140,403	134,549	138,658	138,824	138,658	139,530
Total energy output	6,936,229	6,147,279	6,751,118	6,814,472	6,751,118	6,209,395
EROI yr	**2.35**	**2.18**	**2.32**	**2.34**	**2.32**	**2.12**
EROI 21 yr	49.4	45.7	48.7	49.1	48.7	44.5

Table 9: Global warming power for 100-year expressed in $kg\ CO_{2-eq}\ m^{-3}$ of wood produced per year.

	Total biomass	S	CS	Alternative			Mean	Min	Max
				I	II	III			
Tree nursery	0.0024	0.0027	0.0025 (0.2 %)	0.0024	0.0025	0.0024	0.0025	0.0024	0.0027
Soil preparation	0.0783	0.0884	0.0805 (6.6 %)	0.0797	0.0805	0.0794	0.0811	0.0794	0.0884
Plantation	0.0553	0.0624	0.0568 (4.7%)	0.0563	0.0568	0.0560	0.0573	0.0560	0.0624
1^{st} thinning	0.0263	0.0140	0.0128 (1.3%)	0.0127	0.1277	0.0197	0.0547	0.0127	0.1277
2^{nd} thinning	0.1663	0.1293	0.1702 (13.2%)	0.1694	0.1703	0.1683	0.1623	0.1293	0.1702
Harvest	0.8895	0.9387	0.9049 (74.0%)	0.9058	0.9049	0.8973	0.9069	0.8973	0.9387
Total	**1.2181**	**1.2354**	**1.2276**	**1.2263**	**1.2276**	**1.2231**	**1.2264**	**1.2231**	**1.2354**

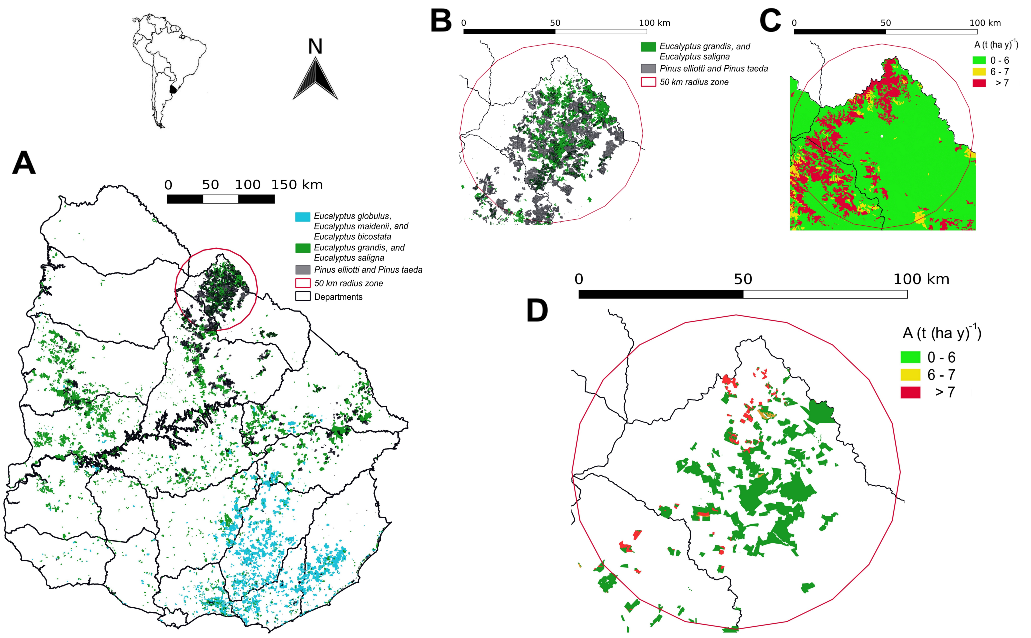

Figure 6. Current forest plantations reported by forest statistics 2019, (B) forest plantations in a 50 km radius zone, (C) soil erosion by water estimated by Carrasco-Letelier and Beretta-Blanco [18] and (D) soil erosion in plantations considered by this study.

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4. Discussion

4.1. Potential wood supply

The wood availability in the different alternative scenarios presented adequate volumes to satisfy the annual demand consumption (30,000 ADt) with options II and III. However, options I and III would not be recommended due to their high export of nutrients. Hernández et al. (2009) found that if the bark and leaves are left on the field it is possible to reduce the total exportations of N, P, K, Ca and Mg to 41%, 55%, 46%, 68% and 66%, respectively, in forest plantations for cellulose in northwestern soils. Nutrients can be restored faster in the soil where residues are buried and incorporated into the soil by tillage compared with soils where residues are left on the surface [62]. The PROBIO project results of plantations of *E. grandis* for solid wood have shown high rates of Ca with a harvest that does not remove bark from the field. These cation exportations in leaves and bark can reduce soil fertility and would reduce the yields, as occurred in annual crops in Uruguay in the last decade [20]. In the same trend, Bentancor et al. [64] and Resquin et al. [68] showed the need to find a tradeoff between nutrient removal and wood production for forest plantation developments for bioenergy in northeastern soils, where the plantation density is a second variable that must be considered [67–69].

For the assessed region, wood that was not used by the sawmill industry is sold to the pulp mill plant. At the current development of the forestry sector, two pulp mills are operating in the country, 430 [72] and 471 km [71] from the center of the 50 km radius area proposed in this study, and a third pulp mill will be at 221 km [72]. Regionally, a new pulp industry could constitute the main threat for a sustained feedstock supply for a second-generation biorefinery. Then, because of a decrease in the freight distance, the competition for smaller pieces of *Eucalyptus grandis* will increase, and so will the price. The less favorable wood availability projections determine annual averages in the range of 27,000 to 45,000 ADt. By contrast, the distance from the nearest pulp mill will be four times or more than the harvest radius of the biorefinery. Therefore, there is a willingness to pay a near biorefinery at better than the current price of wood for cellulose pulp, if it included the shipping costs for the farmer and the increase in the CF of cellulose pulp. Moreover, the *E. grandis* plantation area is already increasing, by replacement of pine plantations, and the turn could decrease to 16 years as a consequence of a species replacement of pine plantations. Thus, these forest plantations changes will increase the Eucalyptus wood to 90,000 ADt per year.

Additional strengths of the region proposed are as follows. These plantations have long cycles, the company owners develop long-term plans for wood production and *E. grandis* has shown good sanitary behavior so far, which reduces the risk against the appearance of pests or diseases [73]. This highlights the potential availability of feedstock to support the biorefinery for several decades.

4.2. Soil erosion

The most important soil erosion processes in Uruguay were linked to the agricultural expansion and intensification of the last decade [19]. The situation partially explained the loss of nutrients due to bad fertilization management of rainfed crops, which reduced soil productivity [20]. The second type of water erosion of the soil corresponds to a natural risk, that is, soils with high slope and structural fragility that are present in defined soils of forest priority [18]. This situation was previously reported by Carrasco-Letelier and Beretta-Blanco [19] This last type of erosion was the one detected in the studied plots. Therefore, the erosion was not due to the afforestation of these plots but to their high sand content and steep slopes. Thus, the levels of erosion were not caused by the forest plantations studied. That situation agrees with other soil erosion studies [36,43,74].

4.3. EROI, carbon footprint and other footprints

The EROI for template crops must be in the range between 2 and 4 [75]. The current value was higher than the 3.5, 1.28 and 0.76 reported for corn by Weißbach et al. [76],

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Kim and Dale [77] and Pimentel and Patzek [78], respectively. The EROI of 50 is close to the values reported by Romanelli and Milan [50] for Eucalyptus in Brazil. With this information only it is possible to highlight that the current supply chain of wood for a biorefinery has an adequate EROI; however, how this situation can be used depends on the industrial technology because all this favorable EROI may be lost on the biorefinery [79] or improved with new technologies [80].

The CF result of Eucalyptus solid wood (1.22 $kg\ CO_{2-eq}\ m^{-3}\ yr^{-1}$; 25.62 $kg\ CO_{2-eq}\ m^{-3}$ in 21 years or 2.6 $g\ CO_{2-eq}\ MJ^{-1}$) is close to the 18.71 $kg\ CO_{2-eq}\ m^{-3}$ reported by McCallum [81] and Berg [51] (20.4 $kg\ CO_{2-eq}\ m^{-3}$), but lower than that reported by Martínez-Alonso et al. [82] (423.21 $kg\ CO_{2-eq}\ m^{-3}$) for Spanish chestnut; lower than 0.61 $kg\ CO_{2-eq}\ kg^{-1}$ (with no stored carbon) reported by Symons et al. [83], if a wood density of 0.52 $g\ cm^{-1}$ [84] is considered, our CF should correspond to 0.05 $kg\ CO_{2-eq}\ kg^{-1}$. These differences in favor of Uruguayan solid wood could be higher than those indicated if the reported CF included the potential soil carbon sequestration that was not considered. Mainly by the absence of a longest-running experiments on this kind of Uruguayan agriculture production, which allow estimate theirs impacts. Situation that do not occur with annual rainfed crops that started the longest-running rainfed crop experiments in 1914, updated it 1964 [99] and is complemented by other longest-running experiments in the country [98,100].

This availability of biomass, EROI and CF values suggest that these wood supply chains satisfy the sustainability criteria. However, this is only half of the process because the main goal is bioethanol production. Then, these wood supply chains must be analyzed together with the EROI and CF of the destination biorefinery. In this framework, if this supply chain was considered with the first estimations of the BABET-REAL5 biorefinery (EROI = 1.16 $MJ\ MJ^{-1}$; CF = 0.31 $g\ CO_{2-eq}\ MJ^{-1}$ if bioethanol was considered as the unique product), the average EROI and CF decrease to 1.73 $MJ\ MJ^{-1}$ and 1.39 $g\ CO_{2-eq}\ MJ^{-1}$. That is to say, the total CF would be 1.7% of the CF of petrol (83.8 $g\ CO_{2-eq}\ MJ^{-1}$, [17]). Therefore, this bioethanol will be sustainable according to the European Union norm [17].

Finally, the assessment done by this study allows describing the current condition of these forest plantations according to some of the main potential environmental impacts (availability of resources, soil erosion, EROI and CFs). However, the other dimensions such as water footprint, biodiversity loss [85] and eutrophication need to be studied to improve the LCA estimations as a strategy to identify, categorize and hierarchize the environmental impacts that must be mitigated by its degree of relevance according to the global impacts of the whole supply chain impact. Currently, according to Cravino and Brazeiro [86] grassland afforestation generates a negative impact at a local scale on the assemblage of medium- and large-sized native mammals, reducing cumulative species richness and capture rate compared with grasslands. Freshwater ecosystem modifications have shown that litter decomposition was inhibited at 36% in Uruguay [87] without significant differences in water chemistry between forested and not forested basins, information that does not agree with the water stream acidification reported by Farley [88]. Results that are now important for two dimensions of LCA are water footprint and lost biodiversity. In addition, the hydrological studies of these forest plantations described a decrease in annual specific discharge (17%) for mean hydrological years relative to a pasture watershed [89].

The sustainability of all the supply chains will be highlighted in the near future, in particular by direct and indirect consequences of Global Warming that will discriminate the main supply chains by their total environmental impacts. This fact will change the willingness to pay, feedstock availability will not be enough. Signs in this direction have been started by the Food and Agriculture Organization of the United Nations (FAO) with Livestock Environmental Assessment and Performance guidelines of FAO [90]. The forestry sector will go in the same direction [85,91] and the comparisons between suppliers will be more important [92,93]. Supply chain sustainability will require to systematize research results, mainly in developing countries, at least the minimal descriptions about the common set of environmental categories used in an LCI assessment [94,96]. In this

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framework, the current information pointed out that Uruguay has the feedstock availability to hold a biorefinery and first good results about some environmental impacts, but the current approach is not enough to avoid the impacts on its soils and waters [20,97]. In the future, improvement in the information about water and biodiversity footprints would be required.

5. Conclusions

Based on the current results, it is possible to meet the feedstock requirements of a second-generation biorefinery. First, if it is considered that using logs with diameters between 19 and 6 cm to maintain the soil nutrient balance is a sustainable wood extraction scenario. Second, the plantations for solid wood did not show any significant soil erosion process due to agricultural activity. Third, the EROI and CF showed acceptable values, and therefore this supply chain can be considered sustainable according to the current knowledge about published environmental impacts.

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Abbreviations

The following abbreviations are used in this manuscript:

CF	carbon footprint
EROI	Energy retun on investment
LCA	Life Cycle Assessment

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Table A1

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Table A1. Life cycle inventory of solid wood from 21 years Eucalyptus grandis plantations for sawmill and pulp mill

Operations	Amount	Unit	Source
Nursery			
Diesel oil	497.3×10^{-6}	kg/tree	[58]
Liquid petroleum gas	3.04×10^{-3}	MJ/tree	[58]
Gasoline (used as fuel)	1.7×10^{-6}	m3/tree	[58]
Electricity	19.7×10^{-3}	Kwh/tree	[58]
Heavy fuel oil (used for heat)	4.2×10^{-3}	L/plant/tree	[58]
Wood (for heat)	2.8×10^{-3}	kg/tree	[58]
Carbaryl	14.3×10^{-6}	kg AI/tree	[58]
Glyphosate	8.0×10^{-6}	kg AI/tree	[58]
Granular mixed fertilizer (15–15–15)	7.2×10^{-3}	kg	[58]
Ammonium sulfate fertilizer	545.5×10^{-6}	kg	[58]
Urea fertilizer	545.5×10^{-6}	kg	[58]
Surface water	23.9	L	[58]
Soil preparation			
Ant control			
Fipronil	6	Kg/ha	data from this research
Excentric and Tractor (60kW, 80HP, 3683 kg)	0.5	d/ha	[58]
Excentric and Tractor (54kW, 75HP, 3240 kg)	0.5	d/ha	[58]
Ripper (1 shaft every 5 m) and			data from this research
Tractor (54kW, 75HP, 3240 kg)	0.5	d/ha	[58]
Diammonium phosphate 18/46/0	110	Kg/ha	data from this research
Oxufluorfen	4.5	L/ha	data from this research
Total fuel	200	L/ha	data from this research
CO2 emission	544	kg/ha	
NOx emission	11.3	kg/ha	
Plantation			
Diammonium phosphate 18/46/0	80.0	Kg/ha	data from this research
Glyphosate	12.6	Kg/ha	data from this research
7:6 m boom sprayer 670 kg	0.03	Kg/ha	data from this research
Tractor (37kW, 50HP, 2572 kg)	0.129	Kg/ha	[58]
Tractor (54kW, 3240 kg)	0.5	Kg/ha	[58]
Fipronil	2.5	Kg/ha	data from this research
Tractor (54kW, 3240 kg)	0.97	Kg/ha	[58]
Glyphosate	13.24	Kg/ha	data from this research
Fipronil	12.0	Kg/ha	data from this research
Tractor (54kW, 3240 kg)	0.97	Kg/ha	[58]
Total fuel	80.0	kg/ha	data from this research
CO2 emission	246	kg/ha	[51]
NOx emission	5.08	kg/ha	[51]
1st thinning			
Chainsaw 50 cc	6	trees/ha	data from this research
Harvested trees	165	trees/ha	data from this research
Harvest time	27.5	h	data from this research
50:1 mixture of gasoline and 2-cycle engine oil	12.8	L/ha	data from this research
Lubricant	22.5	Kg/ha	data from this research
Grapo EcoLog 574F 20000kg	1.6	kg/ha	data from this research
Truck	30	m3/roundtrips	data from this research
Load and distance	287	t*km	data from this research
Total fuel	15.6	kg/ha	data from this research
CO2 emission	42.5	kg/ha	[51]
NOx emission	0.9	kg/ha	[51]
2nd thinning			
Feller Tigercat 720	1.7	kg/ha	data from this research
Harvester:Forwarder (1:2)			data from this research
X 2 forwarders mass	50.7	kg/ha	data from this research
Grapo EcoLog 574F	27.3	kg/ha	data from this research
Truck Volvo 400	106.7	kg/ha	data from this research
Load and distance	3126.0	t*km	data from this research
Total fuel	527.3	kg/ha	data from this research
CO2 emission	1433.7	kg/ha	[51]
NOx emission	29.7	kg/ha	[51]
Harvest			
Feller Tigercat 720	8.48	kg/ha	data from this research
Performance	150.0	m3/h	data from this research
time of work	5.3	h/ha	
Harvester:Forwarder (1:2)			
Harvester Tiger Cat 845	33.3	kg/ha	data from this research
Performance	49	m3/h	data from this research
time of work	11.9	h/ha	data from this research
Forwader PONSSE Buffalo	10.49	kg/ha	data from this research
time of work	16	h/ha	data from this research
Performance	37.6	m3/hr	data from this research
Grapo EcoLog 574F	132.8	kg/ha	data from this research
Truck	30	Ton/round trip	data from this research
Harvested mass	303.74	ton	biomass yield from INIA's model
Load and distance	15187	t*km	data from this research
Total fuel	3259.7	kg/ha	data from this research
CO2 emission	8862.4	kg/ha	[51]
NOx emission	183.4	kg/ha	[51]