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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 of 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

Citation: Rachid-Casnati, C.; Resquin, F.; Carrasco-Letelier, L. Availability and Environmental Performance of Wood for a Second-Generation Biorefinery. *Forests* **2021**, *12*, 1609. https://doi.org/10.3390/f12111609

Academic Editor: Tripti Singh

Received: 5 October 2021
Accepted: 29 October 2021
Published: 22 November 2021

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 assessment (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 overlapping or to contradict these goals and new proposals such as the circular economy, reuse economy, and bioeconomy (Figure 1), mainly for reduction of raw material consumption, fossil energy, and production of waste. Along the same lines, 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 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 they are based on the coproduction of several biobased products.

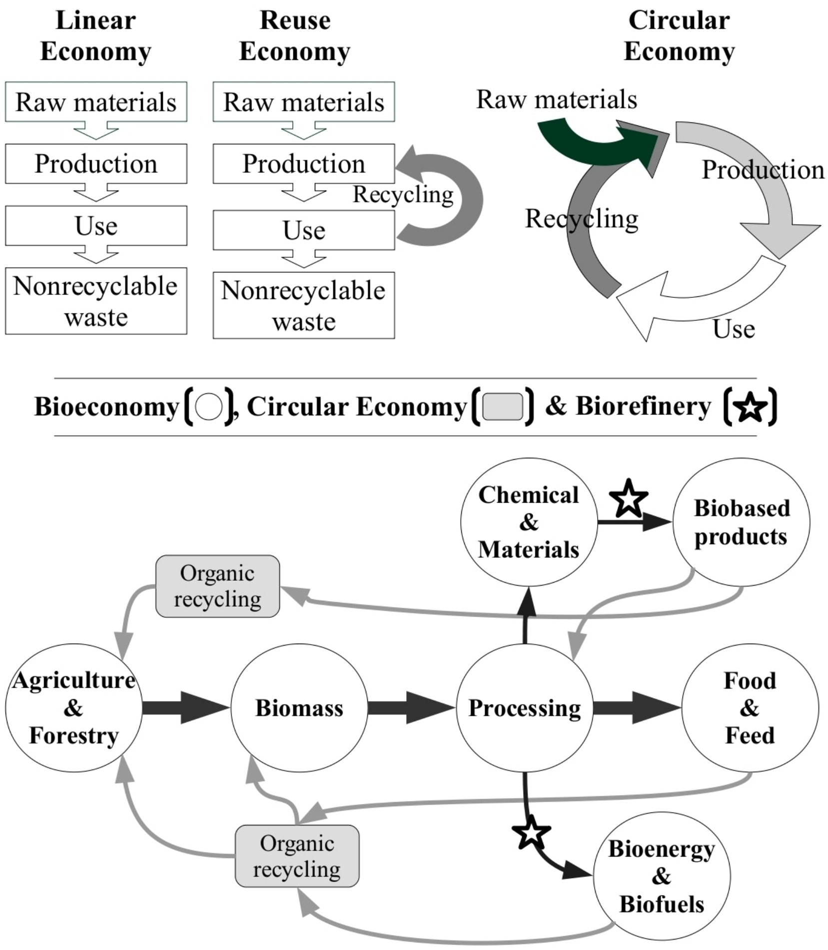

Figure 1. Flux diagrams of a linear economy, reuse economy, circular economy, bioeconomy, and the potential niches for biorefineries.

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 why 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 field can only be harvested in the amount that is required to maintain the soil organic matter and soil fertility. If these variables are not considered, the harvest of agriculture/forest residues would reduce 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 meet the requirements 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 afford a circular economy scheme and a bioeconomy using biorefineries mainly, using harvest residues or wood from forests planted for solid wood purposes 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.) that are prioritized for forestry by law (Figure 1) due to their low suitability for food production. Currently, forest plantations cover over 1,000,000 of the 4,420,000 hectares prioritized 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 discarded due to small diameter of logs. In the country's northwest, currently, these solid wood plantations occupy almost 200,000 ha [26] (Table 1). The genera planted are *Eucalyptus* (*E. grandis*) and *Pinus* (*P. taeda*, *P. elliottii*) at a ratio of 70% and 35%, respectively, and the harvest age varies from 18 to 22 years. 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 of solid wood forest production to supply 30,000 t of 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 catchment in the northeast by applying biomass coefficients. Second, the acceptability of environmental performance of this wood supply chain was evaluated through EROI, carbon footprint (CF), and soil erosion. These analyses assumed that a conservative scenario (e.g., area planted, growth behavior, and tree species) would remain constant for the next 25 years.

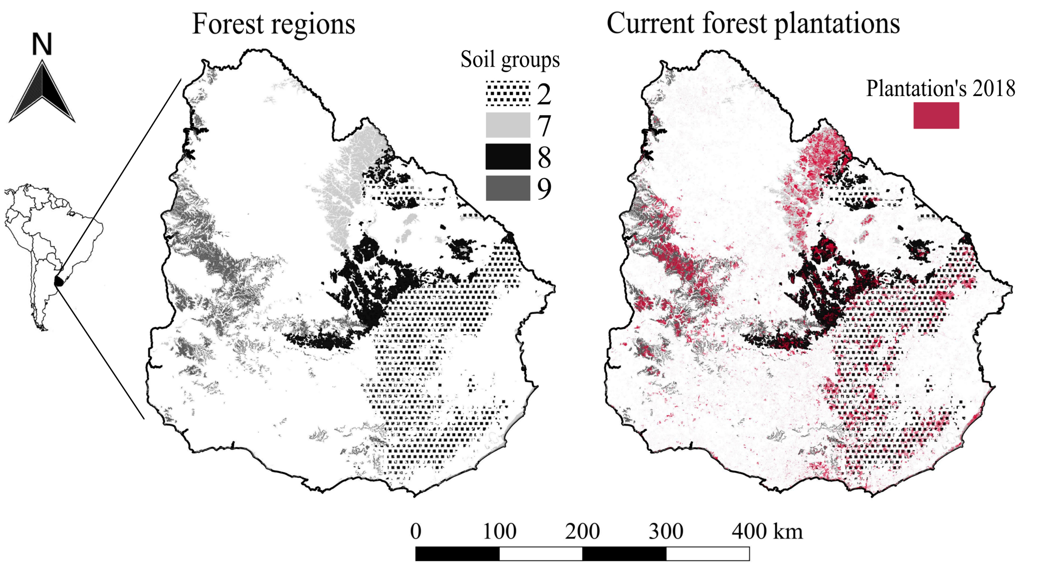

Figure 2. Left map: Regions prioritized for forest plantations (black and gray patterns) according to the National Commission for Agroeconomic Studies of the Land Classification (CONEAT), soils corresponding to groups 2, 7, 8, and 9 have adequate soil fertility for forest plantation. Right map: The current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

Table 1. Plantation area (ha) according to the species planted in the region [26].

Species	Department		Total Planted Area
	Rivera	Tacuarembó	
Pinus taeda *Pinus elliotii*	74.107	62.158	136.265
Eucalyptus grandis *Eucalyptus saligna*	45.038	23.441	68.479

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 2).

Table 2. 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

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 km^2 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 1.5–3 m). These soils were classified as acrisols and luvisols according to the Uruguayan soil taxonomy [33]. The parent material are sandstones from the Tacuarembó or Rivera [34–36].

2.2. Estimation of Potential Wood Supply

Plantation management changes considering the final product (i.e., pulp or solid wood). Solid wood production of *Eucalyptus* is the main target of the forest plantations analyzed (Figure 4, Tables 3 and 4). The forest plantation considered: (1) a mean harvest rotation age of 11 and 21 years for thinning and clear cut, respectively (Table 5), (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 Appendix A. The potential wood supply was estimated through the four following sequential steps.

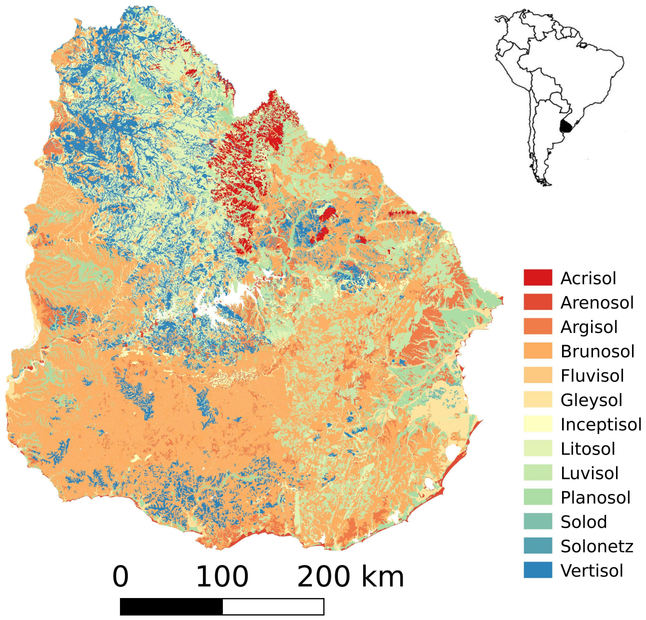

Figure 3. Soil taxonomy map of Uruguay according to Durán and García-Préchac (2007) elaborated by Beretta-Blanco and Carrasco-Letelier [18].

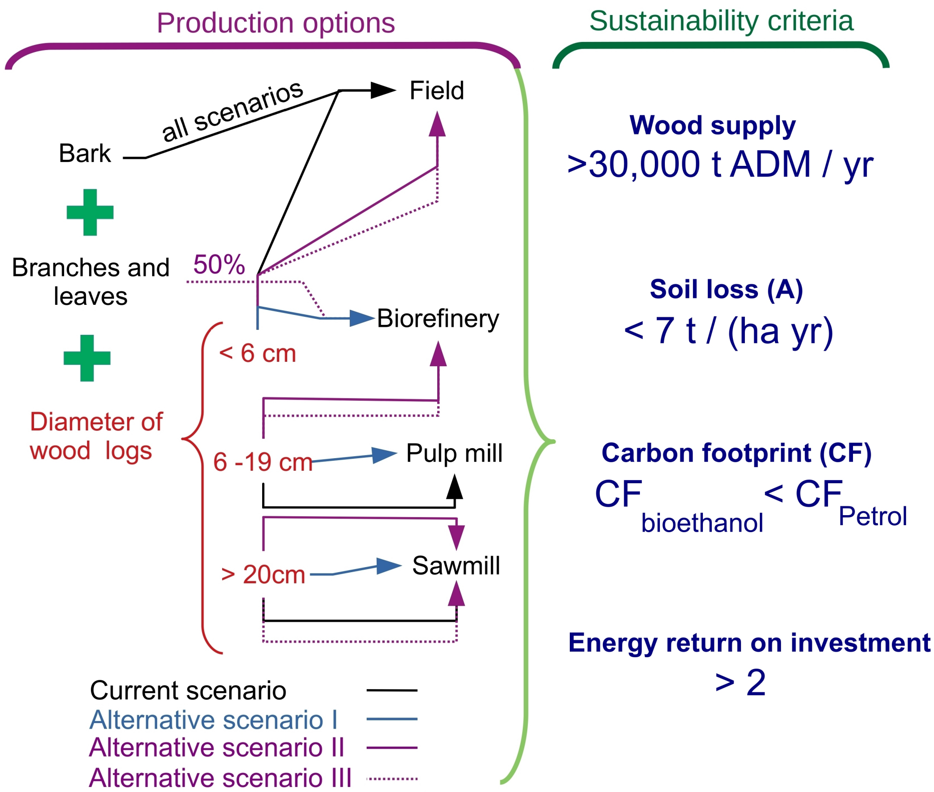

Figure 4. Production scenarios and sustainability criteria assessed.

Table 3. *Eucalyptus grandis* wood composition expressed in percentage, according to Lima et al. [37].

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

Table 4. Solid wood production with *Eucalyptus* plantations.

	Planting	Thinnings		Harvest
		1st	2nd	
Age (years)	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 5. Operations of *Eucalyptus* plantations for sawmills and plywood mills.

Operation	Year	Description
Ant control	0–1.5	2–4 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	0–2	Postemergent previous plantation, pre-emergence on the plantation and postemergence one or two times up to canopy closure
Thinnings	2–11	2–3 thinnings depending on site quality and company purposes
Prunings	2–11	2–3 prunings depending on site quality and company purposes up to 6.5 or 9 m
Preharvest	16–19	Ant's control
Harvest	16–21	Cut-to-length systems mainly, but full-tree systems can occur depending on topography and density

Solid wood production of *Eucalyptus grandis* was the analyzed supply chain. Based on the current management practices and biomass coefficients available, the forest plantation considered: (1) a mean harvest rotation age of 11 and 21 years for thinning and clear cut, respectively (Table 5), (2) a minimum log diameter of 19 cm for supplying local sawmills and board mills, and (3) the remaining portion of the stems was considered as a potential source of biomass Appendix A. The potential wood supply was estimated through the four following sequential steps.

1. Plantation plans recorded by the Government (Dirección General Forestal, DGF) for the region since 1975 were gathered and classified for the species and purpose of interest. This information included registration number of the plantation plan, the species (pines and eucalypts), plantation date, intended product (solid, pulp, etc.), number of trees per hectare, effective planted area, and cadastral number (land registration number).
2. Plantation plans were georeferenced through its corresponding cadastral number (land registration number) within the georeferenced national cadastral records [38]

and checked with the geographical information system (GIS) of the National Forest Inventory for years 2010, 2011, and 2014 [39]. The GIS information was processed and analyzed with QGIS [40].

3. Based on biomass coefficients provided for *Eucalyptus grandis* in the northern region by previous work [41], we applied coefficients considering different tree fractions and stem portions usage: (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. Coefficients applied are depicted in Table 6.
4. Considering the plantation date of each record, we assumed one commercial thinning at age 11 years and the clear cut at age 21 years (Table 4). We also assumed that the biomass formed at the first thinning was not exported and therefore was not computed. For year 11 and 21, the planted area for each record was multiplied by the estimated amount of dry matter per hectare considering tree fractions and stem portions usage listed in step 3. The maximum amount of forest biomass was calculated for a catchment area of 50 km radius located in the center of the most planted area.

Table 6. Biomass coefficients applied for *Eucalyptus grandis* in the North region [41].

Wood and Fractions	Biomass (tDM yr^{-1})	
	Commercial Thinning	Clearcut
Total biomass considering wood under <19 cm diameter	47.5	45.9
Debarked wood between 6 and 19 cm diameter plus 50 % of branches	35.0	21.2
Debarked wood between 6 and 19 cm diameter	31.7	17.8
Tips (wood < 6 cm diameter)	0.7	1.3

In the framework of potential harvestable biomass, this work analyzed the potential production of different feedstock scenarios (Table 7). Steps 1–4 provided 4 datasets comprising information for a 25-year period of potential biomass yearly harvested, summarized by land registration number for the species and region assessed. Those corresponded to the 3 feedstock scenarios analyzed and total residues.

Table 7. Potential feedstocks scenarios using different fractions of trees.

Options	Branches and Leaves	Bark	Diameter of Logs		
			>20 cm	19–6 cm	<6 cm
Current Scenario	Field	Field	Sawmill and plywood mill	Pulp mill	Field
Scenario I	Field	Field	Sawmill and plywood mill	Pulp mill	Biofuel plant
Scenario II	Field	Field	Sawmill and plywood mill	Biofuel plant	Field
Scenario III	50% Field 50% Biofuel plant	Field	Sawmill and plywood mill	Biofuel plant	Field

2.3. Estimation of Soil Loss

Estimation of the mean annual soil erosion (A in Figure 4) was performed using the information required by the universal soil loss equation/revised universal soil loss equation (USLE/RUSLE) model (Equation (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 (Equation (1)), where each factor of the equation 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 performed 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 far 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.

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 processes (engines and machinery, pesticides and fertilizers [50]) were estimated according to their corresponding rate and conversion factors into energy units (MJ) (Table 8). When the primary national data of a particular input or emission were not available, information from the literature with similar regional conditions was used [51]. In the worst scenario, when the regional data were not available, international databases were used [52–55].

2.4.2. Carbon Footprint (CF)

LCI was evaluated in a spreadsheet using information from interviews and forest company records. This information was transferred to the OpenLCA software [55] 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 [56], 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 [52] because there are no national records of these fuel consumptions. These conversion factors have low variability between countries [53]. The NO_x emissions were not taken into account because no validated model is available.

Table 8. Energy conversion factors used for EROI estimation.

Inputs	Units	MJ Unit^{-1}	Reference
Fuel	L	38.6	[57]
Herbicide	L	327	[58]
Machines	kg	68.9	[57]
Lubricant	L	38.6	[57]
Formicide	kg	184.7	[58]
Electricity	Kwh	3.6	
Liquefied petroleum gas	Kg	30.33	[59]
Gasoline	L	39.61	[59]
Glyphosate	Kg	476	[60]
N-fertilizer	Kg	51.47	[61]
P-fertilizer	Kg	9.17	[61]
K-fertilizer	Kg	5.96	[61]
Ammonium sulfate fertilizer	Kg	1.12	[59]
Urea	Kg	75.63	[59]
Insecticide	Kg	325	[61]
Eucalyptus globulus	Kg	19	INIA's data

3. Results

3.1. Potential Wood Supply

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 39,772 ha. Based on this area and using biomass coefficients [41], 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 5).

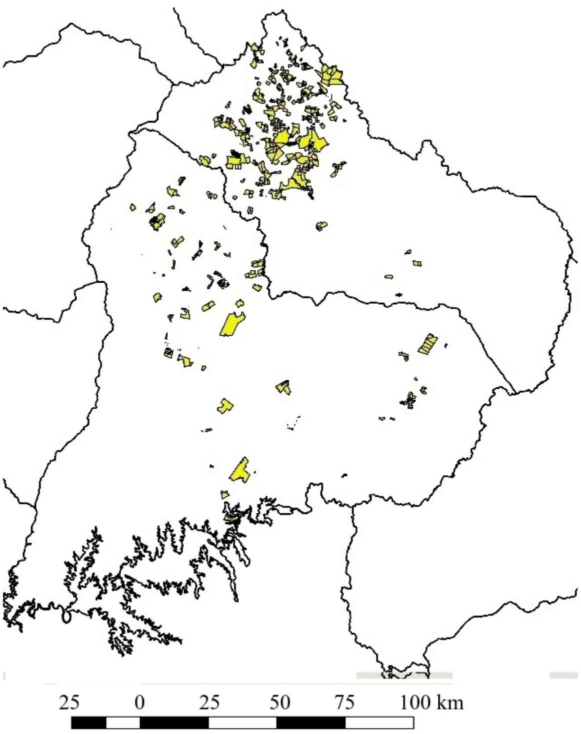

Figure 5. *Eucalyptus grandis* plantations for sawmilling and plywood purposes in Rivera and Tacuarembó (in yellow).

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 each year. However, harvests can be delayed or advanced depending on market prices, feedstock needs, etc. The potential feedstock production for the scenarios of Table 7 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 6. Tips (scenario I) with a diameter smaller than 6 cm provide small amounts of biomass (3.9 t yr^{-1}), whereas logs with a diameter between 6 and 19 cm (scenario II) showed an annual average yield of 81,800 t air-dry matter (ADM) and a range of 40,000–150,000 t ADM. Finally, scenario III shows an annual average yield of 91,900 t ADM, with a range between 50,000 and 160,000 t ADM.

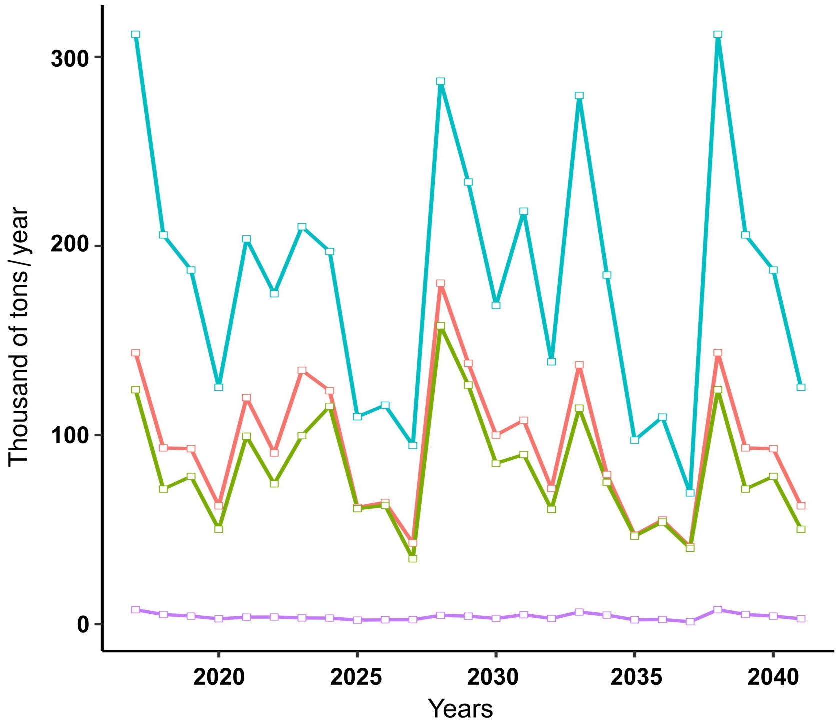

Figure 6. Projections of *Eucalyptus grandis* biomass production considering scenarios described in Table 7. Total residues (cyan); scenario I, wood and branches below 6 cm in diameter (purple); scenario II, wood from logs with a diameter between 6 and 19 cm (green); and scenario III, wood from logs with a diameter less than 19 cm and 50% of harvested branches (orange).

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 7C) with an annual erosion higher than the tolerable value (7 Mg ha^{-1} yr^{-1}). This occurs in steep, sandy loam soils [19,36,62]. In this catchment area of 73,152 ha (Figure 7D), 7.8% is found on soils with erosion greater than tolerable.

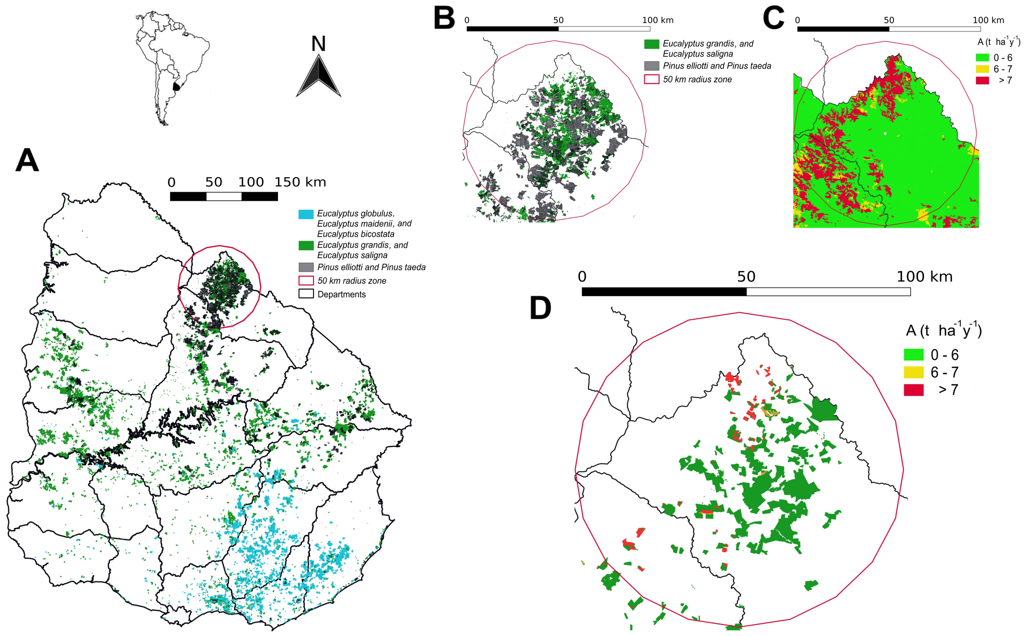

Figure 7. (**A**) Current forest plantations reported by forest statistics 2019, (**B**) forest plantations in a 50 km radius zone, (**C**) soil erosion by water estimated by Carrasco-Letelier and Beretta-Blanco [18] and (**D**) soil erosion in plantations considered by this study.

3.3. EROI and CF

Most of the information about inputs, machinery characteristics, lifespans, fuel consumption, and other subjects were obtained from interviews with different forest companies. When the data were not available, the information was obtained from peer-reviewed publications. In exceptional cases, the information was obtained from the non-peer-reviewed literature. Most of the information gap was on tree nurseries; in this case, the data contained in Heller et al. [60] 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 (Table 9). 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.

Table 9. Energy inputs and energy output of agroindustrial forestry chain. All values are expressed in MJ ha^{-1}.

	Total Biomass	Solid Wood	Current Scenario	Scenario I	Scenario II	Scenario 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	1912	1912	1912	1912	1912	1912
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

The CF results showed a mean value of 1.22 Kg CO_{2-eq} per cubic meter of wood per year or 25.8 Kg CO_{2-eq} m^{-3} for a 21 year-old wood (Table 10). 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.

Table 10. Global warming power for 100 years expressed in kg CO_{2-eq} m^{-3} of wood produced per year. Percentage of carbon footprint of current scenario in brackets.

	Total Biomass	Solid Wood	Current Scenario	Scenario I	Scenario II	Scenario III	Mean	Minimum	Maximum
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
First thinning	0.0263	0.0140	0.0128 (1.3%)	0.0127	0.1277	0.0197	0.0547	0.0127	0.1277
Second 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

4. Discussion

4.1. Potential Wood Supply

The wood availability in the different scenarios presented adequate volumes to satisfy the annual demand consumption (30,000 ADt) with scenarios II and III. However, scenarios 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 [63,64]. 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 the annual crops in Uruguay in the last decade [20]. In the same trend, Bentancor et al. [65] and Resquin et al. [66] 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 [66–69].

For the assessed region, the wood that is 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 [70] and 471 km [71] far from the center of the 50 km radius catchment area proposed in this study, and a third pulp mill will be located 221 km [72] far from the catchment center. Regionally, a new pulp industry could constitute the main threat for a sustained feedstock supply for a second-generation biorefinery. Therefore, because of a decrease in the freight distance, the competition for smaller pieces of *Eucalyptus grandis* increases, as does the price. The less favorable wood availability projections determine annual averages in the range of 27,000–45,000 ADt. By contrast, the distance from the nearest pulp mill would be four times or more than the harvest radius of the biorefinery. Therefore, there is a willingness to pay a near biorefinery 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 the 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 would increase the Eucalyptus wood to 90,000 ADt per year.

The 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]. Water erosion of the soil corresponds to a natural risk, that is, soils with high slope and structural fragility that are present in soils prioritized for forestry [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 area. Therefore, the erosion was not due to the afforestation but to their high sand content and steep slopes. Thus, the higher 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 remain 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], Kim and Dale [77], and Pimentel and Patzek [78], respectively. The EROI of 50 is close to the values reported by Romanelli and Milan [51] 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, this potential advantage depends on the industrial technology since 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 [52] (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], and 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 the longest-running experiments on this kind of Uruguayan agriculture production, which allow one to estimate their impact. The situation that does not occur with annual rainfed crops that started the longest-running rainfed crop experiments in 1914, updated it 1964 [85], is complemented by the other longest-running experiments in the country [15,86].

This availability of biomass, EROI, and CF values suggests 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, bioethanol would be sustainable according to the European Union norm [17].

Finally, the assessment performed by this study allows the description of 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, other dimensions such as water footprint, biodiversity loss [87], 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 given its relevance according to the global impacts of the whole supply chain impact. Currently, according to Cravino and Brazeiro [88], 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 [89] without significant differences in water chemistry between forested and nonforested basins. This information does not agree with the water stream acidification reported by Farley [90]. The results that are relevant to the 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 [91].

The sustainability of all the supply chains will be highlighted in the near future, in particular by the direct and indirect consequences of global warming that will categorize the main supply chains by their total environmental impacts. This fact will change the willingness to pay, and feedstock availability will not be enough. Signs in this direction have been shown by the Food and Agriculture Organization of the United Nations (FAO) with Livestock Environmental Assessment and Performance guidelines of FAO [92]. The forestry sector will go in the same direction [87,93], and the comparisons between suppliers will increase in relevance [94,95]. Supply chain sustainability will require one 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 [96,97]. In this framework, the current information pointed out that Uruguay has the feedstock availability to hold a biorefinery and first results about environmental impacts. However, the current approach is not enough to avoid the impacts on its soils and waters [20,98]. In the future, the 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 considering the following criteria: (i) biomass availability larger than 30,000 tDM ha^{-1}; (ii) soil loss originated by crop less than 7 t (ha yr)$^{-1}$; (iii) EROI larger than 2; and (iv) a CF lower than Petrol's CF. First, we considered *Eucalyptus grandis* plantations specifically planted and managed for sawmill and plywood mill to use basal portions of stems up to a small-end diameter of 19 cm. For biorefinery purposes, using debarked logs with diameters between 19 and 6 cm would be recommended to attain at least twice the minimum amount of biomass required while maintaining the soil nutrient balance in a sustainable wood extraction scenario. Second, soils corresponding to plantations for solid wood did not show any significant soil erosion process due to agricultural activity. Although 17.8% of the catchment area show soil erosion larger than the tolerable thresholds, the soil erosion by water is rather linked to terrain and soil local characteristics. Third, the EROI considering cradle to gate analysis, and CF, showed acceptable values. Therefore, this supply chain can be considered sustainable according to the current published knowledge about environmental impacts. Future studies should focus on assessing water and biodiversity footprints for complementing this feedstock analysis.

Author Contributions: F.R., C.R.-C. and L.C.-L. planned and designed the research. F.R., C.R.-C. and L.C.-L. conducted fieldwork and performed experiments. F.R., C.R.-C. and L.C.-L. contributed to data elaboration and analysis. L.C.-L. wrote the manuscript, with contributions from all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the European Commission in the frame of the BABET-REAL5 project (Horizon 2020 Program, Project No. 654365, accessed on 1st November 2021. http://www.babet-real5.eu).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request to corresponding author.

Acknowledgments: The authors thank the INIA (accessed on 1st November 2021) http://inia.uy, MGAP https://www.gub.uy/ministerio-ganaderia-agricultura-pesca and forest companies for their collaboration with the information and databases.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CF	Carbon footprint
EROI	Energy return on investment
LCA	Life cycle assessment

Appendix A

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	[60]
Liquid petroleum gas	3.04×10^{-3}	MJ/tree	[60]
Gasoline (used as fuel)	1.7×10^{-6}	m^3/tree	[60]
Electricity	19.7×10^{-3}	Kwh/tree	[60]
Heavy fuel oil (used for heat)	4.2×10^{-3}	L/plant/tree	[60]
Wood (for heat)	2.8×10^{-3}	kg/tree	[60]
Carbaryl	14.3×10^{-6}	kg AI/tree	[60]
Glyphosate	8.0×10^{-6}	kg AI/tree	[60]
Granular mixed fertilizer (15–15–15)	7.2×10^{-3}	kg	[60]
Ammonium sulfate fertilizer	545.5×10^{-6}	kg	[60]
Urea fertilizer	545.5×10^{-6}	kg	[60]
Surface water	23.9	L	[60]
Soil preparation			
Ant control			
Fipronil	6	Kg/ha	data from this research
Excentric and tractor (60 kW, 80 HP, 3683 kg)	0.5	d/ha	[60]
Excentric and tractor (54 kW, 75 HP, 3240 kg)	0.5	d/ha	[60]
Ripper (1 shaft every 5 m) and			data from this research
Tractor (54 kW, 75 HP, 3240 kg)	0.5	d/ha	[60]
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
CO_2 emission	544	kg/ha	
NO_x 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 (37 kW, 50 HP, 2572 kg)	0.129	Kg/ha	[60]
Tractor (54 kW, 3240 kg)	0.5	Kg/ha	[60]
Fipronil	2.5	Kg/ha	data from this research
Tractor (54 kW, 3240 kg)	0.97	Kg/ha	[60]
Glyphosate	13.24	Kg/ha	data from this research
Fipronil	12.0	Kg/ha	data from this research
Tractor (54 kW, 3240 kg)	0.97	Kg/ha	[60]
Total fuel	80.0	kg/ha	data from this research
CO_2 emission	246	kg/ha	[52]
NO_x emission	5.08	kg/ha	[52]

Table A1. *Cont.*

Operations	Amount	Unit	Source
First 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 574 F 20,000 kg	1.6	kg/ha	data from this research
Truck	30	m^3/round trips	data from this research
Load and distance	287	t*km	data from this research
Total fuel	15.6	kg/ha	data from this research
CO_2 emission	42.5	kg/ha	[52]
NO_x emission	0.9	kg/ha	[52]
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 574 F	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
CO_2 emission	1433.7	kg/ha	[52]
NO_x emission	29.7	kg/ha	[52]
Harvest			
Feller Tigercat 720	8.48	kg/ha	data from this research
Performance	150.0	m^3/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	m^3/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	m^3/hr	data from this research
Grapo EcoLog 574 F	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
CO_2 emission	8862.4	kg/ha	[52]
NO_x emission	183.4	kg/ha	[52]

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