

Article

Harvest Residue Decomposition from *Eucalyptus* sp. Plantations in Temperate Climate: Indicators and Contribution to Nutrient Cycling

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Abstract: The sustainable management of forest plantations by keeping the harvest residues on site improves the soil's chemical, physical and biological properties while constituting an important nutrient reserve. Our objectives were: (a) to identify and quantify the characteristics of *Eucalyptus dunnii*, *Eucalyptus grandis* and *Eucalyptus globulus* that affect the decomposition rates of harvest residues, as well as indicators that can explain the process and (b) to quantify the potential recycling of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) to the soil from residue decomposition and the quantitative and qualitative differences between the species. We analyzed the information of five commercial plantations of Uruguay. At the harvest, the biomass of leaves, thin and thick branches, bark and their respective N, P, K, Ca and Mg contents were quantified. At each site, bags with samples of the different residues were left to decompose and were periodically collected throughout 24 months. *Eucalyptus dunnii* presented the largest amounts of residues of all parts. The decomposition rates of the different residues depended on their chemical constitution, part size and the species. *Eucalyptus dunnii* leaves showed the shortest half-life (0.94 years), while the bark of the same species presented the longest (5.62 years). Total nitrogen and carbon (total and soluble) contents, which can be easily determined, emerged as good predictors for half-life estimation. The release patterns of nutrients depended more on their dynamics in the plant and their parts than on the species itself. The results highlight the importance of nutrient recycling to ensure the sustainability of the productive system in the medium and long term.

Keywords: harvest residues half-life; nutrient recycling; sustainability of the forest system; Uruguay



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1. Introduction

Eucalyptus sp. plantations cover almost 1 million hectares in Uruguay, being the main source of wood production in the country [1]. Of these, around 40,000 ha are harvested annually, expecting a significative increase in the short term. The sustainable management of these plantations is based on practices that seek to conserve the stocks of soil organic matter (SOM) and nutrients, both key components of soil fertility, and are mainly supported via the contributions of mulch (litter) and root replacement during the plantation cycle and through the harvest residue decomposition in the replanting of the site. Therefore, keeping these residues in the field has a great impact on soil nutrients [2] and SOM stocks [3], further helping to sustain the initial growth of trees [4].

Maintaining soil with residues improves the different chemical, physical and biological properties of the soil, resulting in an improvement in soil quality, while constituting a proportionately important nutrient reserve [5].

Harvest residues, although they represent a smaller proportion of the total aerial biomass produced (about 30%), contain most of the nutrients absorbed [6], which, through their decomposition, can be used by the next plantation. Understanding the dynamics and the factors that affect the decomposition and their effects on soil fertility is relevant to the management of forest plantations [7].

Spangenberg et al. [8] established that both the quantification of the nutrient content in the different forest plantations and the knowledge of the relationship between the export of nutrients and those that are available in the soil for subsequent reuse are essential for defining management strategies with the aim of maintaining the sustainability of the ecosystem.

The decomposition of the different components of the aerial biomass that remain at the site (bark, branches and leaves) on the soil occurs at variable rates and depends on the intrinsic characteristics of the residue itself in terms of its physical and chemical structure [9], specific climatic conditions such as humidity and temperature [10,11], and the period of time during which the processes occur. Regarding the effect of these factors on the process, [12] indicates that there is still little knowledge about the decomposition of lignified woody residues, particularly in ecosystems of *Eucalyptus* sp., recognizing that the climate has an important control on a regional scale but not so when evaluated in narrower ranges. Ferreira et al. [13] reported that the decomposition of residues and the nutrient release were more controlled by the chemical properties of the residues than by climatic or soil characteristics. Similarly, De Souza [14] identified that rainfall increases did not accelerate the decomposition times of surface residues, even though it did for residues that were buried.

N contents, as well as the carbon (C):N ratio, are very important in the decomposition rate of plant materials [15], since microorganisms, although they base their activity on the availability of carbon, need certain amounts of the other nutrients, and given the scarcity of the latter, decomposition is slowed. In residues of large physical size and little contact with the soil—such as branches—their slow decomposition acquires even more relevance, because, when residues are incorporated, the mineral N of the soil is immobilized by the microbial biomass and, in this way, the soil provides the N necessary for growth [16]. The lignin (L) and phenolic compounds content in plant residues also affect the N mineralization [17]. Higher lignin content makes the materials more resistant to decomposition, so residues with high L:N ratios tend to decompose slowly [10,18]. In turn, phenolic compounds act as microbial inhibitors affecting the decomposition processes and nutrient cycles of the soil through multiple mechanisms [19].

Since *E. grandis* and *E. globulus* are widely planted species of the genus *Eucalyptus* (*E. grandis* is found in Brazil, Argentina, South Africa, Sri Lanka, India or New Zealand and *E. globulus* in Spain, Portugal and Chile), experimental information for both regarding the decomposition of residues is widely available, although it is mostly derived from climates different from that of Uruguay. However, experimental information on the recycling of nutrients from the harvest residues is limited, despite its importance for developing a fertilization program for the future replanting of the site. On the other hand, for the species *E. dunnii*, there is little information available worldwide regarding the rates of residue decomposition or the process of nutrient recycling, since this species has only rarely been planted across the globe—although today it shows a clear expansion in temperate regions—despite being the species most commonly planted in Uruguay. Thus, there is a need for comparative experimental information about the decomposition rates of residues and recycling of nutrients to the soil by these species, which will allow researchers to obtain specific parameters that can be used in models of decomposition and cycling of nutrients from regions climatically such as the one corresponding to this research.

The hypothesis of this work was that the decomposition rate of the different harvest components of *Eucalyptus* sp. is variable and highly dependent on particle size and chemical constitution, as well as on the species itself.

The main objectives of this work were:

- (a) To identify and quantify the characteristics of each species (*E. dunnii*, *E. grandis* and *E. globulus*) that affect the decomposition rates of the different harvest residues, as well as the indicators that can explain the process.
- (b) To quantify the potential recycling of N, P, K, Ca and Mg to the soil from the decomposition of these residues and assess the quantitative and qualitative differences between the species evaluated.

2. Materials and Methods

The studies of the residue decomposition “in situ” were carried out after harvest of commercial plantations of the genus *Eucalyptus* (*E. dunnii*, *E. grandis* and *E. globulus*), destined for the production of cellulose, between 9 and 10 years old and located in the northeast and west of the country. In 2 of the 5 cases, previously published information was used [20,21]. At all the sites, the methodology regarding the quantification of harvest residue, soils and plant sampling was similar. The harvests were carried out between 2007 and 2011, between the months of June and September.

- Location of experimental sites

The coordinates of the different experimental sites as well as some of the properties of the soils (A horizon) are presented in Table 1.

Table 1. Coordinates, species, chemical and physical parameters of the A horizons (0–20 cm) of the soils.

Coordinates		Species	Soil Taxonomy	A Horizon Depth	pH (H ₂ O)	Clay	P (+)	TB	ECEC	OC
				cm		g kg ⁻¹	mg kg ⁻¹	cmol _c kg ⁻¹		g kg ⁻¹
32° 25' 56" S	57° 17' 40" W	<i>E. dunnii</i> *	Alfic Argiudoll	33	5.3	184	3	6.35	7.12	9.8
31° 52' 55" S	57° 30' 35" W	<i>E. grandis</i>	Abruptic Argiudoll	33	5.2	187	3	6.36	7.05	9.9
33° 25' 18" S	57° 48' 25" W	<i>E. globulus</i> **	Typic Hapludert	30	5.4	199	4	6.43	7.01	12.5
31° 08' 44" S	55° 37' 22" W	<i>E. grandis</i>	Humic Hapludult	57	4.5	118	3	2.53	3.57	6.3
31° 45' 40" S	56° 05' 35" W	<i>E. globulus</i>	Humic Hapludult	49	4.7	122	3	2.59	3.54	6.5

Note: pH 1:2.5 soil:water ratio; (+) P: available P (Bray 1); TB: total bases; ECEC: effective cation exchange capacity; OC: organic carbon (Walkley–Black). * [20], ** [21].

- Climatic characteristics of the study areas

According to the Köppen–Geiger climate classification, the territory of Uruguay corresponds to the temperate climate zone (Cf), with an average temperature of 17.5 °C (16 °C and 19.5 °C range, in the south and northwest, respectively), with hot summers, similar monthly average rainfall throughout the year and four clearly differentiated seasons. The highest temperatures occur in January and February, and the lowest in June and July, with greater thermal amplitude in the north than in the south. The relative humidity is high, ranging from 70% to 75% throughout the country.

The precipitation and average monthly mean temperature data recorded at the sites and the respective historical averages [22] are presented in Figure 1.

- Plant sampling and chemical analysis

Samples of known leaf weight (100 g) and thin branches (diameter < 1 cm, 150 g) were placed in mesh bags (1 mm²), while the pieces of thick branches (diameter > 1 cm and 15 cm long) and bark (15 cm long and 3–4 cm wide) were weighed and individually identified. As many samples of each component of the residues were prepared, sampling dates were planned, and they were placed on the ground in three zones (replications) according to topographical position. Each group of samples was protected with a wire mesh fabric (100 mm²). At pre-established sampling dates (1, 2, 4, 6, 9, 12, 18 and 24 months post-harvest), samples were taken from each residue (one by replication). At the time of harvest, samples were also taken from each component.

The samples of the different residues were dried at 65 °C to constant weight and subsequently milled to particle sizes of less than 0.5 mm for subsequent chemical analysis.

The concentrations of P, Ca, Mg and K of the samples were determined after dry combustion at 550 °C and ash dissolution through 10% HCl. In the extracts, P was determined via colorimetry [23], Ca and Mg via atomic absorption spectrophotometry and K via emission spectrophotometry. The determination of the N concentration in the sample was performed through the wet digestion of the sample (H₂SO₄ and catalyst mixture) and the subsequent distillation of N, according to the method by Kjeldahl [24]. The total carbon and soluble carbon contents of the residues were measured via oxidation with K₂Cr₂O₇ at 150 °C followed by colorimetric determination [24]. The determination of lignin was performed using acid hydrolysis with H₂SO₄ then diluted to an acid concentration of 3%, with subsequent boiling for 4 h and the filtering and determination of the remaining materials via gravimetry [25]. For the analysis of soluble polyphenols (Pol), the extraction was performed using H₂O and determination was carried out via colorimetry using the Folin–Ciocalteu method [26].

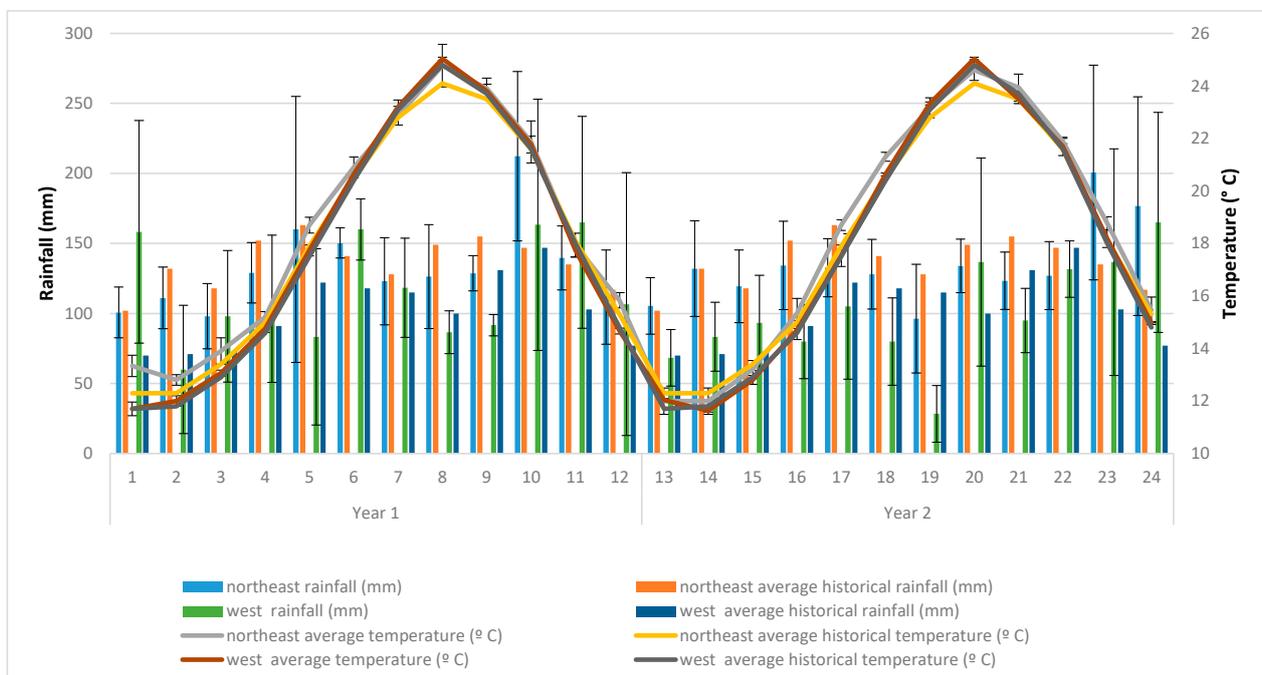


Figure 1. Precipitation and average monthly mean temperature of the sites were evaluated, as well as their deviations (between experiments) during the evaluations and historical averages [22].

- Calculations and statistical analysis of the information

The biomass data of harvest residues were annualized (dividing them by the age of the plantation) to facilitate their analysis and comparison.

The biomass decomposition was calculated as: biomass at time t (P)/initial biomass (P_{inic}) \times 100. From this, the rate of decomposition was calculated by adjusting an exponential decay model type $P/P_{inic} = e^{-kt}$, where P/P_{inic} is the proportion of the remaining material at a time t measured in years and k is the decomposition constant [27]. This model also allowed the calculation of the half-life in the years of the different crop residues ($t_{1/2}$).

For the three species studied: (1) analysis of variance was performed for (a) the amount of biomass residue according to species and (b) the half-life according to species and type of residue; (2) multivariate analysis was performed through the analysis of main components (PCA) of decomposition after 24 months, considering the different parts and species; and (3) the regression models for the decomposition of the different components according to different ratios (C:N, Pol:N and L:N) and the soluble carbon concentration.

As a first step, the normality of the variables under study (half-life) was verified via the Shapiro–Wilk test ($p > 0.05$ for normal data). The differences were considered statistically significant when $p < 0.05$ (Tukey’s test).

The correlations between the half-life of the different components were analyzed with respect to the ratios C:N, Pol:N and L:N, as well as in relation to the concentration of soluble carbon. For the correlation analysis, Spearman’s coefficient [28] was used since some of the variables did not have a normal distribution.

The nutrient contents of the residues were calculated considering the biomass of each component and the concentration of the nutrients at each date. In turn, the total nutrients released during the first 12 months and the entire period was calculated as the difference between the nutrient present in the residues at the end of the decomposition period (12 and 24 months) and the amount determined immediately after harvest.

3. Results

3.1. Amounts of Harvest Residues

Table 2 shows the annualized amounts of biomass residues by species. Most of the residues in all species corresponded to bark, followed by thick branches, with leaves and thin branches being the minority parts.

Table 2. Harvest residue biomass (dry matter) of *Eucalyptus* sp. annualized by species and percentage of each residue in the total of each species. Different letters in the same row indicate statistically significant differences.

Sample Type	<i>E. dunnii</i>	<i>E. grandis</i>	<i>E. globulus</i>	<i>E. dunnii</i>	<i>E. grandis</i>	<i>E. globulus</i>
	Mg ha ⁻¹ year ⁻¹			%		
Bark	3.0 (A)	1.9 (B)	1.8 (B)	33.3	36.6	46.2
Leaves	1.3 (A)	1.0 (B)	0.6 (C)	14.5	19.2	15.4
Thin branches	2.0 (A)	0.9 (B)	0.5 (C)	22.2	17.3	12.8
Thick branches	2.7 (A)	1.4 (B)	1.0 (C)	30.0	26.9	25.6
Total residues	9.0 (A)	5.2 (B)	3.9 (C)	100.0	100.0	100.0

For all sample types, the amount of residue biomass was significantly higher for *E. dunnii* than for the other two species; in turn, for *E. grandis*, the amount of residues was higher than *E. globulus* (except regarding bark) ($p < 0.05$).

3.2. Decomposition of Harvest Residues

Table 3 shows the parameters obtained from the adjustment of the decomposition model to the different residues of the three species during the 2 years following harvest.

The part with the highest decomposition rate were leaves, with a lower half-life and losses between 57% and 83% of their biomass in 2 years. The remaining components (bark, thick and thin branches) showed lower rates, reaching an average decomposition at the end of 2 years of 30% for bark and thick branches and 32% for thin branches. The weighted average determined that 37% of the total residues were degraded during the 2 years following harvest (*E. globulus* = 35.8%, *E. dunnii* = 37.1%, *E. grandis* = 38.2%).

Regardless of the species, the decomposition constant (k) was higher for the leaf part (range 0.43–0.74), and the lowest values were found, depending on the species, in bark (*E. dunnii*) or thick branches (*E. grandis* and *E. globulus*).

The analysis of variance for half-life determined differences in the interaction between species and parts. The leaves differ significantly from the other parts but also between species (*E. grandis* vs. *E. dunnii*). The *E. dunnii* bark was the part with the longest half-life, and for this species, the branches (thick and thin) had a shorter half-life than the bark, although without differences between them. In contrast, for *E. grandis* and *E. globulus*, the branches had a longer half-life than the bark. For *E. grandis*, the differences were significant between branches (thick and thin) and bark, while in *E. globulus*, differences were found between thick branches and bark.

The chemical characteristics of the different components at the beginning of the experiments are presented in Table 4. In the leaf parts, higher concentrations of carbon (total and soluble) as well as of N were observed. In turn, the C:N, Pol:N and L:N ratios were lower for this part, regardless of the species. For polyphenols, the highest concentrations were seen in leaves, while lignin concentrations did not differ greatly between the different components. The N concentration showed higher values in *E. dunnii* for the different parts, except for leaves.

Table 3. Adjustment of the decomposition model to the average of the sites for each species: percentage loss of biomass in 2 years, decomposition constant (k), model r^2 and half-life according to species and part. For half-life, different letters indicate statistically significant differences for species–part interaction.

Species	Sample Type	Biomass Loss (%)	K (year ⁻¹)	r ²	Half-Life years
<i>E. dunnii</i>	Bark	22	0.12	0.91	5.62 (A)
	Leaves	83	0.74	0.93	0.94 (G)
	Thin branches	35	0.19	0.95	3.61 (DE)
	Thick branches	33	0.18	0.95	3.75 (CD)
<i>E. grandis</i>	Bark	38	0.21	0.89	3.30 (E)
	Leaves	57	0.43	0.98	1.62 (F)
	Thin branches	31	0.17	0.95	4.09 (CD)
	Thick branches	29	0.16	0.87	4.32 (BC)
<i>E. globulus</i>	Bark	32	0.17	0.86	4.04 (CD)
	Leaves	68	0.51	0.94	1.37 (FG)
	Thin branches	30	0.16	0.97	4.25 (BCD)
	Thick branches	27	0.14	0.97	4.90 (B)

Table 4. Average concentration of total and soluble carbon, polyphenols, lignin and N, and C:N, Pol:N and L:N ratios in samples of the different harvest residues from *E. dunnii*, *E. grandis* and *E. globulus* at the beginning of the experiments.

Sample Type	Total C	Soluble C	Polyphenols	Lignin	N	C:N Ratio	Pol:N Ratio	L:N Ratio
<i>E. dunnii</i>			g kg ⁻¹					
Bark	413	39	76	359	2.9	142	26	123
Leaves	505	179	122	330	16.3	31	7	20
Thin branches	457	68	83	322	4.4	104	19	73
Thick branches	454	30	25	332	2.5	182	10	133
<i>E. grandis</i>								
Bark	411	54	55	334	2.6	160	21	130
Leaves	436	142	117	322	18.3	24	6	18
Thin branches	402	60	70	285	3.0	135	24	96
Thick branches	378	34	18	294	1.4	262	13	204
<i>E. globulus</i>								
Bark	462	74	41	362	2.4	190	17	149
Leaves	569	143	91	306	13.4	43	7	23
Thin branches	517	46	67	285	4.2	124	16	68
Thick branches	493	28	26	244	1.3	394	21	195

The study of the residues' quality parameters as indicators of the decomposition process through PCA is shown in Figure 2. Therein, 78% of the variability of the data is explained through the principal component 1 (PC1) and 94% by adding the principal component 2 (PC2), and it includes four variables with similar relative weights (C:N, Pol:N and L:N ratios and soluble carbon concentration).

Analyzing the same dataset by species (Figure 3), the same four variables explain 69% of the variability of PC1 (100% when adding PC2), with a lower relative weight of the Pol:N ratio compared to the other variables. For *E. globulus*, the parameter that differed the most from the other species was the C:N ratio, for *E. dunnii* it was the concentration of soluble

carbon and for *E. grandis* it was the L:N ratio. These variables explain the greater variability between species.

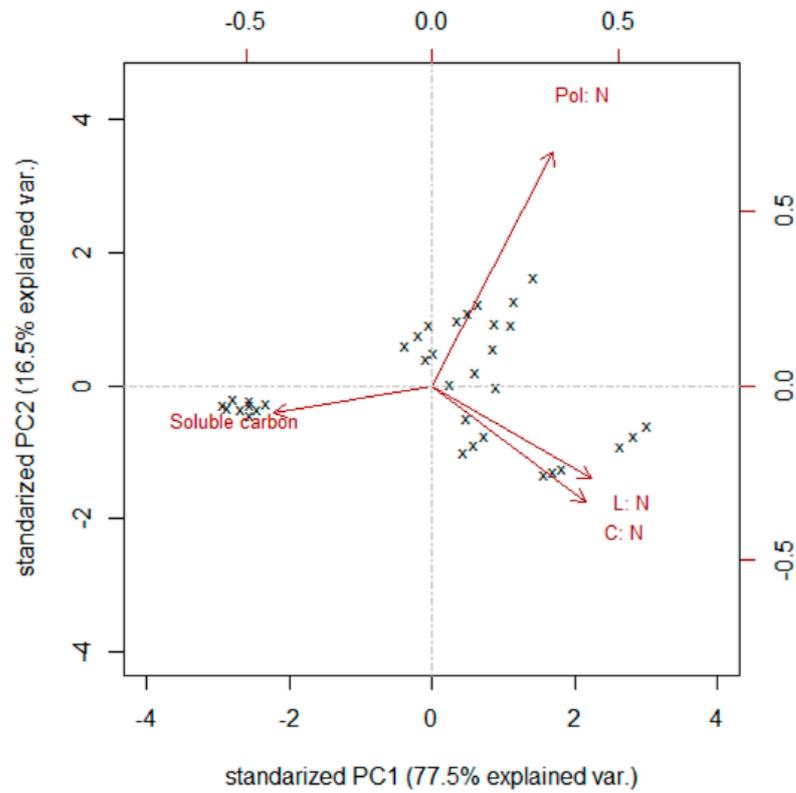


Figure 2. Biplot obtained via the PCA of harvest residues for decomposition 24 months after harvest.

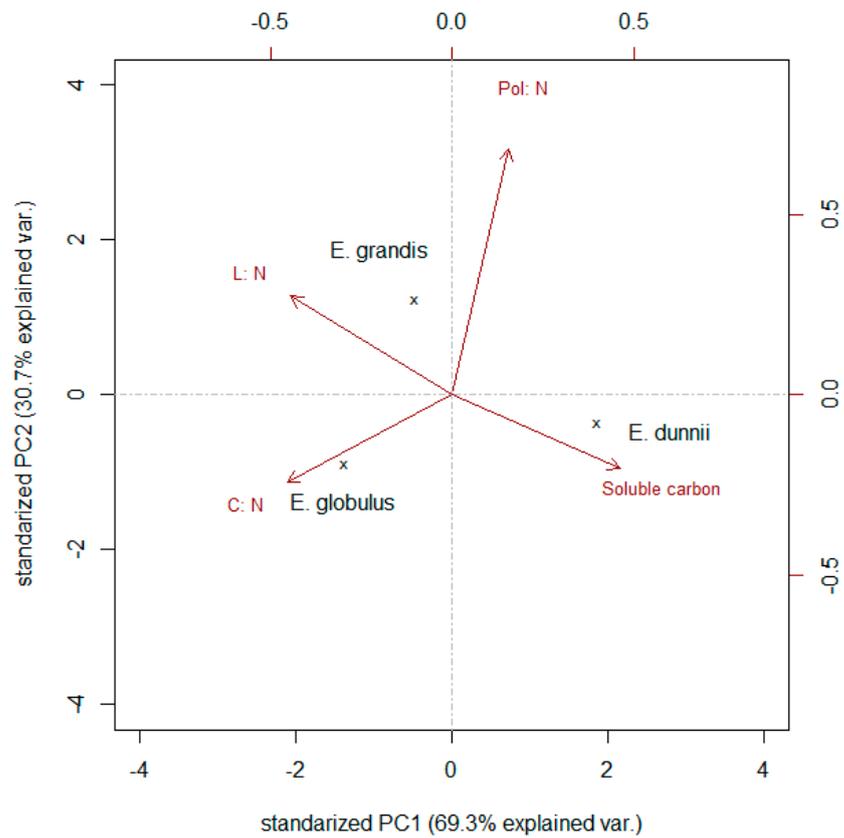


Figure 3. Biplot obtained by PCA of species for decomposition 24 months after harvest.

Considering all the species and parts, regressions were adjusted for the four variables as a way of estimating the relationship between them and the decomposition found at 24 months post-harvest (Figure 4).

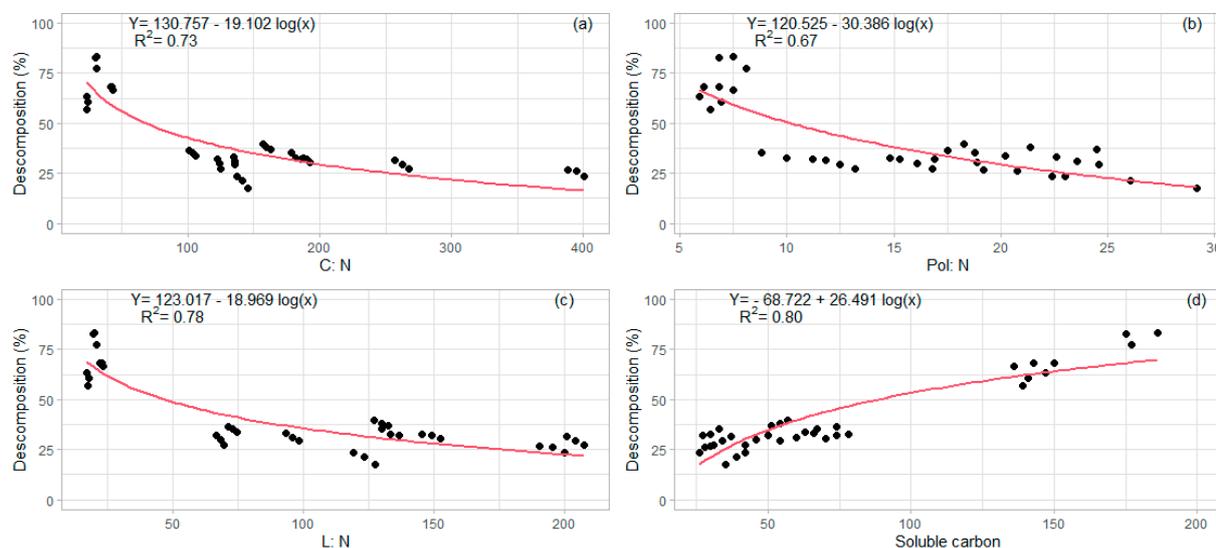


Figure 4. Relationships between decomposition of the harvest residues and the variables (a) C:N, (b) Pol:N, (c) L:N and (d) soluble carbon measured at the beginning of the decomposition process.

For the C:N, Pol:N and L:N, the lower the ratio, the greater the decomposition of the residue; for the fourth variable, higher concentrations of soluble carbon determined higher rates of decomposition.

The correlations between the different variables (C:N, Pol:N, L:N and soluble carbon concentration) and the half-life of the residues were also studied, finding highly significant associations in all cases (Table 5).

Table 5. Spearman's correlation coefficient between the half-life of the residues and the variables C:N, Pol:N, L:N and soluble carbon of residues ($p < 0.01$) (the number of samples is indicated in the "variables" column between brackets).

Variables	Half-Life (Years) Correlation Coefficient
C:N ratio (36)	0.69 (<0.01)
Pol:N ratio (36)	0.69 (<0.01)
L:N ratio (36)	0.66 (<0.01)
Soluble carbon (36)	-0.59 (<0.01)

3.3. Nutrient Cycling

Tables 6–8 show the nutrient contents for each species at the beginning, in the middle and at the end of the decomposition period (0, 12 and 24 months post-harvest, respectively), as well as the amount of nutrients released from residues over 24 months.

At harvest, higher total amounts of all the nutrients were observed in the residues of *E. dununii*, followed by *E. grandis* and, finally, in *E. globulus*. This was associated, in part, with the differences in the biomass amounts (Table 2). Almost 60% of the total nutrients evaluated present in the residues corresponded to Ca, being similar in the three species.

After 2 years, the absolute recycled amounts were also higher in *E. dununii* than in *E. grandis* and *E. globulus*, since the release patterns were more dependent on the nutrients and the parts than on the species itself. However, in percentage, *E. dununii* released slightly less (40%) compared to *E. grandis* and *E. globulus* (42% in both).

Table 6. Nutrient contents in the harvest residues at the beginning (month 0), in the middle (month 12) and end (month 24) of the decomposition period, and nutrients released throughout 24 months from the *E. dununii* residues.

Nutrient	Sample Type	Month			Nutrient Released from Residue	
		0	12	24		
Nitrogen	Bark	92	78	124	−32	kg ha ^{−1} %
	Leaves	225	114	44	181	
	Thin branches	93	76	70	23	
	Thick branches	72	53	64	8	
	Total	482	321	302	180	
Phosphorus	Bark	11.1	5.8	7.0	4.1	
	Leaves	18.8	7.3	3.1	15.7	
	Thin branches	7.4	4.9	3.9	3.5	
	Thick branches	4.9	5.0	3.9	1.0	
	Total	42.2	23.0	18.4	24.3	
Potassium	Bark	127	10	12	115	
	Leaves	105	5	3	102	
	Thin branches	95	14	8	87	
	Thick branches	57	20	12	45	
	Total	384	49	35	349	
Calcium	Bark	1026	772	781	245	
	Leaves	183	107	50	133	
	Thin branches	211	189	209	2	
	Thick branches	212	168	167	45	
	Total	1,632	1,236	1,207	425	
Magnesium	Bark	76	51	39	37	
	Leaves	26	8	3	23	
	Thin branches	26	20	9	17	
	Thick branches	32	25	17	15	
	Total	160	104	68	92	

Table 7. Nutrient contents in the harvest residues at the beginning (month 0), in the middle (month 12) and end (month 24) of the decomposition period, and nutrients released throughout 24 months from the *E. grandis* residues (average data from two sites).

Nutrient	Sample Type	Month			Nutrient Released from Residue	
		0	12	24		
Nitrogen	Bark	51	42	55	−4	kg ha ^{−1} %
	Leaves	181	152	96	85	
	Thin branches	28	22	23	5	
	Thick branches	19	16	20	−1	
	Total	279	232	194	85	
Phosphorus	Bark	11.1	5.0	5.2	5.9	
	Leaves	11.0	7.7	5.4	5.6	
	Thin branches	3.2	2.0	1.7	1.5	
	Thick branches	2.6	2.9	2.4	0.2	
	Total	27.9	17.6	14.7	13.2	

Table 7. Cont.

Nutrient	Sample Type	Month			Nutrient Released from Residue		
		0	12	24			
<i>E. grandis</i>	Potassium	Bark	79	5	5	74	
		Leaves	72	6	5	67	
		Thin branches	26	4	2	24	
		Thick branches	18	7	4	14	
		Total	195	22	16	179	92
	Calcium	Bark	606	443	376	230	
		Leaves	87	66	49	38	
		Thin branches	65	59	64	1	
		Thick branches	93	81	85	8	
		Total	851	649	574	277	33
	Magnesium	Bark	29	18	9	20	
		Leaves	25	14	8	17	
Thin branches		11	9	4	7		
Thick branches		13	11	8	5		
Total		78	52	29	49	63	

Table 8. Nutrient contents in the harvest residues at the beginning (month 0), in the middle (month 12) and end (month 24) of the decomposition period, and nutrients released throughout 24 months from the *E. globulus* residues (average data from two sites).

Nutrient	Sample Type	Month			Nutrient Released from Residue		
		0	12	24			
<i>E. globulus</i>	Nitrogen	Bark	45	37	54	−9	%
		Leaves	77	63	31	46	
		Thin branches	21	18	18	3	
		Thick branches	12	10	13	−1	
		Total	155	128	116	39	
	Phosphorus	Bark	7.9	3.7	4.4	3.5	
		Leaves	5.0	3.2	1.7	3.3	
		Thin branches	1.4	0.9	0.7	0.7	
		Thick branches	1.3	1.3	1.0	0.3	
		Total	15.6	9.1	7.8	7.8	50
	Potassium	Bark	86	6	7	79	
		Leaves	28	2	2	26	
Thin branches		17	3	2	15		
Thick branches		26	8	6	21		
Total		157	19	17	141	90	
Calcium	Bark	386	274	257	129		
	Leaves	63	46	26	37		
	Thin branches	43	40	42	1		
	Thick branches	61	52	57	4		
	Total	553	412	382	171	31	
Magnesium	Bark	34	21	15	19		
	Leaves	7	4	1	6		
	Thin branches	6	5	2	4		
	Thick branches	8	5	4	4		
	Total	55	35	22	33	60	

In the study period, on average, the majority of K (91%), slightly more than half of Mg and P (59 and 53%, respectively), 33% of N and only 29% of Ca were released from the residues. Potassium, in addition to being the nutrient that was proportionally released the most from residues, was also the fastest to do so (88% at 12 months post-harvest). Others, such as Mg and P, showed a more gradual release, while for N and Ca, some residue immobilization was recorded in part of the study period.

The order of release of the nutrients differed slightly between species. For *E. dunnii*, it was $K > Mg = P > N > Ca$, while for *E. grandis* and *E. globulus*, it was $K > Mg > P > Ca > N$.

4. Discussion

The little experimental information that exists worldwide on *E. dunnii* has shown that this species is characterized by a higher proportion of harvest residues in relation to the total aerial biomass [29,30], compared to other widely planted and studied species, such as *E. grandis* and *E. globulus* [7,31].

In this study, the proportion of harvest residues reached 35% in *E. dunnii* and 24% in the other two species (*E. grandis* and *E. globulus*). Furthermore, the growth of this species and *E. grandis* was higher than that of *E. globulus* [32]. Shammas et al. [31], in a 7-year-old *E. globulus* plantation in the SW of Australia, in relation to the aerial biomass of residues, found a similar proportion for thick branches, a lower proportion for bark, and a higher proportion for thin branches and leaves compared to the same species in this research. In the present investigation, although the bark was the part with the highest proportion in all species (Table 2), its proportion was higher in *E. globulus* compared to *E. dunnii* and *E. grandis*. Likewise, differences were also registered in the minority parts, i.e., the leaves in *E. dunnii* and the thin branches in *E. grandis* and *E. globulus*, which can be explained by the differences in the structure of the crown, with more branches in *E. dunnii*.

Although the decomposition studies analyzed in this work were not carried out in the same period, differences in the climatic conditions between them were not of great magnitude (Figure 1). On the other hand, it has been observed that in long evaluation periods (24 months), the significance of extreme climate events is mitigated [12,33]. Likewise, in studies of forest litter decomposition in northern Uruguay, Baietto et al. [11] tested the effect of the starting litter season of the decomposition period on the pattern of biomass loss, finding that this effect was not significant. Similarly, Ferreira et al. [13] reported that the release of nutrients was more controlled via the management and the physical and chemical properties of the residues than by the climate or the soil properties.

The highest decomposition constants (k) were reported in the leaves part. Rezende et al. [9] for *E. grandis* in incubation experiments under controlled conditions in Brazil, reported an annual decomposition constant for leaves (k) of 0.59, slightly higher than that found in the present work for the same species.

Rocha et al. [7], for 12-year-old *E. grandis* in Sao Paulo, Brazil, found higher values of k in leaves than in bark and in branches, which resulted in the same order as in the present research for this species, although with higher values in all cases (3.6, 1.2 and 0.5 for leaves, bark and branches, respectively) when compared with the same sample types in our research. Beyond the climatic differences between the sites, the higher k values reported by these authors in a humid sub-tropical climate [34] could also be explained by the addition of various nutrients as fertilizers at the time of reforestation (130, 44, 125, 480 and 120 kg ha^{-1} of N, P, K, Ca and Mg, respectively), which stimulates decomposition through microbial biomass.

Shammas et al. [31], for 7-year-old *E. globulus* trees in Australia, found the highest values of k in leaves, then in bark and, finally, in branches, that is, a similar order to that of the same species in the present work. The values reported by these authors were slightly higher than those of this study for bark and thin and thick branches (0.22, 0.21 and 0.16, respectively) and higher for leaves (1.54). Considering similarities in the climate (rainfall and temperature), the slight variations could be explained by differences in age (7 and 10 years, for Australia and Uruguay, respectively), with younger tissues in the case of

Australia. From the decomposition constant (k) the half-life of each of the remains can be estimated. In this sense, the half-life showed significant differences in the interaction between species and part, with the *E. dunnii* bark being the component with the highest durability ($t_{1/2} = 5.62$ years). This species' bark thickness, which was significantly higher than the others, could help explain the above. In the other species (*E. grandis* and *E. globulus*), the branches (thick and thin) were the parts with the highest half-life, similar to the result reported by different authors for the same species [7,31,33,35]. In general, and except for the leaves, the harvest residues decomposed slowly, which is positive considering the protection they exert against possible erosive events on the soil. In Entre Ríos, Argentina, with similar climatic conditions, the authors of [36], in a field decomposition experiment with *E. globulus*, found a half-life for leaves similar to that of this study for this species (1.5 years).

Jones et al. [33], for plantations of 11-year-old *E. globulus* in Monte Jarrio, Spain, with similar rainfall ($1,119 \text{ mm year}^{-1}$) and lower average annual temperatures ($13.1 \text{ }^\circ\text{C}$), reported a similar half-life for thin and thick branches (4.0 and 5.0 years, respectively) compared to the same species in our study. The same authors, for the same species and age, in Furadouro and Vale Pequeno, Portugal, with a mean annual temperature of $15.6 \text{ }^\circ\text{C}$ and much lower rainfall (630 mm yr^{-1}), indicated a longer half-life for thin and thick branches (5.6 and 6.1 years, respectively) compared to the same species in our research. The low rainfall in these areas of Portugal (about 50% less) helps explain the lower decomposition found. In these studies, the soils differed from each other (ranges $6.5\text{--}53 \text{ g kg}^{-1}$ and $85\text{--}290 \text{ g kg}^{-1}$ for organic carbon and clay, respectively, in the first 20 cm of soil), although no differences were reported for this cause. Coincidentally, the authors of [37] indicated that the parent material and the soils did not significantly influence the decomposition of the litter or the nutrient dynamics for the different forest species studied (*Eucalyptus*, *Pinus* and *Quercus*). Similar results were obtained in the present research, being the relative homogeneity of the soils, all of them acidic and poor in nutrients, a possible explanation for this behavior (low variability in the population and activity of microorganisms).

In their study with *E. globulus*, the authors of [31] found slightly lower half-lives for bark, and thin and thick branches parts (3.1, 3.4 and 4.3 years, respectively), and lower half-lives for leaves (0.4 years). The younger age of the trees (7 year old) compared to those of the present work could explain these small differences. Likewise in Australia, similar values for the components thin and thick branches of *E. globulus* were indicated by [35]. Rocha et al. [7] for *E. grandis* in Sao Paulo, Brazil, reported lower half-life values compared to the same species in this study ($t_{1/2}$ of 0.2, 0.6 and 1.5 for leaves, bark and branches, respectively), although adding all the nutrients at the time of new planting, which could accelerate the decomposition process, in addition to the temperature differences mentioned above.

Several causes could explain differences in the rates of decomposition of the various residues. The specific surface of each part was an important factor, being smaller in those of greater size (bark, branches), which, in turn, were those of slower decomposition and, therefore, had a longer half-life.

The contents of more unstable components or a more labile chemical structure, such as soluble organic compounds (e.g., soluble carbon), also influence decomposition of the residues with longer half-lives and the most resistant constituents, as shown by [31]. In the present investigation, the highest soluble carbon contents were found in the leaf part, which regardless of the species, presented the highest rates of decomposition (Tables 3 and 4). The thick branches, meanwhile, showed the lowest concentrations. Data reported by [9,15] in *E. grandis* residue mineralization studies in Brazil and Australia, respectively, also indicated a high concentration of leaf-soluble carbon.

The N contents as well as the C:N ratio also differed between the residues. According to [38], the incorporation to the soil of residues with a C:N < 25 ratio can cause net N mineralization, while C:N > 25 ratio tends to cause net immobilization of N. The present study showed that the highest concentrations of N were found in the leaves, as well as

lower C:N ratios (Table 4). The other parts presented very low N concentrations and high C:N ratios. In addition, the ratios of lignin and polyphenols with N were even more decisive than the concentrations of the former, as reported by [10]. Higher Pol:N or L:N ratios resulted in lower rates of decomposition (Figure 4).

The results of the PCA showed that with the first two components, it was possible to explain almost the entire variation. The C:N, Pol:N and L:N ratios showed an acute angle that suggests a positive correlation, while soluble carbon presented a negative correlation with these variables (opposite vectors and flat angles). It can be inferred that the species under study had distinctive values of these variables since, in the biplot, the observations for the same species appeared grouped.

The high values of the correlations between the half-life of the residues and the chemical parameters indicate a high magnitude of the association. None of the chemical characteristics studied could individually explain the differences between the rates of decomposition, but all of them had a similar influence (Table 5).

The greater total amounts of nutrients present in the residues of *E. dunnii*, then in *E. grandis* and, finally, in *E. globulus* were associated, in part, with the differences in the amounts of biomass at the time of harvest (Table 2), and, in addition, with the differences in the concentrations that for all nutrients occurred in residues, generally greater in *E. dunnii*, intermediate in *E. grandis* and lesser in *E. globulus* [32]. The soils, despite having some differences in depth and fertility, were relatively homogeneous (acid pH and low to medium natural fertility), with little influence on the absorption of nutrients.

The absolute amounts recycled appeared, due to the aforementioned (higher total amount in *E. dunnii* residues), in the same order for all the nutrients (*E. dunnii* > *E. grandis* > *E. globulus*); however, they varied when analyzed at the same percentage. This was explained because the release patterns depended on the nutrient and the parts, which, in turn, differed in their decomposition according to the species.

The high release of K (similar in the three species) can be explained because this nutrient is not part of the organic structures in plants but is found in ionic form (K^+) developing osmotic functions. This characteristic consequently determines its easiness of dissolution and removal via rainwater, regardless of biological factors [39]. Similar results were obtained by [7,31,37].

The Mg release frequently accompanies the loss of biomass of the residues [39], although the amount released in the present investigation was proportionally greater, explained by the lower concentrations of Mg in the different parts towards the end of the study. Rocha et al. [7] for *E. grandis* (Sao Paulo, Brazil) reported that 65% of the Mg remained in the residues at the end of the evaluation (10 months post-harvest), a percentage similar to that found in the present investigation for the three species 12 months after harvest. As mentioned above, the addition of all nutrients at the time of the new planting in the study carried out in Brazil was able to accelerate the decomposition process and reach the same remaining percentage 2 months before our study.

In P, a slight decrease in concentration was observed at 2 years, associated with the loss of soluble compounds, resulting in a slightly higher recycled percentage 2 years after harvest compared to the loss of biomass. For this nutrient, the higher percentage release in *E. dunnii* compared to *E. grandis* and *E. globulus* was explained by the greater biomass loss that occurred in the *E. dunnii* leaf part (83%) and that, in this part, the highest concentrations was recorded. P. Rocha et al. [7] found in *E. grandis* that 45% of the P remained in the residues at 10 months post-harvest, a percentage lower than in our research for the same species at 12 months (63%). The lower half-life for the leaf part reported by these authors compared to our research explains these differences.

Regarding the N, the low overall release from the residues (33% returned to the site in 2 years) was explained because some parts retained or even immobilized mineral N from the soil. For the three species, the net immobilization of N was recorded in the bark part. In addition, immobilization also occurred in the thick branches part of *E. grandis* and *E. globulus*, the latter having the highest C:N ratio (Table 3). In all cases, it was

observed that concentrations were higher after 2 years of harvest (unpublished data). Similar immobilization behavior in woody components has been reported by [9,10,15].

As for P, the greater loss of biomass occurred in the leaf part of *E. dunnii*, explaining the highest percentage of N release in this species, since it showed the highest concentrations of N. In turn, a slightly higher percentage of N was released in *E. grandis* compared to *E. globulus*, despite the lower loss of leaf biomass in this species (57% and 68% at 2 years for *E. grandis* and *E. globulus*, respectively), which could be explained because in *E. grandis* the amount of this nutrient in the leaves was almost two thirds of the total present in the residues, while in the other two species it was slightly less than 50%. Rocha et al. [7] indicated that 70% of the total N remained in the residues of *E. grandis* at 10 months post-harvest, a percentage lower than that found for the same species at 12 months in this research (83%). The differences can be explained, as for the P, by the lower half-life of the leaf part found by these authors and the higher concentration of N present in this part in relation to the woody residues.

Regarding Ca, all parts, in the three species, maintained or increased their concentrations in the 2 years, so its loss was lower compared to that of biomass, and this explained the high contents in the residues after 24 months. This nutrient is found in vegetables as a constituent of the cell wall, a structural function [40], which explains the behavior found, since soluble nutrients are released first. On average across the species, only 29% of the total returned to the soil in the evaluation period, decreasing significantly only in the leaf part. The lowest cycling occurred in *E. dunnii*, which was explained by its bark being the part of greater durability of all those analyzed (Table 3) and considering that this part presented the highest concentration of this nutrient in all species. Rocha et al. [7] reported that 76% of the total Ca remained in the residues of *E. grandis* at 10 months post-harvest, a similar percentage to that found for the same species at 12 months in the present study.

Although for P and cations (K, Ca and Mg) there are few loss mechanisms that occur during the decomposition process and, therefore, their reuse efficiency is very high, there are mechanisms of absolute N losses (passage to gaseous forms and leaching of soluble inorganic forms, such as nitrate anion) and relative losses (immobilization in organic forms). Therefore, for N, it is not possible to ensure that the recycled total will be fully available for the next planting [41].

In Uruguay, commercial plantations only include N and P in the fertilization schemes at the time of planting; therefore, it is particularly interesting to estimate for the cations (K, Ca and Mg) the contribution from the cycling in comparison to their stocks in the A horizon of the soils. Considering the soil mass present in the A horizon (depending on its depth and apparent density) and the concentration of cations under soluble and exchangeable forms (without taking into account non-exchangeable forms or geochemical recycling), K stands out as the nutrient whose contribution via this route presented a greater proportion. Considering the differences observed between the species, as well as the different stocks according to the soil, at 2 years of harvest, the return from the residues in relation to the stocks present in the soil accounted for between 23 to 81% for K, 4 to 19% for Ca and 5 to 16% for Mg.

5. Conclusions

Eucalyptus dunnii presented the highest amounts of residues for all its components, a consequence of their higher proportions in the aerial biomass compared to the other species, as well as a higher production of aerial biomass with respect to *E. globulus*. In turn, *E. grandis* showed greater amounts of residues relative to *E. globulus*, except in bark, a consequence of a higher aerial biomass production.

The decomposition rates of the different parts were highly dependent on their chemical constitution, the part size and the species itself. While the leaves of all species had high rates of decomposition, the bark was the part with the longest half-life in *E. dunnii*, and the thick branches in *E. grandis* and *E. globulus*. Given the strong correlation found between the half-life of the residues and the C:N ratio, as well as the concentration of soluble carbon,

and considering that these parameters are easy to determine, they could be used as good predictive tools.

The decomposition patterns obtained for some of the species studied were similar to those obtained by other authors in similar study and climatic conditions. This would allow using such values—and those corresponding to species such as *E. dunnii*—in predictive decomposition models of harvest residues for these species under the same climatic conditions.

While there were differences between species in terms of the absolute amounts of nutrients in the harvested components, as well as the amounts recycled, which were higher in *E. dunnii*, intermediate in *E. grandis* and lower in *E. globulus*, the release patterns depended more on the nutrients, which were associated with the functions in the plant and the parts where they were present, than on the species itself.

The permanence of harvest residues at the planting site benefits the sustainability of the productive system in the medium and long term, with important nutrient contributions. In addition, these keep the soil surface covered for a long time, reducing its susceptibility to the impact of raindrops and its propensity toward erosive processes.

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References

1. Ministry of Livestock, Agriculture and Fisheries. 2022. Available online: <https://www.gub.uy/ministerio-ganaderia-agricultura-pesca/datos-y-estadisticas/datos/resultados-cartografia-forestal2021#:~:text=La%20cartograf%C3%ADa%20cuantific%C3%B3%20una%20superficie,efectivas%20destinadas%20al%20uso%20forestal> (accessed on 8 September 2022).
2. Mendham, D.; Ogden, G.; Short, T.; O'Connell, T.; Grove, T.; Rance, S. Repeated harvest residue removal reduces *E. globulus* productivity in the 3rd rotation in southwestern Australia. *For. Ecol. Manag.* **2014**, *329*, 279–286. [[CrossRef](#)]
3. Epron, D.; Nouvellon, Y.; Deleporte, P.; Ifo, S.; Kazotti, G.; Thongo M'Bou, A.; Mouvondy, W.; Andre, L.; Roupsard, O.; Jourdan, C.; et al. Soil carbon balance in a clonal *Eucalyptus* plantation in Congo: Effects of logging on carbon inputs and soil CO₂ efflux. *Glob. Chang. Biol.* **2006**, *12*, 1021–1031. [[CrossRef](#)]
4. Versini, A.; Zeller, B.; Derrien, D.; Mazoumbou, J.; Mareschal, L.; Saint-André, L.; Ranger, J.; Laclau, J. The role of harvest residues to sustain tree growth and soil nitrogen stocks in a tropical *Eucalyptus* plantation. *Plant Soil.* **2013**, *376*, 245–260. [[CrossRef](#)]
5. Gonçalves, J.; Alvares, C.; Higa, A.; Silva, L.; Alfenas, A.; Stahl, J.; Ferraz, S.; Lima, W.; Brancalion, P.; Hubner, A.; et al. Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. *For. Ecol. Manag.* **2013**, *301*, 6–27. [[CrossRef](#)]
6. Hernández, J. Dinámica de los Nutrientes y la Materia Orgánica del Suelo en los Sistemas Forestales. Tesis Doctorado en Ciencias Agrarias, Facultad de Agronomía, Montevideo, Uruguay, 2016; 190p.
7. Rocha, J.; Marques, E.; Gonçalves, J.; Hübner, A.; Brandani, C.; Ferraz, A.; Moreira, R. Decomposition rates of forest residues and soil fertility after clear-cutting of *Eucalyptus grandis* stands in response to site management and fertilizer application. *Soil Use Manag.* **2016**, *32*, 289–302. [[CrossRef](#)]
8. Spangenberg, A.; Grimm, U.; Silva, J.; Fölster, H. Nutrient store and export rates of *Eucalyptus urograndis* plantations in eastern Amazonia (Jari). *For. Ecol. Manag.* **1996**, *80*, 225–234. [[CrossRef](#)]

9. Rezende, J.; Garcia, Q.; Scotti, M. Laboratory decomposition of *Dalbergia nigra* All. ex Benth and *Eucalyptus grandis* W. Hill ex Maiden leaves in forest and eucalypt plantation soils. *Acta Botánica Bras.* **2001**, *15*, 305–312. [CrossRef]
10. Sánchez, G. Descomposición de Restos de Cosecha de EUCALYPTUS sp. y Pinus Taeda en Condiciones Controladas de Humedad y Temperatura. Tesis de Maestría en Ciencias Agrarias, Facultad de Agronomía, Montevideo, Uruguay, 2011; 89p.
11. Baietto, A.; Hernández, J.; del Pino, A. Comparative dynamics of above ground litter production and decomposition from *Eucalyptus grandis* Hill ex Maiden and *Pinus taeda* L., and their contribution to the soil organic carbon. *Forests* **2021**, *12*, 349. [CrossRef]
12. Bradford, M.; Warren, R.; Baldrian, P.; Crowther, T.; Maynard, D.; Oldfield, E.; Wieder, W.; Wood, S.; King, J. Climate fails to predict wood decomposition at regional scales. *Nat. Clim. Chang.* **2014**, *4*, 625–630. [CrossRef]
13. Ferreira, G.; Soares, E.; Oliveira, F.; Silva, I.; Dungait, J.; Souza, I.; Vergütz, L. Nutrient release from decomposing *Eucalyptus* harvest residues following simulated management practices in multiple sites in Brazil. *For. Ecol. Manag.* **2016**, *370*, 1–11. [CrossRef]
14. De Souza, I. Decomposição de Resíduos da Colheita e Transferência de Carbono Para o Solo em Plantações de Eucalipto. Tesis de Maestría, Universidad de Viçosa, Viçosa, Brazil, 2012; 80p.
15. Corbeels, M.; O’Connell, A.; Grove, T.; Mendham, D.; Rance, S. Nitrogen release from eucalypt leaves and legume residues as influenced by their biochemical quality and degree of contact with soil. *Plant Soil* **2003**, *250*, 15–28. [CrossRef]
16. Ambus, P.; Jøensen, E. Crop residue management strategies to reduce N losses—Interaction with crop N supply. *Comm. Soil Sci. Plant Anal.* **2007**, *32*, 981–996. [CrossRef]
17. Berg, B.; McLaugherty, C. *Plant Litter: Decomposition, Humus Formation, Carbon Sequestration*; Springer: Berlin/Heidelberg, Germany, 2003; ISBN: 978-3-540-74922-6 (Print), 978-3-540-74923-3 (Online); 338p.
18. Guo, B.; Sims, R. Eucalypt litter decomposition and nutrient release under a short rotation forest regime and effluent irrigation treatments in New Zealand: II. internal effects. *Soil Biol. Bioch.* **2002**, *34*, 913–922. [CrossRef]
19. Hättenschwiler, S.; Tiunov, A.; Scheu, S. Biodiversity and litter decomposition in terrestrial ecosystems. *Annu. Rev. Ecol. Evol. Syst.* **2005**, *36*, 191–218. [CrossRef]
20. Hernández, J.; del Pino, A.; Salvo, L.; Arrarte, G. Nutrient export and harvest residue decomposition patterns of a *Eucalyptus dunnii* Maiden plantation in temperate climate of Uruguay. *For. Ecol. Manag.* **2009**, *258*, 92–99. [CrossRef]
21. González, A.; Hernández, J.; del Pino, A. Extracción y reciclaje de nutrientes por cosecha de *Eucalyptus globulus* en Uruguay. *Bosque* **2016**, *37*, 175–186. [CrossRef]
22. Inumet. Dirección Nacional de Meteorología, Montevideo, Uruguay. 2022. Available online: <https://www.inumet.gub.uy/clima/estadisticas-climatologicas/caracteristicas-climaticas> (accessed on 8 July 2022).
23. Murphy, J.; Riley, J. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* **1962**, *27*, 31–36. [CrossRef]
24. Nelson, D.; Sommers, L. Total carbon, organic carbon, and organic matter. In *Methods of Soil Analysis. Part 3: Chemical Methods*; Page, A.L., Helmke, P.A., Loeppert, R.H., Sparks, D.L., Eds.; John Wiley & Sons: Madison WI, USA, 1996; pp. 961–1010. [CrossRef]
25. Schwanninger, M.; Hinterstoisser, B. Klason lignin: Modifications to improve the precision of the standardized determination. *Holzforschung* **2002**, *56*, 161–166. [CrossRef]
26. Singleton, V.; Rossi, J. Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *J. Enol. Vitic.* **1965**, *16*, 144–148. [CrossRef]
27. Olsen, J. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* **1963**, *44*, 322–331. [CrossRef]
28. Conover, W. *Practical Nonparametric Statistics*, 3rd ed.; John Wiley & Sons: New York, NY, USA, 1999.
29. Bentancor, L. Extracción de Nutrientes por *Eucalyptus Dunnii* Maiden de 4 Años con Destino a la Producción de Biomasa Para Energía y Celulosa. Tesis Maestría en Ciencias Agrarias, Facultad de Agronomía, Montevideo, Uruguay, 2017; 109p.
30. Aguirre, N.; Filippi, C.; Zaina, G.; Rivas, J.; Acuña, C.; Villalba, P.; García, M.; González, S.; Rivarola, M.; Martínez, M.; et al. Optimizing ddRADseq in Non-Model Species: A case Study in *Eucalyptus dunnii* Maiden. *Agronomy* **2019**, *9*, 484. [CrossRef]
31. Shammas, K.; O’Connell, A.; Grove, T.; McMurtrie, R.; Damon, P.; Rance, S. Contribution of decomposing harvest residues to nutrient cycling in a second rotation *Eucalyptus globulus* plantation in south-western Australia. *Biol. Fert. Soils* **2003**, *38*, 228–235.
32. González, A.; Hernández, J.; del Pino, A.; Hirigoyen, A. Nutrient use efficiency in commercial eucalypt plantations in different soils under temperate climate. *South. For.* **2022**, *84*, 123–135. [CrossRef]
33. Jones, H.; Madeira, M.; Herraes, L.; Dighton, J.; Fabiao, A.; González-Rio, F.; Fernandez, M.; Gomez, C.; Tomé, M.; Feith, H.; et al. The effect of organic-matter management on the productivity of *Eucalyptus globulus* stands in Spain and Portugal: Tree growth and harvest residue decomposition in relation to site and treatment. *For. Ecol. Manag.* **1999**, *122*, 73–86. [CrossRef]
34. Alvares, C.; Stape, J.; Sentelhas, P.; Goncalves, J.; Sparovek, G. Koppen’s climate classification map for Brazil. *Meteorol. Zeitschrift.* **2013**, *22*, 711–728. [CrossRef] [PubMed]
35. O’Connell, A.; Mendham, D. Impact of N and P fertilizer application on nutrient cycling in jarrah (*Eucalyptus marginata*) forests of southwestern Australia. *Biol. Fert. Soils* **2004**, *40*, 136–143. [CrossRef]
36. Goya, J.; Frangi, J.; Dalla Tea, F.; Marco, M.; Larocca, F. Biomasa, productividad y contenido de nutrientes en plantaciones de *Eucalyptus grandis* en el noreste de la Provincia de Entre Ríos. In *XII Jornadas Forestales de Entre Ríos*; Concordia University: Montréal, QC, Canada, 1997; Volume III, pp. 1–18.

37. Alvarez, E.; Fernandez, M.; Torrado, V.; Fernandez Sanjurjo, M. Dynamics of macronutrients during the first stages of litter decomposition from forest species in a temperate area (Galicia, NW Spain). *Nutr. Cycl. Agroecosyst.* **2008**, *80*, 243–256. [[CrossRef](#)]
38. Trinsoutrot, S.; Recous, B.; Linères, M.; Chèneby, D.; Nicolardot, B. Biochemical quality of crop residues and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. *Soil Sci. Soc. Am. J.* **2000**, *64*, 918–926. [[CrossRef](#)]
39. O’Connell, A.; Grove, T. Influence of nitrogen and phosphorus fertilizers on amount and nutrient content of litterfall in a regrowth eucalypt forest. *New For.* **1993**, *7*, 33–47. [[CrossRef](#)]
40. Marshner, H. *Mineral Nutrition of Higher Plants*; Academic Press: London, UK, 2003; pp. 229–299.
41. Laclau, J.; Ranger, J.; Goncalves, J.; Maquere, V.; Krusche, A.; M’Bou, A.; Nouvellon, Y.; Saint-Andre’, L.; Bouillet, J.; Cassia Piccolo, M.; et al. Biogeochemical cycles of nutrients in tropical *Eucalyptus* plantations: Main features shown by intensive monitoring in Congo and Brazil. *For. Ecol. Manag.* **2010**, *259*, 1771–1785. [[CrossRef](#)]

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