Extracción y ciclaje de nutrientes en plantaciones de *Eucalyptus* sp. en Uruguay y su efecto en la sostenibilidad del sistema de producción

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DEDICATORIA

A Anahí (por siempre Pitu).

A Dios.

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TABLA DE CONTENIDO

RESUMEN

Para asegurar la gestión sostenible de la producción de *Eucalyptus* sp. en suelos de baja fertilidad de Uruguay se requiere cuantificar las exportaciones de nutrientes con la cosecha, así como caracterizar la descomposición de los restos y el reciclaje de nutrientes al suelo. Los objetivos fueron: a) cuantificar la concentración y distribución de nutrientes en la biomasa aérea cosechada de *E. dunnii*, *E. grandis* y *E. globulus* en suelos de aptitud forestal; b) comparar la eficiencia en el uso de los nutrientes de las especies en los diferentes tipos de suelo, como criterio para evaluar la sostenibilidad del sistema productivo; c) cuantificar las características que afectan las tasas de descomposición de los restos e identificar indicadores que puedan explicar el proceso y d) cuantificar el reciclaje potencial de nitrógeno (N), fósforo (P), potasio (K), calcio (Ca) y magnesio (Mg) al suelo a partir de los restos y en relación con diferencias cuantitativas y cualitativas de las especies. En cada plantación (29) se caracterizó el suelo y se cosecharon árboles con tamaño promedio, cuantificándose la biomasa aérea y la extracción de N, P, K, Ca y Mg en madera comercial y restos de cosecha. En 5 plantaciones, abarcando las tres especies, se estudió la descomposición de residuos durante dos años. La eficiencia de utilización de nutrientes fue menor en *E. dunnii* en relación con las otras dos especies, para todos los nutrientes e independientemente del sitio de plantación. El coeficiente de utilización biológico mostró valores menores para los cationes (K, Ca y Mg) en *E. dunnii* comparado a las otras dos especies, y, además, para N y P, en comparación con *E. grandis*. *E. dunnii* ejerce una mayor presión sobre el recurso suelo, lo cual debe considerarse para realizar un manejo sostenible. Las tasas de descomposición de los restos dependieron de su constitución química, tamaño de partículas y de la especie, siendo los contenidos de N total y C (total y soluble) buenas herramientas predictivas para estimar su vida media. Luego de dos años se liberó la mayor parte del K (91 %), algo más de la mitad del Mg y P, y un tercio del N y Ca. Los patrones de liberación dependieron más de su complejidad estructural en la planta y de la fracción en donde estaban presentes que de la propia especie, siendo este reciclaje fundamental para asegurar la sostenibilidad en el mediano y largo plazo.

Palabras clave: forestación, eficiencia de uso de nutrientes, descomposición de restos de cosecha

EXTRACTION AND CYCLING OF NUTRIENTS IN *EUCALYPTUS* SP PLANTATIONS IN URUGUAY AND ITS EFFECT ON THE SUSTAINABILITY OF THE SYSTEM OF PRODUCTION

ABSTRACT

To ensure the sustainable management of the production of *Eucalyptus* sp. in low fertility soils in Uruguay, it is necessary to quantify nutrient exports with the harvest, as well as characterize the decomposition of residues and the recycling of nutrients to the soil. The objectives were: a) to quantify the concentration and distribution of nutrients in the aerial biomass harvested from *E. dunnii*, *E. grandis* and *E. globulus* in soils suitable for forestry; b) to compare the nutrient use efficiencies of the species in the different soil types, as a criterion to evaluate the sustainability of the production system; c) to quantify the characteristics that affect the decomposition rates of residues and identify indicators that can explain the process, and d) to quantify the potential recycling of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) to the soil from the remains and in relation to quantitative and qualitative differences of the species. In each plantation (29), the soil was characterized and trees of average size were harvested, quantifying the aboveground biomass and the extraction of N, P, K, Ca and Mg in commercial wood and harvest residues. In 5 plantations, covering the three species, the decomposition of residues was studied for two years. Nutrient utilization efficiency was lower in *E. dunnii* in relation to the other two species, for all nutrients and regardless of the planting site. The biological utilization coefficient showed lower values for cations (K, Ca and Mg) in *E. dunnii* compared to the other two species, and, also, for N and P, compared to *E. grandis*. *E. dunnii* exerts greater pressure on the soil resource, which must be considered for sustainable management. Decomposition rates of the residues depended on their chemical constitution, particle size and the species, with the contents of total N and C (total and soluble) being good predictive tools to estimate their half-life. After two years, most of the K was released (91 %), a little more than half of the Mg and P, and a third of the N and Ca. The release patterns depended more on its structural complexity in the plant and the fraction where they were present than of the species itself, this recycling being essential to ensure sustainability in the medium and long term.

Keywords: afforestation, nutrient use efficiency, decomposition of harvest residues

1. INTRODUCCIÓN GENERAL

Desde el año 1989 ha ocurrido en Uruguay una expansión de la forestación comercial, debido a la promulgación de la ley 15.939 de finales del año 1987, en donde se declaró de interés nacional «… la defensa, el mejoramiento, la ampliación, la creación de los recursos forestales, el desarrollo de las industrias forestales y, en general, de la economía forestal» (https://www.impo.com.uy/bases/leyes/15939-1987). Dicha expansión se ha producido con base en especies exóticas del género *Eucalyptus* (*E. grandis*, *E. globulus* y *E. dunnii*, principalmente) y, en menor medida, del género *Pinus* (básicamente, *P. taeda*), cuya madera tiene como destino la producción de pasta de celulosa y madera para aserrío.

Para asegurar la sostenibilidad de la producción forestal en el mediano y largo plazo es necesario aplicar técnicas de manejo apropiadas que aseguren la conservación de los distintos recursos naturales como, por ejemplo, el suelo, lo cual dependerá en buena medida de un adecuado balance de los nutrientes. Poniendo foco en el aspecto nutricional, la sostenibilidad a lo largo del tiempo se basa en un balance adecuado entre la oferta de nutrientes por parte del suelo y la demanda de estos por parte de las plantaciones forestales. Dependiendo del sitio donde se encuentren los bosques, así como del uso que de estos nutrientes haga cada especie (eficiencia de uso de los nutrientes, la cual es variable según la especie), se determinará, consecuentemente, el tiempo en el cual será necesario comenzar con la reposición de los nutrientes extraídos por las especies forestales cosechadas en los sucesivos turnos de plantación (Fox, 2000, Turvey y Smethurst, 1994).

De acuerdo con Schumacher y Caldeira (2001), un ecosistema forestal podrá tener una producción sostenible siempre y cuando las pérdidas de nutrientes de un sitio sean devueltas de alguna manera. Debido a esto es muy importante determinar las concentraciones de nutrientes de los diferentes componentes cosechados, así como la cantidad de biomasa producida, para determinar qué cantidades de nutrientes están siendo exportadas finalmente del sitio con la madera comercial y qué cantidad permanece en los restos cosechados. Finalmente, será importante conocer con qué velocidad se descomponen estos restos y se reciclan los diferentes nutrientes al suelo para ser utilizados por una futura replantación.

Según Goya et al. (1997), en las plantaciones forestales, la meta debería ser lograr una productividad de las plantaciones no declinante o en aumento a través de las sucesivas rotaciones, manteniendo o mejorando la calidad del sitio con base en su capacidad para la disponibilidad de recursos. En este sentido, los principales aspectos a considerar son la protección de la fertilidad de los suelos y manejarse dentro de límites conocidos de resiliencia del sitio. Es por ello por lo que la gestión sostenible de estas plantaciones se basará en prácticas que procuren conservar las existencias de materia orgánica del suelo (MOS) y nutrientes, componentes claves de la fertilidad de estos, y que se sostiene principalmente por el mantenimiento de los restos de la cosecha en la replantación del sitio (corteza, ramas y hojas), sumado a los aportes de mantillo y recambio de raíces durante el ciclo de la plantación (Mendham et al., 2014, Epron et al., 2006).

Los restos de cosecha, si bien representan una proporción menor de la biomasa aérea total producida (alrededor del 30 %), contienen la mayoría de los nutrientes absorbidos (Hernández, 2016), con lo cual mediante su descomposición se produce un reciclaje de estos que pueden ser utilizados por la siguiente plantación. Esta descomposición de la biomasa aérea que permanece en el sitio ocurre a tasas variables y depende de las características intrínsecas del propio resto en cuanto a su estructura física y química (Verkaik et al., 2006, Lovett et al., 2004, Burgess et al., 2002, Rezende et al., 2001), las condiciones climáticas específicas como humedad y temperatura (Baietto et al., 2021, Sánchez, 2011) y del período de tiempo durante el cual ocurren los procesos.

Por lo tanto, los estudios de los ciclos de nutrientes en la biomasa aérea de los bosques son una tarea compleja, tanto porque los residuos son fracciones grandes y permanecen durante intervalos de tiempo muy largos como por la gran cantidad de datos que deben registrarse de los distintos componentes de la vegetación (madera, corteza, ramas, hojas) y del suelo para hacer los balances de nutrientes (Attiwill et al., 1996).

Entre los factores de los cuales depende la extracción y exportación de nutrientes por una plantación forestal pueden citarse, entre otros: 1. la producción de biomasa aérea y su concentración en nutrientes, lo cual se relaciona con la especie, edad y densidad de la plantación (Leite et al., 2010, Santana et al., 2008, Laclau et al., 2003, Guo y Sims, 2002); 2. las fracciones de biomasa finalmente retiradas del sitio y 3. el material parental y tipo de suelo.

Con relación al primero de ellos, y teniendo claro que tanto la densidad de plantación como la edad sean comparables en todos los casos, es importante tener presente las áreas de distribución natural de las distintas especies estudiadas y las características de los suelos existentes en ellas. *E. globulus* se encuentra en el sur de Australia (incluida la isla de Tasmania, promontorio Wilsons y costa adyacente de Victoria), con altitudes desde el nivel del mar hasta los 450 m., presentando una gran capacidad de adaptación a distintos suelos, en tanto tengan un buen drenaje (Brussa, 1994). *E. grandis*, a su vez, proviene del este de Australia (norte de Nueva Gales del Sur y sureste de Queensland), en alturas entre los 0 y 600 m, y, si bien tiene ligeros mayores requerimientos de fertilidad, al igual que la anterior necesita suelos bien drenados (Boland y Brooker, 2006, Brussa, 1994). Por su parte, *E. dunnii* es una especie que crece naturalmente en un área muy restringida del noreste de Nueva Gales del Sur y del sur de Queensland, en los valles y en las partes más bajas de las laderas, prefiriendo los suelos muy fértiles y húmedos, pero con buen drenaje (Boland y Brooker, 2006). Estos diferentes orígenes, a su vez, confieren distintas características a las especies, aunque las tres han mostrado una buena adaptación a las condiciones de suelo y clima en diferentes regiones de Uruguay (más allá de otras cuestiones, ej. sanitarias).

La fracción de biomasa finalmente retirada es un aspecto de gran importancia para la sostenibilidad del sistema de producción. Santana et al. (1999) indicaron que, aunque la corteza de los árboles de *Eucalyptus* sp. representa entre el 10 y 18 % del total de la biomasa aérea cosechada, presenta un alto contenido de nutrientes (73 % del Ca, 65 % del Mg, 46 % del P y 41 % del K total absorbido) como promedio de las especies estudiadas. Por lo tanto, el descortezado en el campo reduce sustancialmente la exportación de nutrientes y, así, contribuye a una mayor sostenibilidad o menor utilización de fertilizantes en plantaciones forestales de *Eucalyptus* en Brasil. En igual sentido, Merino et al. (2005) estimaron la cantidad de nutrientes exportados en plantaciones de distintas especies de *Eucalyptus* bajo diferentes regímenes de intensidad de cosecha donde prácticas corrientes como la remoción de la madera con la corteza resultaba en altas tasas de extracción de P, K, Ca y Mg.

El material parental y tipo de suelo son de relevancia particular, dadas las diferencias que existen en el material de origen de los suelos y los contenidos de MOS, que resultan en distintos reservorios de nutrientes para las plantas, así como distintas condiciones para el desarrollo radicular (Laclau et al., 2003 y 2000, Judd et al., 1997). En Uruguay, los suelos afectados a la forestación, si bien varían en sus propiedades físicas y químicas, presentan en general bajos contenidos de materia orgánica (por tanto, baja disponibilidad de nitrógeno y azufre, principalmente), arcilla y limo (textura franca o más liviana), y baja a media fertilidad natural (baja capacidad de intercambio catiónico, bajos niveles de bases de intercambio y fósforo disponible, y media a elevada acidez) (Califra, 2005). No obstante, los contenidos de materia orgánica y bases de intercambio resultan mayores a los de otras zonas de producción de *Eucalyptus* del mundo, como, por ejemplo, Brasil o Sudáfrica. Anteriormente, Sganga (1980) había señalado que los suelos con aptitud forestal del país son aquellos suelos desaturados, por lo tanto, ácidos, de texturas gruesas, con buena capacidad de retención de agua, pero, a su vez, con drenaje bueno a moderadamente bueno y facilidad para el enraizamiento.

De acuerdo con los criterios del Soil Taxonomy (Soil Survey Staff, 2014), los suelos de mayor aptitud para la producción forestal en Uruguay integran los órdenes ultisoles, alfisoles, inceptisoles y algunos molisoles, los que a su vez se agrupan, según una clasificación por capacidad productiva de la tierra de Uruguay (Comisión Nacional de Estudio Agroeconómico de la Tierra —CONEAT—, Ministerio de Ganadería, Agricultura y Pesca, 2022), en diferentes zonas del país de acuerdo con características físicas, químicas y morfológicas similares, asociadas al material parental (areniscas y rocas ígneas meteorizadas).

Actualmente, Uruguay tiene alrededor de 1,1 millones de hectáreas con plantaciones forestales comerciales (Ministerio de Ganadería, Agricultura y Pesca, 2022), esto es, un 6 % de su superficie, siendo la mayoría ocupada por distintas especies del género *Eucalyptus*, principalmente, *E. grandis*, *E. dunnii* y *E. globulus*, con destino a la producción de pasta de celulosa. De estas, más de 50,000 ha son cosechadas cada año.

De las tres especies, tanto *E. grandis* como *E. globulus* son ampliamente plantadas en diferentes países, mientras que *E. dunnii* resulta una especie en franca expansión en regiones templadas (hoy es la especie con mayor superficie anual de plantación en Uruguay), pero poco plantada en el mundo hasta hace pocos años. Es por ello por lo que la información experimental que se tiene sobre el uso de nutrientes por *E. dunnii* en el ámbito mundial es escasa (Aguirre et al., 2019, Bentancor, 2017, Hernández et al., 2009) y no existe información que compare la absorción de nutrientes por parte de esta especie en diferentes ambientes con otras utilizadas en la producción de pasta de celulosa, como *E. grandis* y *E. globulus*.

De igual manera, si bien para *E. grandis* y *E. globulus* existe información experimental sobre la descomposición de restos, aunque en muchos casos, en climas diferentes al de Uruguay, es muy escasa la información experimental acerca del reciclaje de nutrientes a partir de los restos de la cosecha en estas especies. A su vez, para la especie *E. dunnii*, como fue expresado, es muy poca la información disponible en el ámbito mundial en general y, en particular, acerca de las tasas de descomposición de restos de cosecha, así como del proceso de reciclaje de nutrientes. Por ello, resulta muy importante la necesidad de contar con información experimental comparativa.

Las hipótesis del trabajo fueron:

1. Las distintas especies de *Eucalyptus* sp. difieren en su potencial de extracción de nutrientes del suelo, aunque la expresión de este potencial en términos de eficiencia de utilización de los nutrientes para la producción depende de las características del sitio, en especial el tipo de suelo.
2. La tasa de descomposición de los diferentes componentes de cosecha de *Eucalyptus* sp. es variable y altamente dependiente del tamaño de partículas y constitución química, así como de la propia especie.

A su vez, los principales objetivos del trabajo fueron:

a) Cuantificar comparativamente la concentración y distribución de nutrientes en la biomasa cosechada de *E. dunnii*, *E. grandis* y *E. globulus* en los suelos predominantes de las principales zonas de mayor aptitud forestal del Uruguay.

b) Comparar las eficiencias de uso de los nutrientes de las tres especies mencionadas y en los diferentes tipos de suelo como criterio para evaluar la sostenibilidad del sistema productivo en el mediano y largo plazo.

c) Identificar y cuantificar las características de cada especie (*E. dunnii*, *E. grandis* y *E. globulus*) que afecten las tasas de descomposición de los diferentes restos de cosecha, así como indicadores que puedan explicar el proceso.

d) Cuantificar el reciclaje potencial de N, P, K, Ca y Mg al suelo a partir de la descomposición de estos restos y conocer las diferencias cuantitativas y cualitativas entre las especies evaluadas.

Para dichos efectos, fueron desarrollados dos artículos, los cuales son partes componentes de la tesis que se presenta:

Artículo 1: *Nutrient use efficiency in commercial Eucalyptus plantations in different soils under temperate climate*.

https://doi.org/10.2989/20702620.2022.2066488

Artículo 2: *Harvest Residue Decomposition from Eucalyptus sp. Plantations in Temperate Climate: Indicators and Contribution to Nutrient Cycling*.

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2. NUTRIENT USE EFFICIENCY IN COMMERCIAL *EUCALYPTUS* PLANTATIONS IN DIFFERENT SOILS UNDER TEMPERATE CLIMATE

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2.1. ABSTRACT

The sustainability of forest production is based on an adequate balance between soil nutrient supply and its demand by forest plantations, which may vary depending on the species and the site. In Uruguay, the low to medium fertility of the soils under forest production makes this aspect relevant. The objectives of the study were: a) to quantify the concentration and distribution of nutrients in the harvested biomass of *Eucalyptus dunnii*, *Eucalyptus grandis* and *Eucalyptus globulus* in the predominant soils of the zones of greater forestry aptitude of Uruguay; b) to compare the nutrient use efficiencies of the three mentioned species in different soil types, as a criterion to evaluate the sustainability of the productive system in the long term. In 29 sites located in the three main forest areas of the country, 9 trees with average DBH and height were harvested (8 to 11 years of age). The aerial biomass and nutrient uptake (nitrogen, phosphorus, potassium, calcium and magnesium) in commercial wood, bark, leaves and branches were quantified, and two nutrient use efficiency indexes (Nutrient Use Efficiency and Biological Utilization Coefficient) were calculated. Although the zones offered different conditions for growth and nutrient uptake, *E. dunnii* presented the highest extraction of nutrients in commercial wood, considering all sites, these indexes being lower for *E. dunnii*. Therefore, when planting this species, a greater use of the soil resource must be considered, particularly in less natural fertility soils. Likewise, *E. grandis* presented a greater extraction of cations compared to *E. globulus*, because of more growth.

Keywords: system sustainability, soil resource, nutrient export

2.2. INTRODUCTION

From a nutritional point of view, the sustainability of forest production over time is based on an adequate balance between the supply of nutrients by the soil and its demand by the forest plantations. Soils differ in their ability to supply nutrients, both due to differences in their concentration in the different soil horizons, as well as in the effective depth of root exploration. This determines the stocks of nutrients available in each situation, and, consequently, the time necessary to start replenishing the nutrients extracted by the forest species harvested in successive planting rotations (Turvey and Smethurst 1994). On the other hand, the species differ in their capacity to absorb nutrients, as well as in the production of wood for commercial purposes, each producing a different amount of wood per kg of absorbed nutrient (nutrient use efficiency).

The sustainability of the production system depends on the site and the species planted, and adjustments must be made to supply and replace the necessary nutrients throughout the successive rotations, becoming relevant the adoption of management measures to maintain the productivity of the soil resource (Fox 2000).

By virtue of its high growth rates in temperate and tropical climates, *Eucalyptus*, native of Australia, is one of the most widely used genera in the production of cellulose pulp. Gonçalves et al. (1997) establish a direct relationship between the growth rate and the accumulation of nutrients in *Eucalyptus*. Ericsson (1995) indicates that short harvest cycles (7 to 11 years), associated with high concentrations of nutrients in the tissues, increase nutrient losses. According to this author the assimilability of elements such as Ca and Mg, which are taken in large quantities, can sometimes become a problem for future rotations.

In Uruguay, the soils under forest production generally present low contents of organic matter, clay and silt, and low to medium natural fertility. However, the contents of organic matter and exchangeable bases are higher than those of other *Eucalyptus* production areas in the world (e.g. Brazil or South Africa). The soils most suitable for forest production in Uruguay comprise the Orders *Ultisols*, *Alfisols*, *Inceptisols* and some *Mollisols* (Soil Survey Staff 2014). In general terms, on the surface horizon they present medium to low clay contents; low content of organic matter and consequently, low availability of nitrogen (N) and sulfur (S); medium to high acidity; low cation exchange capacity (CEC), and low levels of exchangeable bases and available phosphorus (P), (Califra 2005).

According to the classification by productive capacity of the land of Uruguay (CONEAT: National Commission for the Agroeconomic Study of the Earth, 1979), these soils are grouped in different areas of the country according to similar physical, chemical and morphological characteristics, associated with the parent material (sandstones and weathered igneous rocks). They constitute the groupings of soils with the lowest productivity for agricultural crops and livestock, but with good aptitude for forest production. These areas, identified as Zones 2, 7, 8 and 9 according to CONEAT classification, are those with the highest concentration of forest plantations of the genus *Eucalyptus*, with the predominance of *E. dunnii*, *E. grandis* and *E. globulus* (Figure 1).

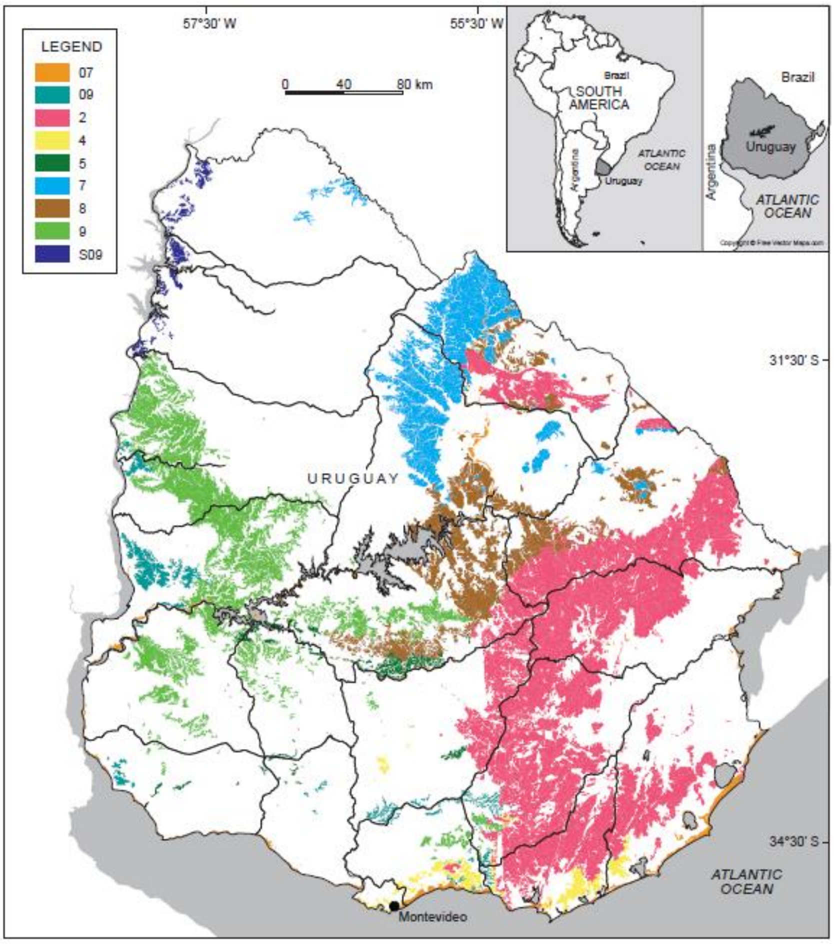

Figure 1. CONEAT Zones: Areas with soils suitable for forestry in Uruguay (Ministry of Livestock, Agriculture and Fisheries. 2021). The numbers in the legend indicate each of the zones

Both *E. grandis* and *E. globulus* are species widely planted in different countries for cellulose pulp production; among others, in Brazil, Argentina, South Africa, Sri Lanka, India or New Zealand, *E. grandis* is mainly planted; while in Spain, Portugal and Chile *E. globulus* is mainly produced. On the other hand, *E. dunnii* had been scarcely planted until a few years ago, but today it is a species in clear expansion in temperate regions. Currently it is the species mostly planted annually in Uruguay, and there are also some areas with plantations in southern Brazil and Argentina. The experimental information on the nutrition of *E. dunnii* worldwide is scarce (Hernández et al. 2009, Bentancor 2017, Aguirre et al. 2019). Similarly, there is no information that compares the absorption of nutrients by this species in different environments, with others used in the production of cellulose pulp, such as *E. grandis* and *E. globulus*, which have been more extensively studied. Therefore, information about their nutritional requirements will complement the knowledge regarding their adaptation to different soils and temperate climatic conditions, as well as their productive performance.

The hypothesis of this study was that the different species of *Eucalyptus* differ in their potential for extraction of nutrients from the soil, although the expression of this potential in terms of efficiency of nutrient use depends on the characteristics of the site, especially the soil type.

The main objectives of the study were:

a) Comparatively quantify the concentration and distribution of nutrients in the harvested biomass of *E. dunnii*, *E. grandis* and *E. globulus* in the predominant soils of the main areas of greater forestry aptitude in Uruguay.

b) Compare the nutrient use efficiencies of the three mentioned species in different soil types, as a criterion to evaluate the sustainability of the productive system in the long term.

2.3. MATERIALS AND METHODS

Twenty-nine plantations were studied in three of the four main forest areas of the country (Zones 9, 7 and 2 of the CONEAT classification). In three of the 29 cases, previously published information was used (Hernández et al. 2009 and 2016, González et al. 2016). In all the sites, the methodology in terms of tree selection, evaluation of aerial biomass, plant and soil sampling was similar. The harvests were carried out between 2006 and 2015.

Selection of experimental sites

The evaluations were carried out in commercial plantations of the genus *Eucalyptus* (*E. dunnii*, *E. grandis* and *E. globulus*) close to harvest for pulp production (8 to 11 years of age, regardless of the zone or species).

The study involved a survey of forests in production, located in different areas of the country, taking as a basis for their selection the following criteria:

a) To be forests plantations destined for the commercial production of cellulose pulp, with good yields and health, and located in soils of forestry aptitude representative of the different production zones (Table 1).

b) The evaluations at each site were performed on selected trees based on the average Diameter at Breast Height (DBH) and Height (H), according to data from neighboring inventory plots; in case of not having them, a plot was marked, and all the trees were surveyed, calculating the averages of DBH and H, then selecting trees with these measurements for felling.

Bearing in mind that the three species are not planted in all areas, given their different adaptation to edaphoclimatic conditions, plantations were distributed as follows: 11 of them of *E. globulus* (Zones 2 and 9), 10 of *E. grandis* (Zones 7 and 9) and 8 of *E. dunnii* (Zones 7 and 9). Although Zone 8 is also apt for forestry, it was not included, because has a smaller area under forest cover, with generally young plantations, and the soils are transitional between zones 7 and 9.

Table 1. Coordinates of the evaluated plantations identified by species.

Coordinates		
Plantation of *E. dunnii*	Plantation of *E. grandis*	Plantation of *E. globulus*
1. 32º 25’ 56’’S 57º 17’ 40’’W[*]	9. 32º 21’ 09’’S 57º 34’ 45’’W	19. 34º 15´ 10’’S 54° 17’ 23’’W
2. 32º 23’ 11’’S 57º 24’ 30’’W	10. 32º 21’ 60’’S 57º 35’ 18’’W	20. 34º 02’ 21’’S 53° 59’ 08’’W
3. 31º 53’ 51’’S 57º 39’ 58’’W	11. 32º 22’ 02’’S 57º 35’ 29’’W	21. 34º 17’ 11’’S 54° 20’ 33’’W
4. 31º 53’ 44’’S 57º 40’ 52’’W	12. 32º 50’ 17’’S 57º 36’ 25’’W	22. 34º 21’ 43’’S 54° 22’ 18’’W
5. 31º 52’ 06’’S 57º 31’ 39’’W	13. 32º 50’ 10’’S 57º 37’ 37’’W	23. 34º 25’ 21’’S 54° 30’ 43’’W
6. 32º 01’ 40’’S 57º 43’ 33’’W	14. 32º 51’ 47’’S 57º 36’ 58’’W	24. 34º 01’ 03’’S 55° 03’ 25’’W
7. 31º 41’ 11’’S 55º 53’ 44’’W	15. 32º 48’ 43’’S 57º 51’ 27’’W	25. 34º 00’ 30’’S 54° 52’ 20’’W
8. 31º 55’ 32’’S 55º 59’ 57’’W	16. 31º 52’ 55’’S 57º 30’ 35’’W[**]	26. 34º 07’ 11’’S 54° 02’ 53’’W
	17. 31º 55’ 55’’S 55º 39’ 15’’W	27. 34º 11’ 29’’S 54° 07’ 07’’W
	18. 31º 42’ 32’’S 55º 54’ 10’’W	28. 33º 25' 18’’S 57° 48’ 25’’W[***]
		29. 32º 50’ 30’’ S 57º 57’ 01’’W

[*] Hernández et al. (2009) [**] Hernández et al. (2016) [***] González et al. (2016)

Plant sampling by site, biomass calculation and chemical analysis

The size of the sample to be taken in the different sites, was based on the information from González (2008). Biomass production and nutrient concentration: N, P, K, Ca and Mg of 36 specimens with average DBH and H of two 10-years stands of *Eucalyptus* were determined and the mean and variance of each parameter was calculated. Considering the variance of each variable found by González (2008), a minimum sample size of 9 trees was calculated in order to keep the relative error below 20%.

After the selected trees were felled, in each of them commercial wood (stem with bark) and tree canopy were weighed separately. In each site, 3 modal trees were selected based on the measurements of DBH and H, in which the component fractions of the crown (thick and thin branches, and leaves) were separated, to quantify the proportions of thick branches (diameter greater than 1 cm), thin branches (diameter less than 1 cm), and leaves in the total crown. In each of these 3 trees, each fraction was weighed separately, taking a composite sample for the subsequent calculation of the dry matter (DM) content and chemical analysis. Samples of fractions from the other 6 trees per site were also taken for DM content and chemical analysis. In all the trees (9), the stem was cut into 2.4 m logs, taking samples, by cutting a disk in the basal portion of each log. In each disk the bark was separated from the wood, and they were weighed and sampled separately. All samples were dried at 65°C until constant weight, to determine the moisture content. A subsample was taken for chemical analysis of each component, grinding it to pass a 0.5 mm mesh.

The concentration of P, Ca, Mg and K of the samples was determined, after mineralization by calcination at 550°C and ash dissolution with 10% HCl. In the extract, P was determined by colorimetry (Murphy and Riley 1962), Ca and Mg by atomic absorption spectrophotometry, and K by emission spectrophotometry. The determination of the N concentration in the sample was made by Kjeldahl distillation.

The amount of aerial biomass of the trees per unit area (hectare) was calculated based on the weights corresponding to the specimens harvested in the plot, and the number of trees per hectare. Based on these data, the weight of the harvest (commercial logs) was obtained, as well as each of the other harvest components which remain in the field (bark, thick and thin branches, and leaves).

From the chemical analysis of nutrients (N, P, K, Ca and Mg) of each fraction, the nutrient contents (stocks) were calculated per tree and per hectare. The results of quantity of biomass and nutrients were annualized (dividing them by the plantation age), because, although the age range was limited (8-11 years), it was the way to compare them.

Soil sampling and analysis of each site

At each site, a morphological description of the soil profile was made, and samples were taken from the A and B horizons. In all the cases, 20 and 10 sub-samples were taken per horizon A and B, respectively, in the plantation interrow, at the upper and middle position in the slope. The samples were dried at 45°C, ground and sieved to pass a 2 mm mesh. The determination of exchangeable bases was carried out by extraction with 1N ammonium acetate at pH 7, and subsequent determination of Ca and Mg by atomic absorption spectrophotometry and K and Na by emission spectrophotometry. Exchangeable acidity was extracted by a KCl solution. The determination of P was carried out by the Bray 1 method and the organic carbon (OC) was analyzed by the Walkley-Black method, while the pH was determined potentiometrically in a soil: water ratio 1: 2.5.

The bulk density was calculated following a model developed for this type of soils, which estimates it from the proportions of the sand, silt and clay fractions, as well as the organic carbon content (Silva et al. 1988). Table 2 shows the average results of the soil chemical analysis for the different zones.

Table 2. Chemical and physical parameters of soils in the three study areas. Average data for soil horizons A and B (standard deviations in parentheses).

Soil Taxonomy Species/ sites per zone/ CONEAT Zone: 9, 7 y 2	Horiz./ depth	pH (H_2O)	P (†)	Ca	Mg	K	Na	TB	EA	ECEC	BS	OC	BD
	cm		mg kg^{-1}	cmol$_c$ kg^{-1}							%	g kg^{-1}	g cm^{-3}
Alfisols, Mollisols *E. dunnii, E. grandis y E. globulus* 16 sites Zone: 9	A 32 (11)	5.3 (0.2)	3 (0.4)	4.60 (0.51)	1.19 (0.22)	0.24 (0.08)	0.35 (0.08)	6.38 (0.37)	0.68 (0.33)	7.06 (0.41)	90 (21)	10.7 (2.1)	1.44 (0.2)
	B 44 (13)	5.5 (0.3)	4 (0.5)	12.47 (2.75)	3.00 (0.75)	0.40 (0.17)	0.43 (0.09)	16.30 (4.92)	0.59 (2.19)	16.89 (3.36)	96 (20)	7.1 (1.7)	1.46 (0.3)
Ultisols, Alfisols *E. dunnii y E. grandis* 4 sites Zone: 7	A 53 (8)	4.6 (0.1)	3 (0.4)	1.40 (0.28)	0.60 (0.12)	0.20 (0.06)	0.36 (0.09)	2.56 (0.40)	1.00 (0.50)	3.56 (0.51)	72 (13)	6.4 (1.8)	1.49 (0.3)
	B 83 (22)	4.7 (0.1)	3 (0.4)	4.60 (0.74)	2.35 (0.53)	0.38 (0.16)	0.41 (0.10)	7.74 (1.25)	1.80 (1.12)	9.54 (0.93)	81 (22)	5.8 (1.5)	1.47 (0.3)
Mollisols, Alfisols *E. globulus* 9 sites Zone: 2	A 19 (8)	5.0 (0.2)	4 (0.5)	2.37 (0.48)	1.35 (0.43)	0.39 (0.24)	0.38 (0.07)	4.49 (0.88)	1.40 (0.69)	5.89 (0.81)	76 (11)	17.4 (2.9)	1.35 (0.2)
	B 39 (9)	5.2 (0.5)	4 (0.4)	5.49 (2.48)	4.61 (2.17)	0.43 (0.20)	0.73 (0.36)	11.26 (4.91)	1.89 (1.40)	13.15 (3.83)	85 (20)	9.9 (1.9)	1.40 (0.2)

Note: (†) P: Available P (Bray 1); exchangeable Ca, Mg, K y Na; TB: Total Bases; EA: Exchangeable Acidity; ECEC: Effective Cation Exchange Capacity; BS: Base Saturation at soil pH; OC: Organic Carbon (Walkley Black); BD: Bulk Density

In each soil, the stock of exchangeable cations (K, Ca and Mg) was estimated in the profile, where the highest root exploration occurs (horizons A and B). For the calculation, the exchangeable cation concentration and the soil mass of each horizon were used, according to their depth and bulk density. From the stock and considering the respective nutrient extractions by the wood for each species and site, the amounts of maximum rotations that the site would be able to produce without the addition of these elements were estimated. In commercial plantations these nutrients are not included in the fertilization scheme, including only N and P at the time of planting. It is assumed that the cation extraction rate per site will be similar in the short and medium term to that corresponding to the evaluated planting turn.

Climatic characteristics of the different study areas

According to the Köppen-Geiger climate classification, the entire territory corresponds to the temperate climate zone (Cf), with an average temperature of 17.5 °C (range 16 °C-19.5 °C, on the south and northwest coast, respectively), hot summers, homogeneous rainfall throughout the year and four clearly differentiated seasons. It is almost entirely humid subtropical climate (Cfa), except for a very small strip of oceanic climate (Cfb) in the southeast. The highest temperatures occur in January and February, while the lowest in June and July, with greater thermal amplitude in the north than in the south. Humidity is high, ranging between 70% and 75% throughout the country.

Particularly, the three zones studied have some climate differences (Table 3).

Table 3. Climatic characteristics of the study areas (Uruguayan Institute of Meteorology (Inumet) 2021. Average 1961-1990.

Zone	Annual rainfall (mm)	Annual temperature (°C)	Annual insolation (h)
		Range	
9	1 150-1 300	17.5-18.0	2 500-2 600
7	1 350-1 550	17.5-18.0	2 450-2 500
2	1 100-1 250	16.0-17.0	2 350-2 450

Radiation increases from southeast to northwest, with approximately half an hour a day difference between the extremes (Zones 2 and 9). Temperature increases in the same direction as radiation, with around 1.2°C more in Zones 7 and 9 than in Zone 2. Precipitation markedly increases from southwest to northeast, raining annually, on average, in Zone 7 around 300 and 250 mm more compared to Zones 2 and 9, respectively.

Statistical analysis of the information

For the three species studied, the following were compared: (1) the concentration of each of the macronutrients (N, P, K, Ca and Mg) in the wood, (2) the amount of wood biomass produced per hectare and per year, and (3) the total contents per hectare and per year of each of the nutrients in the wood and harvest fractions. In addition, two nutritional efficiency indices were calculated: Nutrient Use Efficiency (NUE) in total wood production, as kg of dry matter (DM) of wood produced per kg^{-1} of nutrient in aerial biomass, and the Biological Utilization Coefficient (BUC), as kg of DM of wood produced per kg^{-1} of nutrient in wood.

The differences between species were analyzed considering: a) the set of sites in the three zones; b) the set of sites in Zone 9 (in both cases the three species were present); c) for *E. dunnii* and *E. grandis* the set of sites in Zone 7. On the other hand, the differences between zones were analyzed for each species, considering: i) *E. dunnii* in zones 7 and 9; ii) *E. grandis* in zones 7 and 9; iii) *E. globulus* in zones 2 and 9.

As a first step, the assumption of normality was verified for the variables under study using the Shapiro-Wilks test ($p > 0.05$ for normal data). To the extent that no variable behaved as normal, a natural logarithmic transformation was performed to achieve normality for all variables. In the comparison of means, the least squares adjustment of means was used to contemplate the unbalanced data. Differences were considered significant when $P < 0.05$.

The correlation between the concentration of cations (K, Ca and Mg) in the wood was analyzed with respect to their concentration in the soil A and B horizon, as well as in relation to their stocks per horizon, and in the sum of the A and B horizons. For the correlation analysis the Spearman coefficient (Conover 1999) was used since some of the variables did not follow a normal distribution. The analysis of the number of rotations (10 years each) that the site would sustain was carried out under the assumptions that the available cation content of the soil (exchangeable + solution) was as much as possible to be used in future rotations, and that the roots can absorb nutrients from the B horizon. This analysis did not include cations in non- exchangeable forms, neither the biogeochemical recycling that contributes to the tree's nutrition.

For N and P this type of analysis was not carried out because these nutrients are usually applied through fertilization.

2.4. RESULTS

Nutrient concentration in wood

Table 4 shows the concentrations of N, P, K, Ca and Mg in commercial debarked wood of adult *Eucalyptus* trees according to species and plantation zones.

Table 4. Nutrient concentration in commercial wood of adult *Eucalyptus* trees according to species and planting area. Different capital letters in the rows indicate statistically significant differences between species within the same zone. Different lower-case letters in the columns indicate statistically significant differences between zones for each species.

Nutrient	Sites	*E. dunnii*	*E. grandis*	*E. globulus*
			$g\ kg^{-1}$	
N	All sites	0.85 (A)	0.70 (B)	0.80 (A)
	Zone 9	0.81 (Ab)	0.64 (Bb)	0.79 (Aa)
	Zone 7	1.26 (Aa)	1.22 (Aa)	
	Zone 2			0.81 (a)
P	All sites	0.10 (A)	0.07 (B)	0.08 (A)
	Zone 9	0.10 (Aa)	0.07 (Ba)	0.11 (Aa)
	Zone 7	0.12 (Aa)	0.06 (Ba)	
	Zone 2			0.07 (b)
K	All sites	0.80 (A)	0.53 (B)	0.46 (B)
	Zone 9	0.77 (Aa)	0.53 (Ba)	0.58 (Ba)
	Zone 7	0.99 (Aa)	0.55 (Ba)	
	Zone 2			0.38 (b)
Ca	All sites	2.05 (A)	1.41 (B)	1.03 (C)
	Zone 9	2.01 (Aa)	1.40 (Ba)	1.39 (Ba)
	Zone 7	2.39 (Aa)	1.45 (Ba)	
	Zone 2			0.79 (b)
Mg	All sites	0.96 (A)	0.27 (B)	0.19 (C)
	Zone 9	0.97 (Aa)	0.28 (Ba)	0.24 (Ba)
	Zone 7	0.91 (Aa)	0.23 (Ba)	
	Zone 2			0.16 (b)

In the whole set of sites, higher concentrations of nutrients were observed in the wood of *E. dunnii* related to the other two species, these differences being significant for the cations (K, Ca, and Mg). With respect to N and P, concentrations were lower in *E. grandis* in relation to *E. dunnii* and *E. globulus*. In addition, *E. globulus* presented the lowest concentrations of Ca and Mg in the wood. In Zone 9 the results were like those obtained for the analysis of all the sites, with a superiority in the concentrations of cations in *E. dunnii* with respect to the other two species, and of *E. dunnii* and *E. globulus* with respect to *E. grandis* for N and P ($P<0.05$). Similarly, in Zone 7, *E. dunnii* had higher wood concentrations of all nutrients, except for N. That is, regardless of the site, this species always presented higher values of the concentration of nutrients in its wood.

In the comparison between zones, the concentration of nutrients in wood of *E. dunnii*, as well as *E. grandis,* no significant differences were observed between Zones 7 and 9, except for N, which was higher in Zone 7 for both species. *Eucalyptus globulus* showed higher concentrations of all nutrients in the wood (except for N) in the plantations of Zone 9 compared to those of Zone 2.

Biomass and nutrients accumulated in wood

Table 5 indicates the accumulated amounts per hectare and per year of wood biomass N, P, K, Ca and Mg in commercial wood comparing the data through species and plantation zones.

Table 5. Wood biomass produced and nutrients accumulated in the commercial wood of adult *Eucalyptus* trees according to species and plantation area. Different capital letters in the rows indicate statistically significant differences between species within the same zone. Different lower-case letters in the columns indicate statistically significant differences between zones for each species.

Variable	Sites	*E. dunnii*	*E. grandis*	*E. globulus*
			Mg ha^{-1} yr^{-1}	
Wood Biomass	All sites	16.7 (A)	16.3 (A)	12.3 (B)
	Zone 9	16.4 (Ab)	16.0 (Ab)	14.0 (Ba)
	Zone 7	18.8 (Aa)	18.8 (Aa)	
	Zone 2			11.4 (b)
Nutrient			kg ha^{-1} yr^{-1}	
N	All sites	14.6 (A)	10.9 (B)	10.1 (B)
	Zone 9	13.2 (Ab)	9.6 (Bb)	11.2 (ABa)
	Zone 7	23.8 (Aa)	22.9 (Aa)	
	Zone 2			9.0 (a)
P	All sites	1.7 (A)	1.1 (B)	1.1 (B)
	Zone 9	1.6 (Ab)	1.0 (Ba)	1.6 (Aa)
	Zone 7	2.3 (Aa)	1.3 (Ba)	
	Zone 2			0.7 (b)
K	All sites	13.8 (A)	8.2 (B)	5.8 (C)
	Zone 9	12.6 (Ab)	7.9 (Ba)	8.3 (Ba)
	Zone 7	19.3 (Aa)	11.0 (Ba)	
	Zone 2			4.2 (b)
Ca	All sites	34.8 (A)	22.0 (B)	12.9 (C)
	Zone 9	32.8 (Ab)	20.9 (Bb)	19.7 (Ba)
	Zone 7	45.2 (Aa)	29.1 (Ba)	
	Zone 2			8.8 (b)
Mg	All sites	16.3 (A)	4.2 (B)	2.4 (C)
	Zone 9	15.6 (Aa)	4.1 (Ba)	3.4 (Ca)
	Zone 7	17.2 (Aa)	4.7 (Ba)	
	Zone 2			1.8 (b)

The amount of wood biomass produced by *E. globulus* was significantly lower compared to the other two species for all the sites and for those plantations that grew on *Alfisols* and *Mollisols* from Zone 9. In Zone 7 the species *E. dunnii* and *E. grandis* produced a higher amount of wood biomass compared to Zone 9. On the other hand, in Zone 9, the production of *E. globulus* was higher than in Zone 2.

In the whole set of sites, higher amounts of nutrients were accumulated in the wood of *E. dunnii* compared to the other two species, because of their higher concentration and, compared to *E. globulus*, to a higher biomass production. In turn, in cations, the amounts in *E. grandis* were higher compared to *E. globulus*, explained by a higher biomass production, and, for Ca and Mg, to higher concentrations of its in wood. The nutrient that showed the greatest accumulation in wood was Ca, with an important difference between species, since *E. dunnii* presented 37% more than *E. grandis*, and this 41% more than *E. globulus*. *Eucalyptus dunnii* presented 25% more N than *E. grandis,* and this species, 7% more than *E. globulus*. Also *E. dunnii* showed 35 % more P in wood than the other two species, which did not differ from each other. For its part, for K, *E. dunnii* absorbed 41% more than *E. grandis* and this, in turn, 29% more than *E. globulus*. For Mg, the extraction of *E. dunnii* was 4 times higher than that of *E. grandis*, and this was almost twice that of *E. globulus*.

When comparing the amounts of nutrients accumulated in the wood of the plantations that grew in *Alfisols* and *Mollisols* from Zone 9, higher amounts of K, Ca and Mg were found in *E. dunnii* in relation to the other two species. Although *E. dunnii* showed higher amounts of N compared to *E. grandis*, no differences were found with *E. globulus,* while also for P, the amount of *E. grandis* in wood was significantly lower than that of the other two species. Finally, for Mg, *E. grandis* had greater accumulation compared to *E. globulus*. On Ultisols and Alfisols from Zone 7, *E. dunnii* showed higher nutrient accumulation than *E. grandis,* except for N.

In the comparison between zones for each species, *E. dunnii* showed higher accumulated nutrients in Zone 7 than in Zone 9 (except for Mg), which was explained by higher growth in the first one. For *E. grandis,* despite the higher growth in Zone 7, only N and Ca accumulations were higher compared to Zone 9. *Eucalyptus globulus* presented higher amounts of nutrients (except N) in the wood in Zone 9 compared to

Zone 2, explained by higher concentrations and further growth in the first mentioned zone.

Nutrient Use Efficiency in total wood production (NUE) and Biological Utilization Coefficient (BUC)

The estimation of the NUE takes into consideration, in addition to the biomass production, the concentration of nutrients in each component. This information is provided in Table 6, except for wood, which has already been presented in Table 4.

Table 6. Nutrient concentration in the different components of adult *Eucalyptus* trees according to species and planting area. Average data from all evaluated sites. Different letters in the rows indicate statistically significant differences.

Fraction	Nutrient	*Eucalyptus dunnii*		*Eucalyptus grandis*		*Eucalyptus globulus*	
		Zone 7	Zone 9	Zone 7	Zone 9	Zone 2	Zone 9
		g kg^{-1}					
Bark	N	3.9 (A)	2.8 (B)	3.0 (B)	2.1 (C)	2.5(C)	2.4 (C)
	P	0.4 (B)	0.4 (B)	0.6 (A)	0.3 (B)	0.4 (B)	0.4 (B)
	K	4.5 (B)	4.2 (BC)	4.7 (B)	3.1 (C)	4.0 (BC)	5.6 (A)
	Ca	25.3 (C)	34.8 (B)	18.8 (D)	45.0 (A)	12.3 (D)	30.0 (B)
	Mg	2.1 (A)	2.5 (A)	1.6 (B)	1.3 (C)	1.2 (C)	2.5 (A)
Leaves	N	17.5 (A)	16.2 (A)	20.0 (A)	16.6 (A)	13.7 (B)	13.1(B)
	P	1.3 (A)	1.3 (A)	1.0 (AB)	1.4 (A)	1.0 (AB)	0.7 (B)
	K	7.7 (A)	7.5 (A)	7.6 (A)	7.2 (A)	5.2 (B)	4.5 (B)
	Ca	9.0 (B)	13.7 (A)	6.6 (B)	12.7 (A)	10.0 (AB)	12.6 (A)
	Mg	1.3 (C)	1.9 (B)	2.6 (A)	2.6 (A)	1.4 (C)	1.0 (C)
Thick branches	N	3.4 (A)	2.4 (B)	1.8 (B)	1.1 (C)	1.4 (C)	1.1 (C)
	P	0.2 (A)	0.2 (A)	0.2 (A)	0.2 (A)	0.1 (A)	0.1 (A)
	K	2.5 (B)	1.9 (BC)	1.3 (C)	1.4 (C)	1.3 (C)	3.3 (A)
	Ca	4.8 (B)	7.2 (A)	4.6 (B)	8.2 (A)	4.2 (B)	7.5 (A)
	Mg	0.9 (A)	1.1 (A)	1.3 (A)	0.6 (B)	0.4 (B)	1.0 (A)
Thin branches	N	4.9 (A)	4.3 (A)	3.7 (A)	2.3 (B)	4.3 (A)	4.1 (A)
	P	0.5 (A)	0.4 (A)	0.4 (A)	0.3 (AB)	0.3 (AB)	0.2 (B)
	K	5.7 (A)	4.7 (B)	2.6 (D)	3.3 (C)	2.6 (D)	4.5 (B)
	Ca	6.6 (B)	11.2 (A)	6.0 (B)	9.3 (A)	7.9 (B)	9.8 (A)
	Mg	0.6 (C)	1.3 (B)	1.4 (B)	1.1 (BC)	0.6 (C)	2.0 (A)

Except for Ca and Mg (in some species/Zones), the leaves presented the highest nutrient concentrations among the components of the crown. In this fraction, the concentration of N, P, K and Mg was significantly higher in *E. dunnii* and *E. grandis* than in *E. globulus*, comparing soils from the same Zone (Zone 9).

The concentration of Ca in the bark was the highest of the different components of the tree, with significantly higher values in those trees of Zone 9, regardless of the species.

Comparing the nutrient concentrations of the different components of the *E. dunnii* canopy in Zones 7 and 9, it showed significant variable differences according to the nutrient and the canopy component, without an overall superiority. Similar behavior was observed for *E. grandis* and *E. globulus* in the areas where they were evaluated.

Table 7 shows the NUE and BUC values for N, P, K, Ca and Mg comparing the data through species and plantation zones.

Table 7. NUE (kg of wood produced per kg of total nutrient absorbed) and BUC (kg of wood produced per kg of nutrient absorbed in wood) for nutrients accumulated in the total aerial biomass and wood of adult *Eucalyptus* trees according to species and planting area. Different capital letters in the rows of each index indicate statistically significant differences between species within the same zone. Different lower-case letters in the columns indicate statistically significant differences between zones for each species.

		NUE			BUC		
Nutrient	Sites	*E. dunnii*	*E. grandis*	*E. globulus*	*E. dunnii*	*E. grandis*	*E. globulus*
		kg wood kg nutrients in total aerial biomass^{-1}			kg wood kg nutrients in wood^{-1}		
N	All sites	279 (C)	412 (B)	493 (A)	1 164 (B)	1 422 (A)	1 249 (B)
	Zone 9	276 (Ba)	483 (Aa)	518 (Aa)	1 236 (Ba)	1 556 (Aa)	1 274 (Ba)
	Zone 7	287 (Aa)	308 (Ab)		796 (Ab)	821 (Ab)	
	Zone 2			420 (b)			1 236 (a)
P	All sites	2 864 (C)	3 866 (B)	4 403 (A)	10 097 (B)	14 618 (A)	11 849 (B)
	Zone 9	2 836 (Ba)	3 866 (Aa)	4 273 (Ab)	10 405 (Ba)	14 328 (Aa)	8 866 (Bb)
	Zone 7	3 072 (Ba)	3 866 (Aa)		8 350 (Ba)	15 835 (Aa)	
	Zone 2			4 817 (a)			15 367 (a)
K	All sites	331 (B)	578 (A)	513 (A)	1 262 (B)	1 882 (A)	2 165 (A)
	Zone 9	321 (Ca)	608 (Aa)	459 (Bb)	1 300 (Ba)	1 901 (Aa)	1 720 (Ab)
	Zone 7	352 (Ba)	534 (Aa)		1 011 (Ba)	1 826 (Aa)	
	Zone 2			699 (a)			2 670 (a)
Ca	All sites	86 (B)	145 (A)	158 (A)	488 (C)	709 (B)	973 (A)
	Zone 9	82 (Bb)	120 (Ab)	128 (Ab)	498 (Ba)	713 (Aa)	721 (Ab)
	Zone 7	110 (Ba)	206 (Aa)		420 (Ba)	685 (Aa)	
	Zone 2			276 (a)			1 274 (a)
Mg	All sites	528 (C)	1 200 (B)	1 422 (A)	1 043 (C)	3 678 (B)	5 219 (A)
	Zone 9	513 (Bb)	1 141 (Aa)	1 164 (Ab)	1 033 (Ba)	3 605 (Aa)	4 146 (Ab)
	Zone 7	639 (Ba)	1 313 (Aa)		1 097 (Ba)	4 273 (Aa)	
	Zone 2			2 416 (a)			6 374 (a)

For all the nutrients, and regardless of the area, the NUE was significantly lower in *E. dunnii* compared to the other two species (except N in Zone 7). Likewise, for N, P and Mg, the efficiency in *E. globulus* was higher than in *E. grandis,* explained mainly by lower concentrations of nutrients in the wood of *E. globulus* of the Zone 2. Also considering all the sites, lower BUC values were observed for *E. dunnii*, with significant differences in relation to the other two species for cations (K, Ca, and Mg). For N and P, the BUC of this species and *E. globulus* was lower than for *E. grandis,* while the latter presented lower values for Ca and Mg compared to *E. globulus*.

Considering the forests that grew on *Alfisols* and *Mollisols* in Zone 9, the results resemble those of the complete data set, with a lower NUE of *E. dunnii* compared to *E. grandis* and *E. globulus*. For K, *E. grandis* showed greater efficiency compared to *E. globulus*.

For the BUC there was also a lower utilization efficiency for the cations in *E. dunnii* in relation to the other two species. Likewise, for N and P, a lower efficiency of *E. dunnii* and *E. globulus* compared to *E. grandis* was observed. In the comparison between *E. dunnii* and *E. grandis* in Ultisols and Alfisols from Zone 7 for both indices, lower values were found in *E. dunnii* (except N).

In the comparison of each species in their two plantation zones, for *E. dunnii*, the NUE values were significantly higher in soils of Zone 7 than in soils of Zone 9 for Ca and Mg, due to higher concentration values in the crown and bark in the plantations of Zone 9. For BUC, differences were only observed for N, the efficiency being lower in Zone 7 (due to a higher concentration of N in the wood of the forests of Zone 7).
For *E. grandis,* no differences in NUE were found between Zones 7 and 9, except for N, that showed higher values in Zone 9, and Ca, which was the opposite. Similar results were observed for BUC, but differences were observed only in N values (like *E. dunnii*). In *E. globulus,* except for N, the use efficiencies were higher in the forests of Zone 2 than in Zone 9 (by virtue of being soils of less fertility than those of Zone 9).

Soil exchangeable cations: relationship with their concentration in wood and availability for future rotations

The correlations between the concentration of nutrients in the wood and the respective concentration in A and B horizon, as well as the stock in A, B and A+B horizons, were studied. The highest correlation coefficients were obtained for the concentration in the A horizon (Table 8). The same correlations were also studied but considering the concentration of nutrients in the total aerial biomass, with moderate to low results.

Table 8. Spearman's correlation coefficient between the concentration of nutrients in the wood and its concentration in the A horizon of the soil. The values in parentheses below the species indicate the number of observations. The values in parentheses indicate de p-value for the correlation coefficients.

Species	Concentration in Wood	Concentration in A horizon of soil		
		K	Ca	Mg
		Correlation coefficient		
E. dunnii (8)	K	0.82 (<0.01)		
	Ca		0.39 (<0.01)	
	Mg			0.51 (<0.01)
E. grandis (10)	K	0.29 (0.02)		
	Ca		0.31 (0.01)	
	Mg			0.53 (<0.01)
E. globulus (11)	K	-0.34 (<0.01)		
	Ca		0.73 (<0.01)	
	Mg			0.27 (0.01)

Considering the assumptions described in the methodology, the highest possible numbers of rotations were calculated for each species (Table 9). From this estimation, K is the nutrient that will first be limiting, regardless of the species and site analyzed.

Table 9. Estimation of the availability of K, Ca and Mg by type of soil and extractions by species in wood, assuming a 10-year rotation. In parentheses, estimate of the number of rotations by species and site (* = 10-year rotation)

Zone/Soil	Horizon	Available on the soil (kg ha^{-1})			Extraction by species in wood (Number of rotations) (kg ha^{-1} rotation^{-1}*)								
					E. dunnii			*E. grandis*			*E. globulus*		
		K	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg
Alfisols, Mollisols 16 sites Zone 9	A	431	4 241	658									
	B	996	15 926	2 299	126	328	156	79	209	41	83	197	34
	TOTAL	1 427	20 167	2 957	*(11)*	*(61)*	*(19)*	*(18)*	*(96)*	*(72)*	*(17)*	*(102)*	*(87)*
Ultisols, Alfisols 4 sites Zone 7	A	616	2 210	568									
	B	1 814	11 260	3 451	193	452	172	110	291	47			
	TOTAL	2 430	13 470	4 019	*(13)*	*(30)*	*(23)*	*(22)*	*(46)*	*(86)*			
Mollisols, Alfisols 9 sites Zone 2	A	390	1 217	416									
	B	915	5 988	3 017							42	88	18
	TOTAL	1 305	7 205	3 433							*(31)*	*(82)*	*(191)*

Estimations of extraction by species and number of rotations to deplete soil resources were calculated assuming that debarked wood is the fraction removed with forest exploitation

2.5. DISCUSSION

The 29 plantations analyzed in this study are representative of the main types of soils where most of the commercial forests of the genus *Eucalyptus* are planted in Uruguay, covering the three main areas of forest production. These zones differ in climatic parameters, determining different conditions for the growth of the forests and consequently, different conditions for biomass production, as well as for the nutrient absorption mechanisms. The climate also determines that for *E. globulus* the growing conditions are not suitable in Zone 7 to reach optimal yield potentials, especially since this species is affected by high temperatures during summer.

Although most of the soils planted with *Eucalyptus* have a fertility below the average of the country (with lower contents of exchangeable bases and organic matter), it has also been observed that they are more fertile than soils from other world production regions (Gonçalves et al. 2007, de Aguiar and Stape 2009). The soils with the highest fertility of the three zones are the *Alfisols* and *Mollisols* of Zone 9 but they present a lower depth than the Ultisols. On the other hand, the soils of Zone 2 are more fertile than those of Zone 7, although their shallower depth results in a lower stock of nutrients if the entire profile is considered. The *Ultisols* (Zone 7), which are the least fertile soils in this study, are at the same time the deepest and present the best rooting conditions, a characteristic indicated as fundamental by Herbert (2005).

Santana et al. (2000) found, for the A horizon of 5 sites (SP, Brazil), exchangeable Ca, Mg and K values 5, 3 and 2 times lower, respectively, compared to the *Ultisols* of this study. Consequently, and considering an average depth of 151cm, these authors reported stocks in soils of 1 710; 1 026 and 762 kg ha^{-1} for exchangeable Ca, Mg and K, respectively, which are 8, 7 and 2 times lower, respectively, than those calculated for *Ultisols* in our research.

Regardless of the site where it was planted, *E. dunnii* presented higher values of nutrient concentration in its wood than the other species. In the components of the harvested biomass, wood presented the lowest concentration of nutrients, in agreement with various authors (Gonçalves et al. 1997, Laclau et al. 2000, Achat et al. 2015). Salvador et al. (2016) for 6.7-year-old *E. saligna* in Telêmaco Borba (PR, Brazil), in a Latossol (21.5 g kg^{-1} organic carbon in the first 40cm); Couto Guimarães et al. (2015) for 4-year-old *E. dunnii* in Alegrete (RS, Brazil), in a Red Argissol (7.8 g kg^{-1} organic carbon in the first 40 cm) and dos Santos et al. (2019) for 4.1-year-old *E. dunnii* in Eldorado do Sul (RS, Brazil), in a Red-Yellow Argissol (8.3 g kg^{-1} organic carbon in the first 60 cm) obtained similar concentration values for N and P (ranges between 0.8-1.0 and 0.09-0.1 g kg^{-1}, respectively). These authors found lower wood concentrations values for Ca and Mg (ranges between 0.5-0.9 and 0.2-0.7 g kg^{-1}, respectively), and higher for K (range 1.0-1.4 g kg^{-1}) compared to those of this study. In all cases the climate is subtropical humid -Cfa-. Dos Santos et al. (2019) also studied other species, among them, hybrids of *E. urograndis* and *E. uroglobulus*, finding higher concentrations in the wood of *E. dunnii* for Ca and Mg.

Beyond the differences in harvest ages, the higher concentrations found in *E. dunnii* wood for Ca and Mg in our study could be explained by the high content of the soils in Uruguay for these nutrients. Likewise, although the soils in Uruguay also present higher K contents, the lower concentration found in our study could be explained by the high fertilization rates in brazilian studies (more than 60 kg ha^{-1} K_2O in the first 9 months after planting).

The comparative analysis of nutrient concentrations in wood between plantation zones (7 and 9) by species, showed similar values for *E. dunnii* and *E. grandis* (except for N, which was higher in Zone 7). This suggests that the greater depth of the soils of Zone 7 would have determined a more extended root system, allowing a greater absorption of nutrients that ended up compensating their lower fertility. On the other hand, in *E. globulus*, the concentrations were significantly higher in Zone 9 in relation to Zone 2 associated to the lower nutrient availability in Zone 2 (for all nutrients except N). The higher concentration of N for *E. dunnii* and *E. grandis* in Zone 7, and for *E.* globulus in Zone 2, could be associated with the fact that the plantations in these zones were carried out on soils that have traditionally been kept under native pastures (without tillage intervention). In this way and considering a stable ratio in the soil of C/N=10 (Weil and Brady 2016), there is a greater availability of N (more mineralization of organic matter) compared to the soils of Zone 9, which had an important agricultural use before afforestation.

Considering all the fractions or components, the highest concentrations of N, P and K observed in leaves, and the highest concentrations of Ca and Mg found in the bark of the three species are in agreement with previous studies (Santana et al. 2000, Leite et al. 2010). The concentration values of N, P and K in the leaves were within the ranges found by Leite et al. (2010) and Eufrade Junior et al. (2017), even though the soils in Brazil presented significantly lower OM values (<1.5%) than those of Uruguay, so a lower contribution of N is foreseeable.

Regarding the bark Ca concentration, although a great variability was found, with the lowest values in *E. globulus*, we found a marked effect of the site, with the highest values in forests of Zone 9, which can be explained by a greater availability of soil Ca. Regardless of the species, these values were higher than those reported by González-García (2016) and Leite et al. (2010), who in Brazilian plantations recorded bark Ca concentrations of 10.9 and 9.9 g kg^{-1}, respectively, associated with lower soil Ca concentrations (range 0.5-1.4 $cmol_c$ kg^{-1}). Similarly, for Mg in bark, slightly higher values were recorded than those found by these authors.

The wood biomass production was significantly higher in *E. dunnii* and *E. grandis* in relation to *E. globulus*, which is explained by a greater growth in volume (greater diameter and height) of the first two species (even considering that the basic density of *E. globulus* wood is higher and therefore the wood is heavier). In turn, the species of greater growth produced a significantly higher amount of wood biomass in Zone 7 compared to Zone 9, explained by the interaction of edaphological (greater soil depth) and climatic (higher rainfall) factors.

In relation to the stock of nutrients in the wood, as mentioned, generally higher amounts were found in *E. dunnii* compared to the other two species, regardless of the area. These differences highlight that *E. dunnii* stands, for the same conditions of nutrient supply can accumulate a greater quantity in wood, with similar yields to other species. This could be interpreted as higher internal nutrient requirements, or a possible luxury consumption to the extent that the supply of nutrients by the soil is sufficient. In the medium or long term, the greater nutrient removal from the site in commercial *E. dunnii* wood can affect the sustainability of the system (Turvey and Smethurst 1994, Fox 2000). Although from the productive point of view *E. dunnii* emerges as a species that manages to accumulate a similar or greater biomass of wood than the other two species, it is at the expense of greater absorption and accumulation of nutrients in its biomass, to the extent of its supply by the soils.

Analyzing the complete data set (or those from zones 9 or 7), the NUE was significantly lower in *E. dunnii* compared to the other two species for all nutrients (Table 7). Morais et al. (1990) for 8-year *Eucalyptus* species (*E. grandis*, *E. saligna*, *E. cloeziana*, *E. citriodora*) in Brazil, Santana et al. (2000) for different *Eucalyptus* species (*E. grandis, E. saligna, E. urophylla, E. camaldulensis, E. cloesiana* and hybrids) also in Brazil, and Herbert (1996), for 7-year *Eucalyptus* species (*E. fastigata, E. grandis, E. macarthurii, E. nitens* and *E. smithii*) in South Africa, with different climatic and edaphic conditions, obtained similar NUE results in relation to *E. grandis* and *E. globulus* in this study for N, P and K (Table 10). It should be noticed that even the lowest values of these ranges were higher than those calculated for *E. dunnii* plantations. In contrast these authors found higher NUE compared to the three species of this study for Ca and Mg. Laclau et al. (2003) in hybrid plantations of *E. urograndis* in the Congo, found similar NUE to those of our study for N, lower for P and higher for cations. From the above, it is possible that the large stocks of Ca and Mg in the soils of Uruguay produced a luxury consumption, and this was enhanced by the low efficiency of *E. dunnii*.

Table 10. NUE (kg of wood produced per kg of total nutrient absorbed) and BUC (kg of wood produced per kg of nutrient absorbed in wood) for nutrients accumulated in the total aerial biomass and wood, respectively, of adult *Eucalyptus* trees according to different authors and species.

NUE			BUC		
kg wood kg nutrients in total aerial biomass^{-1}			kg wood kg nutrients in wood^{-1}		
Nutrient	Morais et al. (1990), Santana et al. (2000) and Herbert (1996) (range)	Laclau et al. (2003)	Freitas Melo et al. (1995)	Couto Guimarães et al. (2019)	dos Santos et al. (2019)
N	320-417	422		1 049	1 317
P	3 750-4 501	1 997	7 490	12 574	11 439
K	434-585	905	933	776	738
Ca	317-406	554	931	2 107	1 431
Mg	1 550-2 252	1 498	4 126	1 546	1 807

For the BUC, the joint analysis of all the sites, and the Zone 9 subset, resulted in lower efficiencies for the cations in *E. dunnii* in relation to *E. grandis* and *E. globulus*. Also, the utilization efficiency of this species and *E. globulus* was also significantly lower for N and P relative to *E. grandis*. Freitas Melo et al. (1995) obtained for 7-years *E. saligna* in RS, Brazil, higher BUC compared to those of this study for Ca, similar for Mg compared to those of *E. grandis* and *E. globulus* in this study, although much higher than those registered for *E. dunnii*; and lower for P and K (Table 10). Couto Guimarães et al. (2019) for 4.5-year-old *E. dunnii* in Alegrete (RS, Brazil), in a Red Argissol obtained higher BUC values for P, Ca, and Mg, similar for N, and lower for K, in relation to those obtained for the same species in this study.

Dos Santos et al. (2019) for 4.1-year-old *E. dunnii* in Eldorado do Sul (RS, Brazil), in a Red-Yellow Argissol obtained higher BUC values for Ca and Mg, similar for N and P, and lower for K, in relation to those obtained for the same species in this study. For the hybrids of *E. urograndis* and *E. uroglobulus*, these authors found higher BUC for Ca and Mg compared to *E. dunnii* (species effect). The lower BUC for Ca and Mg found for *E. dunnii* in our study could be explained by the high content of these in the soils of Uruguay (luxury consumption). In turn, for K, the higher CUB found in our study could be explained by the great availability of this nutrient in Brazilian plantations, because of the high fertilization rates received.

Even though in this analysis the nutrient cycling through residue decomposition was not included, it is important to notice that large amounts of nutrients were returned to the site following harvesting in agreement with previous findings (Gonçalves et al. 2007, Hernandez et al. 2009, González et al. 2016). These nutrients are likely to substantially contribute to the sustainability of the following plantations, but the degree of their availability will depend on the quality of the residue and the considered nutrient.

The highest correlation obtained by relating the wood concentration of cations (K, Ca, and Mg) with their concentration in the A horizon of the soils suggests a greater influence of cation concentration in the upper soil layer, where the highest density of roots that absorb nutrients is found. Although the correlation coefficients, in some cases, were moderate, it is important to bear in mind that the absorption dynamics are also affected by other factors already mentioned. No positive correlations were found between biomass production and cation concentration in this study. This result suggests that the nutritional limitation regarding K, Ca and Mg is not the main determinant of production in these plantations.

From the analysis for exchangeable cations (K, Ca and Mg) in the soil, it turned out that, although the concentrations were higher in the soils of Zones 9 and 2, the higher depth in Zone 7 could counteract the lower fertility. Considering that the nutrient stocks in the soil depend on both their concentration and their rooting depth, it is to be expected that there will be a compensation in Zone 7, achieving an availability like that of the other soils. The estimation of potential rotations was based in the assumptions that future plantation will be able to absorb what is available at the time of sampling, and that they will extract the same amount of Ca, Mg and K as these plantations. Although non-exchangeable forms of these nutrients are likely to be significant sources in the long term (Bel et al. 2020), considering the coarse texture of the soils, and the short-term rotations, this analysis will provide an assessment of sustainability of this production system. Considering this estimate, the species *E. dunnii* would be the first to start with nutritional limitations. Given the large amounts of K exported, and the lower stocks in the soil, it is for this nutrient that the addition will be necessary in the medium term, regardless of the site and the species planted. For both Ca and Mg, considering the available stocks and the recorded extractions, their addition does not appear as necessary, even in the long term.

2.6. CONCLUSIONS

The comparative study of the species *E. dunnii*, *E. grandis* and *E. globulus* showed that *E. dunnii* presented the highest extraction of nutrients in its commercial wood, considering all environments. This difference is explained by a higher concentration of the studied nutrients (N, P, K, Ca, Mg), as well as a higher biomass production of this species compared to *E. globulus*. Consequently, the BUC, registered lower values for the cations (K, Ca, and Mg) for *E. dunnii* in comparison with the other two species, and, in addition, for N and P, in comparison to *E. grandis*. The NUE, in turn, yielded lower values for *E. dunnii* compared to those corresponding to the other two species, for all nutrients and regardless of the planting site. The planting of this species in the different environments will make a greater use of the soil resource through a greater demand for nutrients, with less productive efficiency. This aspect must be especially considered, in those soils with less natural fertility and where the fertilization scheme does not consider this higher demand for nutrients from the species. Potassium emerges as one of the first nutrients to manifest as deficient, depending on the species and type of soil (Zone) where the plantations are located.

The concentrations of cations in wood were related to their concentration in the A horizon of the soils. However, other soil factors, such as rooting depth, and nutrient concentration at greater depths, as well as climate factors such as rainfall, temperature, and solar radiation, may explain the differences, and therefore should be considered in future nutrient extraction studies by commercial forest species.

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3. HARVEST RESIDUE DECOMPOSITION FROM *EUCALYPTUS* SP. PLANTATIONS IN TEMPERATE CLIMATE: INDICATORS AND CONTRIBUTION TO NUTRIENT CYCLING

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3.1. ABSTRACT

Sustainable management of forest plantations, keeping the harvest residues on site, improves soil 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; 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 5 commercial plantations of Uruguay. At harvest biomass of leaves, thin and thick branches, and bark, and their N, P, K, Ca and Mg content were quantified. At each site, bags with samples of the different residues were left to decompose and periodically collected during 24 months. *Eucalyptus dunnii* presented the largest amount of residues of all fractions. The decomposition rates of the different residues depended on their chemical constitution, fraction size and the species. *Eucalyptus dunnii* leaves showed the shortest half-life (0.94 years), while bark of the same species presented the longest (5.62 years). Total nitrogen and carbon (total and soluble) contents, which can be easily determined, emerge as good predictors for half-life estimation. The release patterns of nutrients depended more on their dynamics in the plant and their fractions 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.

3.2. 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, key components of soil fertility, and mainly supported by the contributions of mulch (litter) and root replacement during the plantation cycle, and by 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 bio-logical 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] establish that both the quantification of the nutrient content in the different forest plantations, as well as the knowledge of the relationship between the export of nutrients and those that are available in the soil for subsequent reuse are essential to define 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 on those 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 a certain amount of the other nutrients, and given their scarcity, decomposition is slowed down. In residues of large physical size and little contact with the soil —like branches— their slow decomposition acquires even more relevance since when the 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 its 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 the residues with high L:N ratios tend to decompose slowly [18-10]. 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* in Brazil, Argentina, South Africa, Sri Lanka, India or New Zealand, and *E. globulus* in Spain, Portugal and Chile), experimental information for both on the decomposition of residues is widely available, although mostly generated in climates different from that of Uruguay. However, experimental information on the recycling of nutrients from the harvest residues is limited although it is important 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 rates of residue decomposition or the process of nutrient recycling, since this species was scarcely planted in the world, although today it shows a clear expansion in temperate regions, being the species mostly planted in Uruguay. Hence the need to have comparative experimental information about the decomposition rates of residues and recycling of nutrients to the soil by these species, which will allow to have specific parameters that can be used in models of decomposition and cycling of nutrients from regions climatically like 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 the 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.

3.3. 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 to 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]. In 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		Specie	Soil Taxonomy	A horizon depth	pH (H_2O)	Clay	P (†)	TB	ECEC	OC
				cm		g kg^{-1}	mg kg^{-1}	$cmol_c$ kg^{-1}		g kg^{-1}
32º 25’ 56’’S	57º 17’ 40’’W	*E. dunnii**	Alfic Argiudoll	33	5.3	184	3	6.35	7.12	9.8
31º 52’ 55’’S	57º 30’ 35’’W	*E. grandis*	Abruptic Argiudoll	33	5.2	187	3	6.36	7.05	9.9
33º 25' 18’’S	57° 48’ 25’’W	*E. globulus***	Typic Hapludert	30	5.4	199	4	6.43	7.01	12.5
31° 08’ 44’’S	55 °37’ 22’’W	*E. grandis*	Humic Hapludult	57	4.5	118	3	2.53	3.57	6.3
31º 45’ 40’’S	56º 05’ 35’’W	*E. globulus*	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, on 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.

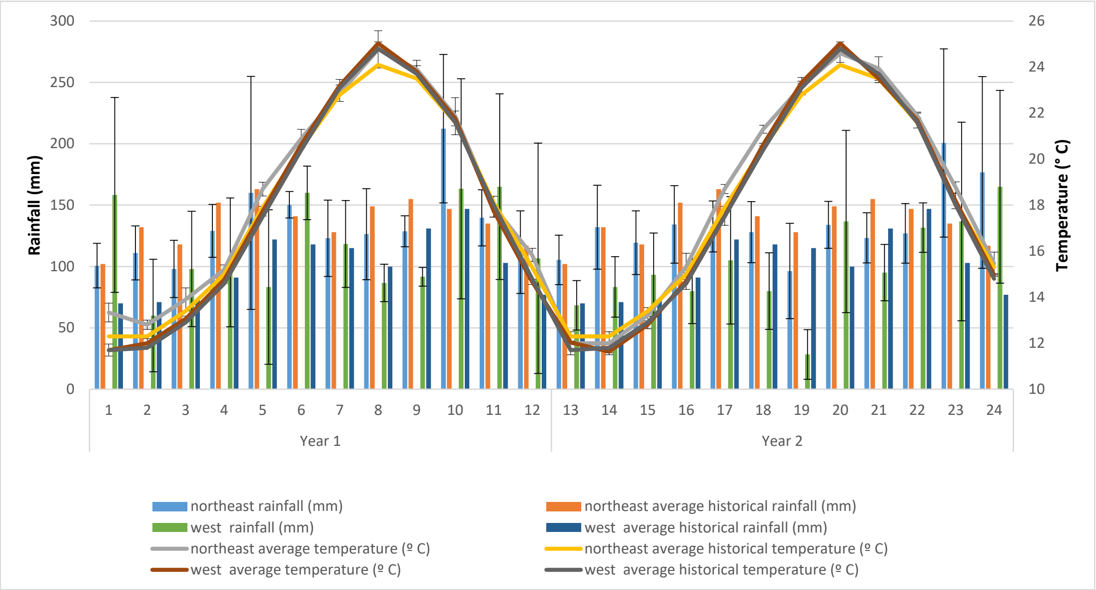

Figure 1. Precipitation and average monthly mean temperature of the sites evaluated, as well as their deviations (between experiments) during the evaluations, and historical averages [22].

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 mm^2), 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 as sampling dates were planned, placing them on the ground in three zones (replications) according to topographical position. Each group of samples was protected with a wire mesh fabric (100 mm^2). 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 concentration of P, Ca, Mg and K of the samples was determined, after dry combustion at 550 °C and ashes dissolution with 10% HCl. In the extract, P was deter-mined by colorimetry [23], Ca and Mg by atomic absorption spectrophotometry, and K by emission spectrophotometry. The determination of the N concentration in the sample was performed by wet digestion of the sample (H_2SO_4 and catalyst mixture) and subsequent distillation of N by Kjeldahl [24]. The total carbon and soluble carbon contents of the residues were measured by oxidation with $K_2Cr_2O_7$ at 150 °C followed by colorimetric determination [24]. The determination of lignin was performed by acid hydrolysis with H_2SO_4 then diluted to an acid concentration of 3%, with subsequent boiling for 4 hours, filtering and determining the remaining material by gravimetry [25]. For the analysis of soluble polyphenols (Pol), the extraction was performed with H_2O and determination was made by colorimetry using the Folin-Ciocalteau method [26].

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 (Pinic) x100. From this, the rate of decomposition was calculated by adjusting an exponential decay model type $P/Pinic = e^{-kt}$, where P/Pinic 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 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 of residues according to species and (b) the half-life according to species and type of residues; (2) multivariate analysis was performed by analysis of main components (PCA) of the decomposition to 24 months considering the different fractions and species, and (3) 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 by the Shapiro-Wilks test ($p > 0.05$ for normal data). The differences were considered statistically significant when $p < 0.05$ (Tukey test).

The correlation between the half-life of the different components was 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, the Spearman 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 nutrient 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.

3.4. RESULTS

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 fractions.

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.

Fraction	*E. dunnii*	*E. grandis*	*E. globulus*	*E. dunnii*	*E. grandis*	*E. globulus*
		Mg ha^{-1} yr^{-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 fractions the amount of residue biomass was significantly higher in *E. dunnii* than the other two species; in turn, for *E. grandis*, the amount of residues was higher than *E. globulus* (except in bark), ($P < 0.05$).

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 fraction 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 fraction (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*).

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 fraction. For half-life, different letters indicate statistically significant differences for species-fraction interaction.

Species	Fraction	Biomass loss	k	r^2	Half-life
		(%)	(year^{-1})		years
E. dunnii	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)
E. grandis	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)
E. globulus	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)

Analysis of variance for half-life determined differences in the interaction between species and fraction. The leaves differ significantly from the other fractions, but also between species (*E. grandis* vs. *E. dunnii*). The *E. dunnii* bark was the fraction 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* the differences were found between thick branches and bark.

Chemical characteristics of the different components at the beginning of the experiments are presented in Table 4. In the leaf fraction 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 fraction, 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 fractions, except for leaves.

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.

Fraction	Total C	Soluble C	Polyphenols	Lignin	N	C:N ratio	Pol:N ratio	L:N ratio
E. dunnii	------------------------------ 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
E. grandis								
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
E. globulus								
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 by 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, L:N ratios and soluble carbon concentration).

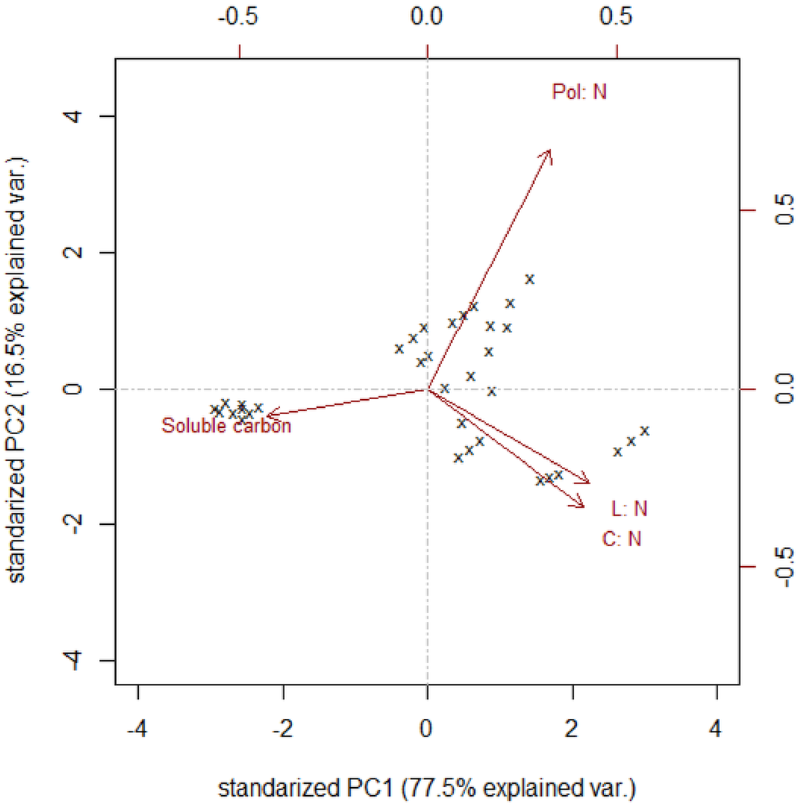

Figure 2. Biplot obtained by PCA of harvest residues for decomposition 24 months after harvest.

Analyzing the same data set 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, while for *E. grandis* it was the L:N ratio. These variables explain the greater variability between species.

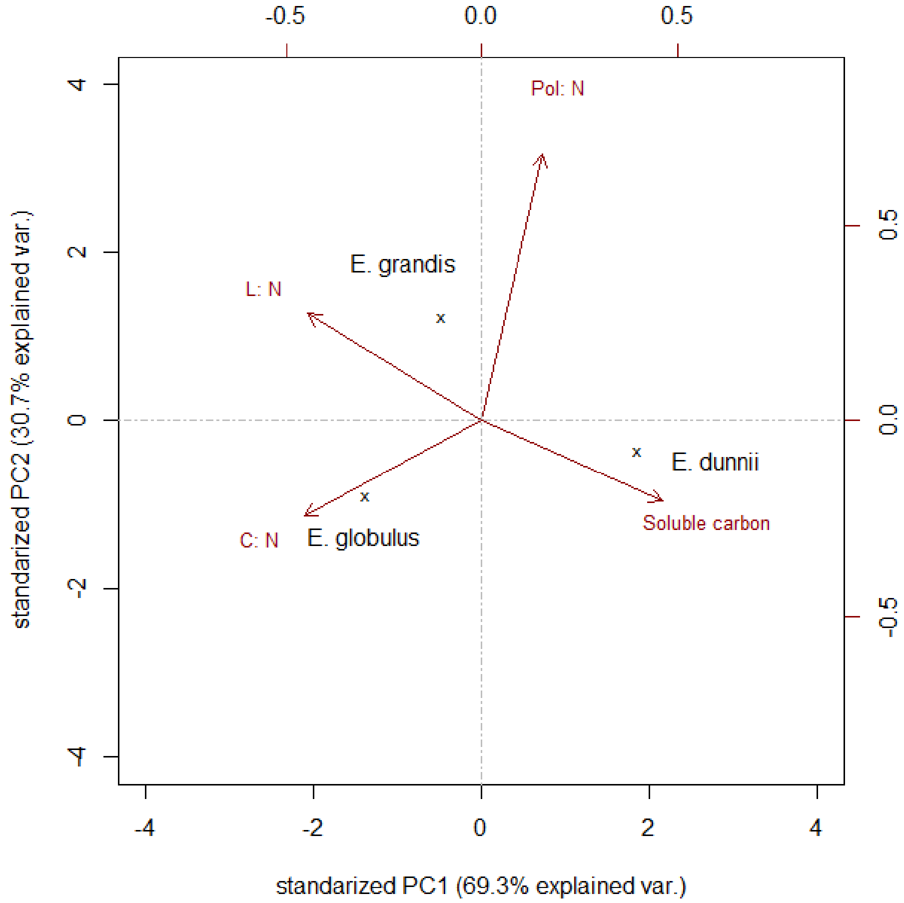

Figure 3. Biplot obtained by PCA of species for decomposition 24 months after harvest.

Considering all the species and fractions, 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).

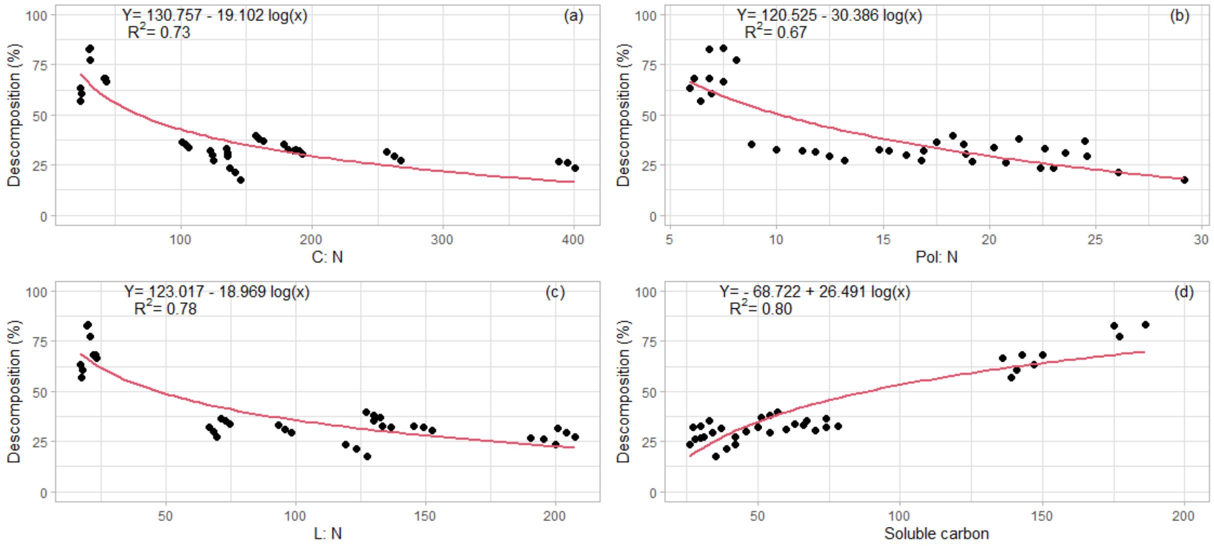

Figure 4. Relationship between decomposition of the harvest residues and the variables (a) C:N, (b) Pol:N, (c) L:N and (d) soluble carbon measured at the beginning of the decomposition process.

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 ($p < 0.01$). (Number of samples are indicated in “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)

Nutrient cycling

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

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 in 24 months from the *E. dunnii* residues.

	Nutrient	Fraction	Month			Nutrient released from residue	
			0	12	24		
			---------------- kg ha^{-1}		----------------		%
E. dunnii	Nitrogen	Bark	92	78	124	-32	
		Leaves	225	114	44	181	
		Thin branches	93	76	70	23	
		Thick branches	72	53	64	8	
		Total	482	321	302	180	37
	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	17.9	24.3	58
	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	91
	Calcium	Bark	1,026	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	26
	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	58

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 in 24 months from the *E. grandis* residues (average data from 2 sites).

	Nutrient	Fraction	Month			Nutrient released from residue	
			0	12	24		
			--------------- kg ha^{-1} ---------------				%
E. grandis	Nitrogen	Bark	51	42	55	-4	
		Leaves	181	152	96	85	
		Thin branches	28	22	23	5	
		Thick branches	19	16	20	-1	
		Total	279	232	194	85	30
	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	47
	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 in 24 months from the *E. globulus* residues (average data from 2 sites).

	Nutrient	Fraction	Month			Nutrient released from residue	
			0	12	24		
			---------------- kg ha^{-1} ----------------				%
E. globulus	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	25
	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	6	79	
		Leaves	28	2	2	26	
		Thin branches	17	3	2	15	
		Thick branches	26	8	6	20	
		Total	157	19	16	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

At harvest higher total amounts of all the nutrients were observed in the residues of *E. dunnii*, 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. dunnii* than in *E. grandis* and *E. globulus*, since the release patterns were more dependent on the nutrients and the fractions, than on the species itself. However, in percentage, *E. dunnii* released slightly less (40%) compared to *E. grandis* and *E. globulus* (42% in both).

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 in some residue's 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*: K > Mg > P > Ca > N.

3.5. 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* [31-7].

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] for a 7-year-old *E. globulus* plantation in the SW of Australia found, in relation to the aerial biomass of residues, a similar proportion for thick branches, a lower one 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 fraction 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 fraction, being 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 [33-12]. Likewise, in studies of forest litter decomposition in northern Uruguay, Baietto et al. [11] tested the effect of the starting 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 by 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 fraction. 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 finally 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 fractions in our research. Beyond the climatic differences between the sites, the higher k values reported by these authors in 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 by microbial biomass.

Shammas et al. [31], for *E. globulus* aged 7 years 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, 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 fraction, with the *E. dunnii* bark being the component with the highest durability ($t_{½}$ = 5.62 years). This species' bark thickness, 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 fractions with the highest half-life, like the result reported by different authors for the same species [33-31-35-7]. 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, [36], in a field decomposition experiment with *E. globulus,* found a half-life for leaves similar to that of this study in 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 mm yr^{-1}) and lower average annual temperatures (13.1 °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 °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 - 53 g kg^{-1} and 85 - 290 g kg^{-1} for organic carbon and clay, respectively, in the first 20 cm of soil), although no differences were reported for this cause. In coincidence, [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*, [31] found slightly lower half lives for bark, and thin and thick branches fractions (3.1, 3.4 and 4.3 years, respectively), and lower half live 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 ($t_{½}$ 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 fraction 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, with longer half-life the residues with the most resistant constituents, as shown by [31]. In the present investigation, the highest soluble carbon contents were found in the leaf fraction, 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] and [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 fractions 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 these, 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 explain alone 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 scarce 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 analyzing the same as a percentage. This was explained because the release patterns depended on the nutrient and the fraction, 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 by rainwater, regardless of biological factors [39]. Similar results were obtained by [31], [37] and [7].

The Mg release frequently accompanies the loss of biomass by the residues [39], although the amount released in the present investigation was proportionally greater, explained by the lower concentrations of Mg in the different fractions 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 like 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 could 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 fraction (83%), and that in this fraction it was recorded the highest concentrations of 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 fraction 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 fractions retained or even immobilized mineral N from the soil. For the three species, net immobilization of N was recorded in the bark fraction. In addition, immobilization also occurred in the thick branches fraction 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], [15] and [10].

As for P, the greater loss of biomass occurred in the leaf fraction of *E. dunnii*, explains 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 fraction found by these authors, and the higher concentration of N present in this fraction in relation to the woody residues.

Regarding Ca, all fractions, 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 —structural function— [40], which explains the behavior found, since soluble nutrients are first released. On the average of the species, only 29% of the total returned to the soil in the evaluation period, decreasing significantly only in the leaf fraction. The lowest cycling occurred in *E. dunnii*, which was explained by its bark being the fraction of greater durability of all those analyzed (Table 3) and considering that this fraction presented in all species the highest concentration of this nutrient. Rocha et al. [7] reported that 76% of the total Ca remained in the residues of *E. grandis* at 10 months post-harvest, 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 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, nor geochemical recycling), K stands out as the nutrient whose contribution by 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.

3.6. CONCLUSIONS

Eucalyptus dunnii presented the highest amount of residues for all its components, a consequence of their higher proportion 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 a greater amount of residues relative to *E. globulus*, except in bark, a consequence of a higher aerial biomass production.

The decomposition rates of the different fractions were highly dependent on their chemical constitution, the fraction size and the species itself. While the leaves of all species had high rates of decomposition, the bark was the fraction 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 are parameters 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 the absolute amounts of nutrients in the harvested components, as well as the amounts recycled -higher in *E. dunnii*, intermediate in *E. grandis* and lower in *E. globulus*-, the release patterns depended more on the nutrient, associated with its function in the plant and the fraction 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 contributions of nutrients. In addition, these keep the soil surface covered for a long time, reducing its susceptibility to the impact of raindrops and its propensity to erosive processes.

3.7. REFERENCES

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4. DISCUSIÓN GENERAL

Las plantaciones estudiadas en la presente investigación se encuentran sobre suelos de aptitud forestal, representativos de las principales zonas donde se localiza la mayoría de los bosques comerciales del género *Eucalyptus* en el Uruguay. Generalmente, dichos suelos presentan una fertilidad por debajo de la media de los suelos del país, aunque con diferencias entre ellos tanto en las concentraciones de nutrientes en sus horizontes como en los stocks de estos, en función de las distintas profundidades efectivas de exploración radicular. A pesar de esto, debe destacarse que, en general, los suelos destinados a la forestación en Uruguay presentan mayor fertilidad en comparación con los suelos donde se suelen realizar plantaciones comerciales en otros países. Es por ello por lo que, en la situación actual, los suelos de este estudio presentan las condiciones nutricionales más favorables para que las plantaciones de algunas especies del género *Eucalyptus* puedan expresar su potencial productivo, aun aquellas más exigentes (*E. dunnii*), más allá de otros factores también muy importantes para el crecimiento como el agua, la luz, la temperatura, la radiación solar o el material genético.

Un aspecto clave de todo sistema productivo es determinar su sostenibilidad en el tiempo, la cual depende principalmente de los requerimientos de la especie, así como de la reserva de nutrientes del sitio. Como promedio ponderado de todos los sitios evaluados y las tres especies estudiadas, un 27 % del total de los nutrientes absorbidos estuvo presente en la madera comercial (25 % en *E. dunnii*, 28 % en *E. globulus* y 29 % en *E. grandis*), exportándose a través de ella en promedio, el 35, 36, 31, 21 y 41 % del N, P, K, Ca y Mg, respectivamente. Por tanto, la mayoría de los nutrientes permanecieron en el sitio y potencialmente podrían ser reutilizados por el nuevo bosque (replantación). Resultados similares en cuanto a la proporción de nutrientes exportados en la madera fueron reportados por Laclau et al. (2003) en el Congo.

En definitiva, resulta claro que, para asegurar la sostenibilidad, el manejo de la cosecha forestal debe encararse teniendo en cuenta la necesidad de evitar la remoción de residuos de las plantaciones, así como propiciar el reciclaje a partir de su descomposición. Es de destacar la importante cantidad de nutrientes presentes en la fracción corteza de las plantaciones de *Eucalyptus* sp. Los resultados de la presente investigación muestran que, si esta hubiese sido retirada del sitio junto a la madera, la exportación de nutrientes habría pasado a ser del 49, 61, 60, 74 y 70 % para N, P, K, Ca y Mg, respectivamente, como promedio de las tres especies. Por ello, Thiers et al. (2007) y Andrade et al. (2011) indican que el retiro de la corteza del sitio de producción muestra consecuencias negativas en el mediano plazo. En el esquema productivo de Uruguay, generalmente, se mantiene este residuo, en conjunto con las ramas y hojas, en el sitio de plantación.

Como han observado distintos autores en sus estudios (Achat et al., 2015, Laclau et al., 2000, Gonçalves et al., 1997, Grove et al., 1996), la madera fue el componente que presentó los menores valores de concentración de nutrientes considerando todos los componentes de la biomasa aérea cosechada. Tanto en el conjunto de sitios como en los correspondientes a la zona 9 (donde estaban presentes las tres especies), *E. dunnii* fue la especie que mostró las mayores concentraciones de nutrientes en la madera con respecto a las otras dos especies, con diferencias significativas para los cationes (K, Ca y Mg). Esto hace que deba atenderse al manejo de cada especie individualmente, siendo el monitoreo de suelos una buena herramienta para evaluar su suministro en función del tiempo. A su vez, la concentración de N y P en *E. grandis* fue significativamente menor a la correspondiente en *E. dunnii* y *E. globulus*.

Sumado a las consecuencias que estas diferencias en las concentraciones tienen sobre la extracción de nutrientes del sitio, también debe tenerse presente cómo estas concentraciones en la madera pueden influir al momento de la producción de pasta de celulosa. Felissia et al. (2007) indicaron que una alta concentración de Ca promueve la formación de precipitados durante la industrialización, mientras que Bentancur et al. (2021) reportaron que la eliminación de P de las aguas residuales requiere tratamientos específicos para evitar efectos negativos sobre el ambiente.

Con relación a los otros componentes del árbol (corteza, ramas y hojas), las hojas presentaron las mayores concentraciones de N, P y K, mientras que en corteza se encontraron las mayores concentraciones de Ca y Mg, en coincidencia con lo reportado por otros autores (Leite et al., 2011, Santana et al., 2000). Las ramas (gruesas y finas) presentaron concentraciones de nutrientes bajas, aunque superiores con relación a la madera.

Los valores de concentración de N, P y K en las hojas fueron mayores en *E. grandis* y *E. dunnii* respecto a *E. globulus* y estuvieron dentro de los rangos encontrados por Leite et al. (2010) y Eufrade Junior et al. (2017), para suelos de Brasil, aun considerando que estos últimos presentaron valores de MO sensiblemente menores (<1 %) a los de Uruguay, aunque, a su vez, recibieron fertilización nitrogenada al momento de la implantación del bosque. Para la concentración de Ca en la corteza, la variabilidad fue mucho mayor, con valores menores en *E. globulus*. Por otra parte, hubo diferencias entre sitios, siendo mayor la concentración de Ca en la corteza —así como en las otras fracciones— en los árboles de la zona 9, lo cual estaría explicado por una mayor disponibilidad de Ca en los suelos de esta zona. Estos valores resultaron ser superiores, más allá de la especie, a los reportados para plantaciones en Brasil (González-García, 2016, Leite et al., 2011). A su vez, para Mg y en la fracción corteza, las concentraciones fueron mayores en *E. dunnii* respecto a *E. grandis* y *E. globulus*. En general —al igual que el Ca— se dieron las mayores concentraciones en los árboles de la zona 9 y, a su vez, en todos los casos superiores a los encontrados por González-García (2016) y Leite et al. (2011) en suelos de Brasil.

Con relación a la biomasa de madera producida, fue significativamente mayor en *E. dunnii* y *E. grandis* en comparación con *E. globulus* (plantaciones seminales en todos los casos), lo que puede explicarse por un mayor crecimiento en volumen de las dos primeras especies mencionadas, aun teniendo en consideración que ambas tienen una menor densidad de la madera que *E. globulus*. La significativamente mayor cantidad de biomasa de madera que ambas especies (*E. dunnii* y *E. grandis*) produjeron en la zona 7 en comparación con la zona 9 puede explicarse por la suma de factores edafológicos (mayor profundidad de los suelos, lo cual permite una mayor exploración radicular) y climáticos (mayores precipitaciones). Como promedio ponderado de las tres especies, un 72 % de la biomasa aérea total correspondió a la madera.

Analizando el stock de nutrientes presentes en la madera por unidad de superficie y teniendo presente que la densidad de plantación fue similar en todos los casos (inicial, entre 1,300 y 1,400 árboles ha^{-1} y final -al momento de la cosecha-, entre 930 y 970 árboles ha^{-1}), en general se encontraron mayores cantidades absorbidas para todos los nutrientes en *E. dunnii* respecto a las otras dos especies, independientemente de la zona, consecuencia de su mayor concentración en la madera y, además, en algún caso (comparado con *E. globulus*) de una mayor producción de biomasa. Analizando las otras dos especies, para los cationes (K, Ca y Mg), las cantidades totales absorbidas en la madera de *E. grandis* fueron significativamente mayores a las de *E. globulus*, explicado por una mayor producción de biomasa de *E. grandis*, sumado, en algún caso (Ca y Mg), a mayores concentraciones de nutrientes en su madera. De modo general, cuanto mayor fue la producción de biomasa, mayor fue la cantidad de nutrientes en la madera.

Estas diferencias en la acumulación de nutrientes en la madera de las distintas especies muestran que *E. dunnii* es la especie que, para las mismas condiciones de oferta de nutrientes por parte del suelo, acumula una mayor cantidad de estos en la madera, aun con rendimientos similares a otras especies como *E. grandis*. Lo anterior puede interpretarse como la necesidad de mayores requerimientos de nutrientes de dicha especie para un mismo nivel de rendimiento o un posible consumo de lujo en la medida que la oferta de nutrientes por parte del suelo es suficiente.

Respecto a la evaluación de la eficiencia de uso de los nutrientes, en este trabajo se utilizó un índice que evalúa la nutrición, es decir, cómo se usan los nutrientes (EUN), y otro que evalúa lo productivo, o sea, cuál es la producción de madera respecto a los nutrientes que absorbió el árbol (CUB). La eficiencia de utilización de nutrientes (EUN) se define como los kg de madera producida por kg^{-1} de nutrientes totales absorbidos mientras que el coeficiente de utilización biológico (CUB) son los kg de madera producida por kg^{-1} de nutrientes absorbidos en la madera. La EUN fue significativamente menor en *E. dunnii* respecto a las otras dos especies para todos los nutrientes en el conjunto de datos. De igual modo (en el mismo conjunto de datos), la EUN para N, P y Mg fue significativamente mayor en *E. globulus* con relación con *E. grandis*, básicamente explicado por menores concentraciones de nutrientes en la madera de los árboles de *E. globulus* de la zona 2. Los análisis para las zonas 9 y 7 mostraron similares resultados, con una menor eficiencia en *E. dunnii* en comparación con las otras especies, con lo cual, si bien, desde el punto de vista productivo, *E. dunnii* surge como una especie que logra acumular un similar o mayor volumen de madera que las otras dos especies, es a expensas de una mayor absorción y acumulación de nutrientes en su biomasa, en la medida de su suministro por parte de los suelos.

Santana et al. (2000), Morais et al. (1990) y Herbert (1996), los dos primeros en Brasil y el tercero en Sudáfrica, con distintas condiciones edafoclimáticas y árboles de entre 7 y 8 años, obtuvieron resultados similares de EUN a los del presente estudio para N, P y K en *E. grandis* y *E. globulus* (y mayores en ambas especies con relación a *E. dunnii*). Por otra parte, la EUN para Ca y Mg fue superior a la correspondiente a los sitios de Uruguay. Puede identificarse, así, un efecto sitio, considerando los stocks de Ca y Mg en los suelos de Uruguay (mayores comparados a los de los países citados) produciéndose, por lo tanto, un consumo de lujo que se concentra en distintos componentes; y el efecto especie, considerando la baja eficiencia de la especie *E. dunnii*.

Para el CUB, el análisis conjunto de todos los sitios muestra una menor eficiencia de utilización para los cationes en *E. dunnii* con relación a *E. grandis* y *E. globulus*, y también una menor eficiencia de utilización de esta especie y de *E. globulus* para N y P comparados con *E. grandis*. En bosques de las zonas 9 y 7 se observaron resultados similares. En Rio Grande do Sul (Brasil), Freitas Melo et al. (1995) obtuvieron, en promedio, para *E. saligna* de 7 años CUB superiores respecto a los de este trabajo para Ca, similares para Mg comparados a los de *E. grandis* y *E. globulus* (aunque muy superior a los registrados para *E. dunnii*), e inferiores para P y K. Con referencia al Ca, la mayor eficiencia encontrada por estos autores puede explicarse por los niveles altos que existen de este nutriente en los suelos de Uruguay, que lleva a consumos de lujo por parte de los árboles.

Considerando ambos índices, en *E. dunnii* la eficiencia de uso fue significativamente menor respecto a las otras dos especies para los cationes (K, Ca y Mg), independientemente de la zona, y también para N y P cuando la comparación se realiza con *E. grandis*. En la EUN, además, su eficiencia fue menor, en relación con *E. globulus* para N y P. La información resultante de estos índices es importante y complementaria a la de las extracciones de nutrientes por parte de los árboles en su madera a la hora de detectar posibles futuras limitantes nutricionales. Por tanto, son una buena herramienta como ayuda para realizar las correcciones necesarias en el tiempo indicado. Las implicancias prácticas de estos resultados indican la mayor demanda de nutrientes por las plantas de *E. dunnii* para producir el mismo volumen de madera que las otras especies de *Eucalyptus* estudiadas.

Si bien se analizó la correlación existente entre la concentración de los cationes (K, Ca y Mg) en la madera respecto a su concentración en el horizonte A del suelo, así como en relación con los stocks de estos en la suma de los horizontes A y B (horizontes con presencia de raíces que pueden absorber nutrientes), las mayores correlaciones se observaron con la concentración de estos en el horizonte A. Lo anterior sugiere la mayor influencia dada por el lugar donde se encuentra la mayor densidad de raíces que absorben nutrientes, más allá de que también otros factores como la profundidad de arraigamiento, el agua disponible en el suelo, otros nutrientes, la radiación solar o la temperatura influyen en la dinámica de absorción. Si bien se registraron importantes diferencias entre especies en las concentraciones de nutrientes y para una misma especie —en menor medida— entre sitios, no se observaron correlaciones entre la producción de biomasa y los stocks de nutrientes en los diferentes sitios, lo cual sí fue registrado en estudios de otros países, en donde se observó una correlación positiva, sumado a que ambos parámetros fueron menores (producción y stock de nutrientes) en las regiones con menor disponibilidad de agua (Santana et al., 2008). Este resultado sugiere que la limitación nutricional respecto a K, Ca y Mg, como fue dicho anteriormente y en la situación actual, no es la principal determinante de la producción en estas plantaciones.

Si bien las concentraciones de los cationes intercambiables (K, Ca y Mg) fueron mayores en los suelos de las zonas 9 y 2, la mayor profundidad de los suelos de la zona 7, lo cual resulta en una mayor exploración radicular, logra que la disponibilidad (stock) final resulte parecida a la de los otros suelos, pese a niveles de fertilidad menor en los suelos de la zona 7 desarrollados sobre areniscas. Si se considerara que lo disponible (intercambiable) al momento del muestreo fuese el total posible por usar en futuras rotaciones, que, a su vez, cada especie extrajera la misma cantidad de nutrientes en su madera en las rotaciones futuras y que el horizonte B presente raíces que puedan absorber nutrientes, puede determinarse que en las plantaciones de *E. dunnii* es en donde primeramente comenzarán las limitantes de nutrientes. Dentro de los cationes, el K es el nutriente en donde el agregado en el mediano plazo será necesario, independientemente del sitio y de la especie plantada, lo que resulta importante, ya que en el Uruguay los programas de fertilización no suelen incluir el agregado de cationes. Por tanto, y más allá de que para el Ca y el Mg, su agregado no surge como necesario aun en el largo plazo, resulta destacable la necesidad de un monitoreo de la disponibilidad de los cationes en el tiempo.

El manejo comercial poscosecha de las plantaciones estudiadas, que, a su vez, es el mayoritario en el país, mantuvo los residuos (corteza, ramas y hojas) en el sitio de plantación, lo cual significa un gran aporte de nutrientes y materia orgánica al sistema. En la presente investigación, el 28 % del total de la biomasa aérea (promedio ponderado de las 3 especies) correspondió a los residuos forestales y, como muestra la escasa información experimental que existe en el ámbito mundial sobre *E. dunnii* (Aguirre et al., 2019, Bentancor, 2017), esta especie mostró una mayor proporción de la biomasa de restos con relación a la biomasa aérea total, en comparación con las otras especies, ampliamente plantadas y estudiadas, como *E. grandis* y *E. globulus* (Rocha et al., 2016, Shammas et al., 2003). En este estudio, la proporción de restos de cosecha alcanzó el 35 % de la biomasa en *E. dunnii* y el 24 % en las otras dos (*E. grandis* y *E. globulus*), además del ya mencionado mayor crecimiento de *E. dunnii* y *E. grandis* comparado con *E. globulus*. La corteza fue la fracción de mayor contribución entre los restos de todas las especies, con una proporción mayor en *E. globulus* en comparación con *E. dunnii* y *E. grandis*. A su vez, la fracción minoritaria en *E. dunnii* fueron las hojas y en *E. grandis* y *E. globulus* las ramas finas, lo que marca las diferencias entre las especies en la estructura de la copa, con más ramas en *E. dunnii*.

En el total de los residuos forestales se encontró (promedio ponderado) el 73 % del total de los nutrientes absorbidos por los árboles durante todo su ciclo de crecimiento en su biomasa aérea. Además, y si bien no fue objeto de este estudio, estos restos realizan un importante aporte de C al suelo acompañando los nutrientes. En Australia, Shammas et al. (2003) indican lo perjudiciales que son las prácticas de quema de los residuos forestales, ya que traen aparejado una significativa pérdida de nutrientes, especialmente N. También en Australia, Carlyle (1993) muestra el efecto de decrecimiento a largo plazo en la productividad de las plantaciones por efecto de remover los residuos durante las etapas de preparación del sitio. En España y Portugal, Jones et al. (1999) encontraron que los crecimientos en *E. globulus* eran menores cuando los residuos eran removidos del sitio en comparación con los tratamientos en los que se incorporaban al suelo. En el Congo, Nzila et al. (2002) encontraron que después de 24 meses de haber removido todos los residuos hubo un marcado efecto negativo en la biomasa total producida en comparación con aquellos tratamientos en los que se habían dejado (12,0 m^3 ha^{-1} $año^{-1}$ vs. 22,2 m^3 ha^{-1} $año^{-1}$, respectivamente).

Como indican Santana et al. (1999) y Morais et al. (1990), para plantaciones de *Eucalyptus* sp. en Brasil, la permanencia de los residuos en el sitio de plantación reduce sustancialmente la exportación de nutrientes, lo que aumenta las posibilidades de mantener los niveles de nutrientes en el suelo próximos o por encima de los niveles críticos, lo cual conduce a una mayor sostenibilidad o una menor utilización de fertilizantes en las plantaciones forestales.

En los estudios de descomposición de restos de cosecha, las constantes de descomposición más altas (k) se encontraron en la fracción hojas, en coincidencia con lo reportado por Rezende et al. (2001) en experimentos de incubación en condiciones controladas y Rocha et al. (2016) en experimentos de campo, ambos en *E. grandis* en Brasil. Estos últimos reportaron, además, que luego les siguieron la corteza y finalmente las ramas, lo que resultó en el mismo orden al de la presente investigación para esta especie, aunque con valores mayores en todos los estudios mencionados por dichos autores. Shammas et al. (2003), para *E. globulus* de 7 años en Australia, encontraron los mayores valores de k en hojas, luego en corteza y finalmente en ramas, orden coincidente con el del presente trabajo en esta especie.

A partir de la constante de descomposición (k) se estimó la vida media de cada uno de los restos, lo que resultó en diferencias significativas en la interacción entre especie y fracción, siendo la corteza de *E. dunnii* la componente de mayor perdurabilidad ($t_{½}$ = 5,62 años), lo que podría ser explicado por el espesor de dicha fracción en esta especie, sensiblemente mayor al correspondiente a las otras especies. En las otras especies (*E. grandis* y *E. globulus*) fueron las ramas (gruesas y finas) las fracciones de mayor vida media, al igual que lo encontrado por distintos autores en las mismas especies (Rocha et al., 2016, O’Connell y Mendham, 2004, Shammas et al., 2003, Jones et al., 1999). A su vez, la fracción hojas fue la de menor vida media en las tres especies (rango 0,94-1,62 años), con diferencias significativas entre ellas.

Las diferencias encontradas en las tasas de descomposición de los distintos restos podrían ser explicadas por varias causas, entre las que se destacan la superficie específica de cada fracción, siendo menor en aquellos restos de mayor tamaño y con una mayor vida media, y los contenidos de componentes de estructura química más lábil, como, por ejemplo, compuestos carbonados solubles, los cuales eran más abundantes en la fracción hojas. Datos similares reportaron Rezende et al. (2001) y Corbeels et al. (2003) en estudios de mineralización de restos de *E. grandis* en Brasil y Australia, respectivamente. Sumado a lo anterior, los contenidos de N, así como la relación C:N, fueron importantes para explicar estas diferencias, siendo que en la fracción hojas se encontraron las mayores concentraciones de N y, a la vez, una menor relación C:N. También se observó que mayores relaciones Pol:N o L:N determinaron menores tasas de descomposición.

Los resultados del análisis de componentes principales indicaron que casi toda la variación se pudo explicar con los dos primeras componentes, donde las relaciones C:N, Pol:N y L:N, mostraron estar más relacionadas, mientras que C soluble presentó una correlación negativa con estas variables. A su vez, las especies en estudio poseían valores distintivos de estas variables, ya que, en el biplot, las observaciones para una misma especie aparecieron agrupadas. Dados los altos valores de las correlaciones estudiadas entre la vida media de los restos y los parámetros químicos que la explican, se pudo inferir una alta magnitud de la asociación. Desde un punto de vista práctico, tanto el C (total y soluble) como el N de los restos son parámetros fáciles de determinar, por lo cual podrían ser usados como buenas herramientas predictivas de las tasas de descomposición.

Las mayores cantidades totales de nutrientes presentes en los restos de *E. dunnii*, luego en *E. grandis* y finalmente en *E. globulus* se asociaron, en parte, a las diferencias en las cantidades de biomasa de cada una de estas al momento de la cosecha y, también, a las diferencias en las concentraciones que para todos los nutrientes se presentaron en algunos restos, generalmente mayores en *E. dunnii*, intermedios en *E. grandis* y menores en *E. globulus*. Como fue expresado, los suelos eran relativamente homogéneos en cuanto a sus características químicas, a pesar de presentar algunas diferencias en cuanto a su profundidad y fertilidad, por lo que no se registró influencia de estos en la absorción de los nutrientes.

La estimación de cantidades absolutas de nutrientes reciclados resultó, por lo mencionado anteriormente (mayor cantidad total en restos de *E. dunnii*), en el mismo orden para todos los nutrientes (*E. dunnii* > *E. grandis* > *E. globulus*), pero variaron al analizarlos de forma porcentual, ya que los patrones de liberación dependieron del nutriente y la fracción en donde estaban presentes, las que, a su vez, difirieron en su descomposición según la especie.

El K fue el nutriente con más alta liberación en los restos de las tres especies y se explica por cómo se encuentra en la planta (forma iónica, K^+) cumpliendo funciones osmóticas y no estructurales, por lo que es de fácil disolución y remoción por el agua de lluvia, con cierta independencia de factores biológicos (Rocha et al., 2016, Alvarez et al., 2008, Shammas et al., 2003, O´Connell y Grove, 1993).

Por el contrario, para el Ca, se registraron similares o mayores concentraciones pasados 2 años de la cosecha, en todas las fracciones y las tres especies, por lo que su pérdida fue menor comparada con la de biomasa. Este nutriente cumple funciones estructurales en la planta estando presente en los tejidos vegetales en estructuras de más difícil degradación que explican dicho comportamiento (Marshner, 2003).

En general, la liberación de Mg acompaña la pérdida de biomasa por los restos (O´Connell y Grove, 1993), aunque en la presente investigación la cantidad liberada fue proporcionalmente mayor a dicha pérdida (similar en las tres especies), lo que se explica por menores concentraciones de este nutriente hacia el final del período de estudio en las diferentes fracciones.

En el P se observó, al igual que para el anterior, una ligera disminución en la concentración a los 2 años, asociada, en este caso, a la pérdida de compuestos solubles; por tanto, el porcentaje reciclado fue algo mayor respecto a la pérdida de biomasa.

Con relación al N, la escasa liberación del conjunto de residuos se explicó porque algunas fracciones retuvieron o incluso inmovilizaron N mineral del suelo (fracción corteza en las tres especies y ramas gruesas en *E. grandis* y *E. globulus*), y, en todos los casos, las concentraciones fueron mayores luego de dos años de la cosecha.

Sánchez (2011), Corbeels et al. (2003) y Rezende et al. (2001) reportaron inmovilización en los componentes leñosos. Esto puede ser visto como una forma de conservar el N en el sistema, ya que es el nutriente que presenta mayores riesgos de pérdidas (absolutas y relativas) una vez liberado.

Considerando que tanto para el P como para los cationes (K, Ca y Mg) no existen mecanismos de pérdida que operen durante el proceso de descomposición, puede esperarse que la eficiencia de reutilización sea muy alta. Para el N, a su vez, no ocurre lo mismo, pues, como fue dicho, durante el proceso de descomposición existen mecanismos de pérdidas y, por tanto, no es posible asegurar que la totalidad reciclada estará totalmente disponible para la siguiente plantación (Laclau et al., 2010).

Finalmente, y considerando que en Uruguay las plantaciones comerciales incluyen solo N y P en los esquemas de fertilización al momento de la plantación, es interesante estimar para los cationes (K, Ca y Mg) cuál fue el aporte a partir del ciclaje estudiado en comparación con los stocks de estos en el horizonte A de dichos suelos. Teniendo presente la masa de suelo en dicho horizonte y la concentración de los cationes bajo formas intercambiables (sin tener en cuenta las formas no intercambiables ni el reciclaje geoquímico), se destaca el K como el nutriente cuyo aporte por esta vía presentó una mayor proporción. Considerando las diferencias observadas entre las especies y los distintos stocks según el suelo, a los 2 años de la cosecha, la devolución a partir de los restos (con relación a los stocks presentes en suelo) fue de entre un 23 a 81 % para K, 4 a 19 % para Ca y 5 a 16 % para Mg.

Por tanto, la permanencia de los residuos de la cosecha en el sitio de plantación ayuda a la sostenibilidad de sistema productivo en el mediano y largo plazo, con importantes aportes de nutrientes y materia orgánica. Además, debe considerarse la importancia de la cobertura del suelo por los restos de cosecha, los cuales reducen la susceptibilidad de este al impacto de las gotas de lluvia y su predisposición a los procesos erosivos, ya que mantienen cubierta la superficie del suelo por un cierto período de tiempo, mientras la nueva replantación se desarrolla cubriendo el suelo con su dosel.

En proyección hacia adelante, la presente investigación marca las bases para la generación de modelos de extracción y ciclaje de los nutrientes usados por el bosque durante su crecimiento. Asimismo, sería de interés sumar conocimientos con relación a la cuantificación de la biomasa de raíces y de los nutrientes presentes en la misma.

5. CONCLUSIONES

Eucalyptus dunnii presentó los menores valores de EUN comparados con los correspondientes a las otras dos especies, para todos los nutrientes e independientemente del sitio de plantación. Dicho comportamiento conduce a una menor producción de madera comercial por kg de nutriente total absorbido. La plantación de esta especie en los diferentes ambientes estará realizando una mayor utilización del recurso suelo a través de una mayor demanda de nutrientes, con una menor eficiencia productiva. Este aspecto debe ser especialmente tenido en cuenta, en particular en aquellos suelos de menor fertilidad natural y donde el esquema de fertilización no considere esta mayor demanda de nutrientes de la especie. A su vez, el CUB registró menores valores para los cationes (K, Ca y Mg) para *E. dunnii* en comparación con las otras dos especies y, además, para N y P, en comparación a *E. grandis*. Particularmente, el K surge como uno de los primeros nutrientes a manifestarse como deficiente, dependiendo de la especie y el tipo de suelo (zona) donde se localicen las plantaciones.

Las tasas de descomposición de las diferentes fracciones fueron altamente dependientes de su constitución química, el tamaño de partículas y de la propia especie. Dada la alta correlación encontrada entre la vida media de los restos y la relación C:N, así como la concentración de carbono soluble, y teniendo en consideración de que se trata de parámetros fáciles de determinar, podrían ser usados como buenas herramientas predictivas del proceso.

Los parámetros de descomposición obtenidos para algunas de las especies estudiadas resultaron similares a los obtenidos por otros autores en condiciones climáticas y de estudio comparables. Esto permitiría la utilización de dichos valores —y los correspondientes a *E. dunnii*— en modelos predictivos de la descomposición de restos de cosecha para dichas especies bajo condiciones climáticas similares.

Los patrones de liberación de los nutrientes dependieron más de estos, asociado a su función en la planta, y de la fracción en donde estaban presentes que de la propia especie.

La permanencia de los residuos de la cosecha en el sitio de plantación ayuda a la sostenibilidad de sistema productivo en el mediano y largo plazo, con importantes aportes de materia orgánica y nutrientes. Además, mantienen cubierta la superficie del suelo, protegiéndolo del impacto de las gotas de lluvia y su efecto sobre la desagregación de la estructura de este.

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