



Litterfall production modeling based on climatic variables and nutrient return from stands of *Eucalyptus grandis* Hill ex Maiden and *Pinus taeda* L.

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Abstract Native grasslands in the Pampas of South America are increasingly being replaced by *Eucalyptus* and *Pinus* stands. The short rotation regimes used for the stands require high nutrient levels, with litterfall being a major source of nutrient return. To model the litterfall production using climatic variables and assess the nutrient return in 14-year-old *Eucalyptus grandis* and *Pinus taeda* stands, we measured litter production over 2 years, using conical litter traps, and monitored climatic variables. Mean temperature, accumulated precipitation, and mean maximum vapor pressure deficit at the seasonal level influenced litterfall production by *E. grandis*; seasonal accumulated precipitation and mean maximum temperature affected litterfall by *P. taeda*. The regression tree modeling based on these climatic variables had great accuracy and predictive power for *E. grandis*

($N=33$; MAE (mean absolute error)=0.65; RMSE (root mean square error)=0.91; $R^2=0.71$) and *P. taeda* ($N=108$; MAE=1.50; RMSE=1.59; $R^2=0.72$). The nutrient return followed a similar pattern to litterfall deposition, as well as the order of importance of macronutrients (*E. grandis*: Ca > N > K > Mg > P; *P. taeda*: N > Ca > K > Mg > P) and micronutrients (*E. grandis* and *P. taeda*: Mn > Fe > Zn > Cu) in both species. This study constitutes a first approximation of factors that affect litterfall and nutrient return in these systems.

Keywords Afforestation · Litterfall · Nutrient recycling · Climate modeling · Myrtaceae · Pinaceae

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Introduction

The total area planted with *Eucalyptus* (Myrtaceae) and *Pinus* (Pinaceae) stands on nutrient-poor soils of the Pampas of South America has greatly increased during the last decades (Goya et al 2008; Hernández et al 2016; Reichert et al 2017; Momolli et al 2019a). The original native grasslands have thus been replaced by these forest systems, introducing a new component to the soil–plant system, the forest litter (Baietto et al 2021a). The stands are typically managed in short rotation regimes to produce pulp (on average, 10 years) or wood (on average, 20 years), both of which usually require high nutrient levels (Gonçalves et al 2008; Hernández et al 2009). Because the sustainability of these systems after successive reforestation cycles is of concern (Ferreira et al 2016), understanding the seasonal nutrient fluxes from the litterfall inputs is important for understanding the impacts of these systems and for developing new fertilization strategies for the forest rotations (Albaugh et al 2012; Demessie et al 2011; Queiroz et al 2019).

Litterfall constitutes the main nutrient flow during biogeochemical cycling and is important for maintaining the fertility of soils in native and introduced forest areas (Guo et al 2006; Ribeiro et al 2018; Kulmann et al 2021). These nutrients become available for plant uptake through leaching and litter decomposition (Wang et al 2019; Bessaad and Korboulewsky 2020; Baietto et al 2021b). The study of litterfall allows for quantifying the magnitude of the flow of different nutrients, which can vary greatly depending on the forest species, stand characteristics, and environmental conditions (Demessie et al 2011; Erkan et al 2018; Voigtlaender et al 2019; Espinosa et al 2020; Kulmann et al 2021). At the same time, quantifying litterfall production can also provide information about the effects of climate on forest systems (Hansen et al 2009).

Climatic variables are among the main factors that influence litter production on a global scale (Hansen et al 2009; Zhang et al 2014; Shen et al 2019). However, the climate at a specific site greatly impacts litterfall production on a local scale (Liu et al 2004; Chase et al 2016; Queiroz et al 2019; Giweta 2020). In this sense, material deposition under some species can have a seasonal pattern (Pook et al 1997; Li et al 2005; Demessie et al 2011) that strongly fluctuates in response to the weather, being the seasonal temperature and precipitation the most important variables that regulate the litter production (Chave et al 2010; Parsons et al 2014). At the same time, stand density, age, basal area, volume, aerial biomass, mean annual increment, and site index, also may influence litterfall deposition (Blanco et al 2006; Erkan et al 2018; Bueis et al 2018).

Here we sought to model litterfall production in 14-year-old stands of *Eucalyptus grandis* Hill ex Maiden and *Pinus taeda* L. using climatic variables and to assess and compare the nutrient return from litterfall between the two species. We hypothesized that (1) litterfall production is dependent on a group of climatic variables that differ according to the forest species, (2) climatic variables can be used to predict litterfall on a local scale, and (3) the nutrient return through litterfall differs between forest species even in stands of equivalent stand density in the same environment.

Materials and methods

Site characterization

The *E. grandis* and *P. taeda* stands were planted in 2003 at a density of 816 ind. ha⁻¹ (3.5 m × 3.5 m spacing) in Rivera Department, Uruguay (coordinates: 31°23'55" S, 55°41'44" W). The mean elevation in the study site is 187 m a.s.l. The study area comprises 0.27 ha divided into three plots (each plot is 30 m × 30 m) for each species. The soils in the area are thermic humic hapludults (Soil Survey

Staff 2014). The climate is humid temperate (Cfa) (Köppen 1936). The mean rainfall is around 1605 mm per year, with a high interannual variation (Castaño et al 2011). The mean temperature is 18.6 °C, with the minimum in July (12.4 °C) and maximum in January (24.6 °C). The experimental area and forest stands have been described in detail previously (Hernández et al 2016; Baietto et al 2021a, b). The plantations replaced an original cover of native grassland. Litterfall sampling was begun in June 2017 (Southern Hemisphere) and carried out seasonally for 2 years. Year 1 was thus June 2017 to May 2018 and year 2 was June 2018 to May 2019. The mean diameter at the breast height (DBH) was 29.7 cm for *E. grandis* and 31.7 cm for *P. taeda*. The mean height was 36.3 m for *E. grandis* and 22.5 m for *P. taeda*.

To characterize the climatic conditions during the study, the relative humidity (%) and air temperature (°C) were measured using iButton Hygrochron loggers (DS1923) (Maxim Integrated Products, CA, USA). The wind speed (km h⁻¹) and the accumulated rainfall (mm) were obtained from an automatic Davis Vantage PRO 2 Plus wireless meteorological station (Davis Instruments, CA, USA) near the site (coordinates: 31°42'32" S, 55°49'36" W) (INIA-GRAS 2019). The recorded data was used to determine the seasonal values for mean relative humidity (MRH) (%), mean minimum relative humidity (MMINRH) (%), mean maximum relative humidity (MMAXRH) (%), mean temperature (MT) (°C), mean minimum temperature (MMINT) (°C), mean maximum temperature (MMAXT) (°C), accumulated precipitation (AP) (mm), mean wind speed (MW) (km h⁻¹), mean vapor pressure deficit (MVPD) (kPa), mean minimum vapor pressure deficit (MMINVPD) (kPa) and the mean maximum vapor pressure deficit (MMAXVPD) (kPa) (Table 1).

Litterfall sampling

Nine conical traps for each species (three/plot) that were installed in random locations across the considered stands to measure litterfall. The sample size was chosen based on a previous report that found a minimum sample size of five was needed to ensure accurate estimations of litterfall (Finotti et al 2003). The traps were 1 m in diameter and 0.5 m deep and made of 1 mm² plastic mesh fabric attached to a circular steel frame. The traps were set 1 m above the ground and equidistant from the tree rows (Fig. 1). Litterfall sampling began in June 2017 (Southern Hemisphere) and was seasonal (i.e., for 3 months) during 2 years. The litter material was collected, processed in the laboratory, and dried at 65 °C until constant mass (48 h) before weighing the total dry mass.

Table 1 Mean seasonal climatic conditions during the study period (June 2017 to May 2019) near the study site

Season	MRH	MMINRH	MMAXRH	MT	MMINT	MMAXT	AP	MW	MVPD	MMIN-VPD	MMAXPDP
	%			°C			mm	km h ⁻¹	kPa		
Winter 2017	87.58	63.85	97.43	15.89	11.61	24.70	563	6.54	0.31	0.04	1.35
Spring 2017	78.10	57.82	93.12	19.17	14.08	25.36	327	5.91	0.61	0.12	1.52
Summer 2018	68.88	44.13	88.77	23.73	17.84	31.82	147	5.12	1.11	0.24	2.77
Autumn 2018	86.04	68.78	94.69	17.36	13.25	25.31	312	4.20	0.37	0.09	1.26
Winter 2018	91.11	78.32	96.9	12.98	9.37	19.30	382	6.91	0.17	0.04	0.58
Spring 2018	82.04	64.87	94.03	19.36	14.86	24.54	528	6.34	0.48	0.10	1.13
Summer 2019	84.73	69.72	94.78	22.63	18.43	27.90	524	5.94	0.50	0.11	1.22
Autumn 2019	90.47	69.88	97.16	17.61	13.77	26.18	319	5.24	0.25	0.05	1.31

MRH mean relative humidity, *MMINRH* mean minimum relative humidity, *MMAXRH* mean maximum relative humidity, *MT* mean temperature, *MMINT* mean minimum temperature, *MMAXT* mean maximum temperature, *AP* accumulated precipitation, *MW* mean wind speed, *MVPD* mean vapor pressure deficit, *MMINVPD* mean minimum vapor pressure deficit, *MMAXPDP* mean maximum vapor pressure deficit

Chemical analyses

Each dried litter sample collected at each moment by species was thoroughly mixed, divided into three subsamples, and ground into particles < 0.5 mm. Then 1.0 g of the ground material was mineralized in a muffle furnace at 550 °C for 5 h. The resulting ashes were treated with 10% v/v/ HCl and filtered. The extract was then analyzed using atomic absorption spectrophotometry to determine concentrations of calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) and potassium (K) by emission spectrophotometry (Isaac and Kerber 1971). Then, in the

same extract we determined phosphorus (P) concentration by colorimetry (Murphy and Riley 1962). Another ground subsample (0.5 g) was used to determine nitrogen (N) concentration using mineralization with H₂SO₄ and a mix of catalysts (CuSO₄ and K₂SO₄) at 350 °C for 90 min, followed by a Kjeldahl distillation (Bremner and Mulvaney 1982).

Statistical analyses

For the seasonal litterfall production, a linear mixed-effect model by species was fitted including two fixed effects: the year of evaluation and the sampling season nested in the

Fig. 1 Conical traps to collect litterfall in *Pinus taeda* and *Eucalyptus grandis* stands



year. The litter trap was considered a random effect in the models because the measures were repeated for the same litter trap during the sampling period. Further, the variance structure was modeled using the *varIdent* function. Nutrient amounts in the samples from each species were calculated using the seasonal litterfall dry mass records and nutrient concentration (Table S1). These data were analyzed using the same statistical model described above. Litterfall and nutrient amounts were compared between seasons within each year using Fisher's least significant difference (LSD) multiple comparison test.

For comparing litterfall and nutrient inputs between years by species, paired *t*-tests were done. For assessing the differences between species in these variables, *t*-tests for independent samples were used.

For climatic variables, a regression tree was performed using the *rpart* function relating this data with the litterfall records by species and calculating a relative importance value (RIV). We used a minimum node size of 5 to avoid overfitting according to the sample size (Weiss and Indurkha 1994; Fan and Gray 2005). For this purpose, the data set was randomly split into two groups, a training set containing 70% of the total data and a validation set with the remaining records. A regression tree by species was fitted to the training set. Then a prediction was carried out using the validation set data through the trained model. Additionally, to test the model accuracy for independent data, we used previous climatic and litterfall records from 2011 and 2012 for *E. grandis* and *P. taeda* in the same study area as test sets (Table S2, 3) (Hernández et al 2014). The procedure allowed us to assess the model accuracy for both species by determining the mean absolute error (MAE), root mean squared error (RMSE), and the determination coefficient (R^2) in the training, validation, and test sets.

All statistical analyses were performed using R statistical software (version 4.3.0) (R Foundation for Statistical Computing, Vienna, Austria) throughout RStudio interface (version 2023.06.0) (RStudio PBC, Boston, MA, USA).

Results

Litterfall production and nutrient return

Litterfall production of *E. grandis* during the study period had the same seasonal distribution in both years (Table 2). The most was deposited in spring, an intermediate amount in summer, then winter, and the least in the autumn. When comparing litter production between years, more was deposited the first year than in the second.

For nutrient return, N, K, Mg, Mn, and Cu followed the same trend evidenced for litterfall deposition throughout the first year. Fe presented deviations from this pattern, with

Table 2 Mean (\pm SE) seasonal and total biomass and nutrients in litterfall of *E. grandis* by year

Season	Biomass Mg ha ⁻¹	N kg ha ⁻¹	P	K	Ca	Mg	Fe g ha ⁻¹	Mn	Cu	Zn
<i>Year 1</i>										
Winter	1.44 (0.16) c	15.12 (1.17) c	0.48 (0.06) b	2.55 (0.35) c	13.03 (1.32) b	2.13 (0.28) c	253 (14) b	468 (71) c	6 (1) c	19 (2) b
Spring	3.60 (0.16) a	27.00 (1.17) a	1.26 (0.06) a	9.65 (0.35) a	30.16 (1.32) a	6.62 (0.28) a	309 (14) a	1994 (71) a	21 (1) a	43 (2) a
Summer	3.16 (0.16) b	19.93 (1.17) b	1.14 (0.06) a	6.11 (0.35) b	27.71 (1.32) a	5.88 (0.28) b	263 (14) b	1281 (71) b	19 (1) b	41 (2) a
Autumn	0.46 (0.16) d	3.88 (1.17) d	0.20 (0.06) c	0.89 (0.35) d	3.15 (1.32) c	0.73 (0.28) d	33 (14) c	181 (71) d	2 (1) d	18 (2) b
Total	8.66 (0.40) A	65.93 (2.82) B	3.08 (0.14) A	19.20 (0.90) A	74.05 (3.38) A	15.36 (0.73) A	858 (35) A	3924 (187) A	48 (2) A	121 (6) A
<i>Year 2</i>										
Winter	1.42 (0.10) c	15.76 (1.01) c	0.58 (0.04) c	2.73 (0.19) c	13.12 (0.91) b	2.48 (0.18) b	85 (7) b	495 (36) b	9 (1) c	24 (2) c
Spring	2.92 (0.10) a	24.55 (1.01) a	1.02 (0.04) a	5.20 (0.19) a	22.15 (0.91) a	4.70 (0.18) a	193 (7) a	955 (36) a	15 (1) a	47 (2) a
Summer	2.57 (0.10) b	20.47 (1.01) b	0.69 (0.04) b	3.21 (0.19) b	22.01 (0.91) a	4.62 (0.18) a	180 (7) a	899 (36) a	10 (1) b	31 (2) b
Autumn	1.11 (0.10) d	12.05 (1.01) d	0.38 (0.04) d	2.55 (0.19) c	12.14 (0.91) b	2.40 (0.18) b	84 (7) b	366 (36) c	4 (1) d	21 (2) c
Total	8.02 (0.29) B	72.83 (2.80) A	2.67 (0.10) B	13.69 (0.51) B	69.42 (2.55) A	14.20 (0.51) B	542 (19) B	2715 (100) B	38 (1) B	123 (4) A

Different lowercase letters in the same column for a year indicate significant differences within that year based on Fisher's LSD test ($P < 0.05$). Different uppercase letters in the same column indicate significant differences in the total biomass and nutrient deposition between years based on paired *t*-test ($P < 0.05$). ($N = 9$)

Table 3 Mean (\pm SE), seasonal and total biomass and nutrient in litterfall of *P. taeda* by year

Season	Biomass Mg ha ⁻¹	N kg ha ⁻¹	P	K	Ca	Mg	Fe g ha ⁻¹	Mn	Cu	Zn
<i>Year 1</i>										
Winter	1.56 (0.14) c	12.67 (1.07) c	0.61 (0.07) c	1.66 (0.21) c	7.01 (0.53) c	1.36 (0.14) c	143 (7) b	519 (45) c	3 (1) c	35 (3) c
Spring	2.34 (0.14) b	20.86 (1.07) b	1.24 (0.07) b	3.88 (0.21) b	10.11 (0.53) b	2.19 (0.14) b	128 (7) b	796 (45) b	9 (1) b	47 (3) b
Summer	4.84 (0.14) a	33.39 (1.07) a	2.52 (0.07) a	7.45 (0.21) a	17.08 (0.53) a	4.60 (0.14) a	203 (7) a	1505 (45) a	14 (1) a	87 (3) a
Autumn	1.24 (0.14) c	8.86 (1.07) d	0.55 (0.07) c	1.60 (0.21) c	3.88 (0.53) d	1.33 (0.14) c	50 (7) c	391 (45) d	2 (1) c	30 (3) c
Total	9.98 (0.40) A	75.78 (3.13) A	4.92 (0.21) A	14.59 (0.65) A	38.08 (1.51) A	9.48 (0.41) A	524 (18) A	3211 (134) A	28 (1) A	199 (8) A
<i>Year 2</i>										
Winter	1.27 (0.13) c	11.08 (1.03) c	0.57 (0.05) b	1.08 (0.10) b	4.37 (0.48) c	1.31 (0.14) c	61 (7) c	390 (35) b	6 (0) a	34 (3) b
Spring	0.34 (0.13) d	2.57 (1.03) d	0.15 (0.05) c	0.44 (0.10) c	1.06 (0.48) d	0.32 (0.14) d	24 (7) d	78 (35) c	1 (0) c	7 (3) c
Summer	2.00 (0.13) b	14.87 (1.03) b	0.62 (0.05) b	1.28 (0.10) b	6.09 (0.48) b	1.94 (0.14) b	138 (7) a	386 (35) b	4 (0) b	40 (3) b
Autumn	3.06 (0.13) a	25.29 (1.03) a	0.92 (0.05) a	2.35 (0.10) a	14.13 (0.48) a	3.72 (0.14) a	110 (7) b	948 (35) a	6 (0) a	58 (3) a
Total	6.67 (0.27) B	53.81 (2.21) B	2.26 (0.10) B	5.15 (0.23) B	25.65 (1.05) B	7.29 (0.29) B	333 (13) B	1802 (78) B	17 (1) B	139 (6) B

Different lowercase letters in the same column for a year indicate significant differences within that year based on Fisher's LSD test ($P < 0.05$). Different uppercase letters in the same column indicate significant differences in the total biomass and nutrient deposition between years based on paired *t*-test ($P < 0.05$). ($N = 9$)

the highest input in spring, intermediate values in summer and winter, and the lowest in autumn. P and Ca was higher in spring and summer, intermediate in winter, and lowest in autumn. Zn was highest in spring and summer and lowest in autumn and winter.

Throughout the second year, the seasonal deposition of N, P, and Cu was the same seasonal found for litterfall. K and Zn deviated in being highest in spring, intermediate in summer, and lowest in autumn and winter. For Ca, Mg, and Fe, the inputs were higher during spring and summer and lower in winter and autumn. Mn was higher in summer and spring, intermediate in winter, and lowest in autumn.

For nutrient return by year, higher P, K, Mg, Fe, Mn, and Cu inputs were recorded in the first year, but N was lower in the first year. For Zn and Ca, no differences were verified between the analyzed years.

For *P. taeda*, the seasonal litterfall production varied greatly within a given year (Table 3). During the first year, the highest litterfall was in summer, intermediate in spring, and lowest in autumn and winter. In the second year, the highest production was in autumn, followed by summer, then winter, and finally spring. Litterfall production for this species, like for *E. grandis* was higher in the first year than in the second.

Nutrient patterns were similar to those of litterfall. P, K, Mg, Cu, and Zn followed the same seasonality as litter deposition in the first year, N, Ca, and Mn deviated in having the highest level in summer, followed by spring, then winter, with lowest in autumn. Fe was highest in summer, intermediate in winter and spring, and lowest in autumn.

During the second year, N, Ca, and Mg showed the same pattern evidenced by litterfall. Other nutrients such as P, K, Mn, and Zn were highest in autumn, intermediate in summer and winter, and lowest in spring. Fe had a different seasonal pattern; the highest value occurred in summer, followed by autumn, then winter, with the lowest in spring. Cu was highest in autumn and winter, intermediate in summer, and lowest in spring. When comparing levels between the two years, all nutrients were higher in the first year.

The yearly mean litterfall did not differ between the two forest species (Table 4). Nutrients such as K, Ca, Mg, Fe, Mn, and Cu had higher return ratios in *E. grandis* than in *P. taeda*, but P and Zn were higher in *P. taeda* than in *E. grandis*. Finally, the N yearly return did not differ between the species.

Litterfall and climatic relationships

For litterfall by *E. grandis*, the variables used in the tree construction were MT (RIV = 51.3%), AP (RIV = 24.6%), and MMAXVPD (RIV = 24.1%) (Fig. 2). The MT records (node 1 – root node) defined two groups, one with lower litterfall production (1.10 Mg ha⁻¹) for MT below 18 °C (node

Table 4 Yearly mean (\pm SE) litterfall and nutrient incorporation by *E. grandis* and *P. taeda*

Species	Litterfall (Mg ha ⁻¹ a ⁻¹)	Macronutrients (kg ha ⁻¹ a ⁻¹)					Micronutrients (g ha ⁻¹ a ⁻¹)			
		Dry mass	N	P	K	Ca	Mg	Fe	Mn	Cu
<i>E. grandis</i>	8.35 (0.33) a	69.38 (2.68) a	2.88 (0.12) b	16.45 (0.67) a	71.74 (2.81) a	14.78 (0.59) a	700 (26) a	3320 (135) a	43 (2) a	122 (5) b
<i>P. taeda</i>	8.33 (0.33) a	64.80 (2.52) a	3.59 (0.15) a	9.87 (0.42) b	31.87 (1.21) b	8.39 (0.33) b	429 (15) b	2507 (100) b	23 (1) b	169 (7) a

Values with different letters in the same row differed significantly between species based on *t*-test for independent samples ($P < 0.05$). ($N = 9$)

2) and another with higher deposition (3.00 Mg ha⁻¹) for MT greater than or equal to this value (node 3).

For node 2, AP divided the data into two new groups, one with the lowest litterfall production (0.85 Mg ha⁻¹) for AP values lower than 351 mm (node 4) and another for intermediate (1.40 Mg ha⁻¹) for AP higher than or equal

to this value (node 5). For node 3, MMAXVPD defined another split with one group having an intermediate record (2.70 Mg ha⁻¹) for values lower than 1.4 kPa (higher than the node 6 value) and another group (node 7) containing the highest litterfall (3.50 Mg ha⁻¹) for MMAXVPD greater than or equal to this value.

Fig. 2 Regression tree for *E. grandis* litterfall production and seasonal climatic variables. The first value inside the node indicates the mean litterfall production (Mg ha⁻¹) for the group. MT, mean temperature (°C); AP, accumulated precipitation (mm); MMAXVPD, mean maximum vapor pressure deficit (kPa)

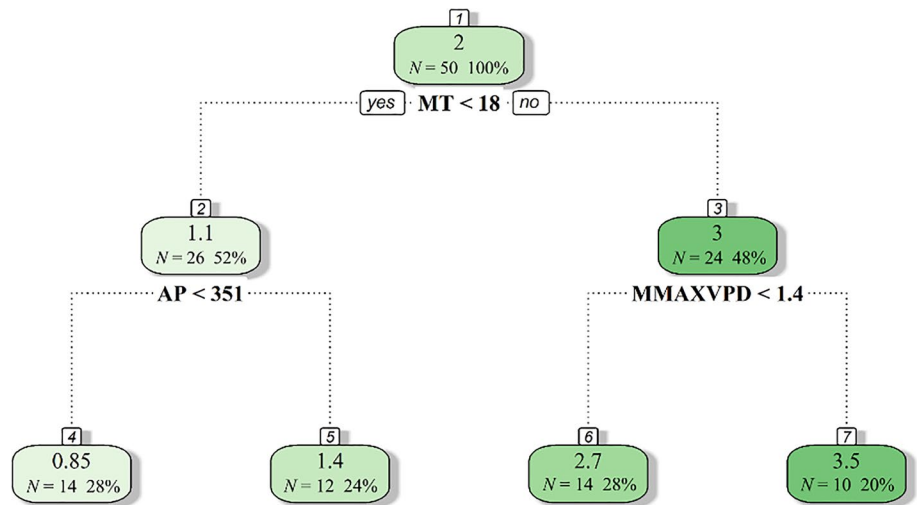


Fig. 3 Regression tree for *P. taeda* litterfall production and seasonal climatic variables. The first value inside the node indicates the mean litterfall production (Mg ha⁻¹) for the group. AP, accumulated precipitation (mm); MMAXT, mean maximum temperature (°C)

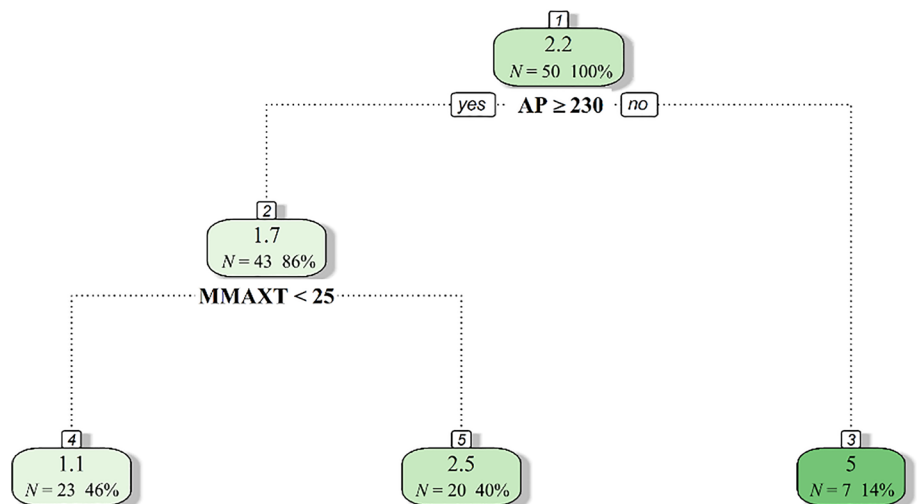


Table 5 Regression model accuracy metrics for training, validation, and test sets for the litterfall and climatic variables in both species

Species	Training set ^a			Validation set ^b			Test set ^c		
	MAE	RMSE	R^2	MAE	RMSE	R^2	MAE	RMSE	R^2
<i>E. grandis</i>	0.35	0.43	0.85	0.38	0.46	0.84	0.65	0.91	0.71
<i>P. taeda</i>	0.51	0.59	0.83	0.44	0.53	0.80	1.50	1.59	0.72

MAE mean absolute error, RMSE root mean squared error, R^2 determination coefficient

^a $N=50$, 70% of total sample size

^b $N=22$, 30% of total sample size

^c $N=33$ for *E. grandis*, $N=108$ for *P. taeda*

For *P. taeda*, the climatic variables used for modeling were AP (RIV = 54.5%) and MMAXT (RIV = 45.5%) (Fig. 3). AP established the first split (node 1 – root node), where values higher than or equal to 230 mm defined a new group (node 2) with lower litterfall (1.70 Mg ha⁻¹) and another (node 3) for records lesser than this value, resulting in the highest litterfall deposition (5.00 Mg ha⁻¹).

For node 2, MMAXT delimits two new groups, one for MMAXT less than 25 °C (node 4), defining the lowest litterfall production (1.10 Mg ha⁻¹), and another for values higher than or equal to this value (node 5), grouping intermediate litterfall records (2.50 Mg ha⁻¹).

The results for model accuracy in Table 5 show good model performance with high R^2 and low MAE and RMSE values for the training, validation, and test sets for both species.

Discussion

The seasonal production of litterfall by *E. grandis* was unimodal, following the same seasonal pattern in both analyzed years with maximum values in spring and lowest in autumn. This pattern was also reported for *Eucalyptus* species in temperate climates (Pook et al 1997; Baker 2009) and is usually attributed to periods with temperature increases that result in higher leaf production (Pook et al 1997; Schlatter et al 2006; Momolli et al 2019a). Our values are in consistent with the climatic conditions during the spring of both years.

For *P. taeda*, the litterfall seasonal pattern varied greatly depending on the year. In the first year, the litterfall was highest in summer and lowest in winter and autumn, which may be related to the drier conditions during summer, given that the leaf detachment is usually related to high temperatures and dry periods in *Pinus* species (Li et al 2005; Erkan et al 2018; Bueis et al 2018). In the second year, litterfall was highest in autumn, with the lowest value in spring, because relative humidity and accumulated precipitation were higher and temperature and vapor pressure deficit lower than in the first year. This possibility is supported by previous studies that showed the highest litterfall production during autumn under nonlimiting water availability for *Pinus* species

(Piovesan et al 2012; Kulmann et al 2021). At the same time, the absence of a strong dry period during the summer season of the second year could delay peak litterfall deposition by 3 months, as previously found for *Pinus radiata* in Australia (Raison et al 1992).

The yearly biomass deposition for both species in the first year was higher than in the second, and the yearly mean values did not differ between the two species. The litterfall for *E. grandis* in both years was within previously reported ranges for *Eucalyptus* species (5–12 Mg ha⁻¹ a⁻¹; Voigtlaender et al 2019; Muqaddas and Lewis 2020), as was also the case for *P. taeda* compared with *Pinus* species (6–12 Mg ha⁻¹ a⁻¹; Li et al 2005; Piovesan et al 2012; Kulmann et al 2021). These results could be related to the lower precipitation volume in the spring and summer of the first year compared to the second, because a precipitation deficit may promote increases in litterfall production (Crockford and Richardson 1998; Muqaddas and Lewis 2020; Kulmann et al 2021).

Our litterfall results were also similar to those previously reported by Baietto et al (2021a) at the same study site during the same years but using a different sampling method. The slight deviations between the studies can be attributed to differences in trap shape, size, number, and sampling position, which have been reported as sources of variability for litterfall estimates (Morrison 1991; Finotti et al 2003; Yang et al 2017).

In our analysis, the most important climatic variables impacting litterfall production were MT, AP, and MMAX-VPD for *E. grandis* and AP and MMAXT for *P. taeda*. These results agree with past studies on climatic variables associated with litterfall in *Eucalyptus* and *Pinus* species (Piovesan et al 2012; Thomas et al 2014; Momolli et al 2019a). Further, these variables explained a large proportion of the litterfall variability through a regression tree model that had high accuracy and predictive power. In a previous study using climatic variables for simple and multiple linear models for coniferous and broad-leaf forests, R^2 values ranged between 0.27 and 0.54 (Liu et al 2004). For *Eucalyptus* species in Australia, Grigg and Mulligan (1999) obtained an R^2 of 0.49 for annual litterfall production using a simple linear regression with rainfall as the independent variable.

Similarly, simple linear associations were found between litterfall of several *Pinus* species and climatic variables in Europe (R^2 between 0.23 and 0.79; Berg and Meentemeyer 2001). Although litterfall estimation models based only on climatic predictors usually are very accurate, biotic variables are important for increasing the representativeness and scope of the models (Geng et al 2022), especially if spatial heterogeneities in stand characteristics are ignored, potentially biasing predictions (Liu et al 2019).

The levels of most nutrients in the litterfall had a similar seasonal pattern in both years but with slight deviations for some in both species. Similarly, nutrient return was highest when litterfall was highest for *Eucalyptus* species in New Zealand (Guo et al 2006) and *P. taeda* stands in sandy soils in southern Brazil (Kulmann et al 2021). These results show that the differences in nutrient remobilization before litterfall production cannot counteract the effect of the amount of litter biomass, which is the key factor in nutrient recycling. For macronutrients, the order of return for *E. grandis* was $\text{Ca} > \text{N} > \text{K} > \text{Mg} > \text{P}$, comparable to the order obtained for the same species in Brazil on sandy soils ($\text{N} > \text{Ca} > \text{K} > \text{Mg} > \text{P}$; da Silva et al 2011), for *Eucalyptus dunnii* ($\text{Ca} > \text{N} > \text{K} > \text{Mg} > \text{P}$; Garlet et al 2019) and a group of *Eucalyptus* species in New Zealand (Guo et al 2006). The order for micronutrients was $\text{Mn} > \text{Fe} > \text{Zn} > \text{Cu}$, as reported for *E. dunnii* on sandy soils in southern Brazil (Momolli et al 2019b). For *P. taeda*, the macronutrient order of importance was $\text{N} > \text{Ca} > \text{K} > \text{Mg} > \text{P}$, identical to the one for the same species in southern Brazil (Kulmann et al 2021), and the order for micronutrients ($\text{Mn} > \text{Fe} > \text{Zn} > \text{Cu}$) was the same as in a long-term study in southern Brazil (Viera and Schumacher 2010). In general, when we compared the mean yearly nutrient return by species, *E. grandis* returned more than *P. taeda*, even though the mean yearly rate of litterfall did not differ for the two species. These results could be associated with the higher concentration of most nutrients in *E. grandis* as frequently reported for comparisons of litter nutrients from most broadleaf species compared with those of conifers (Pallardy 2008; Kang et al 2010; Wang et al 2019). The litterfall and the associated nutrient return constitute a significant resource for forest ecosystems and frequently vary depending on the species (Nazrul Islam et al 2021), which is an important consideration for forest managers due to the significant differences in litterfall nutrients among species in forest systems.

Our results showed that the seasonality in litterfall production and the nutrient return in *P. taeda* stands were highly sensitive to changes the air temperature and precipitation, as reported for this species in Brazil (Kulmann et al 2021). Litterfall production by *E. grandis* seems to be less vulnerable to climatic factors than *P. taeda*, varying somewhat in litter and nutrient quantity without any strong changes in seasonal production. These results are in line with those of Liu et al

(2004) who found that the climatic influence of litterfall can differ between coniferous and broadleaf forests. Even though the interannual litterfall variations are usually associated with the current climate, their effects could increase as the climate changes (Kouki and Hokkanen 1992; Pook et al 1997; Cheng et al 2020).

Conclusions

The yearly climatic conditions may be an important influence on seasonal litterfall. Air temperature, air capacity to retain humidity, and precipitation levels were principally associated with litterfall amounts during the 2-year study, but this climatic influence on litterfall levels can differ between species. *P. taeda* was more sensitive than *E. grandis* to climatic influences. The two species also differed in which climatic variables had the most influence on litterfall levels. Thus, these climatic variables could serve as important predictors for developing predictive models and understanding the dynamics of litter production. At the same time, nonclassical approaches such as regression trees will allow us to detect relationships between variables that otherwise will go unnoticed. The regression tree modeling based on climatic variables was highly accurate and predictive, but the scope of the fitted models can be limited by variability of the samples due to factors such as tree age, stand density, and management practices. Additionally, because nutrient return is closely related to litterfall biomass, we should be able to model these returns using climatic variables. In the present study, the main differences in the yearly nutrient return ratio between species were associated with the higher nutrient concentrations in the litter of *E. grandis* compared to *P. taeda*. This study is a first approximation for modeling litterfall production and nutrient return of *Eucalyptus* and *Pinus* stands in nutrient-poor soils in the Pampean region of South America. In the future, longer-term studies should provide a better understanding of the influence of climatic and biotic variables on litterfall production and provide data to develop better models to estimate litterfall and the dynamics of the associated nutrient return, predict the response of different forest species in different climatic scenarios, and develop optimal fertilization strategies.

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Author contributions AB did the sampling, statistical analyses, and laboratory work and led the article writing with revision from all authors. AH was involved in article writing, data organization, and statistical analyses. JH participated in litter sampling and article writing. AP contributed to the development of the sampling methodology and laboratory analyses. All authors have read and agreed to the published version of the manuscript.

Data availability Data are available upon request to the corresponding author.

Declarations

Conflict of interest No author has any conflicts or competing interests.

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