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# Litterfall and Accumulated Nutrients in *Pinus taeda* Plantation and Native Forest in Southern Brazil

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**Abstract:** The dynamics of the production, chemical composition, and accumulated nutrients in litterfall are essential to understand the availability of nutrients and, consequently, possible gains in productivity in different forest types. Thus, the objective of the present study was to evaluate the litterfall and the accumulated nutrients in litterfall in a *Pinus taeda* plantation and native forest from southern Brazil. Two forest types: (i) an eight-year-old *Pinus taeda* L. plantation; and (ii) a native forest fragment, located in southern Brazil, were studied for four years. The monthly and annual litterfall production, chemical composition, accumulated nutrients, and nutrient use efficiency of the litterfall were evaluated. The *Pinus taeda* plantation showed higher values of leaves/needles litterfall and N, P, K, Ca and Mg use efficiency. This demonstrates that *Pinus taeda* plantations have a high production of needle biomass, which, in turn, has increased cell division, favoring the entry of these nutrients into the soil via decomposition. Our results show that total litterfall production did not significantly influence the accumulated nutrient and nutrient efficiency of litterfall, demonstrating that evaluating litterfall fractionation, such as leaves/needles, twigs and miscellaneous, is essential to understand the quantity and quality of litterfall and, thus, the nutrient cycling, which can contribute to possible silvicultural practices to be implemented, which can provide growth gains in forest types.

**Keywords:** forest native; forest nutrition; nutrient cycling; pine



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## 1. Introduction

The growth in global demand for wood products led to the establishment of reforesting areas, reaching 131 million hectares of forest stands for commercial purposes worldwide [1]. The crops used in the establishment of such stands are common species with rapid growth and short rotation, but in the long run, critical problems may arise, such as reduced productivity and soil degradation [2]. For example, studies carried out in China and Brazil regarding the harvest of *Eucalyptus* sp. plantations in short rotations (two to six years) resulted in large nutrient exports and possible declines in plantation productivity [3,4]. The genus *Pinus* spp. is the second largest forestry base in Brazil silviculture, grown on 1.64 million hectares, representing 18% of the national area, being predominantly located in the subtropical region of the south of the country [5]. *Pinus taeda* L. (loblolly pine) is the most used species, due to its fast growth, high yield, excellent wood quality and several ends use, such as the production of long fiber cellulose, sawn wood, plywood and laminated panels [6]. Despite high growth rates, relevant concerns are raised about the continued decline in productivity and soil fertility of *Pinus taeda* plantations, as reported in other conifers [7–10]. However, maintaining productivity in subsequent rotations is one of the central principles of long-term sustainability in commercial plantations [11]. A strategy to maintain the productivity of the population in the subsequent rotation is the management of soil nutrients, which can contribute to decisions on forestry practices, such as plantations fertilization. However, there is still a dearth of such information for *Pinus taeda* plantations.

Native forest ecosystems have numerous environmental functions, such as conservation of fauna and flora diversity, in addition to playing an important role in the global nutrient cycle, as climate change continues as well as the increase in anthropogenic emissions of atmospheric gases [12]. The cycling of nutrients in forests involves several pathways of nutrients entering and leaving, however, litterfall is considered one of the most important pathways, except for potassium (K), for which throughfall has equal importance [12,13]. Litterfall acts to maintain soil fertility in both native and planted forest types, as it is the main source of soil organic material, composed of organic fragments, from plant shoot, leaves, flowers, fruits, twigs, branches, bark and other plant materials, as well as animal remains and fecal material [13,14]. In addition to the cycling of nutrients, litterfall has an important role against erosion, as a source of organic carbon, a substrate for microorganisms, and soil respiration [13].

Accumulated nutrient in litterfall is directly related to the return of nutrients to the soil and, consequently, plays an important role in forest biogeochemical cycling [2,15]. The quantity and quality of litterfall production directly influence the productivity of natural or planted forest stands [2]. The climate is the factor affecting most litterfall on a global scale [13,16]. However, on a regional scale, the production and nutritional quality of the litterfall depends on the composition of the species and forest types [2]. Studies in five deciduous broadleaved forests and four evergreen coniferous forests in South Korea found that the litterfall from coniferous forest produced 5.56 Mg ha$^{-1}$, while in deciduous forests the production was 4.36 Mg ha$^{-1}$ [17]. Another study [18] found a 17% increase in total litterfall production in perennial coniferous forests, when compared to deciduous forests. On the other hand, [19] an 11-year study in China reported greater production of litterfall in a tropical ravine forest (1.26 Mg ha$^{-1}$) compared to the pine forest (3.56 Mg ha$^{-1}$). In addition, the authors found the highest litterfall production in the summer season, between April and September. Thus, the knowledge of litterfall effects on forest types contributes to the selection of species for reforestation, and possible silvicultural practices [13].

Litterfall quality is directly related to the nutritional composition of the plant material fractions deposited under the soil [16]. Understanding litterfall production, chemical composition and accumulated nutrients in litterfall are essential to identify nutrient availability and, consequently, productivity gains in forest types [2]. Studies report that the annual accumulated N in litterfall can reach 70 kg ha$^{-1}$, 5.5 kg ha$^{-1}$ for P, and 49 kg ha$^{-1}$ for K in *Castanopsis kawakamii* plantations [2,20]. The rate of nutrient return from the litterfall to the soil is directly related to the chemical composition and, thus, the nutritional efficiency of the litterfall [21]. The nutritional efficiency of nutrient return from accumulated nutrients in litterfall to the soil can be assessed through nutritional efficiency indexes, such as the nutrient use efficiency (NUE), parameters that reflect processes of mobilization, storage, and decomposition of nutrients in the soil organic material [16,22]. Therefore, the NUE is a tool used worldwide to evaluate the production per unit of resource used, or resource available in the environment, since the standardization of different parameters used for the calculation makes it possible to compare and, thus, identify populations, species, and fractions that are nutritionally more efficient [21].

Several studies show that the oscillation of climatic factors, especially temperature and precipitation, has significant effects on litterfall production [2,12–14,16]. However, studies comparing commercial forest stands, such as *Pinus taeda*, with native forest, and their relationship to production, the chemical composition of fractions, rate of accumulated nutrients in litterfall, and nutrient use efficiency of litterfall, are scarce in the literature. Thus, the current study aims to evaluate the monthly and annual litterfall production, chemical composition, accumulated nutrients in litterfall, and nutrient use efficiency of litterfall in *Pinus taeda* plantations and native forests in Southern Brazil. We hypothesized that litterfall production dynamics varies according to forest types and over months; plant fractions, such as leaves and needles, contribute mostly to the total litterfall production and can be an important source of accumulated nutrient in litterfall.

## 2. Materials and Methods

### 2.1. Site Description

The study was conducted in two forest types: an eight-year-old *Pinus taeda* L. plantation and a fragment of native forest, consisting of a Subtropical Seasonal Forest, located in Quedas do Iguaçu County, Southwest region of Paraná State, Brazil (25°27′22″ S; 52°54′39″ W) (Figure 1). The relief of the area was characterized as smooth undulating, at an altitude of 450 m in relation to the average sea level [23]. The region's climate is the fundamental Cfa type, humid subtropical, according to the Köppen classification, characterized by hot and rainy summers, with an annual average temperature of 20 °C, and winters with physiological drought, with an average temperature below 15 °C. The average annual precipitation of 1780 mm and 60 mm in the driest month [24]. Data of accumulated monthly precipitation and average monthly temperature during the period (2007–2010) provided by the weather station of the Araupel S.A. company are shown in Figure 2. The soil in the experimental area was classified as a Rhodic Hapludox [25], characterized by deep soils (>100 cm), reddish color, clayey texture, and $Fe_2O_3$ levels varying from 18 to 36% [26].

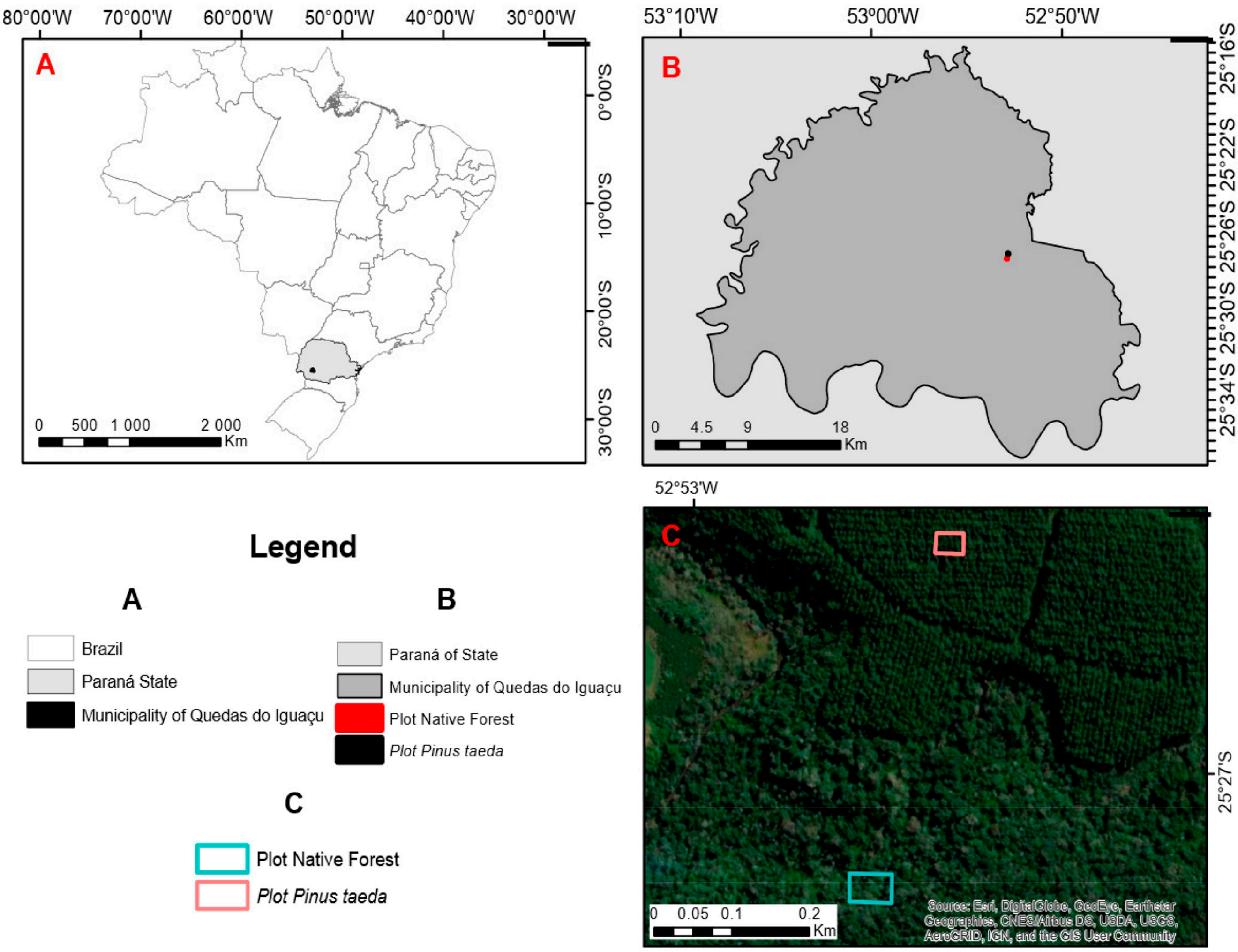


**Figure 1.** Location of the experimental area of *Pinus taeda* plantation, and native forest in the municipality of Quedas do Iguaçu, southwest region of the Paraná state, Brazil.

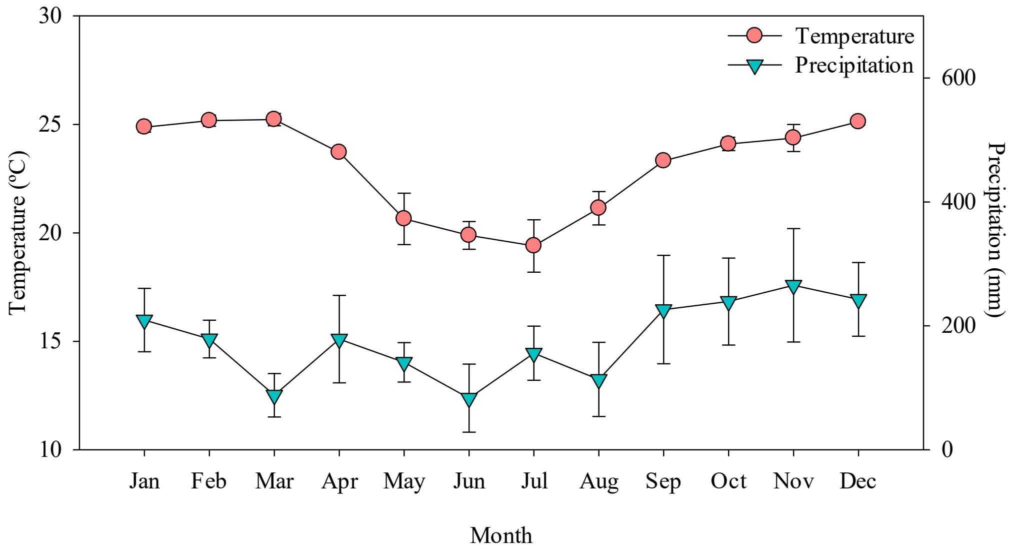


**Figure 2.** Monthly temperature (°C) and monthly accumulated precipitation (mm) during the study period in Quedas do Iguaçu, southwest region of the Paraná state, Brazil. Source: Weather station of the Araupel S.A. company. Plotted values indicate average. Vertical bars indicate the standard error.

The planting of the *Pinus taeda* plantation was performed in 1999, without fertilizing, and is in the first rotation. Spacing is 2.0 m between plants and 3.0 m between lines (1667 trees ha$^{-1}$). In August 2008, a dendrometric inventory of the experimental area was carried out. The plantation had 1257 trees ha$^{-1}$, an average height of 11.8 m, average diameter at breast height (DBH) of 18.3 cm and a mean annual increment (MAI) of 23.5 m$^3$ ha$^{-1}$ year$^{-1}$.

The native forest is a preservation area in advanced stages of succession, without anthropic intervention for more than 50 years, and characterized through a floristic survey by [27]. The main botanical families described were: Fabaceae (16 species), Lauraceae (8 species), Myrtaceae (7 species) and Solanaceae (7 species). The basal area of 46.2 m$^2$ ha$^{-1}$, average density of 1500 trees ha$^{-1}$, and the most abundant species were: *Actinostemon concolor* (Spreng.) Müll. Arg.; *Nectandra megapotamica* (Spreng.) Mez; *Lonchocarpus campestris* Mart. ex Benth.; *Syagrus romanzoffiana* (Cham.) Glassman, *Sebastiania brasiliensis* Spreng.; *Diatenopteryx sorbifolia* Radlk.; and *Balfourodendron riedelianum* (Engl.) Engl., typical species in subtropical semideciduous seasonal forests in advanced stages of succession.

## 2.2. Litterfall Collection

Three 21 × 20 m plots in each forest types (*Pinus taeda* and native forest) were installed to quantify the litterfall deposition. The plots were installed at distances greater than 30 m from each other and 20 m from the edge of each forest type, randomly distributed. Four litterfall traps were installed in each plot, totaling 24 traps. The litterfall traps are of the tray type, with a collection area of 1.0 m$^2$ (1.0 m long × 1.0 m wide), arranged at 0.7 m high in relation to the soil surface. The litterfall traps had wooden sides equipped with nylon mesh at the bottom (1.0 mm mesh). In the native forest the litterfall traps were randomly distributed, while in the *Pinus taeda* plantation they were systematically distributed, one on the planting line between two trees, one between the lines between two trees, one diagonally between four trees, and one against the tree trunk. The contents of the tray were collected monthly between January 2007 and December 2010, totaling 48 collections. At the end of the experimental period, 1152 samples were processed and analyzed. The litterfall content was manually classified into leaves/needles, twigs, miscellaneous (unidentified materials fine vegetable tissue, such as bark, cones, flowers, fruits, seeds, and other residues), and total (sum of fractions). The sample fractions were dried in an oven with forced air circulation at 65 °C for 72 h. Then, samples were weighed on a digital scale (Bel Engineering, Precision balance L, Piracicaba, Brazil), for determination of the dry matter. Immediately after weighing, samples were ground in a Wiley mill, passed through a 2 mm mesh sieve, and reserved for chemical analysis. The calculation of the annual litterfall (AL) of each fraction was estimated according to data from monthly litterfall and collector area and, later, the sum of monthly productions for the period of one year, as described in Equation (1):

$$AL = (\sum ML \times 10{,}000)/(CA), \tag{1}$$

where: AL refers to annual litterfall (Mg ha$^{-1}$ year$^{-1}$); ML is the monthly litterfall (Mg ha$^{-1}$ month$^{-1}$); and CA the collector area (m$^2$), according to the methodology proposed by [28].

### 2.3. Accumulated and Nutrient Use Efficiency

The samples of the reserved fractions were subjected to chemical analysis. Part of the fraction samples was submitted to sulfuric digestion for the determination of N by micro-Kjeldahl distiller (TE 0363, Tecnal, Piracicaba, SP, Brazil). Another part was submitted to nitro-perchloric digestion, to determine the concentrations of P, K, Ca and Mg, following the methodology of [29]. The P concentration was determined by colorimetric method [30], using a UV-visible spectrophotometer (Model SF325NM, Bel Engineering, Monza, MB, Italy); K concentration by flame spectrophotometry (Micronal B 462, Tecnal, Piracicaba, SP, Brazil); and Ca and Mg concentration by atomic absorption spectrophotometry (AAS; Varian SpectrAA—600, Victoria, Australia). Nutrient concentrations and accumulations were calculated for all litterfall fractions. To do so, we multiplied the monthly nutrient concentration by the monthly litterfall production to calculate the accumulated nutrient, and the total accumulated nutrients over 12 months was added as the annual accumulated nutrients, according to the methodology reported by [2].

The values of N, P, K, Ca, and Mg annual accumulated in litterfall (Tables S1 and S2) were used to estimate the nutrient use efficiency (NUE), following Equation (2):

$$NUE = AL/AANL, \tag{2}$$

where: NUE refers to the nutrient use efficiency (kg kg$^{-1}$); AL is the annual litterfall (kg litterfall ha$^{-1}$ year$^{-1}$); and AANL refers to the annual accumulated nutrients in litterfall (kg nutrient ha$^{-1}$ year$^{-1}$), according to methodology reported by [16].

### 2.4. Statistical Analysis

The results were subjected to analysis of the assumptions of normality of residuals and homogeneity of variance by the Shapiro–Wilk and Bartlett test, respectively. The results obtained were analyzed analysis of variance using the R Studio program [31], and when the effects pointed out by the analysis of variance reached significance, the comparison of means by the Student's *t*-test ($p < 0.05$) was performed. The effects of forest type factors and months on the dynamics of monthly litterfall, and an average monthly accumulated nutrient were assessed through descriptive data analysis, based on the standard error of the mean. In addition, to verify the effects of correlation between the response variables and the treatment distribution, we performed a multivariate principal components analysis (PCA) through the package FactoExtra [32], with the aid of R *software* [31]. PCA is carried out according to a set of main components (in this case we used PC1 and PC2), which are composed of a set of standardized, orthogonal linear combinations, and which together explain the original variance of the data.

## 3. Results

### 3.1. Monthly and Annual Dynamics of Litterfall Production

The monthly dynamics of litterfall production of leaves/needles, miscellaneous and total fractions were significantly affected by the months ($p < 0.001$) (Table 1). The monthly litterfall production of leaves/needles showed seasonality among forest types (Figure 3a). The *Pinus taeda* plantation had the highest needles production from January to June, when compared to the leaves fraction in the native forest. Litterfall production in the native forest was higher from August to November, when compared to the *Pinus taeda* plantation. The *Pinus taeda* plantation had the highest values of monthly litterfall production in June (1112.96 kg ha$^{-1}$), while the native forest in August (1233.72 kg ha$^{-1}$). The dynamics of the monthly litterfall production of the twigs and miscellaneous fractions were significantly affected by the forest type ($p < 0.001$) (Table 1). Overall, the native forest showed the highest monthly production of twigs and miscellaneous litterfall independent of the month of the year, when compared to the *Pinus taeda* plantation (Figure 3b,c), which was observed for September (137.98 kg ha$^{-1}$) and November (127.81 kg ha$^{-1}$), respectively. The *Pinus taeda* plantation, on the other hand, had the highest monthly production of twigs and miscellaneous litterfall in October (33.49 kg ha$^{-1}$) and September (43.85 kg ha$^{-1}$). The forest types did not significantly affect the leaves/needles and total fraction of litterfall monthly production (Table 1).

**Table 1.** *p*-values of analysis of variance (ANOVA) for variables of litterfall fractions and nutrients in a *Pinus taeda* plantation and native forest in Southern Brazil.

| Variables | Effect | | |
|---|---|---|---|
| | Forest | Month | Interaction |
| Leaves/needles litterfall (kg ha$^{-1}$) | 0.1341 ns | <0.001 * | <0.001 * |
| Twigs litterfall (kg ha$^{-1}$) | <0.001 * | 0.3838 ns | 0.7551 ns |
| Miscellaneous litterfall (kg ha$^{-1}$) | <0.001 * | <0.001 * | 0.0735 ns |
| Total litterfall (kg ha$^{-1}$) | 0.3273 ns | <0.0001 * | <0.0001 * |
| Accumulated N in litterfall (kg ha$^{-1}$) | <0.001 * | <0.001 * | <0.001 * |
| Accumulated P in litterfall (kg ha$^{-1}$) | <0.001 * | <0.001 * | <0.0001 * |
| Accumulated K in litterfall (kg ha$^{-1}$) | <0.001 * | <0.001 * | <0.001 * |
| Accumulated Ca in litterfall (kg ha$^{-1}$) | <0.001 * | <0.001 * | <0.001 * |
| Accumulated Mg in litterfall (kg ha$^{-1}$) | <0.001 * | <0.001 * | <0.001 * |

* = Significant ($p < 0.001$); ns = not significant ($p > 0.05$).

The annual production of needles was significantly higher in the *Pinus taeda* plantation than the leaves in the native forest (6.68 vs. 5.81 Mg ha$^{-1}$ yr$^{-1}$) (Figure 4a). The highest annual production values for twigs and miscellaneous litterfall occurred in the native forest, when compared to the *Pinus taeda* plantation (1.15 vs. 0.22 Mg ha$^{-1}$ yr$^{-1}$ and 0.80 vs. 0.24 Mg ha$^{-1}$ yr$^{-1}$, respectively) (Figure 4b,c). The value of annual total litterfall production did not differ statistically between forest types (Figure 4d).

### *3.2. Monthly and Annual Dynamics of Accumulated Nutrient*

The dynamics of accumulated N, P, K, Ca and Mg in litterfall had a significant effect on forest type, months, and interaction between factors ($p < 0.001$) (Table 1). In general, the highest values of accumulated N, P, K, Ca, and Mg in litterfall were observed in the native forest, when compared to the *Pinus taeda* plantation (Figure 5a–e). The dynamics of accumulated N, P, K, Ca and Mg in litterfall had seasonality among forest types. The highest values of accumulated N, P, K, Ca, and Mg in litterfall of native forest soil were seen in August (22.11, 4.20, 11.57, 33.62, and 5.36 kg ha$^{-1}$, respectively). The peaks of accumulated N, P, K, Ca, and Mg in litterfall of native forest soil in August, September, and October represented 38.2, 41.6, 45.3, 41.3, and 36.6%, respectively, of total annual accumulated nutrients. The *Pinus taeda* plantation showed the highest values of accumulated P, K and Mg in litterfall in June (0.70, 2.33, and 1.43 kg ha$^{-1}$, respectively), and accumulated N and Ca in litterfall in May (6.76 and 4.77 kg ha$^{-1}$, respectively). The peaks of accumulated N, P, K, Ca, and Mg in litterfall in the *Pinus taeda* plantation in April, May, and June represented 36.6, 41.6, 42.0, 41.5, and 40.9%, respectively, of the total annual accumulated nutrients.

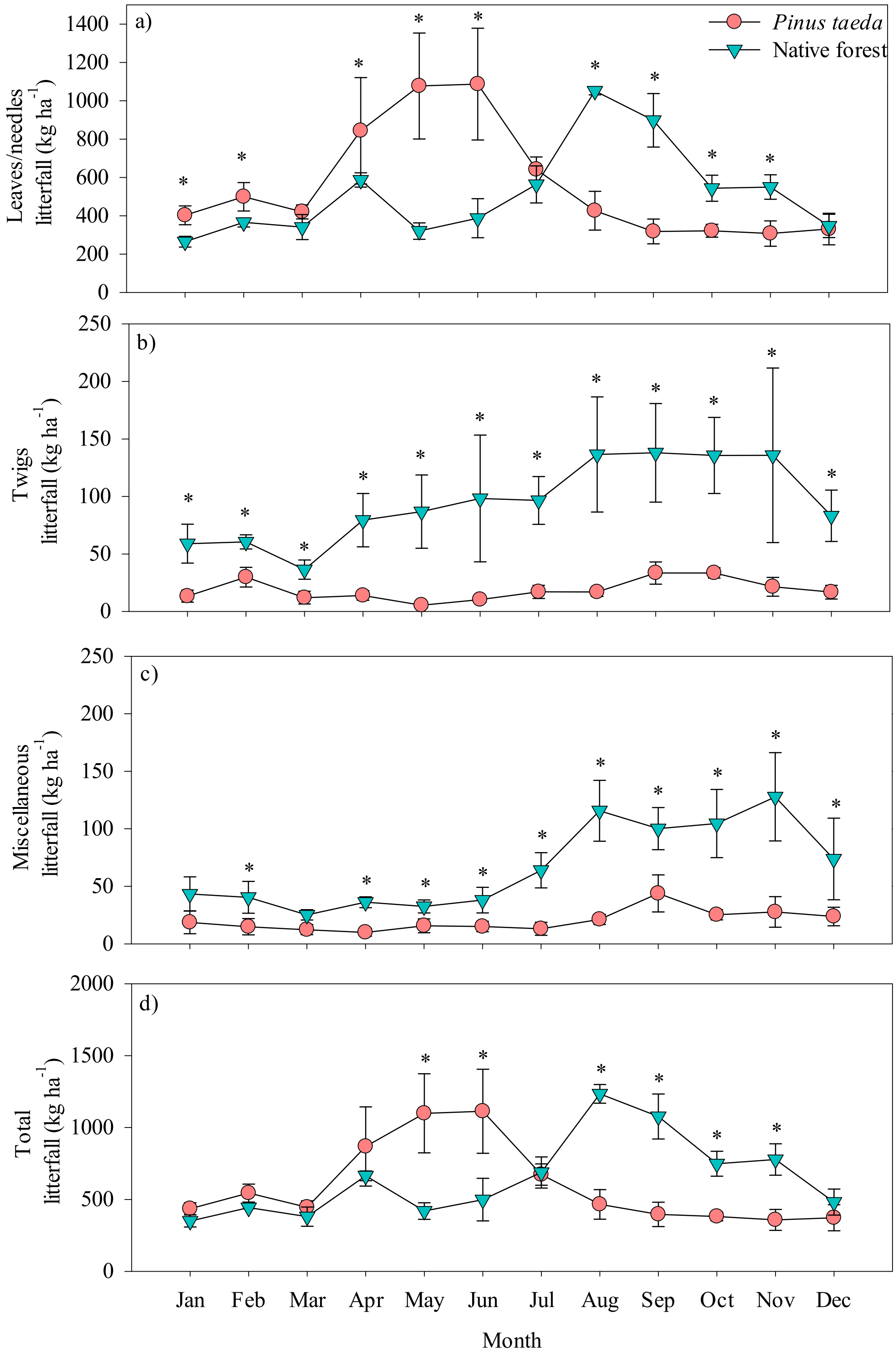


**Figure 3.** Monthly amounts of leaves/needles (**a**), twigs (**b**), miscellaneous (**c**) and total (**d**) litterfall (kg $ha^{-1}$) in a *Pinus taeda* plantation and native forest in southern Brazil. Plotted values indicate average. Vertical bars indicate the standard error. Asterisk (*) on top indicate a statistically significant difference by Student's *t*-test ($p < 0.05$).

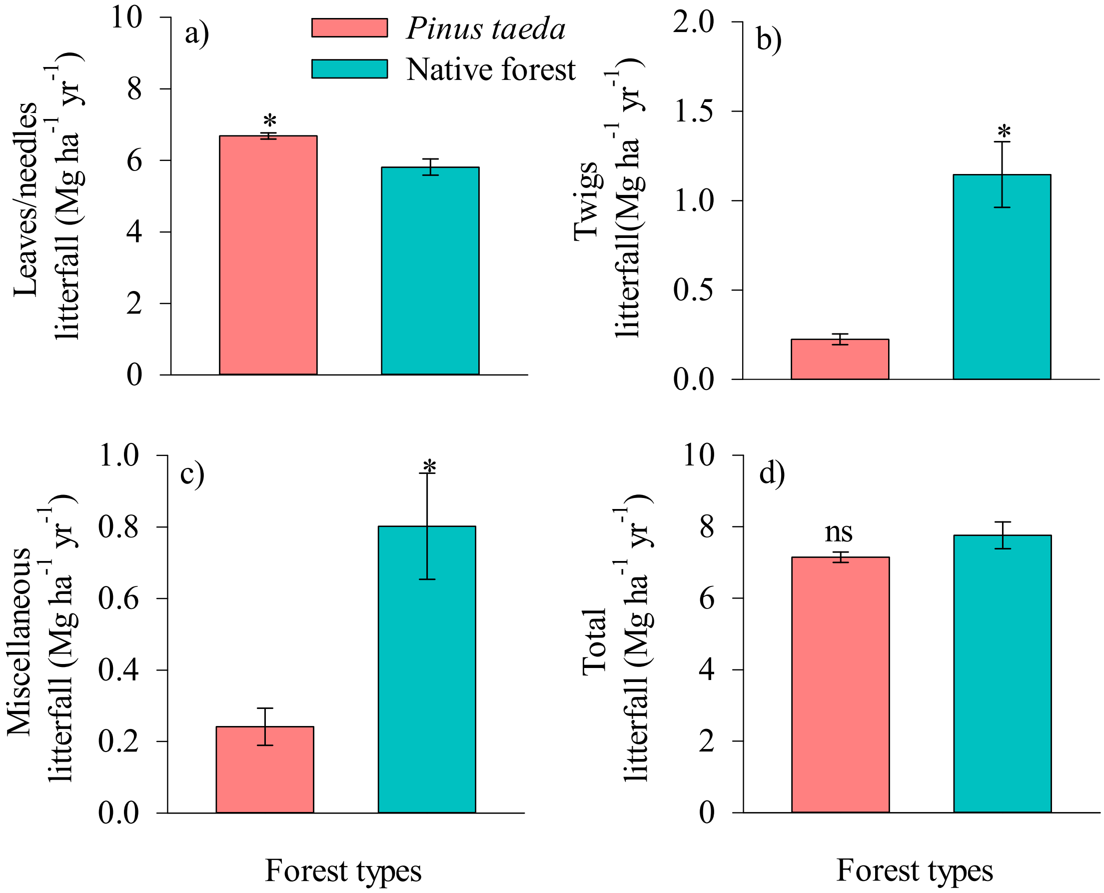


**Figure 4.** Annual litterfall (Mg ha$^{-1}$ yr$^{-1}$) of leaves/needles (**a**), twigs (**b**), miscellaneous (**c**) and total (**d**) of a *Pinus taeda* plantation and native forest in southern Brazil. Plotted values indicate the average. Vertical bars indicate the standard error. Asterisk (*) on top indicates a statistically significant difference by Student's *t*-test ($p < 0.05$).

The annual accumulated N, K and Mg in litterfall in the native forest was 3.5 times greater than that of the *Pinus taeda* plantation (147.19 vs. 50.53 kg ha$^{-1}$ yr$^{-1}$, 51.77 vs. 13.92 kg ha$^{-1}$ yr$^{-1}$ and 35.75 vs. 9.19 kg ha$^{-1}$ yr$^{-1}$, respectively). While the accumulated P and Ca in litterfall in the native forest was 6.9 times greater than that of the *Pinus taeda* plantation (23.40 vs. 3.02 kg ha$^{-1}$ yr$^{-1}$ and 194.63 vs. 31.75 kg ha$^{-1}$ yr$^{-1}$, respectively).

### 3.3. Nutrient Use Efficiency of Litterfall

The N, P, K Ca, and Mg use efficiency of the litterfall was significantly higher in the *Pinus taeda* plantation than in the native forest (Figure 6a–e). In general, the magnitude of nutrient use efficiency was: P > Mg > K > Ca > N. The *Pinus taeda* plantation showed values 2.7 times higher for N use efficiency of litterfall than the native forest (35.37 vs. 13.18 kg kg$^{-1}$) (Figure 6a). The P use efficiency was 7.1 times lower in the native forest than in the *Pinus taeda* plantation (82.91 vs. 591.26 kg kg$^{-1}$) (Figure 6b). The *Pinus taeda* plantation showed 3.5 times greater K and Mg use efficiency, when compared to the native forest (128.35 vs. 37.47 kg kg$^{-1}$ and 194.42 vs. 54.26 kg kg$^{-1}$, respectively) (Figure 6c,e). The Ca use efficiency was 5.6 times higher in the *Pinus taeda* plantation than in the native forest (591.26 vs. 82.91 kg kg$^{-1}$) (Figure 6d).

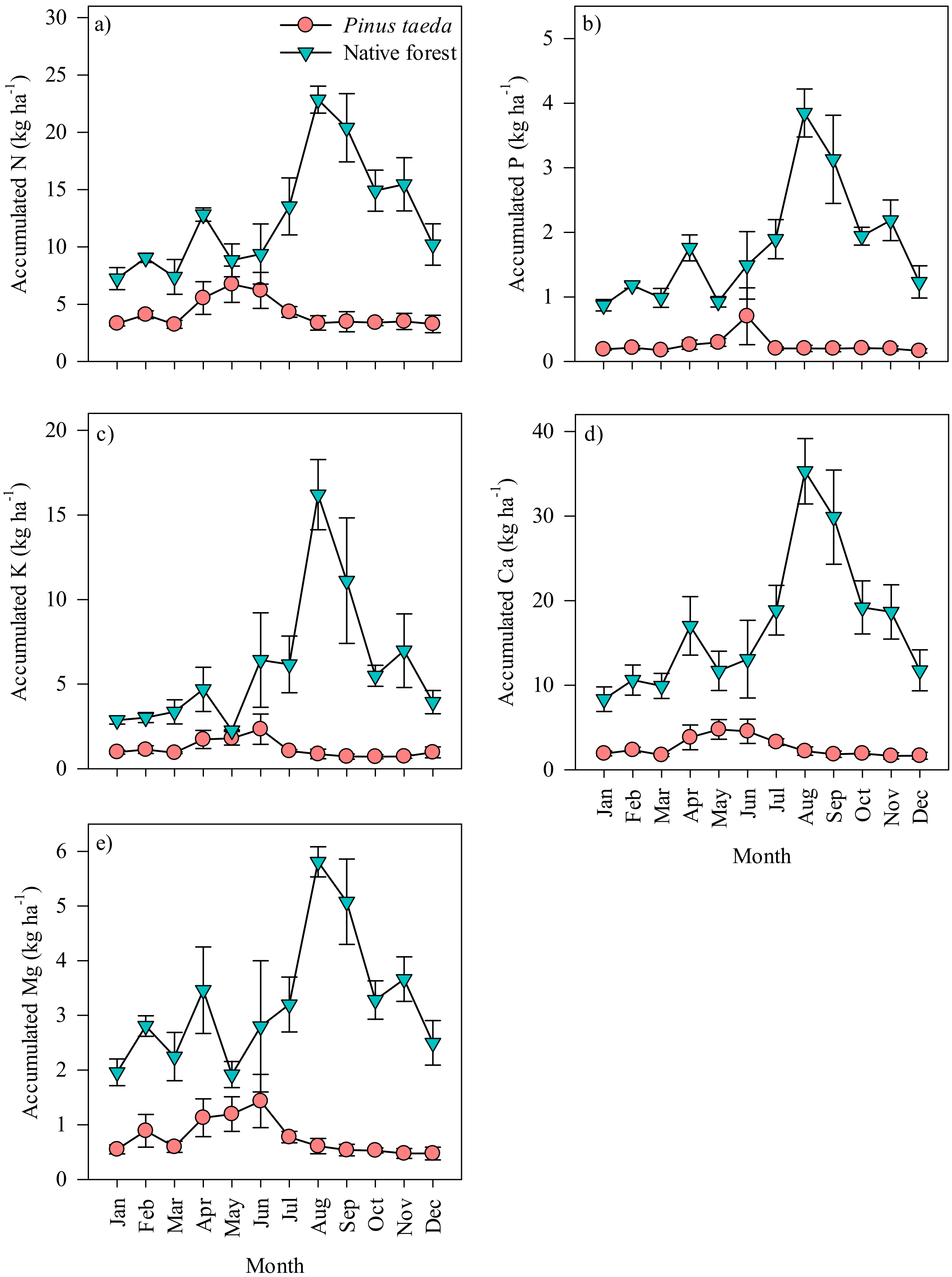


**Figure 5.** Monthly dynamic of accumulated N (**a**), P (**b**), K (**c**), Ca (**d**) and Mg (**e**) in litterfall (kg ha$^{-1}$) of a *Pinus taeda* plantation and native forest in southern Brazil. Plotted values indicate the average. Vertical bars indicate the standard error.

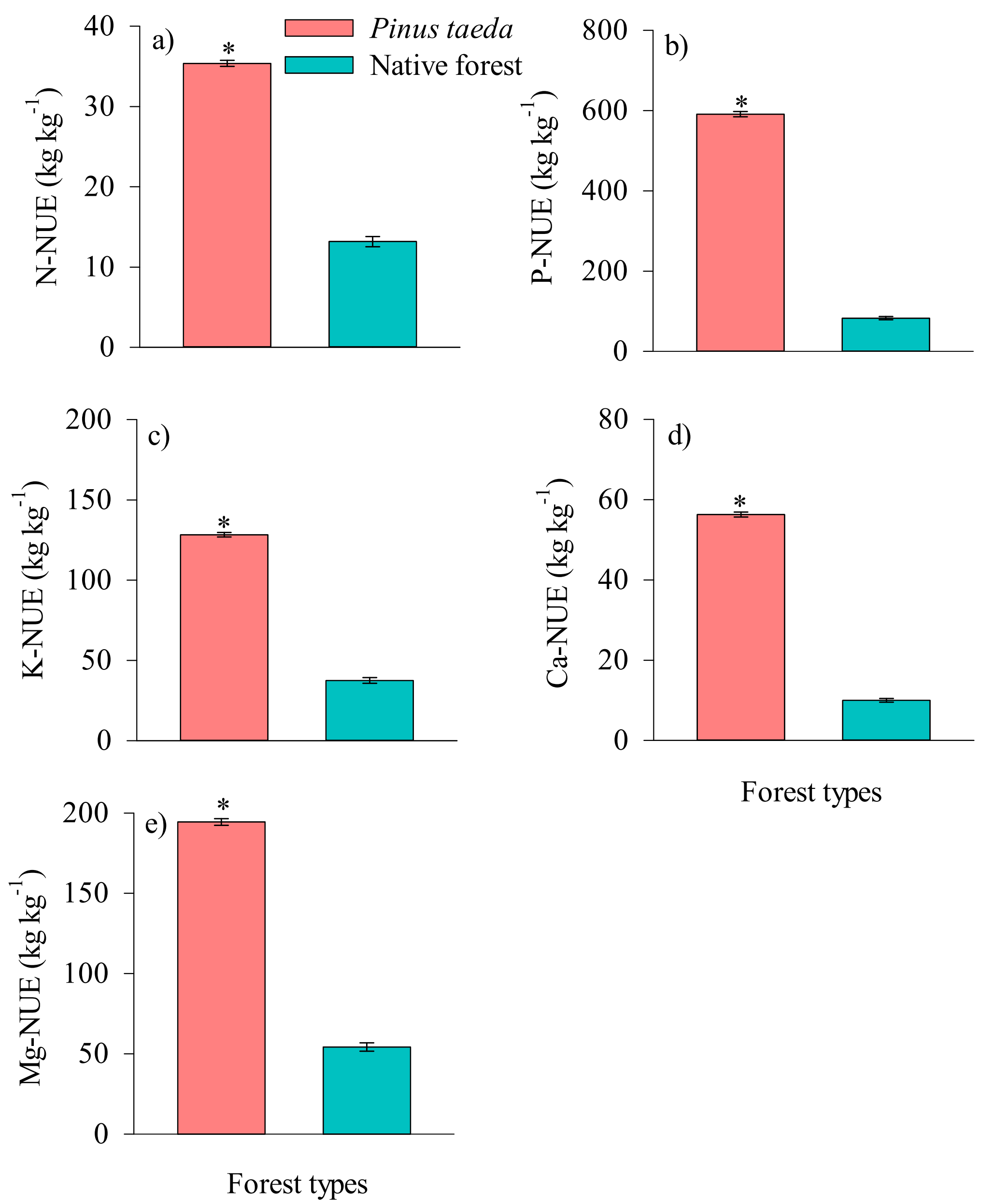


**Figure 6.** Nutrient use efficiency of N (**a**), P (**b**), K (**c**), Ca (**d**), and Mg (**e**) of litterfall in a *Pinus taeda* plantation and native forest in southern Brazil. Plotted values indicate the average. Vertical bars indicate the standard error. Asterisk (*) on top indicate a statistically significant difference by Student's *t*-test ($p < 0.001$).

### 3.4. Principal Component Analysis

Principal component analysis (PCA) was performed by extracting only the first two components. The sum of the components PC1 and PC2 explained 96.56% of the original data variability (Figure 7). Principal component 1 (PC1) explained 88.47% and principal component 2 (PC2) explained 8.09% of data variability. The principal components allowed clear observation of the effect of forest type on litterfall production, accumulated nutrients in litterfall, and nutrient use efficiency. The variables of the *Pinus taeda* plantation were positioned to the left in the spatial distribution and showed a positive relationship between the production of leaves/needles litterfall and N, P, K, Ca, and Mg use efficiency. The behavior of these variables differs in the native forest, which is positioned to the right of the spatial distribution, showing a negative linear relationship between the mentioned parameters. In addition, the native forest showed a positive linear relationship between litterfall production parameters of twigs and miscellaneous and accumulated N, P, K, Ca, and Mg in litterfall. The total litterfall production did not significantly influence the forest type and other response variables.

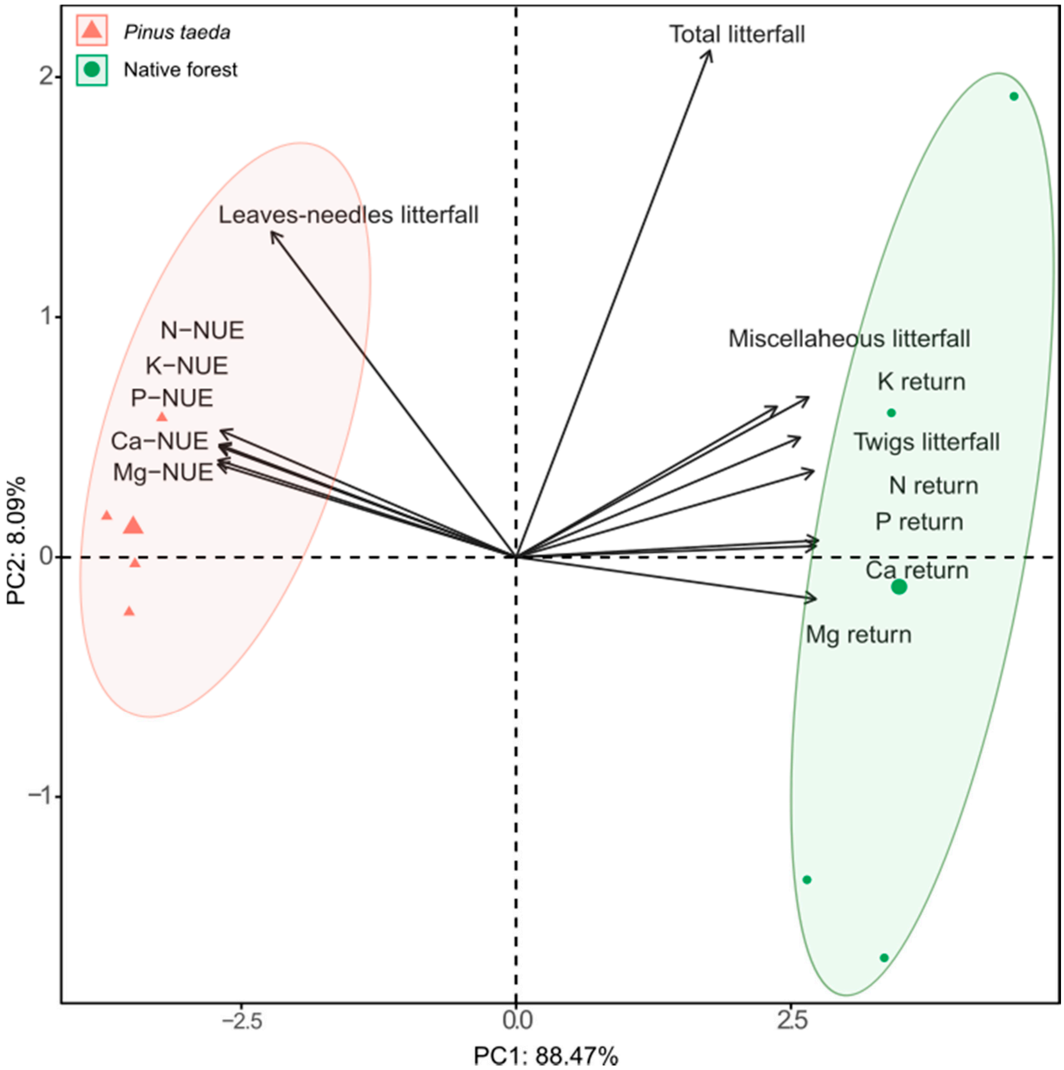


**Figure 7.** Relationship between principal component 1 (PC1) and principal component 2 (PC2) for parameters: leaves/needles, twigs, miscellaneous and total litterfall; accumulated N, P, K, Ca and Mg in litterfall; and nutrient use efficiency (NUE) of N, P, K, Ca and Mg of litterfall of a *Pinus taeda* plantation and native forest in southern Brazil.

## 4. Discussion

### *4.1. Monthly and Annual Dynamics of Litterfall Production*

Litterfall quality and quantity largely affect the nutrient cycle, forest growth, and productivity in forest types [2]. The quantification of litterfall production is, therefore, very important in the choice of species for commercial forest stands, and thus, possible silvicultural practices to be implemented [13]. Our results show that the annual litterfall production of needles in the *Pinus taeda* plantation (6.68 Mg ha$^{-1}$ yr$^{-1}$), was significantly higher than leaves in the native forest (5.81 Mg ha$^{-1}$ yr$^{-1}$). These results are in agreement with previous results from [17], who saw greater litterfall production in coniferous forests than in deciduous broadleaved forests. The high quantity of needles returned from the *Pinus taeda* plantation, compared to the other fractions, may be related to the greater youthfulness of the stand and, thus, allocation of greater amounts of photoassimilates to fractions that exercise atmospheric $CO_2$ assimilation, and photosynthetic rate, such as the needles, could be a mechanism that contributes to the increase in biomass, in particular, of genetically selected plants [33]. In addition, the greater amount of the leaves/needles fraction in the production of litterfall is crucial in accelerating the cycling of nutrients, since this is the fraction of least recalcitrance in litterfall. This is directly related to a lower concentration of difficult-to-degrade materials, such as lignin, which contributes to the formation of labile soil organic matter and, consequently, increasing soil fertility, and promoting greater forest productivity, especially in short rotation planted forests [34,35]. On the other hand, the difference between the annual needles/leaves litterfall production in the forest types may be related to the different tree species composition and/or difference of management practice in the *Pinus taeda* plantation and in the native forest. This result has already been reported, especially on a regional scale, where production and nutritional quality litterfall depend on species composition and forest types [2]. In addition, our results showed that the total annual litterfall production of the *Pinus taeda* plantation (7.15 Mg ha$^{-1}$ yr$^{-1}$) was similar to the native forest (7.76 Mg ha$^{-1}$ yr$^{-1}$). Annual litterfall production values of the *Pinus taeda* plantation found in our study were close to the 4.4, 4.5, and 8.4 Mg ha$^{-1}$ yr$^{-1}$, found in a *Pinus taeda* plantation by [36,37].

Our results show that the dynamics of monthly litterfall production presented seasonality among the forest types. Seasonality of litterfall production, especially the leaves/needles fraction, is highly related to climatic factors, such as temperature drops and precipitation [12,38], as seen in our study. It is worth mentioning that this behavior was immediately pronounced in the *Pinus taeda* plantation, with greater production in June (1112.96 kg ha$^{-1}$), while in the native forest the answer was later, with higher values in August (1233.72 kg ha$^{-1}$). The seasonality of litterfall production shows variation between species and commonly presents higher values in the autumn season, mainly in temperate and cold regions [36,37]. The seasonality of litterfall production can also be related to the physiological characteristics of the species. Perennial conifers, such as *Pinus* spp., differ from deciduous trees, which show leaf fall after the cold season [2], and were verified in our results. In addition, the increase in litterfall production can be a strategy of plants in response to water stress, increasing litterfall, especially of leaves/needles, in order to reduce metabolic activity, in periods of less intense vegetative growth. In this way, nutrients accumulated in the leaves/needles can be mobilized and redistributed to fractions of the shoot, such as the branches and stems, which can assist in biochemical and physiological processes of the plants in the next growing season, such as summer [39].

### *4.2. Monthly and Annual Dynamics of Accumulated Nutrients in Litterfall*

The accumulated nutrients in litterfall represents the major part of nutrient return to the soil, and it shows high variation among different forest species [2]. Our results showed that forest type has a significant effect on the dynamics of accumulated N, P, K, Ca, and Mg in litterfall. In general, higher values of accumulated N, P, K, Ca, and Mg in litterfall were observed in the native forest. Despite the higher litterfall production found in the *Pinus taeda* plantation, especially of needles and in total, the greatest accumulated nutrients in litterfall were verified in the leaves in the native forest (Table S1), due to the higher concentrations of nutrients present in litterfall of this forest type (Table S2). Another study [40] found similar results, where *Pinus caribaea* showed less accumulated nutrients in litterfall than exotic and native tropical species, which indicates that *Pinus* spp. has a high potential for nutrient remobilization between plant fractions and/or less absorption of nutrients from the soil [38]. In this study, the annual accumulated nutrient in litterfall in a *Pinus taeda* plantation had the following order: N > Ca > K > Mg > P, which is consistent with the literature [36,37]. The annual accumulated N, P, K, and Mg in litterfall of *Pinus taeda* was greater than the *Pinus taeda* plantation (20.84 kg ha$^{-1}$ yr$^{-1}$ for N, 2.72 kg ha$^{-1}$ yr$^{-1}$ for P, 7.89 kg ha$^{-1}$ yr$^{-1}$ for K, 29.57 kg ha$^{-1}$ yr$^{-1}$ for Ca and 6.38 kg ha$^{-1}$ yr$^{-1}$ for Mg), *Eucalyptus viminalis* (25.43 kg ha$^{-1}$ yr$^{-1}$ for N, 1.12 kg ha$^{-1}$ yr$^{-1}$ for P, 9.76 kg ha$^{-1}$ yr$^{-1}$ for K and 3.83 kg ha$^{-1}$ yr$^{-1}$ for Mg) [36], but smaller than plantations of *Castanopsis kawakamii* (70 kg ha$^{-1}$ yr$^{-1}$ for N, 5.5 kg ha$^{-1}$ yr$^{-1}$ for P and 49 kg ha$^{-1}$ yr$^{-1}$ for K) [20]. These results show that *Pinus taeda* plantations have high adaptability in soils with low natural fertility and acids, as in the present study. However, ensuring productivity in subsequent rotations is one of the central principles of long-term sustainability in commercial plantations. A strategy for this might be soil nutrient management, such as maintaining litterfall in planted forests, which can help make decisions about forestry practices, such as plantations fertilization [11]. In addition, the accumulated N, P, K, and Mg in litterfall by the *Pinus taeda* were largely greater than conifer plantations, such as *Pinus taeda* and *Castanopsis kawakamii* and, broad leafed trees, such as *Eucalyptus viminalis* [20,36], which shows a possible strategy for using plant nutrients to adapt to low natural fertility soils [2].

Our results show that forest types have seasonality in the dynamics of accumulated N, P, K, Ca, and Mg in litterfall. The peaks of accumulated N, P, K, Ca, and Mg in litterfall in the native forest in August, September, and October represented 38.2, 41.6, 45.3, 41.3, and 36.6%, respectively, of the total annual return. Meanwhile, the peaks of accumulated N, P, K, Ca, and Mg in litterfall of the *Pinus taeda* plantation in April, May, and June represented 36.6, 41.6, 42.0, 41.5, and 40.9%, respectively, of the total annual accumulated nutrients. Therefore, our results show that the accumulated nutrients in litterfall depends directly on the drop in temperature and precipitation. However, the effect of these factors occurred immediately in the *Pinus taeda* plantation and subsequently in the native forest. This suggests that *Pinus taeda* plantations are more vulnerable to changes in temperature and precipitation [12,38]. Thus, a better understanding of biogeochemical phenomena, such as the production and accumulated nutrients in litterfall, are needed to appropriately manage the soil, forest, and mitigate climate change [41].

### 4.3. Nutrient Use Efficiency of Litterfall

Our results show that the N, P, K Ca, and Mg use efficiency of litterfall was significantly affected by forest type. In general, the magnitude of the nutrient use efficiency (NUE) of the forest types in our study was P > Mg > K > Ca > N. This order is consistent with the results reported in a study with *Pinus pseudostrobus* and *Quercus* spp. [16]. Our study showed that *Pinus taeda* plantations have higher N, P, K Ca, and Mg use efficiency of litterfall than in the native forest. The higher NUE of the *Pinus taeda* plantations may be related to the greater development of dry matter of litterfall fractions, especially of leaves and in total. As a result, the *Pinus taeda* plantation may have directed higher amounts of carbohydrates and amino acids for the production of new tissues, such as leaves [33]. In addition, genetically selected plants can develop strategies for biomass production, such as decreasing the allocation of nutrients with structural cellular functions and increasing the availability of nutrients for the production of energy molecules, such as ATP and NADPH, which results in greater amounts of proteins and synthesized amino acids [42]. In addition, the higher NUE values observed by the *Pinus taeda* plantation can be attributed to the affinity of the transporters present in the plant's root membrane, which are directly related to the absorption and transport capacity of nutrients inside the plant through cell membranes, a process known as internal nutrient remobilization, which increases the plant's NUE [43].

### 4.4. Principal Component Analysis

The principal component analysis (PCA) allowed two groups to be separated according to the behavior of the forest types, and their relationship with the production, accumulated nutrients in litterfall, and nutrient use efficiency of litterfall. The first cluster of the PCA was influenced by the *Pinus taeda* plantation, positioned to the left in the spatial distribution and demonstrated a positive linear relationship with the variable responses of production of leaves/needles litterfall and N, P, K, Ca, and Mg use efficiency, showing that *Pinus taeda* plantations have high biomass production of fractions with greater intensity of cell division, such as needles, which may favor the entry of these nutrients into the soil via decomposition of the fractions [44]. Another group was influenced by the native forest, which presented a positive relationship with the variables of production of twigs and miscellaneous and accumulated N, P, K, Ca, and Mg in litterfall. Our results show that the diversity of species of the native forest provided greater litterfall production of the twigs and miscellaneous fractions, and this is related to the diversity and greater quantity of flowers, fruits, and seeds produced by different species, with varied phenological stages, which is commonly found in native forests. It is worth mentioning that the total litterfall production did not significantly influence the forest type and the other variables. This shows that litterfall fractionation is essential to understanding the production, chemical composition, and accumulated nutrients in litterfall and, thus, assists in gains in productivity in forest types [2].

## 5. Conclusions

Our results support the hypothesis that the dynamics of litterfall production may vary in forest types. The native forest had the highest accumulated N, P, K, Ca, and Mg in the soil due to litterfall deposition. However, *Pinus taeda* plantations had greater N, P, K Ca, and Mg use efficiency of litterfall than the native forest. Litterfall of leaves/needles constituted the highest percentage among fractions and had a positive relationship with litterfall production, which may indicate that litterfall fractionation is important for understanding nutrient cycling and tree growth. In addition, our results show a possible relationship between climatic factors, such as low temperatures and precipitation, and litterfall production. The effects of these climatic factors act immediately in *Pinus taeda*, which suggests that the productivity of *Pinus taeda* plantations is more vulnerable to changes in temperature and precipitation. However, new studies on the possible effects of drastic changes in climatic factors and their interference in the dynamics of litterfall production in forest types must be carried out.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/xxx/s1, Table S1: Monthly dynamic of nutrients return to soil (kg ha$^{-1}$) of *Pinus taeda* plantation and native forest in Southern Brazil. Table S2: Monthly dynamic of nutrient concentration (g kg$^{-1}$) in litterfall fractions of *Pinus taeda* plantation and native forest in Southern Brazil.

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