

# Estimation of the Impact of *Teratosphaeria nubilosa* on Wood Production from Commercial Plantations of *Eucalyptus globulus* (L.)

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## Abstract

The arrival of *Teratosphaeria nubilosa* drastically impacted the production of *Eucalyptus globulus* Labill in Uruguay. However, information regarding growth losses is scarce. The objective of this work was to quantify the effect of the disease on the productivity of *E. globulus* plantations through modeling and simulation of growth with different levels of disease. For this, diameter at breast height (DBH) and total height were measured in 7 year-old plantations and individual volume was calculated. This information was used to adjust linear and non-linear mixed models that would allow estimating DBH average, total height average of the stand and volume per hectare, relating growth parameters with the Crown Damage Index (CDI) at 6, 12 and 24 months old. The results indicated a significant negative relationship of CDI<sub>12</sub> ( $P < 0.05$ ) with DBH and volume (predictor variables). The estimated growth at 7 years by modeling with CDI = 0 (without crown damage) was higher than the observed growth (14.5 vs. 13.1 cm for DBH and 116.5 vs. 93.7 m<sup>3</sup>/ha for volume, respectively). The intensity of *Teratosphaeria* Leaf Disease (TLD) and the relative wood volume loss caused by the disease damage did not vary with site quality. This reinforces previous results showing that site selection does not significantly contribute as alternative management to mitigate the impact of the disease. This work allowed an estimation of the negative effect of TLD on *E. globulus* in Uruguay.

**Keywords:** leaf pathogen, *Eucalyptus*, volume reduction, crown damage index

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## Estimación del impacto de *Teratosphaeria nubilosa* sobre la producción de madera de plantaciones comerciales de *Eucalyptus globulus* (L.)

### Resumen

La llegada de *Teratosphaeria nubilosa* impactó drásticamente en la producción de *Eucalyptus globulus* Labill en Uruguay; sin embargo, la información sobre pérdidas de crecimiento es escasa. El objetivo del trabajo fue cuantificar el efecto de la enfermedad en la productividad de plantaciones de *E. globulus* mediante modelación y simulación de crecimiento con diferentes niveles de enfermedad. Se midió diámetro a la altura del pecho (DAP) y la altura total en plantaciones de 7 años y se calculó volumen individual. Esta información se utilizó para ajustar modelos mixtos lineales y no lineales que permitieran estimar DAP promedio, altura total promedio del rodal y volumen por hectárea, relacionando los parámetros de crecimiento con el Índice de Daño de Copa (IDC) a los 6, 12 y 24 meses de edad. Los resultados indicaron una relación significativa negativa de IDC12 ( $P < 0,05$ ) con DAP y volumen (variables predictoras). El crecimiento estimado a los 7 años mediante modelación con IDC = 0 (sin daño de copa) fue mayor que el crecimiento observado (14,5 vs. 13,1 cm para DAP y 116,5 vs. 93,7 m<sup>3</sup>/ha para volumen, respectivamente). La intensidad de enfermedad de las hojas causada por *Teratosphaeria* (TLD) y la pérdida relativa de volumen de madera causada por el daño de la enfermedad no variaron con la calidad del sitio. Esto refuerza resultados previos que muestran que la selección del sitio no contribuye significativamente como manejo alternativo para mitigar el impacto de la enfermedad. Este trabajo permitió una estimación del efecto negativo de TLD sobre *E. globulus* en Uruguay.

**Palabras clave:** patógeno foliar, *Eucalyptus*, reducción del volumen, índice de daño de la copa

## Estimação do impacto de *Teratosphaeria nubilosa* na produção de madeira de plantações comerciais de *Eucalyptus globulus* (L.)

### Resumo

A chegada do *Teratosphaeria nubilosa* impactou drasticamente a produção de *Eucalyptus globulus* Labill no Uruguai, porém as informações sobre perdas de crescimento são escassas. O objetivo do trabalho foi quantificar o efeito da doença na produtividade das plantações de *E. globulus* através de modelagem e simulação de crescimento com diferentes níveis de doença. O diâmetro à altura do peito (DAP) e a altura total foram medidos em plantios com 7 anos de idade e o volume individual foi calculado. Essas informações foram utilizadas para ajustar modelos mistos lineares e não lineares que permitiram estimar o DAP médio, a altura total média do povoamento e o volume por hectare, relacionando os parâmetros de crescimento ao Índice de Dano à Coroa (IDC) aos 6, 12 e 24 meses de idade. Os resultados indicaram relação negativa significativa do IDC12 ( $P < 0,05$ ) com DAP e volume (variáveis predictoras). O crescimento estimado aos 7 anos através da modelagem com IDC = 0 (sem danos à copa) foi maior que o crescimento observado (14,5 vs. 13,1 cm para DAP e 116,5 vs. 93,7 m<sup>3</sup>/ha para volume, respectivamente). A intensidade da doença foliar causada por *Teratosphaeria*, TLD e a perda relativa de volume de madeira causada por danos causados por doenças não variaram com a qualidade do local. Isto reforça resultados anteriores que mostram que a seleção do local não contribui significativamente como uma alternativa de gestão para mitigar o impacto da doença. Este trabalho permitiu estimar o efeito negativo do TLD sobre *E. globulus* no Uruguai.

**Palavras-chave:** patógeno foliar, *Eucalyptus*, redução de volume, índice de danos na coroa

## 1. Introduction

*Eucalyptus globulus* Labill. (Myrtaceae) is one of the preferred species in the world for the production of cellulose pulp (Jackson, 2013). For this reason, it was widely planted in Uruguay, being the predominant species by 2011 and occupying more than 300,000 ha (Oficina de Estadísticas Agropecuarias [DIEA], 2011).

In 2007, the disease called *Teratosphaeria* Leaf Disease (TLD), caused by the fungus *Teratosphaeria nubilosa*, was reported for the first time in Uruguay, observed on the western region of the country in *E. globulus*

plantations (Pérez et al., 2009). Initially, the pathogen produces necrotic spots on juvenile leaves, and later, premature defoliation (Old et al., 2003; Smith et al., 2017). In cases of very severe infections, distortions in stems and branches, death of apical shoots and even death of trees have been observed (Carnegie & Ades, 2002; Jackson, 2013; Smith et al., 2017, 2018).

The results of disease surveys carried out in young plantations of *E. globulus* (less than 2 years old) in Uruguay indicated that TLD was the predominant disease (Balmelli, Simeto, Martínez, et al., 2011; Balmelli, Simeto, Martínez, Torres, González, et al., 2009; Balmelli, Simeto, Martínez, Torres, Pérez, et al., 2009; Pérez et al., 2013; Simeto et al., 2010). Similarly, Maxwell (2004) mentions that TLD is the most frequent and serious disease in 1 and 2-year-old *E. globulus* in southwestern Australia.

Regarding damage, Carnegie & Ades (2003) reported that 10% of foliar damage is sufficient to cause growth loss in *E. globulus*. Other authors (Lundquist & Purnell, 1987) indicate that the growth rate was negatively correlated with the severity of the disease (foliar damage), but this is not affected until defoliation of 25% of the crown is reached.

Balmelli, Simeto, Martínez, Torres, Pérez, et al. (2009) quantified an average crown damage (foliar damage + defoliation) of 35.9% in young plantations (less than 2 years old) of *E. globulus* in Uruguay. In turn, Alonso et al. (2013) and Morales Olmos et al. (2018) emphasized that the severe damage of this disease on young plantations of *E. globulus* poses a question about the convenience of continuing using this species in the country. Currently, the effective area forested with *E. globulus* is less than 103,639 ha (DIEA, 2020; Dirección General Forestal, 2021).

In order to reduce the effects of TLD on eucalypts, different management practices have been proposed, such as increasing the vigor and tolerance of trees through silvicultural management (Carnegie, 2007; Mohammed et al., 2003), the application of activators of plant defenses (Mohammed et al., 2003), the choice of site (avoiding planting in sites with high risk of infection) (Mohammed et al., 2003), the application of fungicides (Alonso et al., 2013) and refertilization (Carnegie & Ades, 2001). However, these alternatives present economic, environmental and operational limitations, making them inefficient for the control of *T. nubilosa* at commercial scale plantations. According to several authors, the most effective way to reduce the damage of this disease is based on the use of genetic resistance (Alfenas et al., 2004; Balmelli et al., 2014; Carnegie et al., 1994; Hunter et al., 2009; Milgate et al., 2005; Simeto et al., 2020).

Currently, most of the studies that estimate the effect of the damage caused by the disease on growth have been carried out during early stages of the plantations (Balmelli et al., 2014; Balmelli, Simeto, Altier, et al., 2011). Therefore, there is little or no information about the impact of TLD on wood production at rotation age for the conditions of Uruguay. The severe crown damage observed in young *E. globulus* plantations (Balmelli, Simeto, Martínez, et al., 2011) and the wide distribution of this disease in Uruguay demonstrate the need to understand the long term effect of TLD on the wood production of this species.

In the search for information of national wood production previous to the first reports of TLD for reference and comparison, it is noticeable that information is very variable. This is explained, in part, because most of the information collected for the southeast region (CIDE 2 zone: soils 2.11A, 2.11B, 2.12 and 2.14) (Dirección General de Recursos Naturales Renovables, 2020) corresponds to provenance trials. Therefore, marked differences in growth (15 to 33.1 m<sup>3</sup>.ha<sup>-1</sup>.year<sup>-1</sup> mean annual increment – MAI) are reported, but masked by genetic background, not only by the performance against the disease (Balmelli, 2002; Giambruno & López, 2010; Methol, 2006; Resquin et al., 2012).

The aim of this study was to estimate the impact of TLD epidemics on wood productivity close to rotation age in commercial plantations of *E. globulus* in Uruguay. Given the difficulty of establishing the baseline, meaning the productivity of *E. globulus* prior to the entry of *T. nubilosa*, a strategy of growth modeling was chosen to compare wood production of *E. globulus* with and without TLD crown damage. For that purpose, i) a model to estimate diameter at breast height (DBH), total height (H) and volume per hectare (VOL) that includes the level of damage as a predictor was adjusted, and ii) the developed model was used to quantify the reduction in productivity caused by the disease, by comparing a scenario with observed damage with a zero-damage scenario predicted through the model.

## 2. Materials and Methods

### 2.1 Study Area and Data Collection to Determine Growth at 7 Years

A total of 66 circular plots in 7-year-old plantations located in the departments of Rocha, Lavalleja and Florida (southeast of Uruguay) were evaluated. In each plot (10 m radius) the diameter at breast height (cm) and total height (m) of all the trees were recorded. The measurements were made at the same points georeferenced by Balmelli, Simeto, Martínez, Torres, Pérez, et al. (2009). These authors assessed crown damage at 6, 12 and 24 months old (Balmelli, Simeto, Martínez, Torres, González, et al., 2009; Balmelli, Simeto, Martínez, Torres, Pérez, et al., 2009; Simeto et al., 2010). Therefore, growth at age 7 could be associated to crown damage by TLD at early stages.

### 2.2 Calculation of Variables

For each plot measured at 7 years of age, the basal area (G, calculated as the sum of the cross-sectional area of all trees at DBH level), the mean dominant height ( $h_{dom}$ ) and the density (number of trees per hectare, N) were calculated. Dominant height was calculated as mean height of the 100 trees with larger DBH of the hectare. This variable is relevant to represent the variability of site productivity among plots.

Total volume per hectare (VOL) was calculated by adding all the individual volumes of each plot estimated through Moras and Vallejos-Barra (2013) equation Eq. 1 and expanding plot volume to the hectare.

$$\ln(vt) = -9.75 + 0.93 * \ln(DBH^2 * H) \quad \text{Eq. 1}$$

Where:  $\ln(vt)$  is natural logarithm of total volume, DBH: diameter at breast height, H: total height.

Several variables associated with damage were assessed: the crown damage index (CDI) at ages 6, 12 and 24 months (CDI6, CDI12, CDI24) and the area under the disease progression curve (AUDPC). The crown damage index (CDI), adapted from Stone et al. (2003), was estimated based on the incidence and severity of leaf spots and defoliation (percentage of fallen leaves) taking values from 0 to 100 (Eq. 2).

$$CDI = \text{Defoliation} + ((1 - \text{Defoliation}/100) * (\text{Incidence} * \text{Severity})/100) \quad \text{Eq. 2}$$

Where: defoliation is the percentage of missing leaves, incidence is the estimated percentage of the leaves in the crown affected by TLD, and severity is the average percentage of damage (necrosis) of the affected leaves.

The AUDPC was calculated from the estimated CDI recorded at different times of the epidemic ages 6, 12 and 24 months, integrating the crown damage over time (Madden et al., 2007).

To consider the different tree genetic materials among the studied plantations, genetics was assessed as a categorical variable. As the data with respect to the genetic material were unbalanced (seven of seminal origin and six of clonal origin), a type III analysis of variance for volume was previously carried out (see ANOVA result in [Table S1](#)). The purpose of this analysis was to classify those genetic materials in terms of volume and, thus, to reduce the number of categories and develop a simple model to estimate wood production. Means were separated using the Duncan test if ANOVA results showed significant differences. Subsequently, the genotypes ( $G_0$ ) were grouped by volumetric performance (based on the order established in the Duncan test), taking two levels: high and low productivity.

### 2.3 Modeling DBH, H and VOL

Linear mixed models were applied for developing DBH and H equations, and non-linear mixed models were used for developing the equation of total volume per hectare (VOL). Mixed models estimate both the expected values of the observations, called fixed effects, and the variances and covariances of the observations (random effects), and allow the analysis of longitudinal data as correlated, incomplete, and with non-constant intervals between observations ([Arnaú & Bono, 2008](#); [Bandera-Fernández & Pérez-Pelea, 2018](#)). These models are characterized by using a combination of fixed effects, common to the entire population, and random effects specific to each sampling unit ([Calama Sainz & Montero González, 2004](#); [Crawley, 2012](#); [Hernández & Usuga, 2021](#); [Morás Loyarte, 2010](#); [Teetor, 2011](#)). For the present study, random effects were associated with the forest farm, assuming that the stands within farms share growing conditions that are more similar to each other. The assumptions of the mixed effects model were subsequently tested.

Given the general expression shown in [Eq. 3](#) for modeling DBH and H, the backward method was applied to test the inclusion of stand ( $G$ ,  $N$ ,  $h_{dom}$ ), disease (AUDPC, CDI6, CDI12, CDI24) and genetic ( $G_0$ ) variables using R statistical software (R Core Team, v.4.22) ([R Core Team, 2022](#)) and R package lmerTest (version 2.0-36) ([Kuznetsova et al., 2017](#)). This methodology eliminates at each stage the variable with a non-significant effect:

$$Y_{ij} = (\beta_0 + u_{0j}) + (\beta_1 + u_{1j})X_{1ij} + \dots + (\beta_n + u_{nj})X_{nij} + \varepsilon_{ij} \quad \text{Eq. 3}$$

Where:  $Y_{ij}$  is the dependent variable (observed DBH or H) of the  $i$ th plot within the  $j$ th forest farm;  $\beta_0$ ,  $\beta_1$  and  $\beta_n$  are parameters;  $u_{0j}$ ,  $u_{1j}$  and  $u_{nj}$  are random effects associated with the forest farm;  $X_{1ij}$  to  $X_{nij}$  are the independent variables tested (stand, disease and genetic variables) observed within the  $i$ th-plot and  $j$ th-forest farm;  $\varepsilon_{ij}$  is the error associated with the model.

For developing the equation of VOL, the exponential model adjusted by Methol ([2003, 2006, 2008](#)) and Rachid & Hirigoyen ([2015](#)), also used by Hirigoyen et al. ([2018](#)), was used as a basis. Given the expression shown in [Eq. 4](#), all dasometric ( $G$ ,  $h_{dom}$  and  $N$ ), disease (AUDPC, CDI6, CDI12, CDI24) and genetic variables were tested using stepwise methodology with R package MASS (version 7.3-58.3) ([Venables & Ripley, 2002](#)) and stepAIC algorithm ([Sakamoto et al., 1986](#)), including only the significant ones. The exponential equations for the total volume were developed with R package nlme (version 3.1-151) ([Lindstrom & Bates, 1990](#)) considering the following expression:

$$VOL_{ij} = e^{[(\beta_0 + u_{0j}) + (\beta_1 + u_{1j})X_{1ij} + \dots + (\beta_n + u_{nj})X_{nij}]} + \varepsilon_{ij} \quad \text{Eq. 4}$$

Where:  $VOL_{ij}$  is the observed volume per hectare of the  $i$ th-plot within the  $j$ th- forest farm;  $\beta_0$ ,  $\beta_1$  and  $\beta_n$  are parameters;  $u_{0j}$ ,  $u_{1j}$  and  $u_{nj}$  are random effects associated with the forest farm;  $X_{1ij}$  to  $X_{nij}$  are the independent variables tested observed within the  $i$ th-plot and  $j$ th-forest farm (stand, disease and genetic variables);  $\varepsilon_{ij}$  is the error associated with the model.

During the adjustment of the equations, the following was confirmed:

1. Absence of multicollinearity. To quantify the intensity of multicollinearity, the variance inflation factor (VIF) was used.
2. Normality of residuals observable in histogram and Q-Q plots. This analysis assumes that the residuals are normally distributed with an expected value equal to zero, constant variance, and no correlation.
3. Graphical analysis of residuals to verify homoscedasticity (equal variance between residuals) and absence of bias in the estimation, on the basis that without homoscedasticity the estimators are not efficient.
4. Detection of outliers using Bonferroni test.

To test that the chosen equations have reliable estimates the following statistics of fit were analyzed:

- Root mean square error (RMSE), which assesses the precision of the estimates and is an absolute measure of fit (Newnham, 1992). Lower RMSE values indicate a better fit.
- Determination coefficient ( $R^2$ ).
- Mean residual, used as a measure of bias.

Other indicators used to assess the goodness of fit of the model were: the Willmott index (d) and the percentage of the standard error of estimation ( $Syx\%$ ). The d index estimates the precision of a model based on the relationship between the estimated and observed values (Willmott, 1981, 1982). The  $Syx\%$  indicates the disparity or dispersion between the values observed and those estimated by the regression, with the lowest value being desirable.

For the statistical procedure R packages *ie2misc* (version 0.9.1), (*dr* algorithm) (Willmott et al., 2012) and *Metrics* (version 0.1.4) (Hamner et al., 2022) were used.

## 2.4 Comparing Growth With and Without Crown Damage

To estimate stand growth (DBH, H and VOL) in the absence of disease and to compare it with the growth observed on trees with different levels of crown damage, the growth was estimated by assuming a CDI equal to zero. The analysis compared both, crown damage (CDI) and growth losses considering different site classes, defined by  $h_{dom}$  quartiles. To calculate the quartiles, the  $h_{dom}$  values were ordered from lowest to highest and then each quartile number (1, 2, 3 or 4) was multiplied by the total number of trees and divided by 4. This resulted in 4 quartiles (Q1, Q2, Q3 and Q4) based on the mean dominant height ( $h_{dom}$ ), where Q1 corresponds to the sites with the lowest  $h_{dom}$  (worst sites) and Q4 to the sites with the highest  $h_{dom}$  (best sites). This analysis allowed to identify any relationship between the effect of damage and site quality (represented by the  $h_{dom}$  quartiles).

Subsequently, losses in cubic meters of wood and percentage of total wood production of Q1 vs Q4 were compared through the non-parametric Mann-Whitney test (R Core Team).

## 3. Results

### 3.1 Statistical Characterization of the Explanatory Variables

The results show a great dispersion of data for the variables density (N, trees per hectare) and area under the disease progression curve (AUDPC). When analyzing the crown damage index at 6, 12 and 24 months (CDI6,

CDI12 and CDI24, respectively), although standard deviations are similar, the coefficient of variation (CV%) is greater for the first disease records (CDI6), explained by the wide range of values observed, compared to CDI12 and CDI24 (Table 1).

**Table 1.** Descriptive statistics of the variables used in modeling

	Minimum	Mean	Maximum	Standard deviation	CV%
N (trees.ha <sup>-1</sup> )	509	935	1273	188.7	20
H (m)	9.65	13.82	20.03	2.5	18
h <sub>dom</sub> (m)	11.45	17.15	25.27	2.7	15
DBH (cm)	11.79	14.45	19.51	1.6	11
G (m <sup>2</sup> .ha <sup>-1</sup> )	8.66	15.30	23.91	3.4	22
CDI 6 (%)	1.2	11.70	63.08	12.2	103
CDI 12 (%)	16.58	44.62	74.05	13.8	30
CDI 24 (%)	29.2	75.05	92.2	10.5	13.8
AUDPC	618.6	931.6	1483	190.5	20
VOL (m <sup>3</sup> .ha <sup>-1</sup> )	14.95	93.64	191.14	37.41	39

Where: N: number of trees per hectare, H: height, h<sub>dom</sub>: mean dominant height, DBH: diameter at breast height, G: basal area, CDI: crown damage index at ages 6, 12 and 24 months (CDI6, CDI12, CDI24), AUDPC: disease progression curve, VOL: volume per hectare.

### 3.2 Modeling DBH, H and VOL

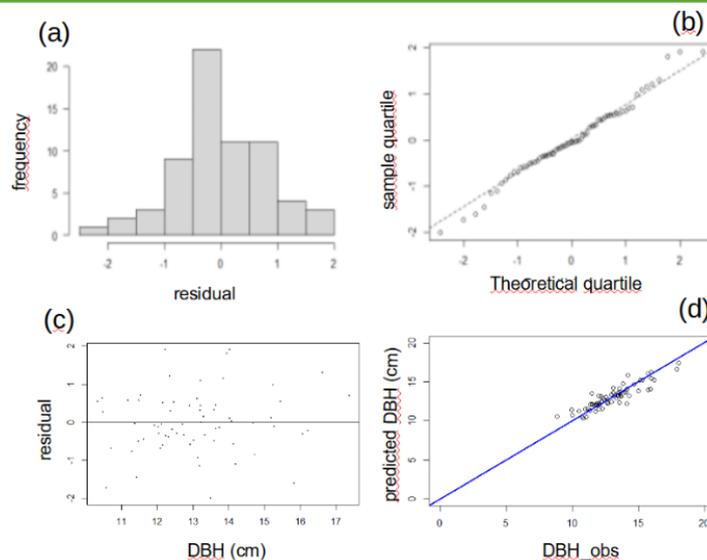
The variance inflation factor (VIF) calculated during DBH adjustment showed multicollinearity of AUDPC with other variables (VIF > 10), so this variable was eliminated from the analysis. The model summary results showed that of all three remaining damage variables assessed (CDI6, CDI12, CDI24), only CDI12 was statistically significant ( $p = 0.017$ ), indicating that the damage evaluated at the age of 12 months is related to growth in DBH at seven years. When comparing the statistical results and the performance of the equation, the inclusion of the variable that represents the genetic factor ( $G_0$ ) improved the fit ( $R^2 = 0.76$ ) compared to the equation that did not include the genetics as a variable ( $R^2 = 0.71$ ).

The equation selected to estimate DBH was the following:

$$DBH = (\beta_0 + b_0) + \beta_1 h_{dom} + \beta_2 CDI12 + \beta_3 N + \beta_4 G_0 \quad \text{Eq. 5}$$

Where:  $\beta_0$ : intercept,  $b_0$ : random effect associated with the intercept,  $\beta_1$  to  $\beta_4$ : parameters of each variable,  $h_{dom}$ : mean dominant height (m), CDI12: crown damage index observed at 12 months, N: number of trees per hectare,  $G_0$ : genetic categorization.

The visual analysis of residual plots demonstrates that the model meets the assumptions of normality and homoscedasticity of residuals (Figures 1a-c). Additionally, the relationship between predicted DBH values and observed DBH values indicates a good fit ( $R^2 = 0.75$ ) (Figure 1d).



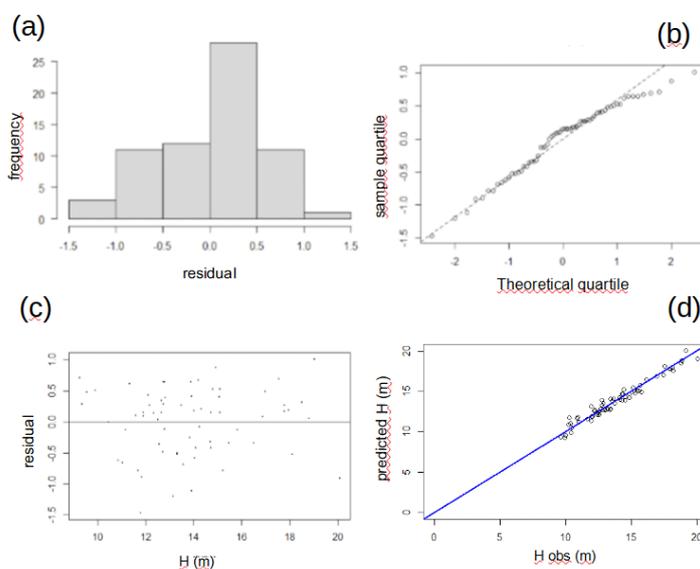
**Figure 1.** Histogram plots (a), Q-Q plot (b), distribution of residuals as a function of predicted DBH (c), predicted vs. observed DBH for the selected DBH equation (d)

For modeling H none of the variables quantifying crown damage were statistically significant (CDI6  $p = 0.74$ , CDI12  $p = 0.87$ , CDI24  $p = 0.24$ , AUDPC  $p = 0.53$ ). The inclusion of genetics also showed no effect on the fit of the equation, so it was not included ( $p = 0.79$ ). The equation to estimate H was the following:

$$H = \beta_0 + b_0 + \beta_1 \text{DBH} + \beta_2 h_{\text{dom}} + \beta_3 N \quad \text{Eq. 6}$$

Where: DBH: average diameter at breast height of the plot (cm),  $h_{\text{dom}}$ : mean dominant height (m), N: number of trees per hectare,  $\beta_0$ : intercept,  $\beta_1$  to  $\beta_3$ : parameters of each variable,  $b_0$ : random effect associated with the intercept.

The visual analysis of residual plots demonstrates that the model selected for H meets the assumptions of normality and homoscedasticity (Figures 2a-c). Furthermore, a good fit for the observed data was obtained ( $R^2 = 0.94$ ), evidenced by the relationship between predicted and observed H values (Figure 2d).



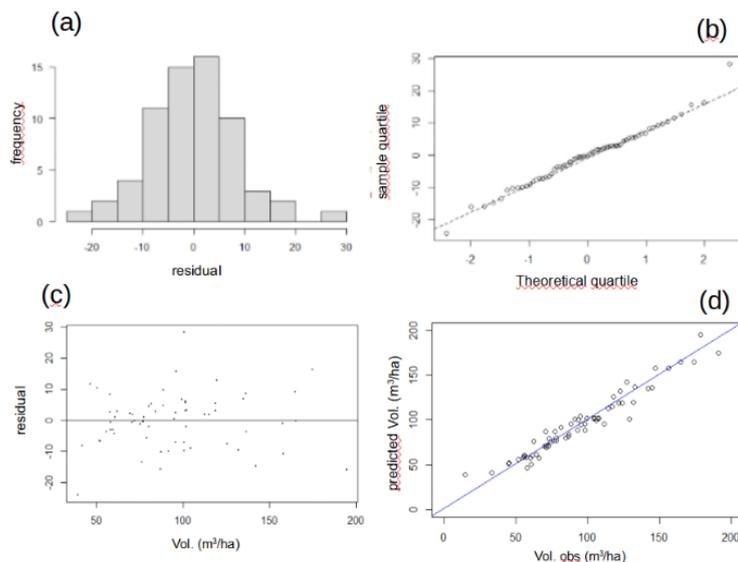
**Figure 2.** Histogram plots (a), Q-Q plot (b), distribution of residuals as a function of predicted H (c), predicted vs. observed H for the selected H equation (d)

The equation selected for estimating VOL corresponds to a nonlinear equation of exponential type. The included explanatory variables were: the product of  $G \cdot H$ ,  $h_{dom}$  and  $CDI_{12}$  ( $p = 3.88e^{-13}$ ,  $3.32e^{-5}$  and  $3.88e^{-8}$ , respectively). Of all three damage variables tested, only the  $CDI_{12}$  was statistically significant, indicating that the damage evaluated at 12 months old is related to wood production at age 7. The adjusted equation to estimate volume was the following:

$$VOL = e^{[\beta_0 + (\beta_1 + b_1) \log(G \cdot H) + \beta_2 CDI_{12} + (\beta_3 + b_3) h_{dom}]} \quad \text{Eq. 7}$$

Where:  $G$ : basal area ( $m^2 \cdot ha^{-1}$ ),  $H$ : mean total height (m),  $CDI_{12}$ : crown damage index observed at 12 months,  $h_{dom}$ : mean dominant height (m),  $\beta_0$ : intercept,  $\beta_1$  to  $\beta_3$ : parameters of each variable,  $b_1$  and  $b_3$ : random effect associated to each variable.

The selected model for volume meets the assumptions of normality and homoscedasticity (Figure 3a-c). A very good fit is observed for the analyzed data ( $R^2 = 0.94$ ), given the relationship between predicted and observed VOL (Figure 3d).



**Figure 3.** Histogram plots (a), Q-Q plot (b), distribution of residuals as a function of predicted VOL (c), predicted vs. observed VOL for the selected volume equation (d)

The statistical indicators obtained from the indexes of model performance reaffirm the results of the graphical analysis regarding the good fit between the predicted and observed values for the three selected equations. The equations for  $H$  and  $VOL$  presented  $R^2$  values close to 1 (in both cases  $R^2 = 0.94$ ), but the  $H$  equation was the one with best fit, given the lower values of the percentage of the standard error of estimation ( $Sy_x\%$ ) (Table 2). Regarding the results of the Willmott  $d$  coefficient, the equations for  $H$  and  $VOL$  presented a  $d$  close to 1. In the case of the  $DBH$  equation, despite obtaining a lower  $R^2$  value, this statistic was still acceptable (Willmott, 1984; Willmott & Wicks, 1980), which indicates a relatively good fit considering the values of  $RMSE$ ,  $d$  and  $Sy_x\%$  (Table 2).

**Table 2.** Coefficients of the fitted equations and their respective fitting statistics

Model	Coefficients					Statistics			
	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	R <sup>2</sup>	RMSE	d	Syx%
DBH (cm)	13.15	0.35	-0.03	-0.004	-0.99	0.75	0.80	0.78	5.52
H (m)	-4.96	0.65	0.51	0.0014		0.94	0.53	0.89	3.86
VOL (m <sup>3</sup> .ha <sup>-1</sup> )	0.084	0.69	-0.004	0.057		0.94	8.65	0.99	9.22

Where: DBH: diameter at breast height, H: height, VOL: volume per hectare.

### 3.3 Comparing Tree Growth and Volume Yield With and Without Crown Damage

A CDI12 around 40% was observed for all site index quartiles. Regarding growth, the results indicate that Q4 presented the highest total volume per hectare and DBH, with and without damage (Table 3).

The Mann-Whitney test indicates that there are statistically significant differences between Q1 and Q4 quartiles ( $p = 0.0001$ ), with Q4 presenting the greatest absolute losses of volumetric growth (38.8 m<sup>3</sup>.ha<sup>-1</sup>) compared to Q1 (16.0 m<sup>3</sup>.ha<sup>-1</sup>). However, when analyzing the percentage of losses for these quartiles, the differences were not significant.

**Table 3.** Average DBH and VOL expected without damage and observed at age 7, categorized by  $h_{dom}$  quartiles

$h_{dom}$ (m)	CDI 12 (%)	DBH (cm)		Volume (m <sup>3</sup> /ha)		Differences	
		Observed	Expected without damage	Observed	Expected without damage	Volume loss (m <sup>3</sup> .ha <sup>-1</sup> )*	Percentage of volume loss(%)
Q1 11.5 -15.2	47.9	11.7	13.2	57.0	73.0	16.0	21.9
Q2 15.2 -17	43.7	12.5	13.8	81.9	98.4	16.5	16.7
Q3 17 -18.6	39.8	13.0	14.4	100.8	122.2	21.4	17.5
Q4 18.6 -23	49.8	15.1	16.5	139.9	178.7	38.8	21.7

Where:  $h_{dom}$ : mean dominant height, CDI: crown damage index, DBH: diameter at breast height, Observed: observed parameter with current damage, Volume loss: expected without damage - observed volume, Percentage of volume loss (%): volume loss with respect to that expected without damage.

## 4. Discussion

The *Eucalyptus* genus is of great importance for the forestry sector in Uruguay. Nonetheless, losses due to pests and diseases in plantations have not yet been adequately quantified. This work represents the first study assessing the impact of a disease on the productivity of commercial plantations in Uruguay.

Analysis of recorded crown damage at 12 months old (CDI12) showed a wide range, with values varying from 20 to 70% (data not shown). This coincides with the results published by Otero et al. (2007), who mention highly variable values of incidence and severity of TLD for different sampling points.

On the other hand, Balmelli, Simeto, Altier, et al. (2013) and Simeto et al. (2010) mention that the great variability observed in the damage levels could be associated with the foliage change velocity, or it could also be explained by the interaction between the pathogen (with different inoculum pressure depending on the area), the host

(diversity of genetic material within the species) and the environment (diversity of soil type, planting date, topographic position and climatic conditions). On their part, Pérez et al. (2017) observed that variability in tolerance to the TLD disease depends on genetics.

The average damage level of all plantations at 12-month-old was high (CDI12= 44.6%), compared to what was reported by Smith (2006), who reports damages of approximately 20% and 10% for young plantations in Australia. Balmelli, Simeto, Torres, et al. (2013) recorded that the damage caused by *T. nubilosa* for the plantations evaluated was moderately high, with an average CDI of 39.1%

Smith (2006) indicates that foliar damage of 20% is sufficient to generate reductions in growth between 4 and 17% in *E. globulus*. In turn, Carnegie & Ades (2003, 2001) mention that only 10% of affected leaf area is enough to cause growth losses in 2-year-old *E. globulus*.

Research carried out in Uruguay showed that a severity of 40% or more for TLD (on 14-month-old trees) produces reductions in growth, and that the greater the damage, the greater the impact on growth (Balmelli, Simeto, Altier, et al., 2013). On the other hand, Carnegie & Ades (2003) report a negative correlation between height and diameter of trees with the severity of TLD in *E. globulus* plantations.

In the present work, a negative correlation is also observed, but between growth in diameter or volume and crown damage evaluated at 12 months old. For an average CDI12 of 44.6% a growth reduction of 22% was estimated for all plantations at 7-year-old. This data arises after calculating the difference in growth with and without damage.

The damage caused by TLD reduces the photosynthetically active area, which results in productivity losses in the affected plantations due to reductions in growth (Balmelli, Simeto, Torres, et al., 2013; Hunter et al., 2009; Lundquist & Purnell, 1987; Milgate et al., 2005; Mohammed et al., 2003). Several authors (Carnegie et al., 1998; Eyles et al., 2013; Hunter et al., 2009; Pinkard & Beadle, 1998; Smith, 2006) report that long-term effect of this damage is difficult to quantify.

When analyzing the data categorized only by  $h_{dom}$  quartiles, no marked relationship between site quality and the level of foliar damage was observed. Thus, the choice of site is not an alternative that leads to a reduction of the crown damage at 12 month-old. These results coincide with those of Balmelli, Simeto, Martínez, Torres, Pérez, et al. (2009), who mention that the characteristics of the site do not have a significant effect on the level of foliar damage. Pinkard and Mohammed (2006) also found that the effect of *T. nubilosa* was similar at the different sites evaluated, regardless of the level of tree infection.

The analysis of the difference between the estimated and the observed volume by site index quartile showed that volume losses in Q1 (worst sites) and Q4 (best sites) were statistically different in terms of absolute values but did not differ when comparing percentages of loss. The absolute values show the overall amount of wood loss between sites but does not consider the productivity among sites. On the other hand, comparing the relative values (i.e. percentage of wood loss) allows to better understand volume loss across sites with different productivity levels. Based on that, the lack of relationship between wood loss and site quality is evident according to our study and coincides with previous work.

The equations adjusted for DBH and VOL in this work are the first that include crown damage variables for plantations in Uruguay. Our work provides useful information for selecting variables to quantify the damage and valuable insights about the most effective age of measurement to relate foliage damage and productivity loss. Furthermore, the equations represent a new tool for production planning aimed at forestry producers who currently maintain *E. globulus* plantations or intend to produce this species.

Because the presented results are based on data from 7-year-old plantations, it would be advisable to continue with these studies until the rotation age (10-12 years) in order to relate the crown damage at young age with final volume of harvested wood.

The damage caused by TLD in *E. globulus* plantations has led to the replacement of this species in Uruguay. Given the lack of information about the effect of TLD damage on productivity, our study provides useful inputs for estimating the balance between production costs and expected wood production on sites with risk of *T. nubilosa* infections. In this sense, this study provides scientifically-based information for assessing the continuity of *E. globulus* plantation in Uruguay.

## 5. Conclusions

The inclusion of crown damage index at 12 months of age in the predictive models made a significant contribution to estimating DBH and volume; however, it was not significant for predicting total height.

The use of models allowed to estimate growth losses at 7 years of age for *E. globulus* in Uruguay.

The volume reduction at 7 years of age for *E. globulus* affected by TLD was on average 22%.

The intensity of TLD and the percentage of wood loss caused by the disease damage did not vary with site quality. This reinforces previous results showing that site selection does not make a significant contribution to managing the impact of the disease.

Although more work is needed to quantify growth losses at harvest age, our work provided valuable input for decision makers to understand mid-rotation losses.

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## Transparency of Data

Data not available: The data set that supports the results of this study is not publicly available.

## Author Contribution Statement

	M Pintos	C Rachid	S Simeto	G Balmelli	C Pérez
Conceptualization					
Data curation					
Formal analysis					
Investigation					
Methodology					
Software					
Supervision					
Validation					
Visualization					
Writing – original draft					
Writing – review and editing					

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## Supplementary Material

**Table S1.** Anova type III for volume

	<b>Sum Sq</b>	<b>Df</b>	<b>F Value</b>	<b>Pr (&gt;F)</b>
Intercept	33305	1	47.9613	5.946e-09***
Genetics	54190	12	6.5031	6.022e-07***
Residual	36804	53		