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Growth Modeling in Complex Forest Systems: CORKFITS a Tree Spatial Growth Model for Cork Oak Woodlands

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Keywords: cork oak, woodlands, growth modelling, spatial explicit competition indices

Abstract: Cork oak (*Quercus suber* L.) woodlands (montado) consist of a multifunctional forest system that covers about 713,000 ha in Portugal. Today, its importance stems from cork production, with Portugal producing half of the cork in the world. As the main economic objectives may change with changes in markets and environment conservation concerns (e.g. biodiversity, water, carbon) there is a need for improved management tools. Spatial tree growth simulators are tools that enable the generation of tree growth scenarios dependent on site and competition status, that allow to simulate large scope management actions. In the present work it is presented a cork oak tree spatial growth simulator, CORKFITS, that was constructed with data generated by the monitoring system installed in 1995. The simulator was built assuming the potential increment modifier principle: $\mathrm{z} = \mathrm{zpot} * \mathrm{modifier} + \varepsilon$, where zpot is the potential growth as function of site; modifier is the reduction factor as function of spatial competition index and the intensity of debark; ε is a random error. CORKFITS is composed by sub growth models (cork, stem, tree height and crown), cork production models and mortality models. Single trees are in cork oak woodlands subjected to natural (genetics and competition) and artificial (debark, crown pruning, root pruning) factors that affects their growth therefore there is a

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large amount of unexplained variability which creates problems in the modeling phase, the solutions for these problems will be discussed in the present work

1. Introduction

Cork oak (*Quercus suber* L.) woodlands (montado) consist of a multifunctional forest system that covers about 713,000 ha in Portugal which represent about 23% of forest area. Cork oak woodlands are complex systems with the conjunction of production activities (agriculture, pasture, grazing; animal stock, etc.) that share the same growing space in a landscape characterized by its site variability especially at the soil/climate/topography levels. The production system is based on trees that create the ecological characteristics that are fundamental to the sustainability of all activities occurring at stand level (Ribeiro *et al.*, 2003b, 2006). The sustainable management of the combination sets of production activities requires a good knowledge of the resilience and elasticity of the forest component in the each particular soil/climate/topographic conditions (Ribeiro *et al.*, 2006).

Cork oak woodlands can be described as open forest systems with external variables and a feedback loops composed by stand structure → growth → tree size and shape → stand structure (Pretzsch, 2009) that controls its stability (Fig.1). Elasticity and resilience of these cork oak woodland forest systems can be disturbed both by random external variables that controls mortality, tree damage and intensity of natural regeneration and management based variables that can affect the system at tree level physiology (debark, crown pruning and root pruning) and at site level mainly by soil structure modifications (soil mobilization, erosion risk, organic matter depletion, fertility loss, etc.) (Fig.1). It easily deducted that the large set of disturbances from external variables combined with the large set of growth responses due to the large genetic variability at tree level (Alpuin and Roldão, 1993, Freitas, 2002) creates large unexplained variability that affects the model construction.

In the last 40 years cork oak woodlands are facing disturbances that are affecting the production system sustainability both by intensification of the activities undercover or extreme extensification of these activities (sometimes abandonment) that are related to agrarian policies modifications. Only adaptive management techniques associated with growth models and decision support systems, constructed in knowledge based monitoring system, are able to prevent cork wood land decline with the adoption of management practices focused in long term objectives (Ribeiro *et al.*, 2010).

As the main economic objectives may change with changes in markets and environment conservation concerns (e.g. biodiversity, water, carbon) there is a need for improved management tools. Spatial tree growth simulators are tools that enable the generation of tree growth scenarios dependent on site and competition status, that allow to simulate large scope management actions.

In the present work it is presented a cork oak tree spatial growth simulator, CORKFITS, that was constructed with data generated by the monitoring system installed in 1995. The simulator was built assuming the potential increment modifier principle: $\mathrm{z} = \mathrm{zpot} * \mathrm{modifier} + \varepsilon$, where zpot is the potential growth as function of site; modifier is the reduction factor as function of spatial competition index and the intensity of debark; ε is a random error.

CORKFITS is composed by sub growth models (cork, stem, tree height and crown), cork production models and mortality models (Ribeiro *et al.*, 2003a, 2003b, 2006). Single trees are in cork oak woodlands subjected to natural (genetics and competition) and artificial (debark, crown pruning, root pruning) factors that affects their growth therefore there is a large amount of unexplained variability which creates problems in the modeling phase, the solutions for these problems will be discussed in the present work.

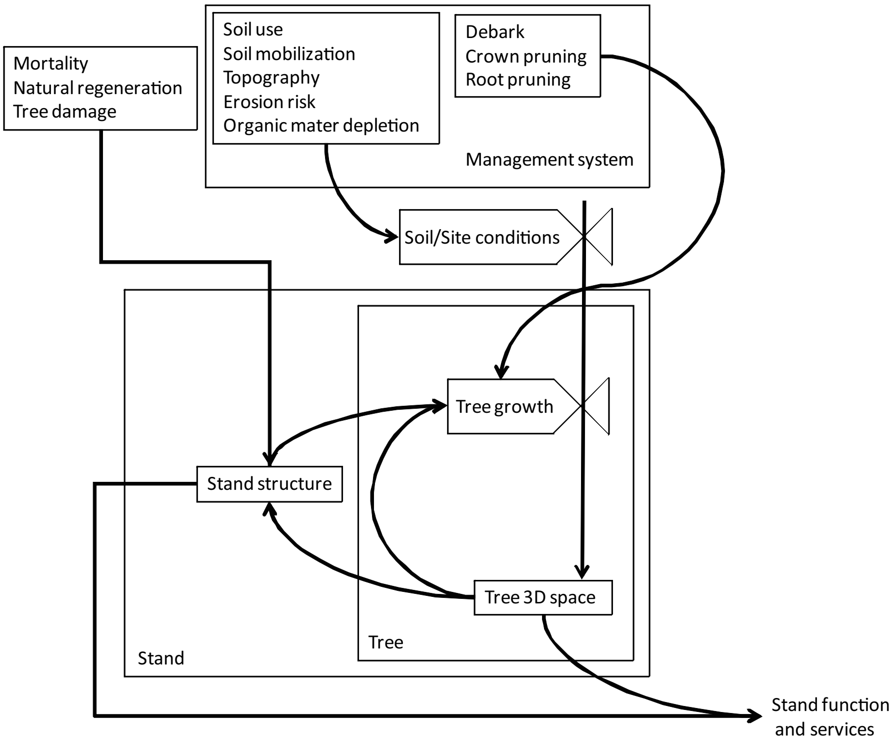

Figure 1. Cork oak woodland open forest system

With the levels tree, stand, the external variables and the feedback loop: stand structure → growth → tree size and shape → stand structure

2. Material and methods

The model construction is based on data collected in a monitoring system based on permanent plots installed since 1995 (Ribeiro *et al.*, 2003a). The monitoring system is spatial explicit and it is centered on the trees were a set of simple and transformed variables are collected in order to precisely characterize the tree dimensions and management including cork weighting and sample collection for dry matter and image analysis laboratory procedures (Fig.2).

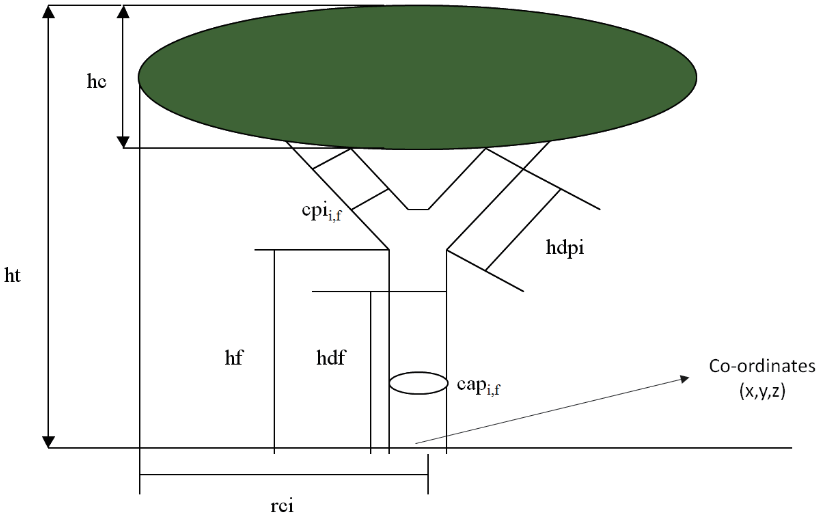

Figure 2. Set of simple dendrometric variables collected at tree level

$cap_{i,f}$ = perimeter at breast height before and after debark (cm), $cp_{i,f}$ = branch perimeter before and after debark (cm), ht = tree height (m), hf = stem height (m), hc = base of crown height (m), hdf = stem height of debark (m); hdp_i = i^{th} branch debark length (m), rc^i = i^{th} cross crown projection radius.

The set of simple variables represented on Figure 2 are used to compute transformed variables that are used in the modeling procedures: (1) production variables (cork dry weight, pcs, kg; cork thickness, ef1.3, cm); (2) Management intensity variables (total length of debark, hdt, m; debark surface, sg, m^2; coefficient of debark, cd; intensity of debark, id); (3) Productivity variables (cork dry weight per debark surface unit, pcm$_s^2$, kg , m^{-2}); (4) Tree dimension variables (crown projection area, ac, m^2; sectional area, (g$_i$ and g$_f$, m^2).

Tree dimension cork growth variables are obtained by repeated measures procedures as it can be seen in Figure 3.

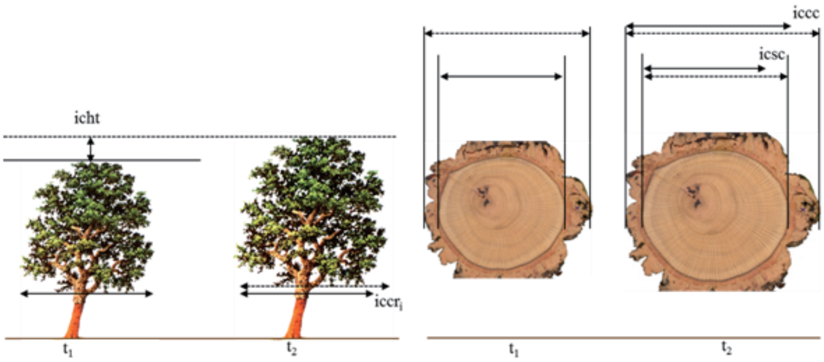

Figure 3. Growth (increment) variables colected at tree level

iccr – Crown projection radius increment; icht – Tree height increment; iccc – Cork radial increment; icsc – Stem radial increment

Additionally, in order to be able to model at tree level with spatial explicitly, it was necessary to model crown profile using the ellipsoid model:

$$\left(\frac{x}{a}\right)^E + \left(\frac{y}{b}\right)^E = 1$$

where a = crown height, hc, m; b = crown projection radius, m; (x, y) = profile point coordinates, and E = Ellipsoid form parameter to estimate with nonlinear regression techniques.

A structure generator STRUGEN based on a filtered Poisson process (Pretzsch, 1992, Pretzsch, 1997) which filters were parameterised for cork oak stands natural spatial structure. The STRUGEN is used to simulate virtual stands as well to simulate regenaration (Ribeiro *et al.*, 2001).

All growth models were built assuming the potential increment modifier principle: $z = \mathrm{zpot} * \mathrm{modifier} + \varepsilon$, where zpot is the potential growth as function of site (Ribeiro *et al*, 2006, 2010); modifier is the reduction factor as function of spatial competition index and the intensity of debark; ε is a random error. The state models were constructed for all dimensions that are important for the spatial 3D approach and use as independent variable at least one growth parameter of the growth models. Therefore it is possible to include the rational of spatiality and management in the estimation of state variables.

All models where fitted using linear and non-linear regression techniques with the method Levenberg-Marquard algorithm for parameter estimation (Sen and Srivastava, 1990).

3. Results and discussion

The construction of CORKFITS growth model is based on growth and state equations and it is time independent being growth dependent on growth driver variables g. In Figure 4 it can be seen the CORKFITS fluxogram.

The growth unit is constructed with the models of table 1 and 2. For potential functions it was selected the Yoshida I model (Zeide, 1993). The model were fitted for total sectional area growth (a), cork sectional area growth (b), and stem sectional area growth (c) (Tab.1). Models constructed for all combinations of soil (0, 1) and sectional area at 1.3m before and after debark (1, 2). In Figure 5 it can be seen the set of potential models fitted.

Observing Figure 5 it becomes clear the difference between soil quality 0 and 1. Although cork growth is equivalent in both soils, it is

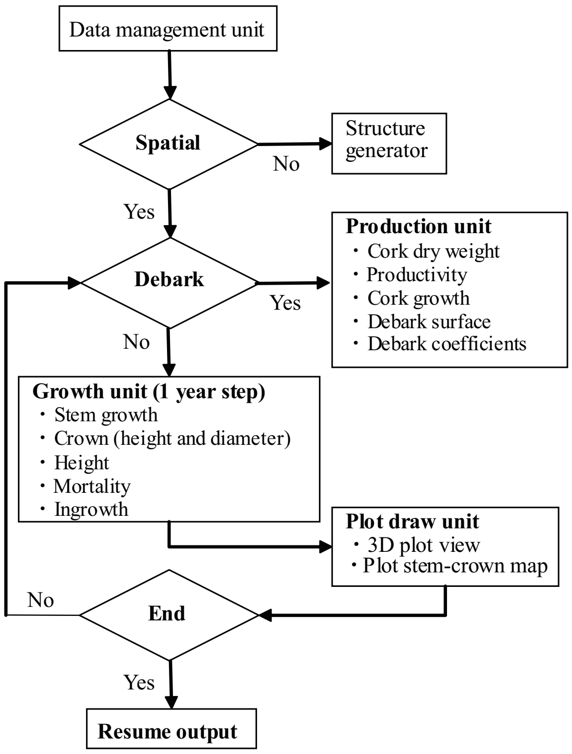

Figure 4. CORKFITS Fluxogram

observed for potential trees a clear reduction in stem growth for soil site quality indicating that the disturbances of these trees closing the limits of resilience.

Table 1. Potential functions for total sectional area growth
(a), cork sectional area growth (b), and stem sectional area growth (c) and all combinations of soil (0,1) and sectional area at 1.3m before and after debark (1,2)

Função (Yoshida I)	**grupo**	a	b	d	$R^2_{ajust.}$
$y' = \frac{a \cdot b \cdot d \cdot x^d}{x\left(b + x^d\right)^2}$	**a01**	0.127*	0.595*	1.830*	0.963
	a02	0.142*	0.776*	1.605*	0.892
	a11	0.138*	1.048*	1.683*	0.921
	a12	0.121*	0.897*	1.531*	0.813
	b01	0.134*	1.096*	1.716*	0.948
	b02	0.180*	1.710*	1.502*	0.889
	b11	0.145*	1.567*	1.617*	0.878
	b12	0.111*	1.111*	1.520*	0.850
	c01	0.027*	0.351*	1.838*	0.707
	c02	0.026*	0.343^{ns}	1.714*	0.712
	c11	0.030*	0.907*	1.666*	0.534
	c12	0.018*	0.352^{ns}	1.700*	0.441

*=Significant for ; ns= non significant

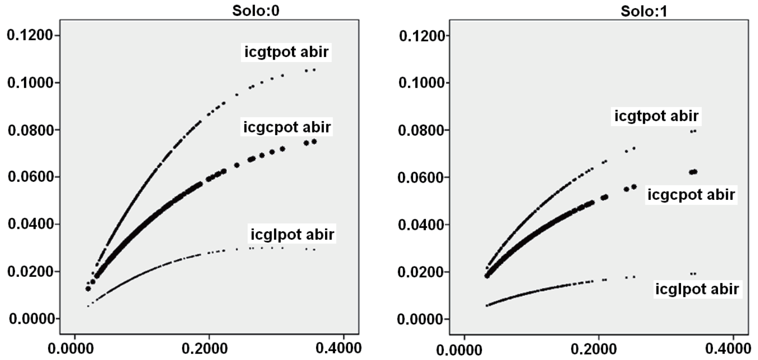

Figure 5. Potential functions for growth

Total sectional area growth (a, icgtpot), cork sectional area growth (b, icgcpot), and stem sectional area growth (c, icglpot) and all combinations of soil (0,1) and sectional area at 1.3m before and after debark (1,2, abir)

For modifier functions the model's were fitted for total sectional area growth (a), cork sectional area growth (b), and stem sectional area growth (c) (Tab.2). Models constructed for all combinations of soil (0, 1) and sectional area at 1.3m before and after debark (1, 2).

Table 2. Modifier functions for growth

Total sectional area growth (a), cork sectional area growth (b), and stem sectional area growth (c) and all combinations of soil (0,1) and sectional area at 1.3m before and after debark (1,2)

Função	**grupo**	a	B	$R^2_{ajust.}$
modifier=$e^{-a*HD2^{b*idf}}$	**a01**	0.352*	0.068*	0.695
	a02	0.445*	0.135*	0.574
	a11	0.239*	0.145*	0.706
	a12	0.369*	0.157*	0.588
	b01	0.362*	0.170*	0.708
	b02	0.466*	0.218*	0.579
	b11	0.282*	0.233*	0.694
	b12	0.369*	0.224*	0.565
	c01	0.577*	-0.004^{ns}	0.301
	c02	0.559*	0.003^{ns}	0.280
	c11	0.364*	-0.004^{ns}	0.319
	c12	0.486*	-0.002^{ns}	0.309

*: Significant for; ns: non significant; idf: intensity of debar over stem; HD2 Hegyi spatial competition index (Daniels, 1976); H: $\sum_{j=1}^{n} \frac{d_j}{d_i} * \frac{1}{dist_{ij}}$, where i: target tree, j: competitor: d: diameter at 1.3 m, $dist_{ij}$: Target tree i competitor j distance; n: Competitor number according with the rule D2 $dist_{ij} \langle 0.33 * d_j$

In Figure 6 it can be seen the potential modifier function for cork sectional area growth (b).

Observing Figure 6 it can be stressed empirically, the proximity of the

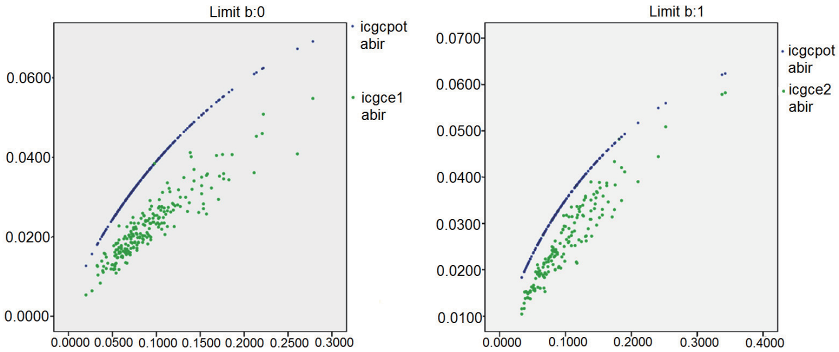

Figure 6. Potential*modifier function

For cork sectional area growth (b) and combination of soil (0,1) and sectional area at 1.3m after debark (2)

trees of soil site quality 1 to the potential indicating what was referred before, about the closure to rupture of resilience and consequence loss of elasticity of the trees under this management options. This indicates that for soil site quality 1 the management should focus on the reduction of debark pressure in all cork oak trees as well in the reduction of soil use in order to balance the system. For the state equations the parameters obtained were in Table 3 for total height (h), Crown projection diameter (dc) and Table 4 for cork dry weight (ln(pcs)).

To all the growth models (Tabs.1 and 2) a random component was added (Ribeiro *et al.*, 2006). Based the sub models of Tables 1 to 4 it was programmed the growth model software application CORKFITS and the results were tested with an independent dataset and the results are presented in Figure 7 for cork growth, which is the variable of interest in this production system. The 95% confidence intervals for the cork growth before and after debark (icgcei, icgcef, m^2) estimation where obtained with 100 repetition runs of simulation for each validation plot data (cork growth before and after debark, icgci, icgcf, m^2).

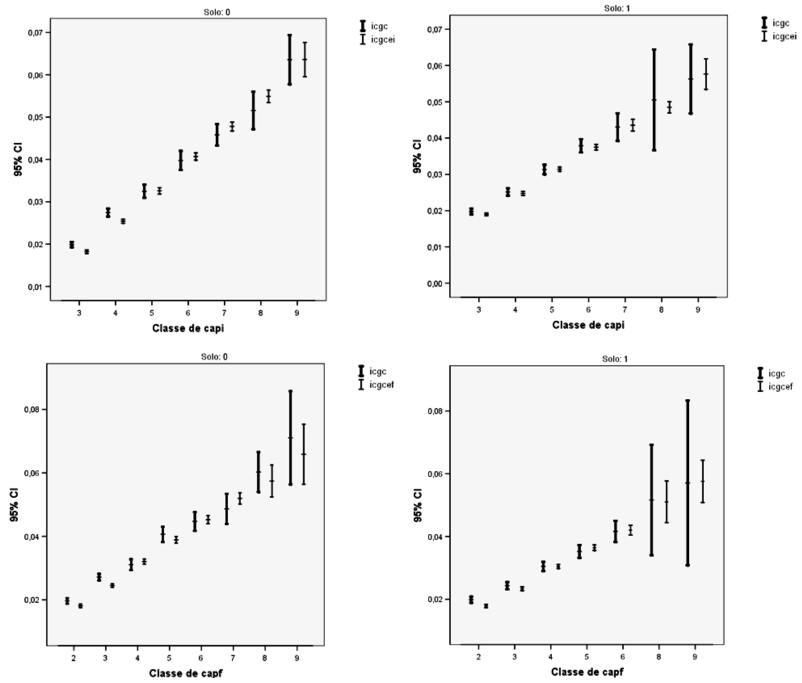

Figure 7. Statistics of estimates

Mean and 95% confidence interval for cork growth estimates before and after debark (icgcei, icgcef) and validation plot data before and after debark (icgci, icgcf). The results are organized in stem perimeter at 1.3m (capf) classes

As it can be seen in Figure 7 no significant differences were found on all classes for all models indicating the good quality of growth models in all tree dimensions. In fact due to the long life span of cork oak trees under this system (200 years) precision in estimations of cork growth are very important in forest planning, for economic reasons, therefore these results indicate that the variability referred before was largely incorporated in the models setting its estimation quality.

Table 3. State equations parameters for total height (h), Crown projection diameter (dc)

Função	Tipo	a	b	c	$R^2_{ajust.}$
$h=e^{\left[a+b*\ln\left(cap_{i,f}\right)+c*\left(\ln\left(cap_{i,f}\right)\right)^2\right]}$	**h01**	-2.798*	1.792*	-0.156*	0.515
	h02	-3.463*	2.157*	-0.201*	0.480
	h11	-4.004*	2.282*	-0.206*	0.472
	h12	-5.188*	2.888*	-0.279*	0.479
$dc=a*\left(cap_{i,f}/100\right)^b$	**dc01**	5.841*	1.107*	----	0.801
	dc02	6.945*	1.039*	----	0.799
	dc11	5.668*	1.090*	----	0.795
	dc12	6.685*	1.024*	----	0.770

*=Significant for ; ns= non significant

Table 4. State equations parameters for cork dry weight (ln(pcs))

Regressores	Tipo	a0	a1	a2	a3	$R^2_{ajust.}$
$\ln(cap_{i,f})$ ln(hdt) ln(ef1.3)	**101**	-3.845*	1.218*	0.751*	0.278*	0.938
	102	-2.868*	1.004*	0.752*	0.173*	0.939
	111	-4.104*	1.285*	0.679*	0.278*	0.926
	112	-3.130*	1.078*	0.671*	0.170*	0.926
$\ln(cap_{i,f})$ ln(hdt)	**201**	-4.145*	1.354*	0.700*	----	0.929
	202	-2.597*	1.062*	0.747*	----	0.908
	211	-4.551*	1.451*	0.623*	----	0.916
	212	-3.041*	1.170*	0.654*	----	0.890
$\ln(sge_{i,f})$	**301**	1.954*	0.935*	----	----	0.918
	302	2.178*	0.873*	----	----	0.905
	311	1.941*	0.904*	----	----	0.895
	312	2.151*	0.849*	----	----	0.881

*=Significant for ; ns= non significant

4. Final remarks

In the present paper it was shown the importance of the inclusion of spatial information in growth models especially in these complex forest systems. Only with the resulting precision it is possible to have good estimation in all tree dimension classes. It is also shown the relevance of a precise and complete monitoring system to generate the simple and transformed variables that can contribute to the knowledge about these complex forest systems.

Finally, it was possible to show that the process of nonlinear regression analysis can be useful in the empirical understanding some ecophysiological processes permitting some inference on resilience and elasticity at tree level in these complex forest systems.

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