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Effects of defoliation by the pine processionary moth *Thaumetopoea pityocampa* on biomass growth of young stands of *Pinus pinaster* in northern Portugal

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Biomass growth models for 13-year-old maritime pine tree stands (*Pinus pinaster* Ait.) in the north-eastern Portugal were developed and used to analyse the effects of the defoliation by the pine processionary moth, *Thaumetopoea pityocampa* (Den. & Schiff.) on biomass increment. For the adjustment of the models, 30 individual pine trees were destructively sampled and non-linear models were tested, using the diameter at 10 centimetre height ($d_{0.10}$), the total height (h), both variables ($d_{0.10}$+h) and $d_{0.10}^2h$ as preditors of biomass growth. The results showed that the best predictor was $d_{0.10}$+h. Application of models to analyse tree biomass after attack by the pine processionary moth showed that the decrease of biomass increment was proportional to the severity of the insect attack, with average values of losses in biomass increment ranging from 37% to 73%, depending on defoliation intensity.

Keywords: Prediction model, *Thaumetopoea pityocampa*, Biomass increment, *Pinus pinaster*

Introduction

The most recent National Forest Inventory (AFN 2006), shows that forest represents 37.7% of the land use in Portugal, with *P. pinaster* covering 25.0% of that area. In northern Portugal, where this study was carried out, forest represents 30.7% of the land use and *P. pinaster* stands cover 40.2% of this area. Young stands, which represent 30% of total pine stands, are extremely important nationally, not only because they represent the future of pine stands, but also because they have a high ecological and economical importance. According to Oliveira (1999), shrub biomass should be removed 3 times before the 10-th years after plantation and the first thinning should be applied before the 15-th year, removing between 20% and 40% of the aboveground biomass. Based on results reported by Lopes (2005), young pine stands can produce an average of 15.8 ton ha^{-1} year^{-1} of arboreal biomass and 6.32 ton ha^{-1} year^{-1} of shrub biomass. If 20% of the main stand is removed after 15 years, a yield of 4.42 ton ha^{-1} year^{-1} is expected, representing high potential for biomass production. This biomass can be sold at up to 30€ per ton (Neto 2008), a significant source of income for forest owners. *Pinus* biomass from adult stands is mainly used for furniture production, pulp production and biomass for energy among other possible applications.

The pine processionary Moth, *Thaumetopoea pityocampa* (Den. & Schiff. - Lep., *Thaumetopoeidae*) is one of the most destructive insects of *Pinus* and *Cedrus* in the Middle East, North Africa and many southern European countries, including Portugal. The urticant hairs of the late instar larvae provokes serious reactions in humans and other mammals (Lamy 1990, Oliveira et al. 2003) but it is also responsible for significant economic damage due to severe defoliation (Buxton 1983, Devkota & Schmidt 1990, Kanat et al. 2005). Defoliation removes both photosynthetic material and sites where chemicals such as growth hormones are produced, affecting many vital functions (Carus 2004). It is well known that in adult trees defoliation, though repeated over consecutive years, seldom causes death (Ruperez 1956, Kailadis 1962), but increases susceptibility to sanitary problems such as pine weevils and bark beetle attack (Kanat et al. 2005, Markalas 1998). In spite of the capability of defoliated trees to refoliate and survive, the effects of defoliation are very significant (Fratian 1973) with losses in volume, radial growth (Carus 2004, Kanat et al. 2005, Laurent-Hervouet 1986) and biomass production (Markalas 1998). Kanat et al. 2005 reported a significant decrease (average 21% over four years) on annual diameter increment of *Pinus brutia* in Turkey while Carus (2004) identified growth reductions on radial height and volume on *P. brutia* after an outbreak of *T. pityocampa*. Cadahia & Insua (1970) identified a decrease in wood volume increment of 14-33% in young *P. radiata* as well as losses in tree volume, while Bouchon & Toth (1971) reported that *T. pityocampa* attack was responsible for an about 45% volume decrease over a 50 year period.

The effect of insect action on trees can be studied using predictive models (Hogg 1999) which allow estimates of dendrometric variables (*e.g.*, height, volume, and biomass) and can be used for inventory techniques in production studies (Komiyama et al. 2008, Sochackia et al. 2007). However, the use of allometric models to estimate the impact of insects on forest dynamics is virtually unknown.

The aims of this paper are: (1) to present growth biomass models for different aboveground components (leaves, stem and total biomass) of young pine trees; and use them (2) to quantify the effects of defoliation by the pine processionary moth on *P. pinaster* biomass increment.

Material and Methods

Study site

The study was conducted in the Natural Park of Montesinho situated in Trás-os-Montes, a mountainous region of north-east Portugal. The Park (area 74 800 ha) is situated in the "Terra Fria Transmontana" climate zone, characterized by hot and dry summers, cold winters (annual mean temperature around 11 ºC) and precipitation falling mainly during the autumn (annual mean precipitation about 900 mm). The area comprises pure stands of several pine species; *P. pinaster* Ait. and *P. nigra* Arn. are the dominant species and *P. sylvestris* L. and *P. strobus* L. the secondary species.

The experimental plots were set up in 13-year-old *P. pinaster* plantation with a density of 650 trees per hectare.

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Biomass models adjustment

Adjustment of the biomass models was performed by destructively sampling 30 pine trees not suffering from defoliation by the pine processionary moth. Trees were cut near the soil surface and the total tree height (h) and live crown were measured. Stem diameters were measured 10 cm from the base of the tree ($d_{0.10}$), diameter at breast height (dbh) and then at intervals of 10%, beginning at 10% of the total height (h) and ending at 90% of the height. Bark thickness was measured at each point. The total stem was measured and weighed.

Each branch of the crown was separated from the stem and the fresh mass of each component measured using scales with one kilogramme precision. Leaves, logs and female cones were separated for each branch to measure the relative contribution of each component to total branch weight. The total volume (v) was determined using the diameters that had been measured across the stem.

Samples of each tree component were collected in order to obtain dry density later in the lab.

Pearson's correlation was calculated between total biomass (including stems, leaves, branches and female cones biomass) and partial biomass (leaves biomass and stems biomass) and measurements of trees size ($d_{0.10}$, dbh, h and v), in order to identify the most appropriate predictor variables. Adjustment of total and partial biomass prediction models was carried out by cross validation. Sampled trees were were randomly assigned to two groups: some 24 trees were selected for the adjustment phase and 6 trees were selected for the validation phase. Based on the methodology used by Mikšys et al. (2007) tree biomass components and tree parameters were evaluated and equations for tree biomass evaluation were derived. Several non-linear regression models were tested, using $d_{0.10}$, h, both variables ($d_{0.10}$+h) and $d_{0.10}^2h$ as independents variables, applying the following equation (eqn. 1):

$$Y = a_0 \cdot P_1^{a_1} \cdot P_2^{a_2} \cdot \ldots$$

During adjustment (Mikšys et al. 2007), the goodness-of-fit of the model was assessed based on the coefficient of determination (R^2), as follows (eqn. 2):

$$R^2 = 1 - \frac{SSR}{SST}$$

where *SSR* is the sum of squares of the residuals and *SST* is the total sum of squares. Validation of selected models from the adjustment phase was carried out using the average deviation (AD) and absolute average deviation (AAD - eqn. 3-4):

$$AD = \frac{\sum (B_{obs} - B_{est})}{n}$$

$$AAD = \frac{\sum |B_{obs} - B_{est}|}{n}$$

where B_{obs} is the observed total or partial biomass, B_{est} is the estimated total or partial biomass and *n* is the total number of trees.

After selection of the best fitting model based on the above validation process, the model was readjusted using the total dataset (the 30 sampled trees).

Effect of T. pityocampa on biomass increment

The effect of defoliation by the pine processionary moth on pine biomass increment was evaluated at the experimental plot on 83 individually selected pine trees with different degrees of defoliation. The degree of defoliation was visually assessed in March of 2003, 2004 and 2005 using five defoliation classes: class 0 - no defoliation (0%); class 1 - light defoliation (1-25%); class 2 - moderate defoliation (26-50%); class 3 - heavy defoliation (51-75%); and class 4 - very heavy defoliation with almost no foliage remaining (76-100%). Moreover, dendrometric measurements ($d_{0.10}$, dbh and h) were also carried out in February of 2004, 2005 and 2006.

Using the selected model, total biomass was calculated for those years, biomass increment was estimated for the growing years, as well as the percentage of decrease in biomass increment for undefoliated and defoliated trees. After testing data for normality and variance homogeneity, ANOVA was applied to determine the variance accounted for by the defoliation class effect, the growth years under study and the variance within each defoliation class. The Tukey-Kramer mean separation test was applied in order to determine the biomass increment differences on the basis of defoliation class.

Results

From the biomass models adjustment

The Pearson correlation matrix showed a significant relationship between total biomass, leaf biomass, stem biomass and dendrometric variables with *r* values varying between 0.64 and 0.94 (Tab. 1). There was a linear relationship between total and partial biomass and the analysed dendrometric variables, mainly $d_{0.10}$, dbh and h.

The dendrometric variable with the strongest relationship with the total and partial biomass was $d_{0.10}$ (Tab. 1). The variable "h" had lower correlation values, although, combined with diameter, model fitting was enhanced. A local model including a single variable (the diameter) as predictor has a limited range of applications. The inclusion of "h" may extend its applicability at a regional scale, allowing a wider range of tree forms to be covered.

Simultaneous use of $d_{0.10}$ and h as predictors in the models resulted in stronger correlations with leaves, stem and total biomass, giving R^2 values ranging from 0.73 to 0.91 (Tab. 2). The most difficult variable to mo-

Tab. 1 - Pearson's r correlation matrix between total and partial (leaves and stem) dry biomass and the available dendrometric variables.

-	$d_{0.10}$	dbh	h	v	B_{stem}	B_{leaves}	B_{total}
$d_{0.10}$	1	-	-	-	-	-	-
dbh	0.772	1	-	-	-	-	-
h	0.723	0.959	1	-	-	-	-
v	0.822	0.944	0.906	1	-	-	-
B_{stem}	0.937	0.831	0.767	0.854	1	-	-
B_{leaves}	0.854	0.744	0.641	0.786	0.849	1	-
B_{total}	0.916	0.819	0.736	0.878	0.940	0.941	1

Tab. 2 - Coefficient of determination (R^2) for different combinations of diameter at 10 cm height ($d_{0.10}$) and tree height (h) for total and partial biomass for the 16 tested database.

Parameters	Total biomass			Leaves biomass			Stem biomass		
	$d_{0.10}$	$d_{0.10}$ + h	$d_{0.10}^2h$	$d_{0.10}$	$d_{0.10}$ + h	$d_{0.10}^2h$	$d_{0.10}$	$d_{0.10}$ + h	$d_{0.10}^2h$
Maximum	0.877	0.898	0.898	0.839	0.841	0.83	0.941	0.95	0.942
Average	0.825	0.835	0.823	0.728	0.733	0.697	0.886	0.907	0.902
Minimum	0.69	0.736	0.736	0.555	0.585	0.583	0.756	0.805	0.803
Std. dev	0.049	0.042	0.041	0.074	0.07	0.065	0.044	0.037	0.037

Tab. 3 - The Average deviation (AD) and the Absolute Average deviation (AAD) from the validation results across the 16 sampled groups.

Para-meter	Total biomass			Leaves biomass			Stem biomass		
	$d_{0.10}$	$d_{0.10}$ +h	$d_{0.10}^2$h	$d_{0.10}$	$d_{0.10}$ +h	$d_{0.10}^2$h	$d_{0.10}$	$d_{0.10}$ +h	$d_{0.10}^2$h
AD	0.109	0.284	0.433	-0.014	0.025	0.180	-0.105	-0.029	0.050
AAD	1.994	1.930	1.995	1.113	1.112	1.152	0.680	0.641	0.662

Tab. 4 - ANOVA results for biomass increment of *Pinus pinaster* Ait. after defoliation by the pine processionary moth.

Source	Sum of squares	DF	Mean square	F-value	P-value
Year	10.66	1	10.66	0.043	0.84
Defoliation class	15882.37	4	3970.59	16.07	0.00
Year · Defoliation class	1535.46	4	383.86	1.55	0.19
Residual (trees/defoliation class)	38532.39	156	247.00	-	-

Tab. 5 - Biomass increment (mean and SD) of *Pinus pinaster* and results of Tukey-Kramer mean separation test based on classes of defoliation. (*): Means followed by the same letter in the same column are not significantly different (significance level: $\alpha < 0.05$).

Defoliation class	N	Mean of biomass increment (Kg/tree)	Percent decrease in biomass increment
4	22	15.14 ± 2.76 a*	73.24
3	52	16.14 ± 2.84 a	71.47
2	44	28.93 ± 5.28 b	48.86
1	44	35.54 ± 10.50 bc	37.17
0	4	56.57 ± 2.06 c	-

del was leaf biomass while the best one was stem biomass.

The adjusted model tendency, measured by the average deviation (AD) showed an overestimation of true biomass values for total and leaves biomass and an underestimation for stem biomass (Tab. 3). Absolute average deviation (AAD) values showed that simultaneous use of $d_{0.10}$ and h provides the best biomass predictions.

The final models for partial and total biomass, adjusted to the total dataset, are reported below:

$$B_{total}=0.989 \cdot d_{0.10}^{1.566} \cdot h^{0.282} \quad (eqn.\ 5)$$

$$(R^2=0.907\ ; RMSE=2.537)$$

$$B_{leaves}=0.375 \cdot d_{0.10}^{1.747} \cdot h^{0.041} \quad (eqn.\ 6)$$

$$(R^2=0.738\ ; RMSE=1.861)$$

$$B_{stem}=0.207 \cdot d_{0.10}^{1.752} \cdot h^{0.519} \quad (eqn.\ 7)$$

$$(R^2=0.843\ ; RMSE=1.230)$$

where B_{total}, B_{leaves} and B_{stem} refer to the total, leaves and stem biomass model, respectively, and *RMSE* is the root mean square error.

The effect of Thaumetopoea pityocampa on biomass increment

ANOVA results for the biomass increment of pine trees attacked by the pine processionary moth using different classes of defoliation (Tab. 4) showed that the interaction between growing years, defoliation class and year itself were not statistically significant. However, a significant difference was found for defoliation class (P<0.001), revealing that the increment of pine tree biomass was affected by the both presence of the insect and by the intensity of the attack.

The average biomass increment was maximum for undefoliated trees (56.6 kg per tree) and minimum for heavily and very heavily defoliated trees (16.1 and 15.1 kg per tree respectively - Tab. 5). The results of Tukey-Kramer mean separation test indicated that biomass increment from trees suffering heavy and very heavy defoliation (classes 3 and 4 respectively) did significantly differ from those with moderate defoliation (class 2), light defoliation (class 1) and undefoliated trees (class 0). There was no significant difference between undefoliated trees and those with light defoliation. The percent decrease in biomass increment during the growing years that were studied was around 70% for heavy and very heavy defoliated trees, 50% for moderated defoliated trees and 37% for light defoliated trees.

Discussion

The first aim of this study was to develop biomass growth models for different aboveground components (leaves, stem and total biomass) of pine trees. Results showed that $d_{0.10}$ and h were the best predictor variables when used in conjunction, in contrast to the d^2h variable tested by Mikšys et al. (2007). The validation process did confirm this option. The most difficult variable to model was leaf biomass (R^2=0.74), since young pine trees are shown to have very heterogeneous crowns. Indeed, the crown of oldest trees tend to become more homogeneous. Stem biomass tended to be much more homogeneous (R^2=0.84), being possible to obtain more precise models for stem and total biomass estimation. Since total biomass combines the effect of both leaves and stem in biomass calculation, the evaluation of the effect of the pine processionary moth on biomass growth was assessed using the total biomass model.

The second goal was to evaluate potential biomass increment after defoliation by the pine processionary moth. Results indicated that the degree of defoliation was a decisive factor in tree biomass increment. Losses of about 49% in biomass increment were observed in moderately defoliated trees (class 2) while losses of about 71-73% were registered in heavily attacked trees (classes 3 and 4; class 4 comprised completed defoliated trees). Moderately defoliated trees values were in agreement with those determined by Markalas (1995), but in completely defoliated trees, the impact was higher. Our results also show that the consequences of *T. pityocampa* activity can be detected immediately after the attack, with biomass losses reported in the same year as the infestation. Carus (2004) also found a sharp decline in host pine growth during and directly after a pine processionary outbreak. However Laurent-Hervouet 1986 reported a decrease in ring growth in the year following defoliation. This may be due to tree physiology, since the total biomass responds in a different way than tree ring growth. However, we realize that these conclusions are the result of a simplistic approach of the problem. The ecosystem and its dynamics are much more complex than we had assumed. While the present study was exclusively focused on the arboreal stratum, next stages should also analyse the impact on tree defoliation on shrubs biomass dynamics. We need to understand how defoliation of trees, increasing light received by the understorey, can lead to an increment of shrubs biomass. Furthermore, we must consider that the presence of defoliating insects on the tree canopy can increases nutrients input on top soil layers, changing its composition. For example, Lovett et al. (2002) has concluded that insect defoliation represents a major perturbation to the internal N cycle of the forest, but this perturbation primarily causes a redistribution of N within the ecosystem rather than a large loss of N. Therefore, among the topics that deserve further research are the impacts of the pine processionary moth on the biomass dynamics of the entire ecosystem.

Conclusions

In conclusion, this work clearly shows that allometric models can be used to estimate the impact of insects on forest dynamics. Furthermore, results showed that the negative effects of insect attack on the biomass growth are visible in the same year at the occurrence of defoliation with a reduction of the biomass increment that is directly proportional to the intensity of the attack.

So far, there was only a notion that attack by the pine processionary moth had an important impact on the *Pinus* forests biomass growth. However, our results provide a tool to economically quantify these impacts. This information is important for forest owners and managers, due to the high economic importance of *Pinus* forest and the potential effect of these impacts on the Portuguese economy. Results from this study indicate that after heavy defoliation, losses can represent around 100 € per hectare, that means 12.6 million € for the entire country.

However, this problem cannot be analysed only from an economic point of view since the ecological importance of these attacks is also relevant. The conservation of pine forests requires appropriate management techniques to counterbalance the negative effects of *T. pityocampa*. Forestry personnel should carefully plan all the new pine plantations and the ecological range of the species should be adhered to avoid additional tree stress, thereby preventing insect attacks.

Further studies should be carried out in order to better understand these phenomena, taking into account uncertainties such as the effect of climate change, which would expose forest stands to even greater stress.

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