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Climate change and forest plagues: the case of the pine processionary moth in Northeastern Portugal

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Abstract

The pine processionary moth, *Thaumetopoea pityocampa* (Den. & Schiff.) (Lep., Thaumetopoeidae) is known as the most defoliating insect in *Pinus* and *Cedrus* in many countries. In the last three decades, climate change has led to a substantial expansion of its range and high attack rates in previously unaffected areas were observed. A 3-year analysis of the effect of several climatic elements on the *T. pityocampa* adult emergence was made and one climatic change scenario was tested in order to predict the insect's behaviour in the future. Results showed that mean air temperature was the climatic element with the best single regression fit to adult emergence, whereas minimum air temperature and relative humidity provided the best multiple regression fits. Results also demonstrated that higher emergence of adults is often related to a maximum temperature above 30°C, a mean temperature above 23°C, a minimum temperature above 17°C, relative humidity lower than 60% and precipitation values lower than 10 mm. Using the same thresholds for future climatic conditions simulated by the COSMO-CLM model, the period for pine processionary moth emergence will be expanded, starting much sooner. Contrasting with the actual emergence period, the insect is projected to have favorable climatic conditions to start emerging in May. This might have serious implications in forest ecosystems, concerning not only ecological issues, but also forest management.

Key words: *Thaumetopoea pityocampa*; mean air temperature; relative humidity; simulation under climate changed scenarios.

Resumen

Cambio climatico y plagas forestales: el caso de la procesionaria del pino en el noreste de Portugal

La procesionaria del pino, *Thaumetopoea pityocampa* (Den. & Schiff.) (Lep., Thaumetopoeidae), es conocido en muchos países como el insecto más defoliador de *Pinus* y *Cedrus*. En las últimas tres décadas el cambio climático ha originado una considerable expansión de su rango de distribución y aumentado la proporción de ataques en áreas previamente no atacadas. Durante tres años fue realizada una monitorización de los efectos de diversos elementos climáticos sobre la emergencia de los adultos de *T. pityocampa* y un escenario de cambio climático fue testado con el fin de predecir el comportamiento de los insectos en el futuro. Los resultados revelan que la temperatura media del aire es el elemento climático que más contribuye en la regresión simple para explicar la emergencia de adultos, seguidos de la temperatura mínima del aire y la humedad relativa. Nuestros resultados también demostraron que el aumento de emergencia de adultos estaba a menudo relacionado con temperaturas máximas superiores a 30°C, temperatura media por encima de los 23°C, temperatura mínima por encima de 17°C, humedad relativa inferior al 60% y valores de precipitación inferiores a los 10 mm. Atendiendo a los resultados para eses umbrales climáticos y el modelo de CLM, el periodo de emergencia de la procesionaria de pino se extenderá, comenzando mucho antes. En contraste con el actual periodo de emergencia, el insecto tendrá condiciones climáticas favorables para comenzar a emerger en Mayo. Esto tendrá consecuencias graves para los ecosistemas forestales no sólo al nivel de las cuestiones ecológicas, sino también para la gestión forestal.

Palabras clave: *Thaumetopoea pityocampa*; la temperatura media del aire; humedad relativa; simulación de escenarios climáticos.

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Introduction

The impact of climate change differs between geographical regions and its effect on ecosystems varies with the extent of temperature increase, changes in irradiance and UV-B levels and changes in the amounts and spatial patterns of precipitation and humidity (Netherer and Schopf, 2010). As poikilothermic animals, insects are strongly affected by climatic elements in all stages of their life. Changes in temperature and precipitation will directly affect their survival, dispersal, reproduction, development and geographical distribution (Bale *et al.,* 2002) or, indirectly, through the behavior of competitors and natural enemies that control the abundance of potential pests. Furthermore, changes in abiotic factors can alter host phenology and chemistry in ways that influence resistance to herbivores and pathogens (Yang and Stamp, 1995; Masters *et al.*, 1998; Ayres and Lombardero, 2000).

The pine processionary moth *Thaumetopoea pityocampa* (Den. & Schiff.) (Lepidoptera, Thaumetopoeidea) is one of the most destructive insects of *Pinus* and *Cedrus* in Portugal, as well as in other Mediterranean countries. The pine processionary caterpillar is nocturnal in feeding and nest building. In Portugal, the adult moths emerge during summer, between late June and mid-August (Arnaldo, 2003). Larval development has five stages and, at the end of the fifth stage, the caterpillars leave the tree in a head-to-tail procession and pupate into the soil. Emergence may take up to a year, depending on climatic conditions. This insect is responsible for significant economic damage due to severe defoliation (Buxton, 1983; Devkota and Schmidt, 1990; Kanat *et al.,* 2005; Arnaldo *et al.,* 2010), while the urticant hairs of the late instar larvae provokes serious reactions in humans and other mammals (Lamy, 1990; Oliveira *et al.,* 2003).

T. pityocampa is a winter feeding insect and, thus, temperature during the cold period is its main survival factor. According to Huchon and Démolin (1971), the expansion of the pine processionary was manly determined by winter air temperature (mean January minimum temperature above –4°C; lethal low temperature of –16°C). However, in the last three decades, warmer winters have led to a substantial expansion of its range, in both latitude and altitude (Benigni and Battisti, 1999; Goussard *et al.,* 1999; Hodar *et al.*, 2003; Hodar and Zamora, 2004). Battisti *et al.* (2005) attributed the range expansion to increased winter survival due to winter warming. This has also resulted in high attack rates in areas that were previously almost unaffected by the insect (Stastny *et al.,* 2006).

Not only is larval survival affected by climate factors, but the diapause period differs between geographical regions. In a Mediterranean-like climate, *T. pityocampa* avoids high summer temperatures by having a longer pupal diapause period, thereby postponing adult emergence until late summer, when conditions for egg and larval development are more favorable. In colder climates, the diapause period is shorter and emergence occurs earlier in summer. Such adaptation allows sufficient time for larval development and nest building before temperatures drop to freezing (Battisti *et al.,* 2005).

Lindner *et al.* (2008) identified the rising of temperatures in combination with decreasing amounts of precipitation (gradually warmer and drier summers) as key climate change factors in Mediterranean climates, however, Carus (2004) refers that outbreaks of the pine processionary moth appear to be associated with dry winter-spring conditions prior to the autumn-winter feeding period.

Climate cannot be predicted, but climatic elements can be estimated or projected using climatic models. In the IPCC (*Intergovernmental Panel on Climate Change*) Special Report on Emissions Scenarios ((Nakiçenoviç *et al.* 2000), a set of emission scenarios —the so-called SRES scenarios— was defined. The emission scenarios are labeled according to likely pathways of human-development and population growth and represent the different storylines of the anthropogenic radiative forcing. The A1B SRES scenario corresponds to an intermediate anthropogenic forcing and to plausible levels of human-driven climate change. It was chosen for the present analysis.

Therefore, the aims of the present study are twofold: (a) to analyze the possible effect of several climatic elements on the adult emergence of the pine processionary moth in Northeastern Portugal; (b) to understand the behavior of this insect in future climatic conditions under the A1B scenario. The outcomes of this study are of utmost relevance to forest ecosystems and to future forest management.

Material and methods

Study site

The present study was conducted in the Natural Park of Montesinho, located in Trás-os-Montes, a mountainous region in northeastern Portugal. The Park (with an area of 74,800 ha) is situated in the «Terra Fria Transmontana» climatic zone, characterized by warm and dry summers, moderately cold winters (annual mean temperature around 11°C) and precipitation occurring mainly during autumn (annual mean precipitation about 900 mm). The area comprises pure stands of several pine species; *Pinus pinaster* Ait. and *P. nigra* Arn. are the dominant species, while *P. sylvestris* L. and *P. strobus* L. are secondary species.

In order to assess the adult emergence of the pine processionary moth, three 13-year-old *P. pinaster* plots with a density of 650 trees per hectare were set up. In June of 1998, 1999 and 2000, four pheromone traps per plot were installed (4 traps × 3 plots = 12 pheromone traps per year). Adult males were captured and weekly registered until September 1998, 1999 and 2000. Adult emergence data defined the flight activity of the insect.

During the same period, weather data was recorded near the study site (10 km). The distance between the experimental plots and the meteorological station cannot be an important source of error, as weather conditions are unlikely to vary significantly over this small geographical scale, particularly when considering weekly means. The following meteorological parameters were recorded and used here: minimum (Tmin) and maximum (Tmax) temperature, relative humidity (RH), precipitation (Prec) and wind (Wind). Daily mean temperature (Tmean) was obtained by averaging Tmin and Tmax.

Statistical analysis

Since the mean number of adults per trap had a skewed distribution with many zero values, the exclusion of early and late weeks of the flight period were made and data were log (x + 1) transformed. Thus, the analysis was made by using a 3-year dataset of weekly (29^{th} to 41^{th}) adult captures. Pearson correlation coefficients were calculated between adults and the six climatic elements studied. Simple linear and multiple linear regression analysis between the pine processionary moth emergence (dependent variable) and the climatic elements (independent variable) were carried out to explore the likely effects of climate on the adult activity of this insect. A skilful regression model might then be used to model/predict the emergence behavior. The analysis was undertaken by year and also for the full 3-year data set. All assumptions of these regression models were properly validated.

The percentage of adults captured in different classes of the climatic variables was also calculated in order to explain changes in flight activity and consequently define upper and lower thresholds for the upcoming analysis. In order to explain any possible relationships between the adult captures and the climatic variables, a Categorical Principal Component Analysis (CATPCA) was performed for the categorized variables, with classes defined upon the aforementioned thresholds.

Each climatic element was categorized in three categories concerning the obtained threshold limits: weekly minimum temperature (Tmi) with values under 11°C (Tmi – 11), and above 17°C (Tmi + 17); weekly mean temperature (Tme) with values under 17°C (Tme – 17), and above 23°C (Tme + 23), relative humidity (RH) with values under 60% (RH – 60) and above (RH + 70); and total weekly precipitation (Pr) under 10 mm (Pr – 10) and above 50 mm (Pr + 50). Adults emergence was categorized in 4 categories: weekly number of adults captures by trap lower than 10 (Ad – 10), between 10 and 25 (Ad), between 25 and 50 (Ad 25 – 50) and above 50 (Ad + 50).

Climatic characterization of the study region and future climate estimation

The climate of the target region was characterized using time series with records over the last 20 years. Mean air temperature and precipitation were selected as they are the most important elements in characterizing the climate of a given region (Peixoto and Oort, 1972). Although the actual emergence period of the pine processionary moth occurs mainly in July-August, the climate characterization is based on annual values over the last 24-year period. These values are then compared to secular data recorded in the region and for the period May-September in order to detect favorable and unfavorable adult emergence periods.

Based on the previously defined climate characteristics of the target region, a climate change projection for the *T. pityocampa* behavior in the period 2011-2031 was developed. This projection is based on simulations produced by the state-of-the-art regional climate model COSMO-CLM (Consortium for Small-Scale Modelling – Climate version of the Lokal-Model; Böhm *et al.,* 2006; Rockel *et al.,* 2008). The COSMO-CLM is nested in the ECHAM5/MPI-OM1 global circulation model for both past and future climate conditions (Roeckner *et al.,* 2006) and the A1B emission scenario is used here (cf. Lautenschlager *et al.*, 2009). Several previous studies have already applied data simulated by the COSMO-CLM to a wide range of research purposes, including studies of viticultural zoning and grapevine yield in Portugal (Santos *et al.*, 2010; Malheiro *et al.*, 2010). As the model output is available over a regular grid of 0.165° latitude × 0.165° longitude (grid size of about 18 km), data was extracted only for the grid point closest to the target area.

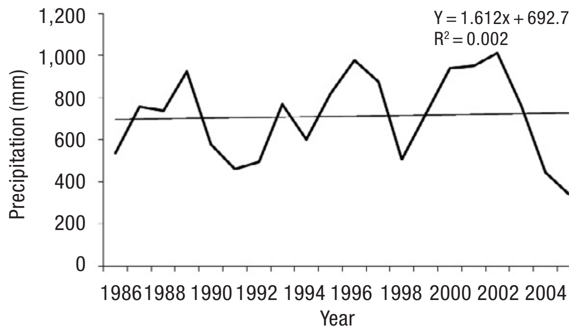

Figure 2. Chronogram of the precipitation at Bragança.

Results

A mean value of 12.7°C, with a minimum of 11.4°C in 1993 and a maximum of 13.5°C in 1995 can be observed. The linear trend is about 0.01°C per year (Fig. 1). Further, the annual total precipitation series shows a mean value of about 700 mm, with a minimum of 339 mm in 2005 and a maximum of 1,011 mm in 2002. The linear trend is of 1.6 mm per year (Fig. 2). As shown below, the air mean temperature plays a key role in the analysis of the flight activity.

The flight activity of the pine processionary moth and its relation to each of the six climatic elements under analysis during the 29^{th} to 41^{st} weeks in 1998-2000 is shown in Figure 3. The Pearson product-moment correlation coefficients for the 3-year dataset reveal that the presence of the insect is positively correlated with Tmin (0.78), Tmax (0.78) and Tmean (0.80), at a significance level of 1%. Conversely, the insect flight is negatively correlated with RH (–0.69), at the same significance level. Correlations with wind speed are less significant (0.40; $p < 0.05$), though higher wind velocities tend to correspond to lower numbers of adult emergences. No significant correlations were found for the precipitation. Annual correlation coefficients are also plotted in Figure 3.

The simple linear regression models adjusted to the full 3-year dataset are largely similar to those adjusted to each year separately. No significant linear regression models were found between *T. pityocampa* and the wind speed in 1998 and 2000 or the precipitation in all studied years. The best simple linear fit to the mean number of adult emergence is obtained for Tmean (linear regression ANOVA: $F(1,37) = 67.327$; $p < 0.001$; $R = 0.803$; $R^2 = 0.645$) and the equation is:

$$\text{Number of adults} = -2.728 + 0.303\text{Tmean}$$

In the multiple linear regression models, although Tmean was expected to be the leading variable, due to its highest correlation with adults, it was found that Tmean excluded all the other climatic variables through multicolinearity. Several multiple regression models, with subsets of independent climatic variables, were thus applied. In this way, results showed that RH and Tmin are the most skilful variables in explaining mean number of *T. pityocampa* adult emergence (multiple regression ANOVA: $F(2,36) = 37.208$; $p < 0.001$; $R = 0.821$; $R^2 = 0.674$) and the corresponding equation is:

$$\text{Number of adults} = 1.984 - 0.041\text{RH} + 0.282\text{Tmin}$$

The Categorical PCA ordination isolated two initial axes that explain 67.7% and 20.3% of the interrelationship between climatic variables (Tmean, Tmin, Prec, RH) and adults. The reliability of the first axis was given by a Cronbach's alpha of 0.881 (Table 1).

The two climate groups in the Figure 4 characterize the summer weekly climate variability during the study period. In the first axis, a group composed by classes with high Tmin (Tmi, Tmi + 17) and Tmean (Tme, Tme + 23), low RH (RH – 60) and a class with low precipitation (Pr – 10) is in opposition to a second group composed by classes with low temperatures (Tmi – 11, Tme – 17), high RH (RH + 70) and high precipitation (Pr + 50). The cat-PCA joint plot highlights these thresholds, as the relationship between the climatic variables and the adult emergences is apparent. Results

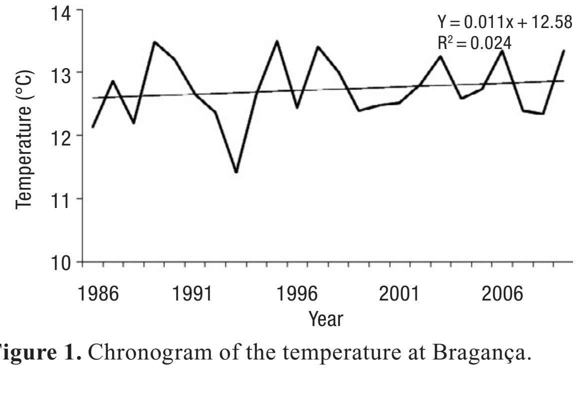

Figure 1. Chronogram of the temperature at Bragança.

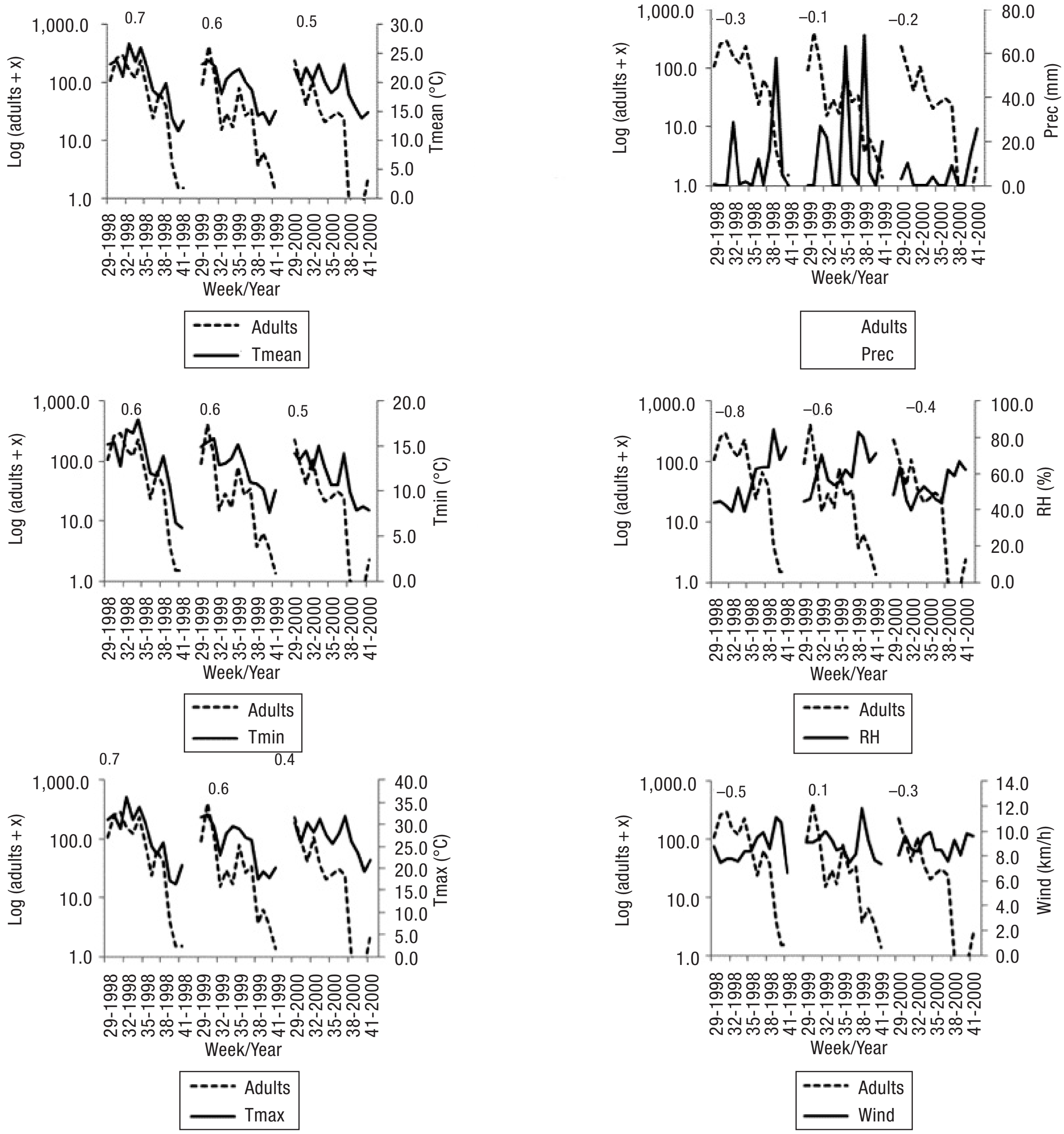

Figure 3. Emergence pattern of T*haumetopoea pityocampa* and its relation with the climatic elements (Pearson coefficients are given above each year curve).

Table 1. Summary statistics of the Categorical Principal Component Analysis (Cat-PCA)

Axes	1	2	Total
Eigenvalues	3.386	1.013	6.889
Cumulative percentage of represented variance	67.714	20.269	87.983
Cronbach's Alpha	0.881	0.017	0.966

clearly demonstrate that emergence of adults are often related and vary in the same direction as Tmean and Tmin. Higher emergences are expected to occur for Tmean above 23°C, while lower emergences are expected to occur for Tmean below 17°C.

Results of the CLM model under the A1B scenario were analyzed in order to estimate the temporal variability of monthly air temperature for the next 20 years (Fig. 5). The linear trend is of 0.05°C per year for the

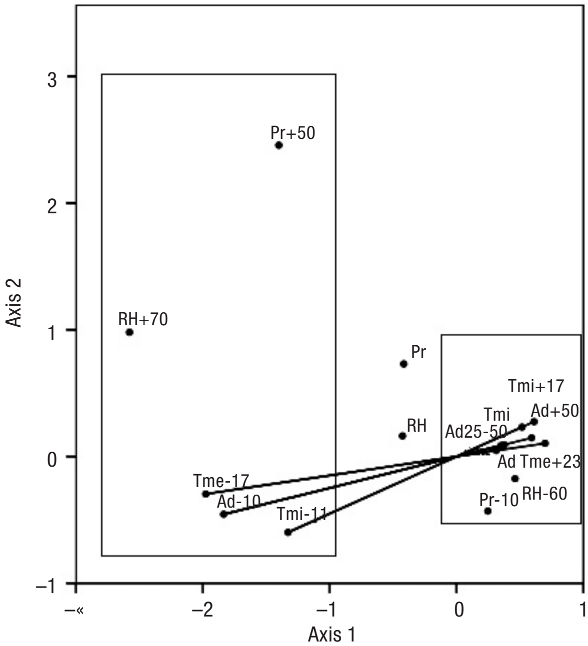

Figure 4. Axes 1 and 2 of the Cat-PCA for the climatic studied elements and the emergence of *Thaumetopoea pityocampa* adults. (The two groups defined are indicated in boxes and lines define the directions of classes of temperature variables and adults emergence).

entire selected period, with determination coefficients of 55% for July and August and 51% for September.

From the previously determined thresholds, values of Tmean of 17°C (lower threshold) and of 23°C (upper threshold) are used to analyze the future flight pattern of *T. pityocampa*. Results suggest that while in the recent-past (Fig. 6a) air temperatures in July-August only reach the upper threshold a few times, for the next two decades (Fig. 6b) July will be a month with air mean temperatures permanently higher than the upper threshold, contributing to a permanent presence of the insect and August will also have long periods favorable

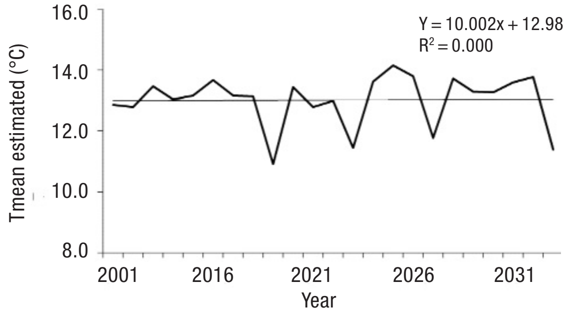

Figure 5. Characterization of the region for the next 20 years (A1B scenario).

to high values of *T. pityocampa* emergences. Changes in September mean temperatures are less significant than for July and August.

Other months close to the July-September period were also analyzed (Fig. 7a and b) in order to detect favorable/unfavorable adult emergence periods. May mean temperatures for the last two decades was permanently lower than the 17°C threshold, contrasting with the pattern for the next two decades, when important periods with temperatures over this threshold are projected to occur, showing the possibility of moderate flight activity. June mean temperatures for the last two decades are almost always between the upper and lower thresholds, while for the next two decades, temperatures will often be higher than the 23°C threshold, showing the possibility of intense flight activity during June. April and October (not shown) are projected to present air temperatures permanently lower than the 17°C threshold.

Discussion

For organisms in which population dynamics is mainly controlled by temperature, positive direct

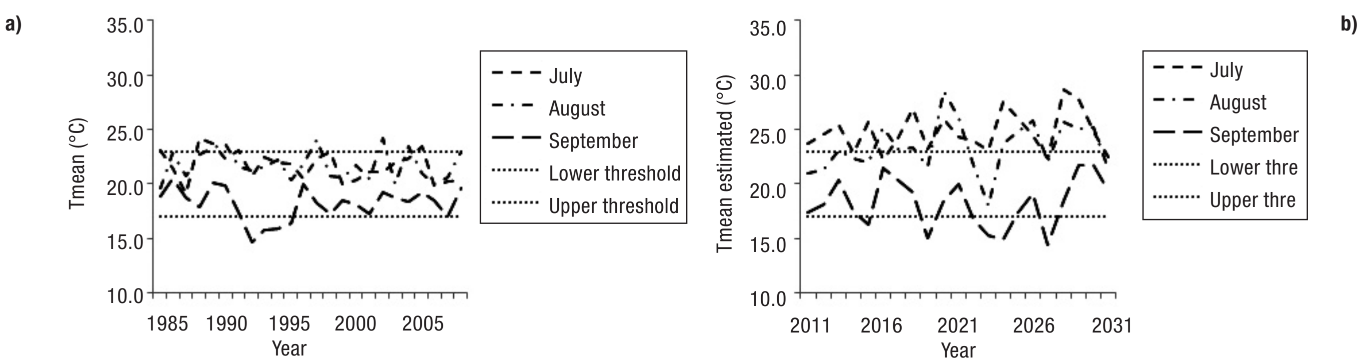

Figure 6. Air mean temperature recorded at the July-September period. a) during the last 24 years and b) during the next 20 years. Lower and upper threshold are 17°C and 23°C, respectively.

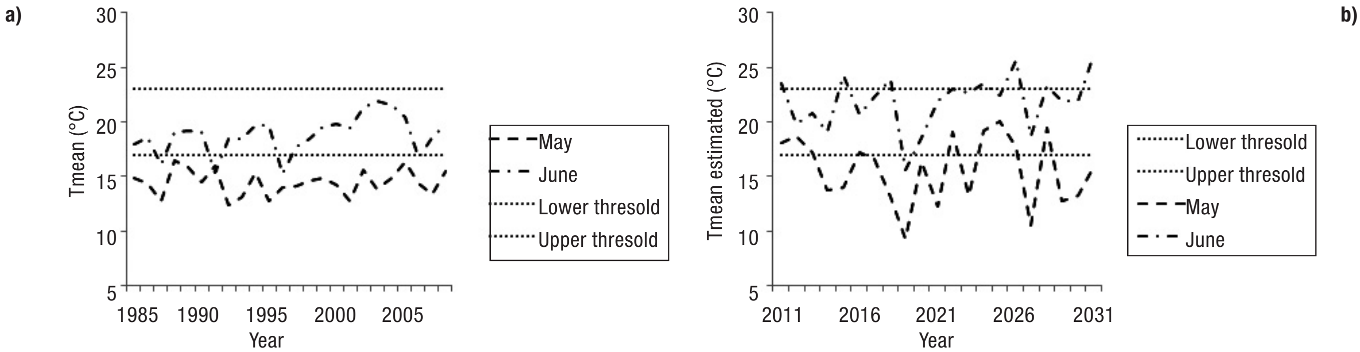

Figure 7. Air mean temperature recorded at May and June. a) during the last 24 years and b) during the next 20 years. Lower and upper threshold are 17°C and 23°C, respectively.

responses to an increase in temperature are expected as long as the stagespecific thresholds for development are not exceeded (Robinet and Roques, 2010). In fact, temperature was the main climatic element that explained adult emergence under analysis during the 29th to 41st weeks of 1998 to 2000. However, relative humidity was also important in that relation; when combined with temperature, about 80% of the variance is explained. It is quite common to observe fewer butterflies on rainy days, but no significant correlation was found between adult emergence and precipitation. This might be owed to the precipitation dataset used on the analysis. Further studies concerning this climatic element should be undertaken.

By determining an upper and lower threshold in temperature for adult emergence, we are able to predict the pattern of the population flight behavior in the future. Battisti *et al.* (2006) refer that as global warming continues, climatic extremes are predicted to become more frequent and their relevance to the range formation of phytophagous insects will be higher. However, according to our future projections for *T. pityocampa*, temperature anomalies will be continuously favorable to an adult, as this implies an earlier and longer flight activity period, probably from May to September. Therefore, development rates are likely to be accelerated with sooner egg position and sooner defoliation action by the larvae. The implications for the growth of the pine plantation will be even more severe because the tree is still active.

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