A peer-reviewed version of this preprint was published in PeerJ on 28 February 2019.

View the peer-reviewed version (peerj.com/articles/6530), which is the preferred citable publication unless you specifically need to cite this preprint.

https://doi.org/10.7717/peerj.6530
Winter temperature predicts prolonged diapause in pine processionary moth across its geographic range

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Corresp. 1

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Prolonged diapause occurs in a number of insects and is interpreted as a way to evade adverse conditions. The winter pine processionary moths (Thaumetopoea pityocampa and Th. wilkinsoni) are important pest of pines and cedars in the Mediterranean region. They are typically univoltine, with larvae feeding across the winter, pupating in spring in the soil and emerging as adults in summer. Pupae may, however, enter a prolonged diapause with adults emerging one or more years later. We tested the effect of spatial variation in winter temperature on the incidence of prolonged diapause, using a total of 64 individual datasets related to insect cohorts over the period 1964-2015 for 36 sites in 7 countries, covering most of the geographic range of the species. We found high variation in prolonged diapause incidence over the species’ range. Insect cohorts exposed to average winter temperatures lower than 0°C were associated with higher prolonged diapause incidence than cohorts exposed to intermediate temperatures. Prolonged diapause may represent a risk-spreading strategy although it is associated with high mortality because of a longer exposure to mortality factors, desiccation, and energy depletion. Climate change, and in particular the increase of winter temperature, may reduce the incidence of prolonged diapause at the colder sites whereas it may increase it at the warmer ones, with consequences on the population dynamics.
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Running head: Prolonged diapause ecology
Abstract

Prolonged diapause occurs in a number of insects and is interpreted as a way to evade adverse conditions. The winter pine processionary moths (*Thaumetopoea pityocampa* and *Th. wilkinsoni*) are important pests of pines and cedars in the Mediterranean region. They are typically univoltine, with larvae feeding across the winter, pupating in spring in the soil and emerging as adults in summer. Pupae may, however, enter a prolonged diapause with adults emerging one or more years later. We tested the effect of spatial variation in winter temperature on the incidence of prolonged diapause, using a total of 64 individual datasets related to insect cohorts over the period 1964-2015 for 36 sites in 7 countries, covering most of the geographic range of the species. We found high variation in prolonged diapause incidence over the species’ range. Insect cohorts exposed to average winter temperatures lower than 0°C were associated with higher prolonged diapause incidence than cohorts exposed to intermediate temperatures. Prolonged diapause may represent a risk-spreading strategy although it is associated with high mortality because of a longer exposure to mortality factors, desiccation, and energy depletion. Climate change, and in particular the increase of winter temperature, may reduce the incidence of prolonged diapause at the colder sites whereas it may increase it at the warmer ones, with consequences on the population dynamics.
Introduction

Although diapause is recognized as a common strategy among insects to overcome unfavourable periods, prolonged diapause spanning more than one year remains hardly studied (Danks, 1987; Soula and Menu, 2005). In general, diapause represents a break in development maximising the chance to survive predictably adverse conditions (Tauber et al., 1986). By contrast, the expression of prolonged diapause varies within a population or cohort and is generally considered as a way to spread the risk due to variably unfavourable conditions amongst years (Menu et al., 2000). If organisms can use a signal to predict an unfavourable condition, which affects fitness consequences, phenotypic plasticity evolves (Pigliucci, 2001). In contrast, if any unfavourable condition can’t be measured or predicted using any signal, a genotype can increase the fitness of the organisms employing the tactic of “risk-spreading” (den Boer, 1968) or “bet hedging” (Slatkin, 1974). In an uncertain fluctuating situation, bet hedging tactic wins over other tactics because it avoids worst-case scenarios (i.e., prolonged diapause in the pine processionary moth may avoid the extinction of an entire cohort in the event of an extremely cold winter) and reduces between-individual variance in fitness by increasing their geometric mean fitness in the long run (Seger and Brockmann, 1987; Starrfelt and Kokko, 2012).

Prolonged diapause, however, can cause increased mortality (Sims, 1983), likely due to longer exposure to adverse factors and enemies, as well as reduced performance (Matsuo, 2006) related to extended energetic expenditure (Hahn and Denlinger, 2007).

If resource availability or some other essential environmental factors show a strong multiannual cyclic component, all individuals in a population may enter in prolonged diapause (Powell, 1974). Cohort splitting (a mixture of individuals with and without prolonged diapause) may occur in a relatively “fine grained” environment. Prolonged diapause can be induced either
density dependently or density independently. Whether current or parent generation is in control of diapause also determines the outcome of a diapause type. If the diapause is independent of population density and individuals are in control of the fate, chance of occurring prolonged diapause is limited. But, when parents control the fate of offspring in a density independent diapause occurrence, prolonged diapause becomes useful. In this case, mixture of offspring with and without prolonged diapause should be same for all the females in a population. The mixture should reflect highest fitness in the particular environment. If induction of diapause is density dependent and either individuals or parents are in control, prolonged diapause should occur. Females in this case may have different mixture of individuals with and without prolonged diapause (Hanski, 1988).

In Europe, Middle East, and Northern Africa, the winter pine processionary moth is represented by two sister species, *Thaumetopoea pityocampa* and *Th. wilkinsoni* (Lepidoptera, Notodontidae), which are pests of conifers and a threat to human and animal health because of urticating setae (Roques, 2015). Larvae feed during winter and generally adopt a univoltine life cycle, with the exception of Corsica where *Th. pityocampa* is strictly semivoltine (Geri, 1983). Temperature influences the duration of both larval and pupal stages (Démolin, 1969; Berardi et al., 2015; Robinet et al., 2015). Completing the development in silk tents, larvae leave the host tree in a typical head-to-tail procession in search of a pupation site in the soil. Burying 5–20 cm into the soil, they spin a cocoon and enter a phase of prepupal diapause, with the duration varying from 20 to 50 days (Salman et al., 2018). Breaking the prepupal diapause, they turn into pupae and enter pupal diapause, with the length varying from 1 month at high elevation/latitude to 5 months at low elevation/latitude. This variation in the length of pupal diapause occurs to match the local conditions for optimal development (Démolin, 1969). Moths generally emerge in
summer, but a variable fraction of the individuals may postpone their emergence and enter pupal
prolonged diapause that may span as long as 9 years in _Th. wilkinsoni_ (Halperin, 1990) and 8
years in _Th. pityocampa_ (Salman et al., 2016).

The mechanisms of prolonged diapause induction and maintenance in the winter pine
processionary moth are unknown. However, a phenology-based model suggests that prolonged
diapause in the pine processionary moth is a developmental strategy to cope with adverse
temperature conditions, at both ends of the scale (Démolin, 1969). Additionally, factors such as
soil moisture (Torres-Muros et al., 2017), food quality, population density, and natural enemies
(Geri, 1983) have been invoked to be linked to prolonged diapause, although without clear
support. Battisti et al. (2005) have identified the temperature of the so-called ‘cold period’
(December-January-February) as key predictor for larval survival, and thus for the successful
establishment of the insect in the expansion range associated with climatic change at both high
elevation and latitude.

Here, to test the temperature hypothesis reported above (Démolin, 1969), we review all
the available evidence of prolonged diapause across the range of _Th. pityocampa_ and _Th.
wilkinsoni_, keeping into account the genetic structure of the group (Kerdelhué et al., 2009; El
Mokhefi et al., 2016) and excluding Corsica populations that are strictly semivoltine. We
specifically test the effect of winter temperature as a driver of prolonged diapause in this species,
and if prolonged diapause implies a cost in terms of mortality. We finally discuss the role of
climate change on prolonged diapause and the potential effects on the population dynamics of
this important pest.
Materials and methods

(a) Data collection

Published and unpublished data were retrieved from scientific databases and from institutional reports provided in the supplementary material (Supplemental file Dataset_S1). Available documents (initial n=42) were screened. Because we predicted winter temperature to be a mechanism causing PD, we only selected studies that included the following criteria: (i) the total number of individuals, (ii) insect collected using one or more of the five methods described below, (iii) the number of moths emerged in the year of collection and in the subsequent year(s), (iv) the number of dead larvae/pupae given for a specific year of sampling (namely a cohort), and (v) the average air temperature of the cold period (December-January-February) of the studied years. Information was obtained for seven countries from a total of 13 documents and 36 sites (Figure 1, Table 1, Supplemental file Dataset_S1). These sites belong to 6 out of 11 genetic subclades of the pine processionary moth described by Kerdelhué et al. (2009) and El Mokhefi et al. (2016) (Figure 1) and cover most of the climatic range of the species (Roques, 2015). The data span a latitude from 31.3° N to 47.8° N and longitude from -7.9° to 35.2° (Figure 1), and an elevation from 10 to 1910 m. For 11 sites, more than one year of observations was available, giving a total of 64 individual datasets on the occurrence of prolonged diapause.

For the year(s) of sampling, the temperature of each site was collected from the source document (n = 41) or from records of the nearest weather station (n = 23) (Supplemental file Dataset_S3). As average monthly temperature of the cold period (December-January-February) (Battisti et al., 2005; Roques, 2015) was available for all datasets, it was used for the analysis. For those sites with both average and minimum temperature, the correlation between the two
predictors was very strong ($R^2=0.94$), indicating that the choice of the metric did not affect the results.

The mortality percentage was calculated as the number of individuals that did not produce moths with respect to the initial number of individuals in the cohort. The prolonged diapause percentage was calculated as the number of individuals that emerged over the year(s) following the year of pupation, or that were still alive when the experiment was over one or more years after pupation (emerged after prolonged diapause + living pupae at the last check), with respect to the total number of emerged or living individuals (emerged univoltine + emerged after prolonged diapause + living pupae at the last check).

Studies spanned an extended period (from 1964 to 2015) and geographic locations (Figure 1, Table 1, Supplemental file Dataset_S1). Five major collection and rearing methods were used. (i) Mature larvae in the pupation procession on the ground were followed in the field. Pupation sites of the larvae were marked and flagged. When the individuals pupated, pupae were dug out of the soil and taken to laboratory and kept in single vials for future observations. (ii) Mature larvae in pupation procession were collected in the field and forced to pupate in pots. After the emergence of the 1st year, leftover alive pupae were kept in vials for further observation in the following year(s). (iii) Mature larvae were intercepted on the tree stems during their way down to the ground with collar traps. Larvae were forced to pupate either in bags or pots, both filled with soil, on site or at laboratory. After the pupation, the pupae were individually kept in single vials and observations made. (iv) Tents full of mature larvae were collected in the field. They were kept either in covered pots filled with soil or in cages with appropriate mesh netting, individually or in group. After the moths emerged, pots/cages were checked, outcome recorded, and observations continued with leftover alive pupae undergoing prolonged diapause. (v) Large
cages were constructed in the field and filled with tents of 4th or 5th instar larvae. Larvae were provided with fresh pine branches and left to feed needles ad libitum. Upon feeding, larvae pupated in the soil. Observations were made until emergence was not observed for three years.

(b) Data analysis

To test the effect of temperature on prolonged diapause incidence, we used a linear mixed-effect model (Supplemental file Dataset_S2). The model included the linear, quadratic and cubic terms of temperature as fixed effects and site nested within genetic subclade as random effects. We omitted one data point using the Cook’s distance (value >5). This very influential point was related to the maximum observed mean temperature. The consideration of subclade and site as random effects accounted for the biological and spatial dependence in the data. It is important to stress that our model tested primarily the effect of spatial variation in winter temperature across the species range, and only secondarily the inter-annual variation in temperature within the sites. The analyses were run using the nlme package in R (Supplemental file Dataset_S3) (R Core Team 2016). A model with the same random structure was used to test the association between the incidence of prolonged diapause and pupal mortality.

Results

Prolonged diapause occurred in all genetic subclades of Th. pityocampa and Th. wilkinsoni for which data were available (Figure 2a). All the 37 sites showed at least one year with occurrence of prolonged diapause, and only 5 out of 65 individual datasets or cohorts did not show occurrence of prolonged diapause. The incidence of prolonged diapause in the first year after
pupation varied greatly among sites and cohorts within sites. The mixed model indicated that temperature affected the incidence of prolonged diapause in a non-linear fashion, i.e. linear \( (t_{1,25} = -5.481, P<0.001) \), quadratic \( (t_{1,25} = 3.687, P=0.001) \) and cubic terms \( (t_{1,25} = -2.395, P=0.025) \) were significant. Cold winters (temperature of December-January-February below 0°C) as well as warm winters (temperature above 10°C) resulted in high prolonged diapause incidence, while prolonged diapause was less frequent at temperatures between 0 and 10°C, irrespective of subclades (Figure 2a). However, the effect at higher temperatures was less pronounced than that at low temperatures. Actually the 5 datasets with no occurrence of prolonged diapause and almost all those with less than 25% of prolonged diapause were observed at temperatures between 0 and 10°C (Figure 2a).

Pupal mortality was positively and significantly correlated to prolonged diapause incidence (Figure 2b). Mortality varied greatly among sites and cohorts within sites. It reached the highest values at both cold (lower than 0°C) and warm (higher than 10°C) winter sites, indicating that cohorts with high incidence of prolonged diapause are more likely to die than those with low incidence of prolonged diapause. In general, mortality rates lower than 25% were associated with low incidence of prolonged diapause, especially in the subclade Rest of Europe. The mortality factors were not systematically addressed in each study, so it was not possible to analyse for these effects.

Discussion

Winter minimum temperature experienced by larvae was found to be a reliable predictor of the prolonged diapause incidence in the processionary moth pupae, as prolonged diapause tends to
increase at both lower and upper ends of the temperature range, although a large variation is observed throughout. The adaptive value of prolonged diapause in this species can be seen at both ends of the temperature range, but for different reasons. At colder sites and years, winter is directly challenging larval survival that depends essentially on suitable feeding conditions (Battisti et al., 2005). Prolonged diapause in this case dilutes the risk of being exposed to unfavourable conditions associated with cold weather among years (Danks, 1987). At warmer sites and years, summer temperatures can impair the development of eggs and young larvae as upper lethal thresholds can be reached (Halperin, 1990; Santos et al., 2011). The relationship with prolonged diapause in pupae is in this case indirect, as winter temperature works as a proxy of another thermal stressor that could become limiting later in the year when moths would emerge and lay eggs. Thus, entering prolonged diapause at the southern edge of the range would also allow risk spreading through time and contribute to persistence of populations (Hanski, 1988). Change of temperature within a few degrees may drastically change the survival rate of a population. This is particularly a problematic for the pine processionary moth in the range edge where temperature is limiting for their survival and spread beyond. In such conditions, temperature may become more limiting any year. Therefore, a certain fraction of individuals always enters prolonged diapause, even at a moderate temperature generally deemed harmless for growth and survival. Had there been any fixed and certain cyclic component available with which pine processionary moth could predict the extreme event of temperature, they would have evolved a fixed life cycle using a fixed number of years with prolonged diapause (as might have happened for the semivoltine population of pine processionary moth in Corsica, Geri 1983). However, unavailability of such component leaves the option of stochastic phenotype switching with frequency of fate depending on the temperature.
Diapause duration could not be tested in this study because most reports did not survey the emergence of the moths for more than 2 years. As durations up to 8-9 years have been found at a few sites (Halperin, 1990; Salman et al., 2016), it could be expected that the intensity of the winter stress would be proportional to the duration of prolonged diapause, causing a longer dilution of the risk in the most severe conditions. It could be also expected that high density of larvae would result in higher incidence of prolonged diapause, as damaged trees may result unpalatable for the larvae of the following generations (Battisti, 1988). This sort of density dependent prolonged diapause would work with different stress mechanism than abiotic stresses, e.g., temperature. Perhaps, the higher the density of larvae, the higher the unpalatability of needles, the longer would be the diapause (Salman et al., 2016). Unfortunately, many studies on prolonged diapause examined here did not report the insect density at the time of the sampling. Other putative factors (such as disease, predation and parasitism) may respond to density variation and thus prolonged diapause can be seen as an escape in time from mortality factors (Hanski, 1988). Most parasitoids and predators of the pine processionary moth are univoltine and cannot track the individuals entering prolonged diapause (Battisti et al., 2000).

Irrespective of the temperature conditions associated with prolonged diapause occurrence, pupal mortality increased with prolonged diapause incidence likely because of a longer exposure to chronic mortality factors (Sims, 1983), desiccation and depletion of the energy reserves (Hahn and Denlinger, 2011). The higher mortality risks associated with prolonged diapause challenge the hypothesis that prolonged diapause of processionary moth pupae represents a diversifying risk-spreading strategy for the species. However, more attention should be given to climatically non-typical years when benefits of such a strategy would be expected, ultimately securing the long term persistence of populations (Menu et al., 2000). Prolonged diapause could also limit the
risks of local extinction after the generally high mortality observed at outbreak density (Salman et al., 2016; Tamburini et al., 2013; Li et al., 2015). Survival, rather than reproduction, is more important in a declining population, and is secured by entering prolonged diapause. However, increased frequency of prolonged diapause helps declining population growth, or population decrease itself causes increased frequency of prolonged diapause is not clear (Hanski, 1988). In addition, the phenology of the pine processionary moth is severely constrained by climatic factors (Robinet et al., 2015), and it could be that in certain years the required physiological conditions to complete univoltine development are not met, thus leaving no alternative to prolonged diapause.

Climate change may affect prolonged diapause in different ways. As winter is experienced in two different life stages, the growing larva and the diapausing pupa, it is likely that their respective vulnerability to stressful conditions differ. Larvae feeding on trees are exposed to low, fluctuating temperatures, but are capable of selecting suitable microclimates and have a silk tent regulating temperature (Battisti et al., 2005), while pupae in the soil are buffered against temperature extremes, but passive. In addition, both stages have complex interactions with precipitations and moisture, and related pathogenic agents (Torres-Muros et al., 2017). Observations carried out between 1999 and 2016 in the coldest edge of the species’ geographical range indicated that prolonged diapause incidence markedly decreased as a consequence of climate warming (Salman et al., 2016). Such changes in prolonged diapause, and related mortality, have to be taken into consideration when modelling population dynamics and range expansion, since prolonged diapause can alter the success of a population in a given area (Li et al., 2015). For example, a reduction of prolonged diapause incidence would make predictions
easier because it will emphasize the role of density-dependent factors, which are important in this species (Tamburini et al., 2013; Toïgo et al., 2017).

Conclusion

Our study has shown winter temperature variation across most of the species range to be an important extrinsic factor for geographic variation in prolonged diapause incidence. Both low and high winter temperature are conducive to high frequency of prolonged diapause in the pupae, likely because different avoidance mechanisms (such as disease, intraspecific competition, predation, parasitism) of lower and upper lethal thresholds, respectively. A number of other factors have to be considered, however, for a better understanding of the physiological mechanism regulating prolonged diapause in the pine processionary moth. Namely, the population density and the nutritional condition of the larvae before pupation may reveal the role of prolonged diapause in the population dynamics of this important defoliating pest.

Acknowledgements

The authors warmly acknowledge Philipp Lehmann for comments on an earlier version of the ms and Paolo Paolucci for drawing the figures. Anonymous reviewers are also warmly acknowledged.

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Table 1: Distribution of the 37 study sites among genetic clades and subclades of pine processionary moths according to Kerdelhué et al. (2009) and El Mokhefi et al. (2016). The time period of sampling and the pine host species are also given.

Figure 1: Sites used for the analysis of prolonged diapause at the pupal stage, indicated with coloured dots within each species and subclade of the pine processionary moth (a), and tree of genetic structure based on Kerdelhué et al. (2009) and El Mokhefi et al. (2016) (b). Data were not available for the subclades indicated in black.

Figure 2: (a) Relationship between the daily mean temperature during the cold period of the larval development (December, January, and February) and the percentage of prolonged diapause in the cohorts of pupae originating from larvae experiencing those temperatures. The fitted line represents predictions of a mixed model including subclade and site as random effects (Diapause = 80.39 -28.69 Temp + 3.96 Temp^2 - 0.15 Temp^3 , all terms P<0.05, n=64).

(b) Relationship between the percentage of individuals entering prolonged diapause and the pupal mortality observed in the first year of prolonged diapause. The fitted line represents a prediction of a mixed model including subclade and site as random effects (Mortality = 37.88 + 0.364 Diapause, P<0.001, n=62).
<p>| Distribution of the 37 study sites among genetic clades and subclades of pine processionary moths according to Kerdelhué et al. (2009) and El Mokhefi et al. (2016). The time period of sampling and the pine host species are also given. |</p>
<table>
<thead>
<tr>
<th>Clade</th>
<th>Subclade</th>
<th>No. of sites</th>
<th>Years</th>
<th>Host plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th. pityocampa</td>
<td>Rest of Europe</td>
<td>14</td>
<td>1971-2015</td>
<td>(Pinus) brutia, P. halepensis, P. nigra, P. pinaster</td>
</tr>
<tr>
<td>Th. pityocampa</td>
<td>N/W Algeria, N Morocco</td>
<td>13</td>
<td>1988</td>
<td>P. halepensis</td>
</tr>
<tr>
<td>Th. pityocampa</td>
<td>S Algeria, S Morocco</td>
<td>3</td>
<td>1988-1995</td>
<td>Cedrus atlantica, P. halepensis</td>
</tr>
<tr>
<td>Eastern North Africa</td>
<td>N/E Algeria, Tunisia</td>
<td>4</td>
<td>1983</td>
<td>P. halepensis</td>
</tr>
<tr>
<td>Th. wilkinsoni</td>
<td>Israel, Lebanon, E Turkey</td>
<td>3</td>
<td>1964-1970</td>
<td>P. halepensis</td>
</tr>
</tbody>
</table>
Figure 1 (on next page)

Location of the study sites in relation to the distribution of the pine processionary moth

Sites used for the analysis of prolonged diapause at the pupal stage, indicated with coloured dots within each species and subclade of the pine processionary moth (a), and tree of genetic structure based on Kerdelhué et al. (2009) and El Mokhefi et al. (2016) (b). Data were not available for the subclades indicated in black.
Species / Major clades

- Th. pityocampa
- Th. wilkinsoni
- Eastern North Africa

Corsica
Rest of Europe
S Algeria, S Morocco
N/W Algeria, N Morocco
Iberian
Libya
N/E Algeria, Tunisia
Crete
Cyprus
Israel, Lebanon, E Turkey
N/W Turkey
Figure 2

Variation of prolonged diapause rate in relation to winter temperature and relationships between prolonged diapause and pupal mortality

(a) Relationship between the daily mean temperature during the cold period of the larval development (December, January, and February) and the percentage of prolonged diapause in the cohorts of pupae originating from larvae experiencing those temperatures. The fitted line represents predictions of a mixed model including subclade and site as random effects (Diapause = 67.02 - 12.50 Temp + 0.85 Temp^2, both terms P<0.001, R^2=0.32, n=65).

(b) Relationship between the percentage of individuals entering prolonged diapause and the pupal mortality observed in the first year of prolonged diapause. The fitted line represents a prediction of a mixed model including subclade and site as random effects (Mortality = 37.88 + 0.364 Diapause, P<0.001, R^2=0.18, n=65).