Chapter 3

Climate Warming and Past and Present Distribution of the Processionary Moths (*Thaumetopoea* spp.) in Europe, Asia Minor and North Africa

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1 Introduction

The pine processionary moth, *Thaumetopoea pityocampa*, has been retained by the Intergovernmental Panel on Climate Change (IPCC) as one of the few model insect used as indicator of global warming (Rosenzweig et al. 2007). Indeed, the most striking feature consists of an expansion of the geographical range of this Mediterranean species, which is acknowledged to be directly associated with the

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recent climate warming up (Battisti et al. 2005). The understanding of the factors possibly governing moth natural expansion has largely progressed during these recent years. Thus, this chapter will first present a synthesis of the current knowledge about the drivers of moth expansion.

Although the range expansion has been precised in France (Robinet et al. 2012, 2014), it remained to be assessed all over Southern Europe in order to understand

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whether the moth response to climate change is identical in the different regions of the continent. Therefore, a first map of the current northern edge of moth expansion, from Western Europe to Turkey, will be presented. Then, the corresponding data will be detailed per country in a quite standardized format

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allowing to compare the moth situation among the different parts of the range. The major part of the moth range will be covered, with a total of 20 countries specifically addressed. Data will concern the present biogeographical range, the population dynamics and the past outbreaks, the particular biological features observed in the country, the host range, the current expansion and the trends expected for the future.

By contrast, the response of the other species of *Thaumetopoea* to climate change remains little known or a matter of debate, and in some cases even their present geographical distribution is still imprecise. The chapter will present a synthesis of the knowledge regarding these species.

Finally, it appeared that moth expansion could combine natural insect dispersal with man-mediated translocations. It is likely that such translocations existed since long ago but climate change may allow at present insect establishment in areas located far beyond the natural range of the insect (Robinet et al. 2012). The last section of the chapter will point out the importance of these man-mediated introductions in the expansion process.

2 What Are the Drivers of the Pine Processionary Moth's Expansion?

Mathieu Laparie and Alain Roques

2.1 Introduction

Climate warming is assumed as the main factor responsible for the aforementioned range expansion of the pine processionary moth in Europe (Battisti et al. 2005). While changes in the distribution of ectothermic organisms as a result of climate change have now been widely acknowledged and often associated with physiological limits of organisms (Walther et al. 2002; Root et al. 2003; Chown et al. 2010), the causal relationship with range edges have rarely been determined. In the pine processionary moth, however, supportive data from a number of experimental and modelling approaches show how climate warming has lowered – or removed – climatic barriers to its expansion towards higher latitudes and elevations. Although the comprehensive response of this species to climate change has not been untangled yet, its developmental limits are being delineated and have revealed the crucial importance of warming on the ongoing expansion.

2.2 Thermal Biology and Susceptibility of Larvae to Climate Change

Battisti et al. (2005) reemphasized that species active during winter are comparatively more impacted by climate warming, as average minimum temperatures have been increasing at a higher pace than average maximum temperatures (Easterling et al. 1997). In winter-developing species such as the pine processionary moth, the expected outcomes of warming winter temperatures are both higher survival rate and higher larval growth rate. While such changes may elicit dynamics in core populations, they become critical at range edges when species are constrained by their developmental thresholds. Provided that host trees are present, progressive warming will push the geographical limits of suitable habitats and enable the colonization of previously inappropriate pristine areas. First, global warming should on average reduce the likeliness of encountering lower lethal temperatures (LLT) in the coldest areas (Gaston 2003), thereby directly enhancing immediate survival. The process may be more complex in nature though, as even with increasing average temperature, lower lethal temperatures mostly occur stochastically for short durations, and climatic models predict increased likeliness of extreme events (Parmesan et al. 2000). Second, increased growth rate allows faster development and improves the ability to complete full development in previously unsuitable areas.

2.2.1 Thermal Changes Directly Alter Larval Survival in the Natural Range and Surrounding Areas

The pine processionary moth was classified as a moderately freezing tolerant insect, with an average supercooling point of −7 °C but a capability to survive cooler temperatures down to a LLT of −16 °C (Battisti et al. 2005; Hoch et al. 2009). Hoch et al. (2009) further demonstrated survival to cooler temperatures for short durations while in tents: they found more than 70 % of survivorship in larval colonies after gradual decrease to −17 °C, sustained exposure for one hour, and gradual return to 5 °C. However, the study revealed cumulative chill injury in larvae: despite the ability to survive short freezing events, larval survival decreases as larvae accumulate exposure to sub-zero temperatures (Fig. 3.1), which are rather frequent during winter in the actual range in nature. This finding further supports the beneficial effects of climate warming in edge populations, as it consolidates fitness and recruitment in colonized areas while broadening past bioclimatic envelope. Of note, Hoch et al. (2009) found rather large variance in individual supercooling points and a significant converse relationship with survival to cold exposure. Such variance may provide fuel for adaptive selection across the range of the pine processionary moth, and further studies should therefore investigate the heterogeneity of the response to temperature. Differentiation among populations may significantly alter pine processionary moth's future expansion.

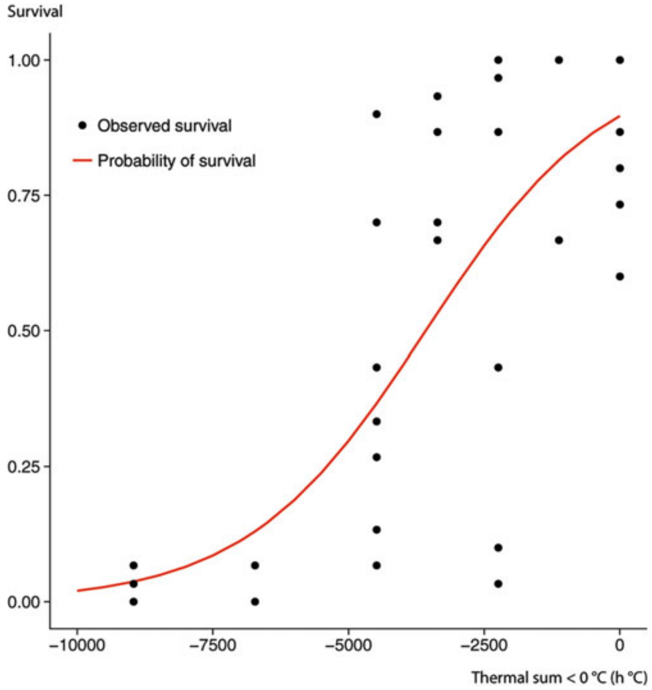

Fig. 3.1 Probability of survival and observed survival of *Thaumetopoea pityocampa* larvae depending on accumulating negative temperatures (sum of h°C below 0 °C) in a laboratory experiment (Modified from Hoch et al. 2009)

2.2.2 Feeding Activity and Its Outcomes Depend on Thermal Thresholds

Using faeces production as a surrogate of feeding activity and an automatic measuring setup, Battisti et al. (2005) have outlined how temperature modulates feeding activity and indirectly impacts growth rate and long-term survival.[1] The authors demonstrated that feeding behaviour of the pine processionary moth is governed by the combination of thresholds during consecutive day and night, *i.e.*, an Activation Temperature (AT) during daytime and a Potential Feeding Temperature (PFT) during the following night. The Realized Feeding Threshold (RFT) is the duration for which both prerequisites are consecutively met, *i.e.*, the duration larvae can actually spend feeding on needles. Battisti et al. (2005) exposed colonies to a range of thermal regimes and determined that foraging is enabled when AT

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[1] Direct effects of temperature on physiological processes and metabolic kinetics are also to be expected in ectothermic organisms (Liu et al. 1995). Their impact on development may be assessed from degree-days summations.

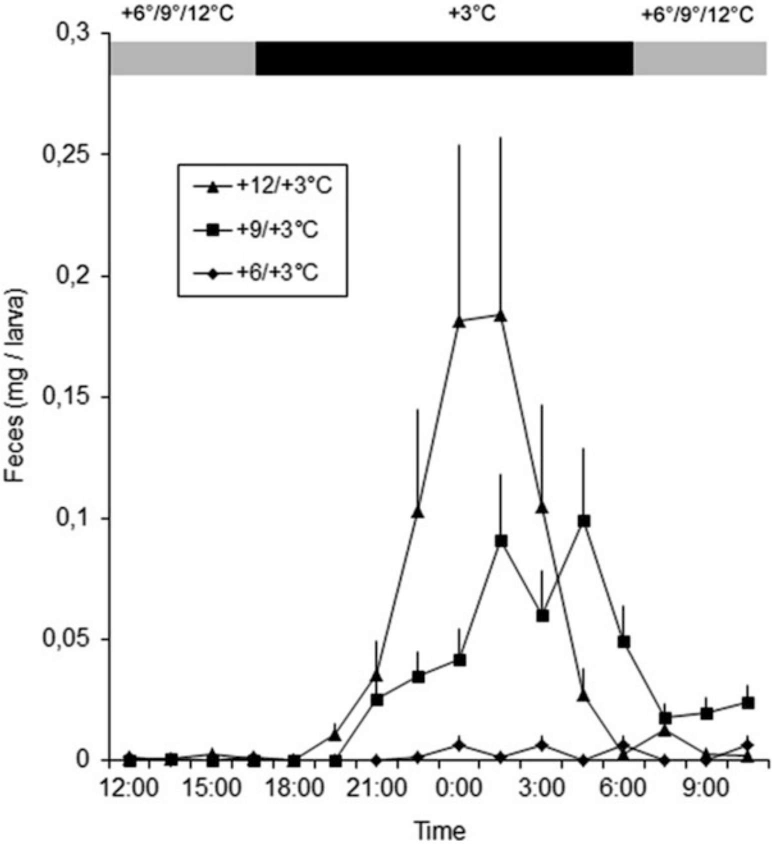

Fig. 3.2 Mean feeding activity of *Thaumetopoea pityocampa* colonies under different temperature regimes, measured as feces production (+SD). Temperature was changed through steps of 0.3 °C/min at the switch of the photoperiod (08:00 and 16:00, shown as *gray*/*black* changes in *horizontal top bar*). No feeding activity was recorded under a +3 °C/+3 °C treatment and +6 °C/0 °C (not shown) (Modified from Battisti et al. 2005)

exceeds 9 °C[2] and PFT exceeds 0 °C the following night (Fig. 3.2). As a consequence, larval feeding is strongly dependent on average winter temperatures, which are consistently rising with climate change. The resulting increased feeding activity may have manifold beneficial effects, such as accelerated development and ability to complete it in due time at high latitude or elevation, shorter fasting periods, and improved survival in areas with adverse conditions.

The feeding model and its role on survival were verified in a seminatural experiment of colony translocations along an expansion gradient from the historical areas to recently colonized areas and areas beyond the contemporary range in north-central France (Battisti et al. 2005). The experiment confirmed a significant decrease in

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[2] Actual feeding was observed starting from AT >6 °C, but 9 °C was chosen as a conservative value to ensure that larvae experienced induction for at least 1 h.

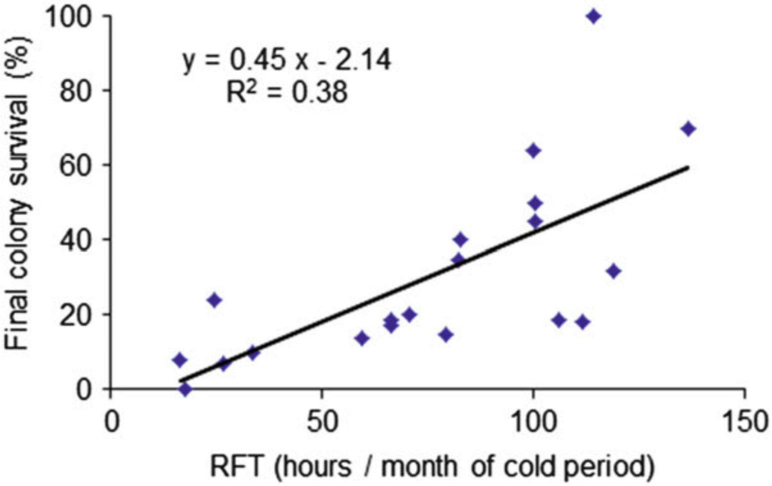


Fig. 3.3 Survival of pine processionary colonies measured at procession time as a function of the number of hours above the realized feeding threshold (RFT) during the winter cold period (October–March) (Modified from Battisti et al. 2005)

larval survival in the newly colonized areas and in those located beyond the front in relation with the harsher winter conditions occurring there. Moreover, the measured feeding activity during comparatively cold months was consistent with the predictions of the feeding model: it gradually decreased with reduced RFT at increasing elevation and latitude, ultimately resulting in lowered survival rates (Fig. 3.3).

2.3 The Causal Influence of Winter Thermal Constraints on Pine Processionary Moth's Range

Firmly demonstrating the not only facilitating but causal effect of climate warming on the ongoing expansion requires confirming that past range limits were determined by thermal constraints. Robinet et al. (2007) used a mechanistic model to reconstruct the temporal evolution of the bioclimatic envelope assumed from both the aforementioned thermo-biological parameters and the long-term climatic records, and observed a partial match with the expansion actually monitored in the Paris basin. The modelling highlighted that the number of feeding nights followed an intense latitudinal gradient, and considerably shifted northwards over time. Moreover, the moving range of habitat suitability confirmed that thermal barriers to the northward expansion existed in 1992–1996 but disappeared in 2001–2004 (Fig. 3.4), concomitantly with the progression of the pine processionary moth towards Paris. Noteworthy, the predictions suggest that the species is no longer limited by climatic constraints in the Paris basin.

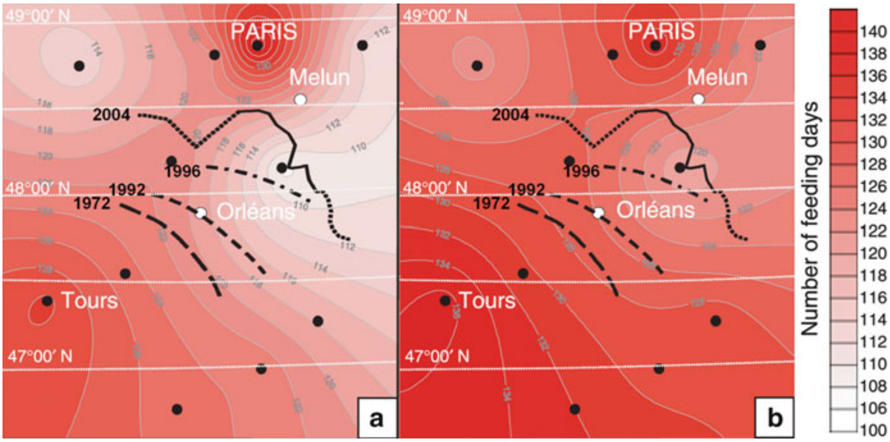


Fig. 3.4 Spatial changes in the feeding potential of processionary larvae in the Paris basin from 1992–1996 (**a**) to 2001–2004 (**b**). The number of nights with potential feeding increases from *white* (low) to *red* (high) according to the scale on the right. *Black lines* indicate the position of the front edge at different years (Modified from Robinet et al. 2007)

Although such a process remains to be verified in other parts of the range, especially in South-eastern Europe, it is likely that the future distribution of *T. pityocampa* rather depends on availability of host trees and dispersal of females (Robinet et al. 2007). Host trees being non-limiting in Europe (Battisti et al. 2005; Robinet et al. 2007), this finding triggers a warning signal as the expansion dynamics could increase dramatically in a near future; they may namely be greatly facilitated by accidental human-mediated long distance dispersal events (Robinet et al. 2012, 2014).

2.4 *Increased Summer Temperature and Extreme Summer Climatic Events Have Mixed Effects on the Pine Processionary Moth's Distribution*

Long-term monitoring of the pine processionary moth provides further support to the tight relationship between its expansion and climate warming (Hill et al. 2002; Crozier 2004; Hickling et al. 2005). Nonetheless, the effects of short-duration changes such as summer heat waves on short-lived adults have long been underestimated (Battisti et al. 2006). Flight activity of females was found to occur starting from 14 °C, and to be significantly correlated with mean night temperature (Battisti et al. 2006). The pine processionary moth can therefore benefit from increased summer temperature to colonize new areas, as long as the heat wave period covers the emergence peak and flight window of females. Consistent with this assumption, unprecedented expansion was observed in the Italian Alps following the historical 2003 heat wave (Battisti et al. 2006). This significant range leap

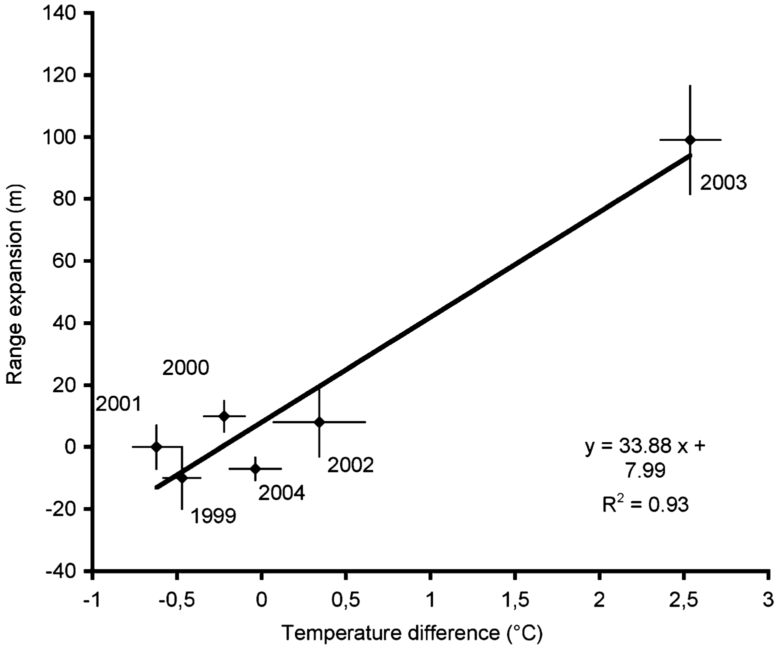


Fig. 3.5 Relationship between the annual expansion (±) of *Thaumetopoea pityo*campa in the Italian Alps and the temperatures conditions occurring during the female flight period. Temperature difference (±) is expressed as the difference between the mean night temperature of this period in each year and the corresponding average of the period 1951–2004 (Modified from Battisti et al. 2006)

was associated with a strong increase of 2.4–3.5 °C in the night temperature during female flight period compared to the mean temperature recorded in the other years of the period 2001–2004, resulting in an average of 5.3 times more nights above the take-off threshold (Fig. 3.5; Battisti et al. 2006),

Contrasting from the increase of winter temperatures which presumably promotes the pine processionary moth's dynamics all over its range, extreme heat events may have mixed effects depending on topography and regions. Although the 2003 summer heat wave dramatically accelerated the expansion in Italian Alps (and putatively other high elevation regions), it had detrimental effects on populations within the Paris basin where a temporary regional collapse occurred (Robinet et al. 2013). Likely explanations are multiple and encompass both direct and indirect factors. Among direct factors, reaching of upper lethal temperatures and disruption of mating behaviour appear as relevant candidates. Increased mortality of eggs – the expected dominant life stage during the 2003 heat wave – under the temperatures experienced during the abnormal summer was experimentally rejected, and no developmental penalties were found in individuals further monitored till third instar (Robinet et al. 2013). Indeed, eggs masses could survive temperatures of 40 °C for several days (also observed in Portugal by

Santos et al. 2011b) and their upper lethal temperature threshold is undoubtedly much higher than the 32 °C previously reported by Huchon and Démolin (1970). Whether the value was underestimated or the discrepancy highlights ongoing adaption to global warming in the expanding populations is not known yet. The susceptibility of first instar larvae should now be similarly investigated because eggs likely better resist heat and desiccation than newly-hatched larvae (Santos et al. 2011b). Moreover, given the expectation that the heat wave accelerated egg development and caused early hatching peak, a significant proportion of first-instar larvae may have experienced the heat anomaly and suffered desiccation and/or thermal stress. Finally, whether and how temperature above the flight threshold alters mating behaviour remains unknown. However, the catches of flying females in 2003 matched the expectations for regular summers, which shows that extreme temperature in the Paris basin did not cause the collapse by disrupting adult dispersal.

Warming during late summer and autumn presumably accelerates the development of early larval instars. The effect of such an acceleration on the overall development of pine processionary larvae is yet unknown but early, erratic processions are at present frequently recorded with the regard to the usual cycle reported in the past (Huchon and Démolin 1970).

Possible outbreaks following favourable years may have indirect detrimental effects on the longer term. Tamburini et al. (2013) reported a negative density-dependant feedback with a 1-year time lag in several alpine populations. Density-dependent factors possibly driving pine processionary moth’s dynamics include lowered host quality and increased risks of pathogen or virus epidemics (Tamburini et al. 2013). Food shortage associated with larval overcrowding may outweigh the beneficial effect of increased temperatures on development time. This may delay processions and result in insufficient time to complete metamorphosis before the emergence and mating peak (Démolin 1990). Completing metamorphosis while maintaining synchronous emergences may therefore rely on prolonged diapause, an adaptive mechanism that was also suggested as a way to dodge outbreak-induced adverse conditions (Tamburini et al. 2013), and contributes to the apparent drop in trapping rates following outbreaks. Prolonged diapause is also generally assumed as a bet-hedging strategy to deal with unpredictable events (Menu and Debouzie 1993), which suggest a density-independent component. This is consistent with comparatively high frequency of prolonged diapause found in pine processionary moth’s populations at high elevation (Géri 1983a, b). Overall, prolonged diapause may prove being fundamental in the sustained expansion of the pine processionary moth despite the mitigating effects the species may encounter at its range margins: it helps both (i) withstanding consequences of outbreaks in areas with few host trees, and (ii) rapidly overcoming the negative effects of stochastic extreme climatic events, as observed with the rapid recovery in the Paris basin after 2003.

3 Mapping the Past and Present Range of the Pine Processionary Moth in Europe and the Mediterranean Basin

Christelle Robinet and Jérôme Rousselet

The pine processionary moth, *Thaumetopea pityocampa*, is present in regions under the Atlantic and Mediterranean climates in Europe (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, France, Greece, Italy, Macedonia, Montenegro, Portugal, Serbia, Slovenia, Spain and Switzerland), in a part of European Turkey and in North Africa (Algeria, Morocco, Tunisia and Lybia) (EPPO 2004; Kerdelhué et al. 2009). Its distribution was considered to be closely related to climatic constraints, especially winter and summer temperatures and annual sunshine duration (Huchon and Démolin 1970). The distribution range was relatively steady until the late 1990s but since then records revealed a significant expansion towards higher latitude and elevations in southwestern Europe, and this expansion was clearly associated to climate warming (Battisti et al. 2005; Rosenzweig et al. 2007).

Although this process has been precisely documented in some areas (see sections below), no global picture of the whole species' range from Europe to the Middle East and North Africa was available until now. Moreover, only partial and scattered maps of the past distribution were available to figure out the magnitude as well as the speed of the moth expansion over the last years. Therefore, it appeared essential to draw a reference map of the present distribution of *T. pityocampa* in Europe in order to allow an accurate measurement of the further moth expansion expected with global warming. Using a standardized method was required so that it can be applied exactly in the same way for comparison in the future.

The moth distribution, or more precisely its northern edge, was thus mapped all over Europe during winter 2011–2012, from Western France (Brittany) to the European part of Turkey (Eastern Thrace), over a regular grid of 16 km × 16 km (European projection Lambert Conformal Conic) (Fig. 3.6). The northern front edge was thus delimited over more than 3,000 km. The altitudinal edge was also precised in the Alps (France, Italy and Switzerland), in the Massif Central and the Pyrenees (France). Two pioneer colonies located far from the main species distribution (at approximately 90 and 160 km) were also clearly identified in France at this spatial resolution. In contrast, the 16 km resolution resulted in merging some other pioneer colonies located near Paris with the main distribution range (see section below; Robinet et al. 2012). In 2013, the most northern population of *T. pityocampa* corresponded to one of these pioneer colonies (N 49°30′; Chamouille).

However, it has not been yet possible to delimit the southern front edge of the species in North Africa due to missing information in this area. Assessing whether the southern edge of the species distribution is contracting or not with climate change thus remains challenging.

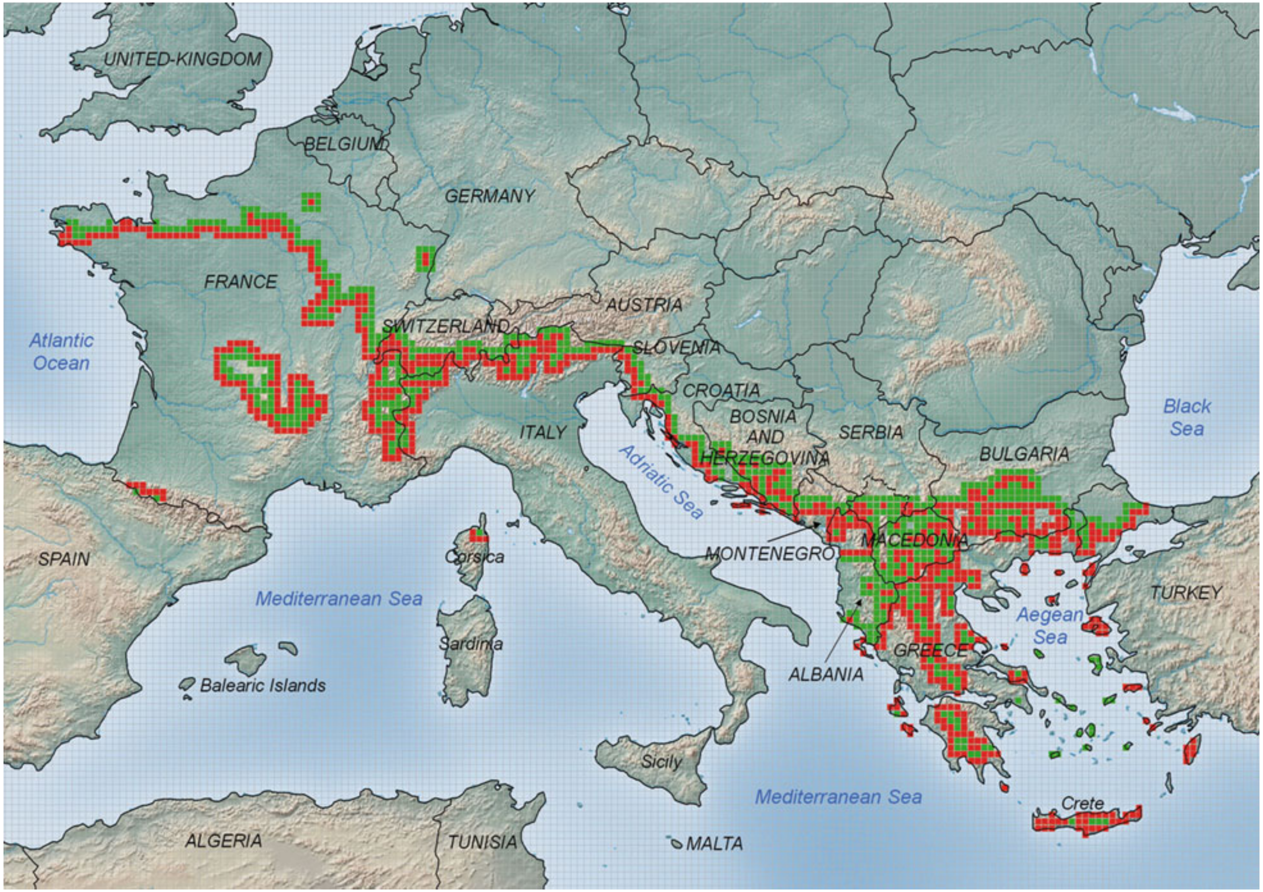


Fig. 3.6 The 2011–2012 front edge of the pine processionary moth throughout Europe figured over a 16 km × 16 km grid. Red squares represent the northern and altitudinal front, defined as the furthest squares where at least one processionary tent was found. *Green squares* indicate areas beyond the front where the absence of processionary moths has been clearly assessed

4 Past and Current Situation of the Pine Processionary Moth, *Thaumetopoea Pityocampa*, in Western and Central Europe

4.1 The Pine Processionary Moth in France

Christelle Robinet, Jacques Garcia, Francis Goussard, and Jérôme Rousselet

A northwards expansion of the pine processionary moth was first detected in the 1990s in the southern part of the Paris basin (Démolin et al. 1996; Goussard et al. 1999). In this region, the existence of historical maps of the species' past distribution allowed to draw accurately the movements of the front edge and assess the expansion patterns (Fig. 3.7). Moth spread rate reached up to ca. 5.6 km/year between 1992 and 2004 (Battisti et al. 2005) and is still reaching 4–5 km/year on average (Robinet et al. 2012).

The range expansion was particularly rapid in the South of the Paris basin (Fig. 3.7), but at country scale, there is also clear evidence of the northwards range expansion from Brittany to the Swiss border (Fig. 3.8) but also towards higher elevations in the Alps, in the Massif Central and in the Pyrenees.

Comparing maps drawn at different periods was anyway problematic because the survey methods differed along the years. Thus, since winter 2005–2006 the mapping of the distribution of the pine processionary moth in France has been standardized over a regular cell grid (e.g., at a spatial resolution of 8 km × 8 km for country scale mapping). It consists in assigning positively a cell as soon as a processionary larval tent is spotted within this cell. As soon as no tent is found when driving on all suitable roads, the moth is considered absent from the cell. However, the next cell beyond is surveyed in order to detect possible close-by satellite colonies, resulting for instance from a lack of host trees in the cell above. Finally, the front edge is drawn by connecting the adjacent positive cells where the species is present. Although time-consuming, this standardized method has to the advantage to be replicable in time and to provide both presence and absence data. It is very convenient to map species distribution at large scales and delimit the northern and southern edges but caution is needed in mountainous areas as the method is not suited to consider altitudinal limits as well as slope exposition which is largely affecting moth distribution.

4.1.1 Population Dynamics and Outbreaking Periods in the Past

Around 500 sites are currently surveyed in France every winter by the French Forest Health Department (DSF) on pine stands infested by the species for several years. This monitoring network allows reconstructing time series of the population dynamics since the early 1980s. Although the frequency and intensity of the

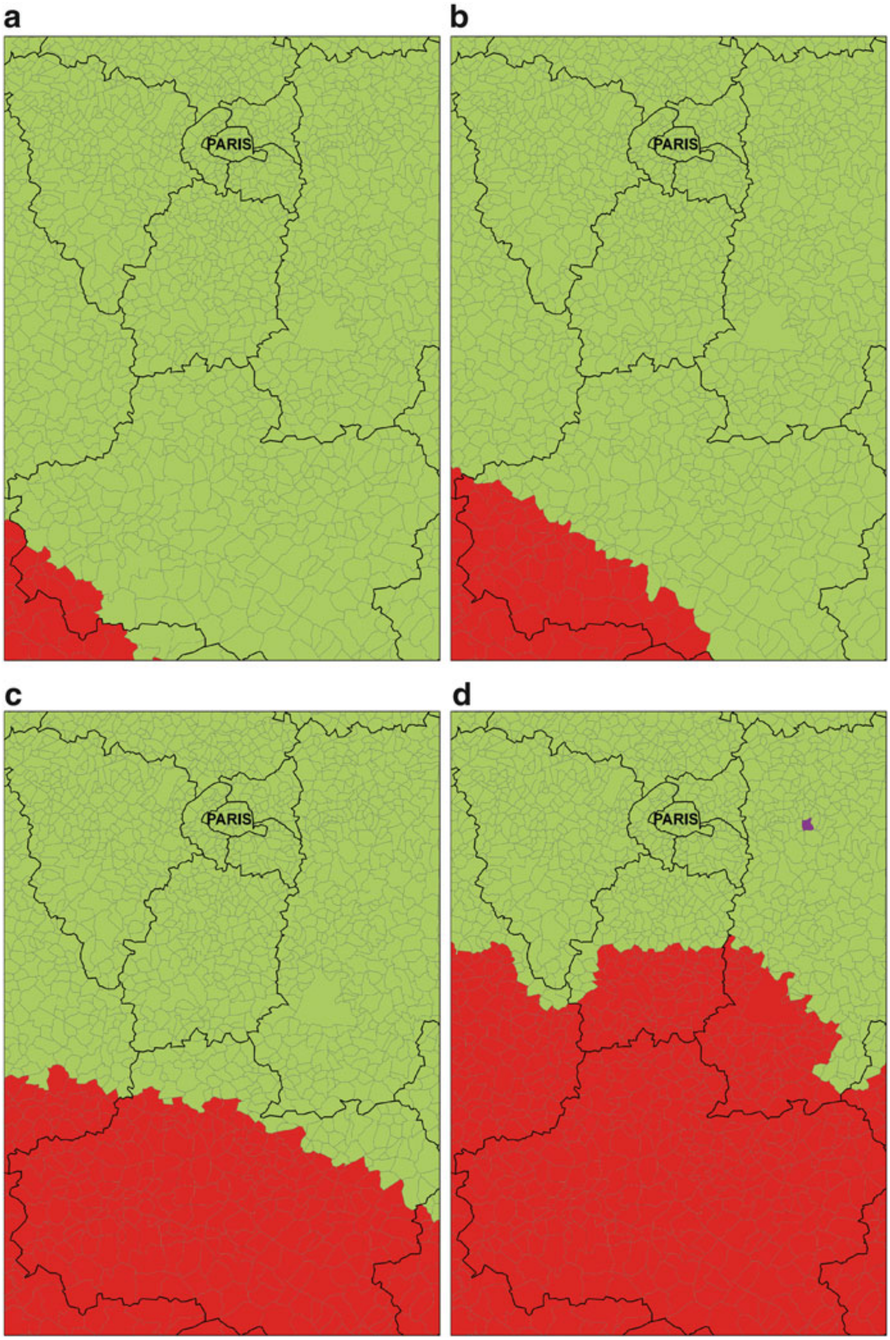


Fig. 3.7 Spatial expansion of the pine processionary moth in the South of the Paris basin from 1972 to winter 2010–2011. Areas with moth presence are figured in *red*. The pioneer colonies discovered near Paris since the 2000s are figured in *purple* (for more details, see Fig. 3.37). (**a**) 1972 (source: Abgrall 2001); (**b**) 1992 (source: Goussard et al. 1999); (**c**) 1996 (source: Goussard et al. 1999); (**d**) winter 2005–2006 (URZF INRA Orléans, unpublished); (**e**) winter 2010–2011 (URZF INRA Orléans, unpublished); (**f**) same as before but showing the new pioneer colonies having appeared or extended during winter 2011–2012. The spatial resolution is at town level, the *thin grey* features representing the administrative limits of the towns, and the *thick black* ones those of the departments

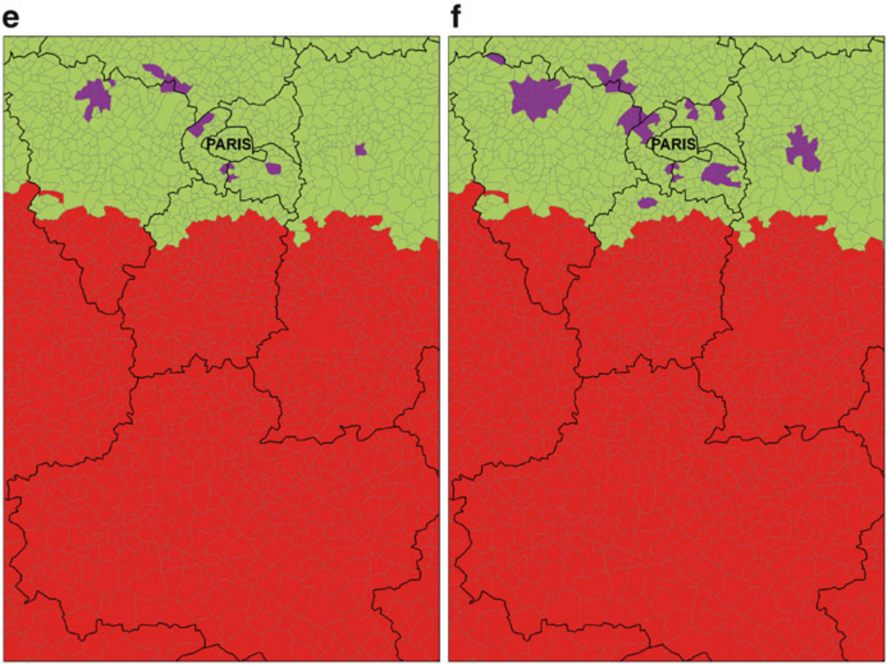


Fig. 3.7 (continued)

outbreaks are highly variable, a 6-year outbreak cycle can be observed in some pine stands colonized for a long time (before the 1980s) (Abgrall 2001; Robinet and Roques 2005). Despite a large geographical variability, the most important outbreaks occurred in 1985, 1992, 1997–1998, and 2003–2004 (Bouhot-Delduc 2005). Climatic anomalies can disturb the population dynamics (Huchon and Démolin 1970), especially in regions more recently colonized (Robinet and Roques 2005). On the expansion range, no outbreak cycle is generally observed (Francis Goussard, personal communication).

4.1.2 Particular Biological Features Observed in the Country

Like everywhere else in the species distribution, the population phenology strongly depends on latitude and elevation (Huchon and Démolin 1970). Several particular biological features occurred in some parts of France. (1) Despite high variability among the regions, larval development takes place in the cold season, generally between September and March. However on a small island, called Île de Ré, the larvae can generally complete their development before winter (i.e., before December) and make processions to burry in the soil before the coldest season. This island is located in the Atlantic Ocean very close to the continent and

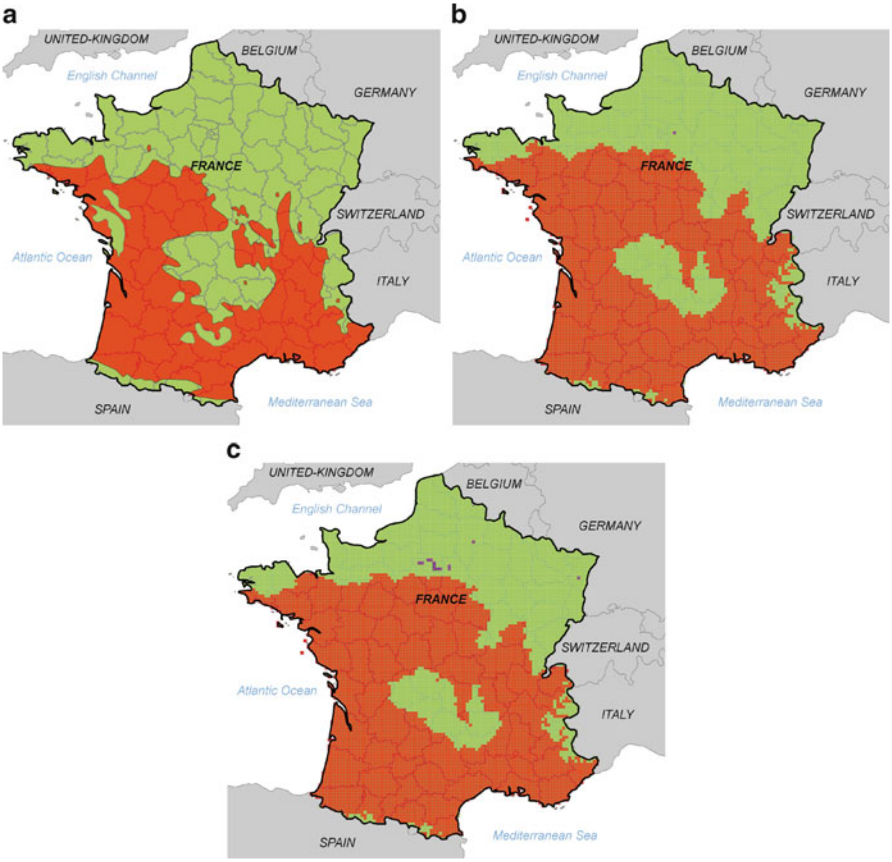


Fig. 3.8 Range expansion of the pine processionary moth in continental France (Corsica excluded) from 1969 to 2011. Areas with moth presence are figured in red. Isolated pioneer colonies discovered after 2000 are figured in *purple*. (**a**) moth presence during 1969–1979 (sources: CTGREF-INRA 1980); (**b**) moth presence during winter 2005–2006 on a 8 km per 8 km grid (Robinet et al. 2010a, b); (**c**) moth presence during winter 2010–2011 8 km per 8 km grid (URZF INRA Orléans, unpublished)

the temperature is mild throughout the year. (2) With increasing variability in temperatures, the species phenology is more and more disturbed. For instance, many processions were locally observed in the Paris basin in late September in 2011 (Jérôme Rousselet, personal communication). These processions were not due to the lack of food but probably due to early adult emergence and suitable climate conditions for a rapid larval development. This phenomenon is supposed to result from various climatic anomalies from the winter 2010–2011 until late summer 2011. (3) Regarding the diapause, a very unusual feature has been happening for many years on the Corsica Island. In these mountains, the diapause is always extended and the life cycle is completed within 2 years or more

(Huchon and Démolin 1970; Géri 1980). However, depending on the valleys, the year of emergence and larval development is not the same. In some valleys, most of the tents are observed in even years, and in other valleys, they are mostly observed in odd years.

4.1.3 Host Range

The pine processionary moth generally attacks pines (notably *Pinus sylvestris*, *P. nigra*, *P. pinaster*, *P. halepensis*), cedars (*Cedrus atlantica*, *C. libani*) and eventually other conifers such as Douglas-fir, *Pseudotsuga menziesii*, and white fir, *Abies concolor* (Martin 2005). These host trees are largely distributed in France, not only in forests but also in urban areas as ornamental trees. Therefore the pine processionary moth does not seem not limited by its host trees in France.

4.1.4 Expansion with Global Warming

One of the most important climate variables for the larval development and winter survival of the pine processionary moth is the mean of minimum temperature from October to March (TNOM, Robinet et al. 2007). This temperature has increased by around 1.1 °C between 1972–1981 and 1994–2003 in the South of the Paris basin (Battisti et al. 2005). Despite large fluctuations, the temperature has increased by around 0.02 °C per year between 1981 and 2011 in the South of the Paris basin, with very warm winters in 1994–1995, 2000–2001, and 2006–2007 (TNOM > 4.5°).

4.1.5 Trends for the Future

A preliminary model was developed to simulate the potential spread of the pine processionary moth in France based on the moth dispersal capability, human-mediated dispersal, potential growth, survival to cold temperatures, and distribution of host trees (Robinet 2006; Robinet et al. 2014). The spread is now mostly limited by the dispersal capabilities but human-mediated dispersal could create satellite colonies and artificially accelerate the spread. It is very likely that northwestern and northern France will be colonized in the coming years. However other factors should be considered in the future such as the sunshine and the possible limitation of the range expansion by unfavorable photoperiod during winter in northern territories. The model should also be improved to determine more precisely the trend in mountainous areas, and more generally, to account for the effects of climate warming on the insect phenology as this change could in turn affect the time-window individuals are exposed to critical weather conditions.

4.2 The Pine Processionary Moth in Italy

Andrea Battisti

4.2.1 Present Biogeographical Range

The pine processionary moth *Thaumetopoea pityocampa* has nowadays an almost continuous distribution in Italy, across both latitudinal and elevation gradients where the host plants (mainly *Pinus* spp.) occur (Fig. 3.9). The only spots that can still be considered free are certain northern-facing slopes in the Alps, where the climatic conditions during winter (especially solar radiation) do not allow the survival of the colonies (Battisti et al. 2005). All the Italian populations belong to the *pityocampa* clade, with the only exception of the small island of Pantelleria, south of Sicily, where a population of the North-African ENA clade is occurring on native *Pinus pinaster* stands (Kerdelhué et al. 2009). Major islands are colonised as

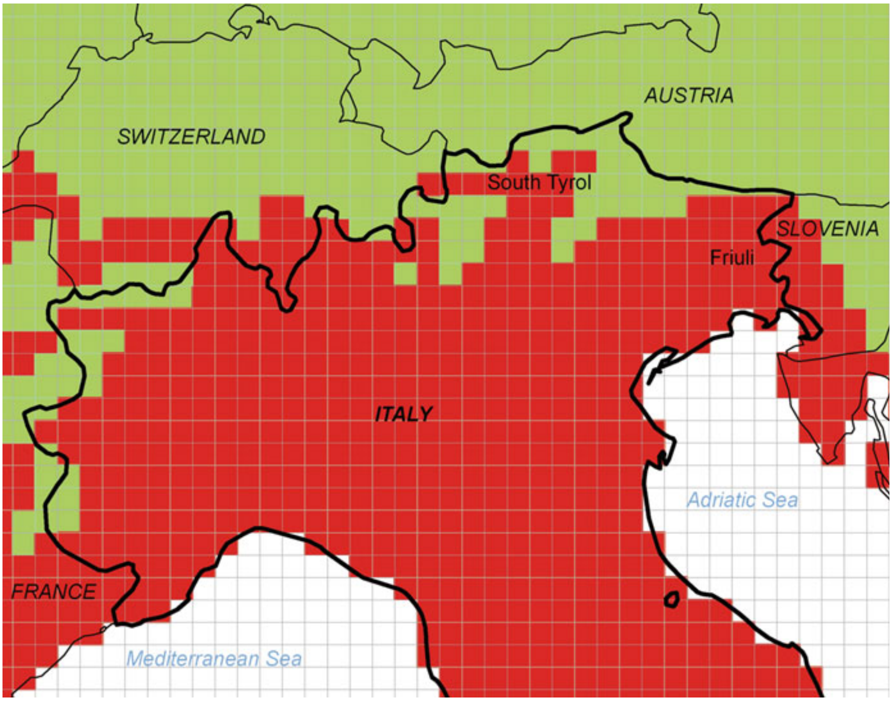


Fig. 3.9 The present distribution range of the pine processionary moth in northern Italy figured over a 16 km × 16 km grid. *Red squares* represent the northern and elevational front, defined as the furthest squares where at least one processionary tent was found. *Green squares* indicate areas beyond the front where the absence of processionary moths has been clearly assessed. South Tyrol and Friuli indicate the regions where most of the studied on the recent range expansion have been conducted

well, including Sardinia which was free of the insect until its discovery in 2006 (Luciano et al. 2007), likely introduced from mainland nurseries with large potted trees (Kerdelhué et al. 2009). An eradication programme based on large-scale *Btk* applications and monitoring has been set up in the island.

4.2.2 Population Dynamics and Outbreaking Periods in the Past

The pine processionary moth is the most destructive insect affecting the growth of some pine species throughout the Italian territory. Its presence in Italy has been well-known for a long time, but it was first recorded in an unequivocal way by Mattioli, who described the larvae and their webs briefly in the "*Commentarii in libros Dioscoridis de medica materia*" (cfr., e.g., Venetian edition of 1568) (Masutti and Battisti 1990). It can be assumed that also the Austrian entomologists Denis and Schiffermüller described their *Bombyx pityocampa* in 1775 on the basis of Italian material, specifically from south Tyrol. In spite of that, the insect had never become a threatening forest pest until several large afforestation programs started at the end of the nineteenth century. Since then, the outbreaks became frequent, although irregular, in various Italian regions.

4.2.3 Particular Biological Features Observed in the Country

The life history follows the pattern observed in northern rim of the Mediterranean basin, with earlier emergence of moths as long as latitude and elevation increase. Prolonged diapause is a typical feature of expanding populations at the northern edge, with individuals of the same cohort spreading the emergence up to 8 years.

4.2.4 Host Range

The pine processionary moth feeds on all native pines with the only exception of *Pinus cembra*, on which it does not grow beyond the third instar (the larvae grow so slowly that they are killed by winter frost in an early instar, Battisti unpublished data). *Pinus nigra*, widespread in afforested areas, is the most susceptible host plant. With the recent climate change effect, however, other hosts became equally susceptible of infestation (Stastny et al. 2006). In addition, the moth is also occurring in town and in agricultural landscapes, thriving on ornamental trees (*Pinus*, *Cedrus* and occasionally other conifers) in gardens and nurseries.

4.2.5 Expansion with Global Warming

The recent shift of the range all over the country is largely explained by climatic change observed in the last decades. The species has reached almost all the upper stands of pine and it is invading the stands of mountain pine as well. In a test carried on this host under extreme mountain conditions, larval mortality and relative growth rate did not differ between host trees grown in ambient or elevated CO_2 (Petrucco Toffolo and Battisti 2008). In relation to the link between global warming and population dynamics, long-term data from two provinces in the Southern Alps (Trento: 1990–2009, Bolzano/Bozen: 1975–2011) were used to evaluate the relative importance of climate and density-dependent factors as regional drivers. Both summer temperatures and rainfall significantly affected population growth rate, with different outcomes depending on the local conditions. Although previous studies indicated that low winter temperatures have negative effects on insect performance, our analyses did not show any negative effect on the population dynamics (Tamburini et al. 2013).

4.2.6 Trends for the Future

As extended snow cover may be an important mortality factor of larval colonies on the dwarf trees of mountain pine, the survival of colonies transplanted at two extreme sites of Eastern Alps was tested. The snow cover extended over more than 1 month proved to be an important mortality factor of larval colonies on mountain pine. We concluded that the first instar larvae of the pine processionary moth are not concerned by unusually low temperature and CO_2 increase whereas they can be later strongly affected by snow accumulation. The decrease of snow cover observed in the last decades, however, may reduce such a risk (Petrucco Toffolo and Battisti 2008).

4.3 The Pine Processionary Moth in Spain

José A. Hódar, Rodolfo Hernańdez, Gerardo Sańchez Peña, and Regino Zamora

4.3.1 Present Biogeographical Range

The pine processionary moth is present almost everywhere in Spain, being limited only where pines are lacking (Fig. 3.10). This happens at the top of the high mountains (The Pyrenees, Central Mountains, Sierra Nevada), in SE Iberian Peninsula due to aridity (Cabo de Gata), and extensive cultivation areas, as the basins of the main rivers (Duero, Tajo, Guadiana, Guadalquivir). Commonly found in urban areas due to use of *Pinus* spp. as ornamental trees in gardens and urbanizations.

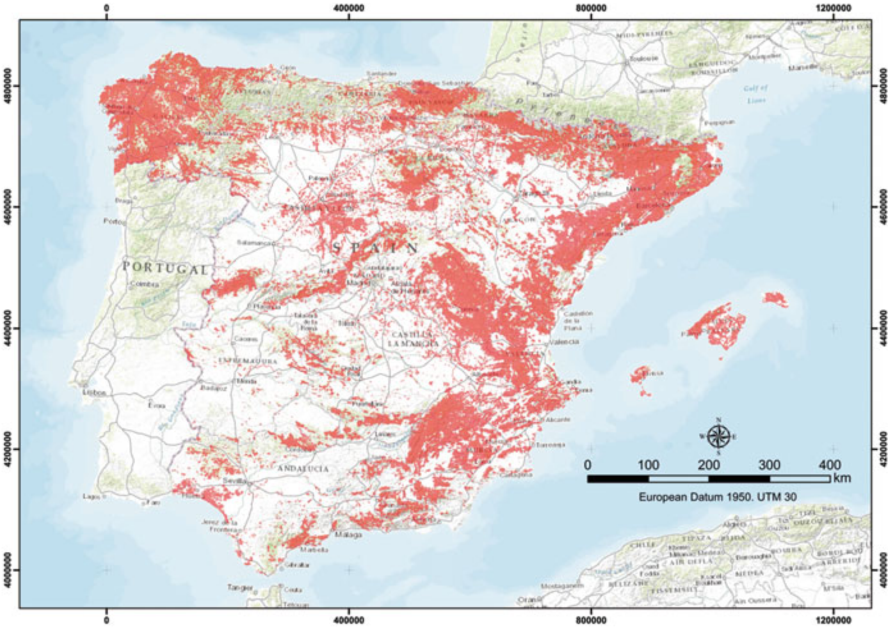


Fig. 3.10 Area covered by pine woodlands in Spain figured in *red*. This area represents the main distribution range of the pine processionary moth in Spain. Moth colonies can also be found in lowlands on isolated trees elsewhere. Only the top of the high mountains and the arid SE Iberian Peninsula are completely free of pine processionary moth (Data from SIG laboratory, Databases and Territory Analysis, INIA-CIFOR)

Absent in Canary Islands, introduced into the Balearic Islands (recently recorded in Formentera). No detailed distribution mapping at the country level, some detailed mapping and monitoring at a regional level.

4.3.2 Population Dynamics and Outbreaking Periods in the Past

No clear trends can be figured out due to the lack of systematic monitoring until last ca. 20 years (except some noteworthy cases as Mora de Rubielos, with systematic records from 1971). However, there is a general agreement in researchers and policymakers that pine processionary moth has increased in abundance and virulence during last decades, noteworthy in pine plantations. It is matter of discussion to what extent this is the result of climatic change, the consequence of massive afforestations during the second half of twentieth century (3.4×10^6 ha afforested, 90 % with conifers, by public administrations between 1940 and 1984), or both. At least in some parts of the country, the incidence of outbreaking levels generally shows a 6-year cycle (excepting diapause disruptions), mainly in planted areas and young stands, while in natural stands cycles are longer or absent.

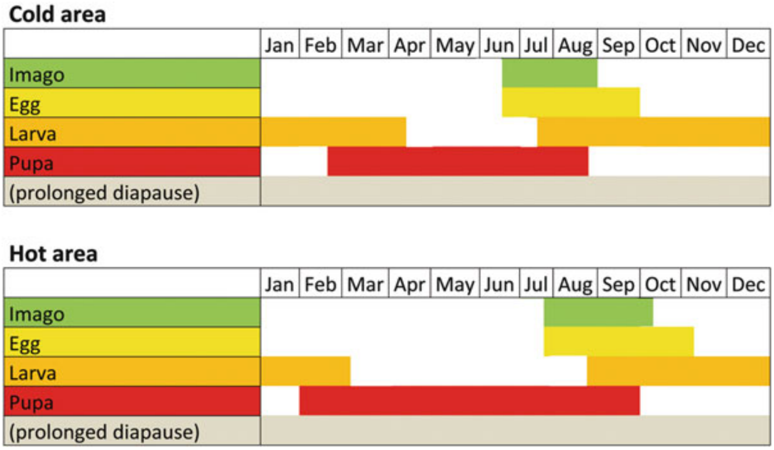


Fig. 3.11 Pine processionary moth phenological differences between cold and warm localities in Spain

4.3.3 Particular Biological Features Observed in the Country

No particular features were observed. A general description of phenology and life history of pine processionary moth in Spain can be found in Montoya and Hernández (2003) and Muñoz López et al. (2007). Cold and mild localities show sharp phenological contrasts due to differences in thermal environment (Fig. 3.11) but, taking apart diapause, the species behaves always as univoltine.

4.3.4 Host Range

Almost every pine present in Spain is attacked by pine processionary moth, but susceptibility depends of the pine species and the mixture of species at the stand level. Thus, *Pinus nigra* and the exotic species are always preferred, and their presence greatly determines the degree of attack to other less palatable species as *P. pinaster* or *P. halepensis*. For instance, *P. pinaster* is in general not very attacked in high mountains of SE Spain when mixed with *P. nigra* and *P. sylvestris*, but it is the staple food in the mild coastal areas of NW Spain in absence of other more palatable pines. *Pinus pinea*, the less susceptible species, suffer nevertheless important defoliations leading to health problems to pine cone collectors. Most of the introduced pines (*P. canariensis*, *P. radiata*, *P. ponderosa*) are heavily attacked by pine processionary moth, being especially problematic the situation of extensive plantations of *P. radiata* in Basque Country. At this area plantations are set at low elevations with mild climate, thus favoring the pine processionary. Occasional attacks to introduced *Cedrus* spp. have also been reported.

4.3.5 Expansion with Global Warming

Expansion in Spain is possible just in elevation, since every lowland area bearing pines also bears pine processionary moth. Recent monitoring suggests moth movements uphill in mountain ranges due to rising temperatures, but also due to conifer afforestations in mountainous areas previously covered by shrublands or pasturelands and devoted to livestock. An increase of 0.48 °C per decade has been reported for the average temperature in the Iberian Peninsula for the period 1973–2005, and a higher increment in future is predicted (AEMET 2009). As a consequence, pine processionary moth has recently been recorded in completely unusual elevations for the species just 20 years ago (2,250 m in Sierra Nevada, 2,200 in Sierra de Baza, 1,800 m in Sierra de Gúdar, 2,000 m in southern slopes of Pyrenees range), but again systematic data are lacking. During last years some programs of detailed population monitoring have been implemented (e.g. in Sierra Nevada, SE Spain), but still is too early for concluding results.

4.3.6 Trends for the Future

The advisable tendency is a progression in elevation and perhaps an increase in virulence in zones with chronic affection until now. Also, a retraction in the arid limit of SE Spain cannot be completely ruled out, depending on the distribution of pine woodlands in future climatic scenarios. There are also some tests for modelling the population dynamics (in Sierra Nevada).

4.4 The Pine Processionary Moth in Portugal

Manuela Branco, Helena Santos, and Maria-Rosa Paiva

4.4.1 Present Biogeographical Range

Pine processionary moth is widespread throughout the territory of continental Portugal, colonizing pure and mixed plantations, as well as dispersed trees. As from the first half of twentieth century, intense forestation campaigns were conducted in Portugal mostly with maritime pine, *Pinus pinaster*. Although the cultivated area decreased from 1,288,000 ha in the 1960s, to 710,600 ha in 2006, *P. pinaster* is still one of the three most representative forest species in Portugal (AFN 2010). Intense outbreaks of pine processionary moth, with average larval densities of over one tent per tree and defoliation above 50 % have been observed, mainly in young stands all over the country (Arnaldo et al. 2010; Barrento et al. 2008; Branco et al. 2008).

In spite of its importance, little or no information on the population dynamics and outbreak periods of pine processionary moth was available until the twenty-first century, mostly due to the lack of long-term systematic monitoring. Similarly, the occurrence of outbreak cycles has not been reported. Still, in urban and peri-urban areas, pine processionary moth often occurs at high densities raising public concern, particularly in schools and public gardens.

4.4.2 Particular Biological Features Observed in the Country

The phenology and life history of pine processionary moth in Portugal follows a pattern similar to those observed for other Mediterranean populations. Thus, egg laying takes place from the end of July to September, larval development from September to February-March and pupation thereafter, until the following summer. In Northern regions of Portugal, the peak of adult emergence occurs between June and August, that is earlier than in southern areas, where it occurs in August–September (Arnaldo and Torres 2006).

In 1997 a pine processionary moth population having an atypical cycle, was discovered in a pine stand, with about 37,000 ha, located in Leiria region, which has been continuously managed since the thirteenth century. The distinctive phenology of this population is characterized by spring adult emergence (May/June), summer larval development (June/October) and pupation in the fall and winter (see Battisti et al. 2014; Chap. 2, this volume).

4.4.3 Host Range

The main host of pine processionary moth in Portugal is the maritime pine, since it represents about one third of the total forested area of the country. *Pinus pinea* comes second, being cultivated for pinion seeds, mainly in regions south from the river Tagus. Still, over the last decade, in consequence of serious damage caused by the pinewood nematode to *P. pinaster*, part of the area occupied by this species has been converted to *P. pinea*.

Although references to pine processionary moth outbreaks in *P. pinea* were not found for Portugal, the authors observed some cases in young plantations such as reported by Paiva et al. (2010). Other pine species are also prone to intense defoliation, namely the exotic *P. nigra* and *P. radiata*. An attack on the ornamental species *Cedrus deodara*. has been observed in Setúbal Peninsula, in December 2012 (Paiva, personal observation).

In a study conducted by Mateus et al. (1998) in an arboretum near Abrantes, central Portugal, the host range of the local pine processionary moth population was found to be wide, although significant differences occurred regarding tent density per tree, *P. pinaster* being one of the most intensively attacked species.

4.4.4 Expansion with Global Warming

Expansion in Portugal is not applicable, as the species is present all over the country from sea level to the highest mountains, provided pine plantations are present. A significant warming of about +2 ° C was reported for the period 1976–2000, which was preceded by a period of global cooling of circa −1 °C, on a previous period from 1946–1975 (Miranda et al. 2002). Furthermore, the increase of the maximum temperatures observed was higher than for the minimum temperatures, thus resulting in a wider range of diurnal temperatures. Possible consequences of these changes for the distribution of pine processionary moth are unknown.

Yet, the atypical population with asynchronous phenology has been observed to expand both northwards and southwards from its original outbreak point, along the coast (Fig. 3.12). Summer "hot days", with maximum temperatures ≥ 35 °C that can be observed in inner regions (Fig. 3.13), might limit the distribution of the summer population. However, an adaptation of this population to hot summers is also plausible (Santos et al. 2011a), thus increasing its potential ecological range of distribution.

4.4.5 Trends for the Future

The present status of the typical winter population is expected to remain stable and severe outbreaks on young pine plantations, of increased severity, particularly on *P. pinea* are predictable. An expansion of the summer population is expected along the coast, with high impact on touristic activities concentrated on this area, such as camping parks, golf facilities and seaside touristic villages. A rate of spread of about 3 km per year was observed over the past 15 years and it is predictable that a similar trend will continue in the future.

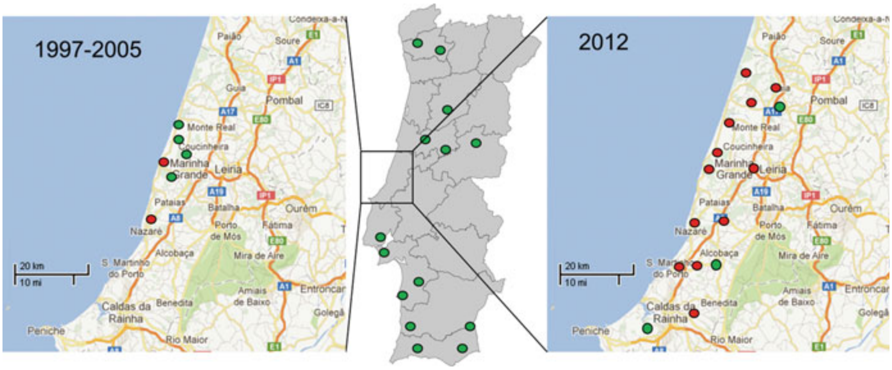


Fig. 3.12 Expansion of an atypical summer population of pine processionary moth in Leiria, from observation of male traps conducted from 1997 until 2005 and in 2012, *red dots* represent presence, *green dots* represent absence

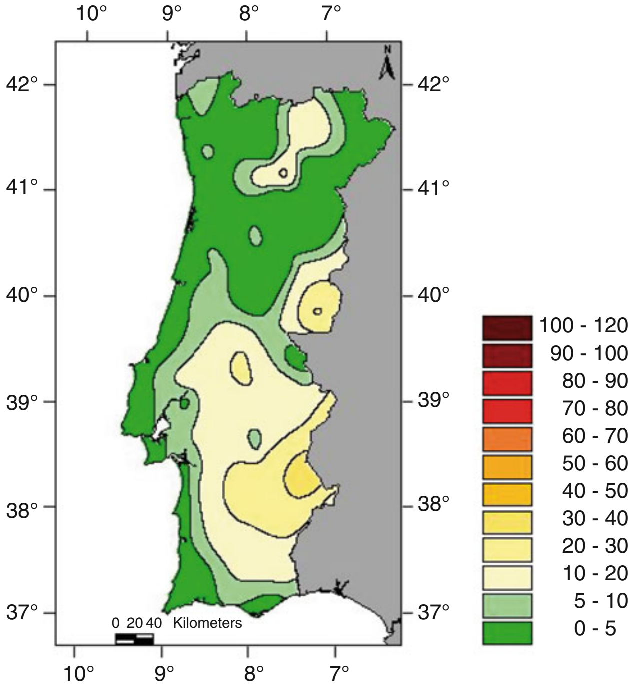


Fig. 3.13 Average annual number of days with maximum temperature ≥35 °C ("hot days"). Data from 1961–1990 observations (Adapted from Miranda et al. 2002)

4.5 The Pine Processionary Moth in Switzerland

Beat Forster, Cynthia Nussbaumer, and Franz Meier

4.5.1 Range of the Moth and Host Trees

The pine processionary moth (*Thaumetopoea pityocampa*) only occurs in southern Switzerland on the south slope of the Alps, in the Valais, an inner alpine valley, and in the basin of Lake Geneva. The range is very stable and did not change in the last 120 years. Only in 1908, a single spot is documented in the region of Erstfeld, in a main valley in the northern Prealps (Fig. 3.14). Probably *T. pityocampa* was introduced there accidentally, maybe along the main transit railroad. Also a flight of adults across the Alps with strong winds is possible. But this Erstfeld occurrence quickly disappeared because of unfavourable climate conditions.

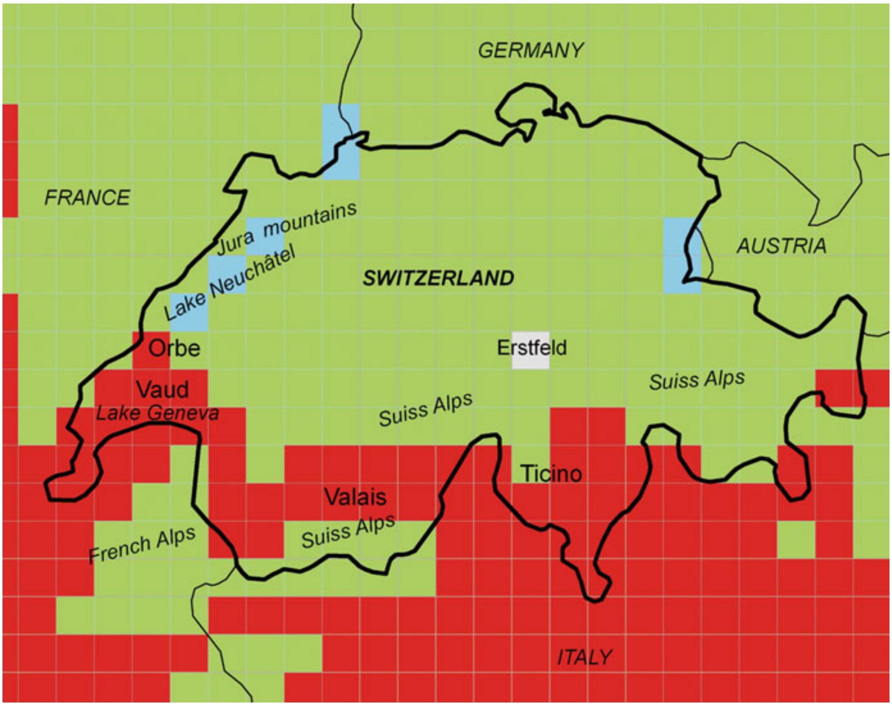


Fig. 3.14 Range of *Thaumetopoea pityocampa* in Switzerland and neighboring countries on a 16 km-cell grid (*red*: presence of one moth colony at least, *green*: absence; *grey*: temporary occurrence in 1908; *blue*: potential range that could be colonised)

Observed host trees are mainly pines (*Pinus sylvestris* and *P. nigra*), rarely larva tents can be found on *Cedrus* spp. and on Douglas fir (*Pseudotsuga menziesii*).

4.5.2 Population Dynamics and Outbreaks

The Swiss population is quite stable in time and range. After warmer years, more tents can be observed in the crowns but there are no real outbreaks. In Southern Switzerland the moth's density was queried in the 1990s and again since 2008 (Fig. 3.15). Stronger defoliations of pines only occur very locally. Attacked trees rarely die. In Valais, a strong population density can often be observed between 900 and 1,000 m a.s.l. (Keller 1903).

Until about 1980 tents occurred in the Alps below 1,100 m a.s.l. Along the Jura mountains in canton Vaud, the moth only reached about 600 m a.s.l. (Barbey 1925). After years with unfavourable weather conditions, attacks sometimes dropped in elevation by 100 m or even more. On the other hand, in the last decades, in Valais

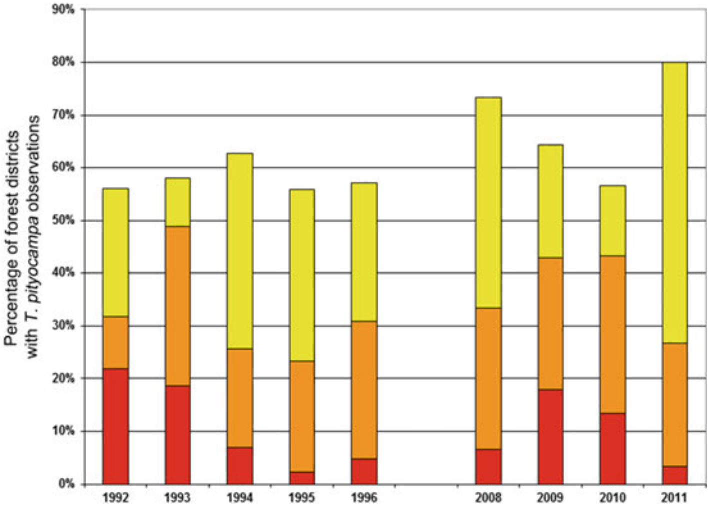


Fig. 3.15 Observed damage intensities of *T. pityocampa* in the forest districts of Southern Switzerland. Fluctuations of damage are well visible, but no real mass attacks. *Red*: strong attack; *orange*: medium attack; *yellow*: slight attack

some single observations could be made up to 1,400 m a.s.l. (Bryner 2000). In Ticino the highest occurrence was even described at 1,600 m (Rezbanyai in Bryner 2000), but in this study only trap catches of adults are concerned.

After Barbey (1925) and Bryner (2000) larvae are consuming needles from September to November and again in March and April. Processions can be observed in April and May. Adults fly from mid of July, in Valais earlier than in Ticino.

4.5.3 Influence of Global Warming

As described above, *T. pityocampa* populations gained new habitats by moving upwards slopes and valleys. But compared with other countries, no dispersions to the north could be registered. One reason may be the barrier of the Alps that cannot be crossed easily. But along the southernmost chain of the Jura mountains, no barrier would prevent the moth's expansion. Along Lake Neuchâtel, habitats seem to be favourable and some lower parts of the Swiss Plateau could be colonized by the moth (Fig. 3.14). But for decades, its northernmost occurrence remains stable near the city of Orbe. Therefore the local climate was analysed (Nussbaumer, unpublished) and compared with the moth's exigencies to habitats after Huchon and Démolin (1970). It was demonstrated that a further expansion of the moth in Switzerland could be possible, but it did not occur, probably because the local climate did not change enough. Despite a distinctive global warming for whole Switzerland, the region of Orbe to Lake Neuchâtel does not show exactly the same trend. The mean temperature of January, for example, was even slightly dropping during the last decade.

4.6 The Pine Processionary Moth in the Upper Rhine Valley: Climatic Resistance and Development of an Isolated Occurrence

Paula Halbig, Lars Henke, Jean Poirot, Eiko Wagenhoff, Horst Delb,
and Dietrich Klimetzek

4.6.1 Development of a Pine Processionary Moth Population in Obernai, Alsace

Immediately after its accidental introduction with plant material in 2007, the Mediterranean pine processionary moth settled successfully in Obernai, Alsace, France. A pheromone trap-based monitoring resulted in more than 600 and appr. 400 moths caught in 2008 and 2009 respectively. Furthermore, expansions to ambient villages within distances up to 5 km were recorded in 2009; these pine processionary moth tents, however, were instantly destroyed. Although the population declined in subsequent years, pine processionary moth is still active: Traps caught a dozen moths each in 2010 and 2011 and more than 30 tents were found both years. In 2012, despite an exceptional cold period in February with night temperatures of −19 to −15 °C and of only −8 °C at maximum during the day for more than two weeks, appr. 20 tents were counted and check of tents in April resulted in vigorous larvae. No mortality was detected in the centre of Obernai, but half of the larvae died at the edge of the town (F. Bronner, Greenspace Service Obernai, written communication 25.09.2012). Thus the population suffered from cold temperatures, but pine processionary moth larvae mainly resisted, confirming their classification as moderate freezing tolerant (Hoch et al. 2009).

4.6.2 Monitoring of Potential Expansion of Pine Processionary Moth to Germany

Triggered by the eastwards spread of pine processionary moth in Obernai, situated in a distance of appr. 21 km to the German frontier, a monitoring in the German Upper Rhine Valley was initiated in July 2009. 10 pheromone traps were placed in largely pine dominated stands along the German-French border from Bad Krozingen to Karlsruhe, which, however, did not confirm any expansion of pine processionary moth. Due to the continuing risk of introduction or spreading, pine processionary moth monitoring in Baden-Württemberg was intensified in the summer 2010, employing 15 delta traps with commercial lures mainly installed in pine stands of the most endangered region between Rheinhausen and Neuried during the whole flight period from June to August. Just as in 2010 no spread of pine processionary moth to Germany was ascertained.

4.6.3 Climate and Habitat Analysis

To assess the potential risk of pine processionary moth establishment in Baden-Württemberg, climatic and stand data were analysed in context of the so far known habitat requirements of pine processionary moth. A state-wide climate analysis from 2000 to 2009 was conducted using GIS-Software SAGA and ArcGIS. For a potential distribution, absolute mortality limits of ≥1,800 h annual insolation and a mean minimum of −4 °C in January must be reached (Battisti et al. 2005). That way two-thirds of Baden-Württemberg's territory were classified as a potential range. A long-term permanent distribution requires >0 °C as minimal January air temperature plus 1,800 h insolation per year. Each degree colder in January can be compensated by 100 h additional annual insolation, leading to a combination of −4 °C with 2,200 h (Huchon and Démolin 1970). These conditions were only partly fulfilled in Baden-Württemberg. However, areas in red mark the highest and light shading mark the lowest risk of becoming long-term distribution regions (Fig. 3.16).

In the monitoring area Lahr, winter temperatures for larval feeding were examined in some detail. Air temperatures >0 °C at night as potential feeding temperatures are required from December to February; moreover an activation temperature >9 °C must be reached during the day (Battisti et al. 2005). Lethal temperature values for larvae were checked, using −13.7 °C for L2 from October to November as well as −16 °C for L3/L4 in November and December (Buffo et al. 2007). Both, temperature values for larval feeding and lethal temperatures were rarely attained from 1995 to 2010 and 1961 to 2010 respectively at Lahr. The presence of suitable host trees was analysed in the Upper Rhine Valley, applying FoGIS (Forest GIS of Baden-Württemberg) and ArcGIS to locate pine stands with ≥50 % pine (*Pinus sylvestris*) proportion, resulting in 25 % of the forest area as potentially endangered by pine processionary moth.

4.6.4 Conclusion

Although the abundance of the pine processionary moth population in Obernai has been decreasing since 2010, an expansion or introduction to Germany is still possible. Increasing temperatures could lead to a doubling of expansion rate (Robinet et al. 2012). Based on the climatic analysis, the monitoring areas appear neither currently nor in the near future endangered by pine processionary moth. However, annual insolation and January air temperature undergo an increase leading to more favourable conditions. Additionally its plastic lifestyle increasingly

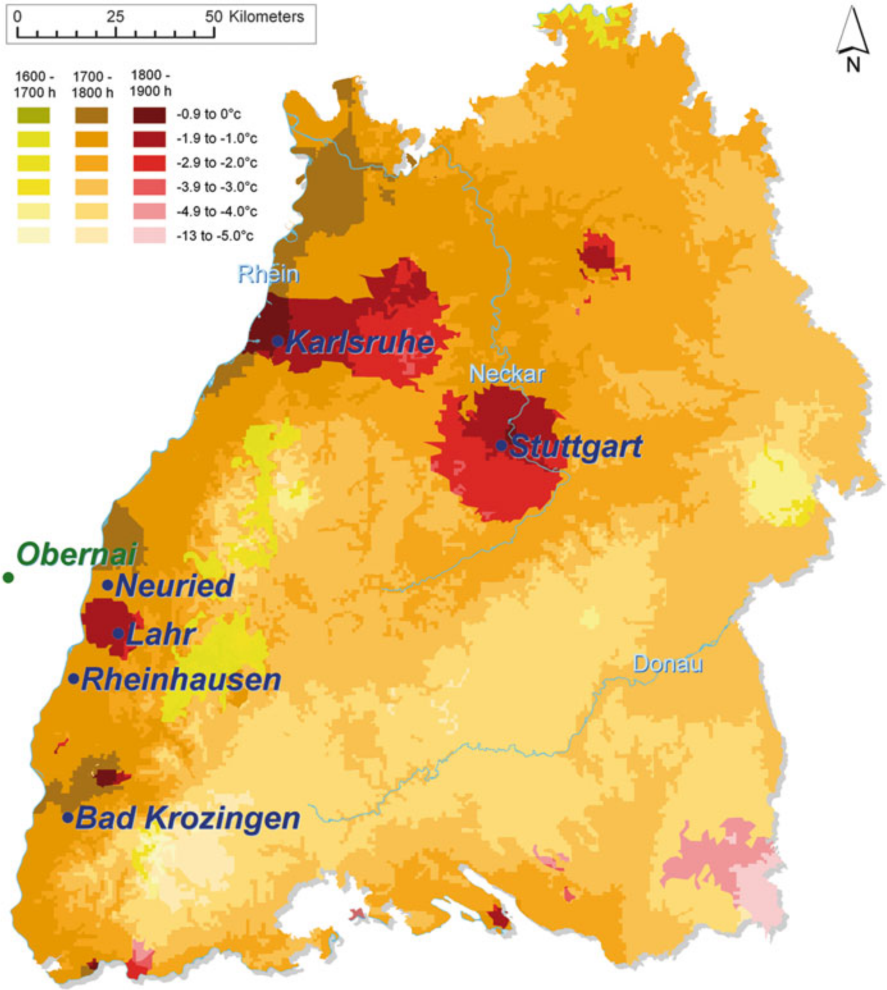


Fig. 3.16 Potential long-term permanent distribution areas of pine processionary moth (*red*/*dark*) and areas at medium (*orange*) and small (*yellow*/*light shading*) risk of settlement in Baden-Württemberg according to annual insolation and average minimum January air temperature (cf. text)

enables pine processionary moth to survive extreme climatic conditions. It is able to shift critical instars in course of the year as well as extending its diapause (Pimentel et al. 2006; Seixas Arnaldo et al. 2011). Taking continuous trends of global warming and pine processionary moth's lifestyle into account it must be assumed that sooner or later pine processionary moth will establish steadily in the Upper Rhine Valley.

5 Past and Current Situation of the Pine Processionary Moth, *Thaumetopoea Pityocampa*, in the Balkans

5.1 The Pine Processionary Moth in Slovenia

Jan Podlesnik and Maja Jurc

5.1.1 Present Biogeographical Range

The first record of *Thaumetopoea pityocampa* in Slovenia dates to 1903 (location: Sela on Karst). It spread from Friuli in Italy, where it was recorded since 1898 (Kafol 1951). Nowadays *T. pityocampa* is present all across the western part of Slovenia; i.e., the regions of Istria, Karst, Primorska and Tolmin (Jurc et al. 2003). In the last 10 years individual sightings were made in the upper Primorska region around Bovec and above Log pod Mangartom at 1,200 m.a.s.l., which is one of the northernmost locations of pine processionary moth in Slovenia. In 2011 it was recorded in an alpine valley in northern Slovenia near Bohinjska Bistrica (Notranji Bohinj), in the heart of the Julian Alps. In 2010/2011 it spread across a wider area in the southern part of Slovenia near Ilirska Bistrica (Slovenian Forestry Service 2011; Fig. 3.17).

5.1.2 Population Dynamics and Outbreaking Periods in the Past

The outbreaks of *T. pityocampa* mostly occurred during years with higher average temperatures and lasted only for short periods of time. Gradations were recorded in years 1928–1929, 1937–1938, 1944–1945, 1948–1950, 1953–1954, 1958–1959, 1965–1966, 1969–1970, 1972–1973, 1976–1979, 1982–1983, 1992–1993, mostly in the Karst region around Črni Kal, Osp, Socerb, Sočerga, Kubed, Dekani and Škofije. Particularly pronounced gradations were reported between 1944 and 1950, when only in 1949 there was a 25–100 % defoliation rate on 259 ha of *Pinus nigra* stands. In 1950 in the Karst region larvae were suppressed by removing their tents and using insecticides – more than 1,502 ha of pine plantations were treated with 16.5 % DDT emulsion (Titovšek 1994; Jurc 2001).

5.1.3 Particular Biological Features Observed in the Country

In Slovenia *T. pityocampa* develops one generation a year. The flight period begins in the beginning of July and lasts until August; during these months it also disposes eggs. Larvae overwinter in fourth instar inside their tents. In late winter or early spring the larvae become active again and start feeding until they reach the fifth larval instar. From 15th of March to 1st of May the larvae move to the ground where

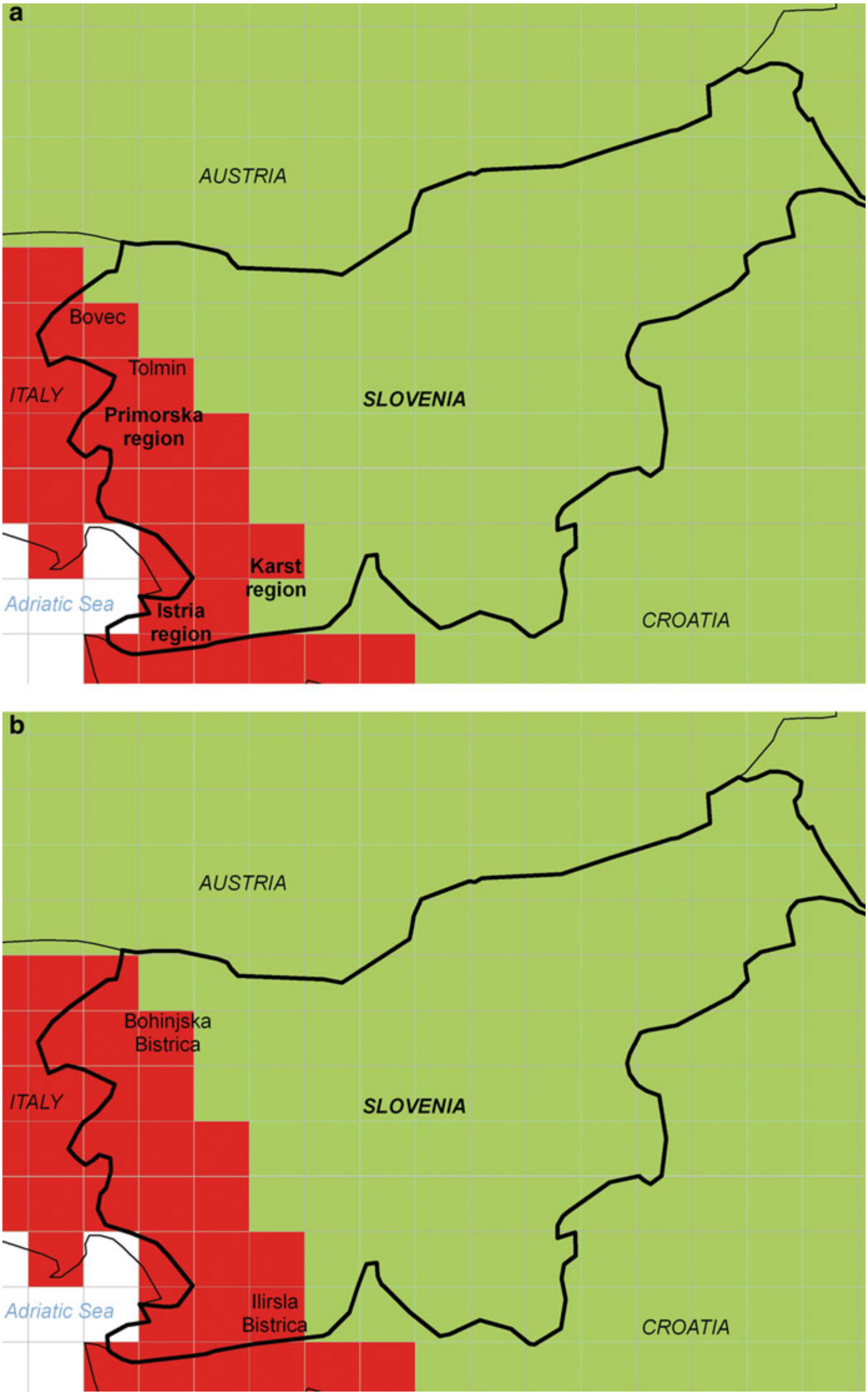


Fig. 3.17 Distribution of *Thaumetopoea pityocampa* in Slovenia and neighboring countries on a 16 km-cell grid. *Top*: before 2000; *bottom*: during winter 2011–2012. *Red squares* show the presence of *T. pityocampa* whereas the moth is absent in areas figured in *green*

they pupate buried in the ground. A severe winter (−25 to −29 °C) does not harm the larvae, but humid winters can cause high larval mortality (Kafol 1951). In Slovenia *T. pityocampa* appears on *Pinus nigra*

5.1.4 Expansion with Global Warming

The past and present distribution of *T. pityocampa* is shown in Fig. 3.17 (Slovenian Forestry Service 2011). Average 10 year temperatures around year 1970 were from 0.5 to 1.5 °C lower than the average temperatures of last 10 years, measured by 6 weather stations in the relevant areas (ARSO 2012). This is probably one of the reasons why *T. pityocampa* spread and started to appear at higher elevations in the northern Tolminska region, around Log pod Mangartom. In 2010/2011 it spread to an alpine valley near Bohinjska Bistrica. In the last 2 years it also spread to new locations in southern Slovenia around Ilirska Bistrica.

5.2 The Pine Processionary Moth in Croatia

Dinka Matošević

5.2.1 Present Biogeographical Range

The first record of moth infestation in Croatia was from island of Mljet in 1889. Then, severe infestations in pine forests were noticed on the northern coast of Croatia during the period 1902–1926. At that time, Knin was the farthest location from the coast where pine processionary moth was observed (Langhoffer 1927). Observing severe outbreaks on pines in the coastal region of Croatia, Radčenko (1927) concluded that pine processionary moth is distributed in the area up to 1,000 m a.s.l. although rarely found at such elevation. He also concluded that the moth prefers dry and warm years. Later, Beltram (1947) noticed that the moth is not found above 800 m a.s.l. because of the too cold climate there.

Androić (1957) supplied a distribution map of pine processionary moth in Croatia, showing that it is present on all Croatian islands and on the coast, and Harapin (1984) precised the range limits in the early 1980s (Fig. 3.18). Moth range is not completely overlapping with pine distribution in Croatia because temperature limits its presence to the coastal belt only. Thus, the distribution of pine processionary moth is coinciding with the July isotherm of 22 °C (precisely between 22 and 23 °C) which corresponds to the yearly isotherm between 13 and 14 °C (Androić 1957). Actually, the moth range is overlapping with the northern border of the optimal growing zone for pubescent oak (*Quercus pubescens*), which is also the southern border of the natural range of silver fir (*Abies alba*) and common beech (*Fagus sylvatica*) in Croatia (Androić 1957). Topographically, this area corresponds to the mountain

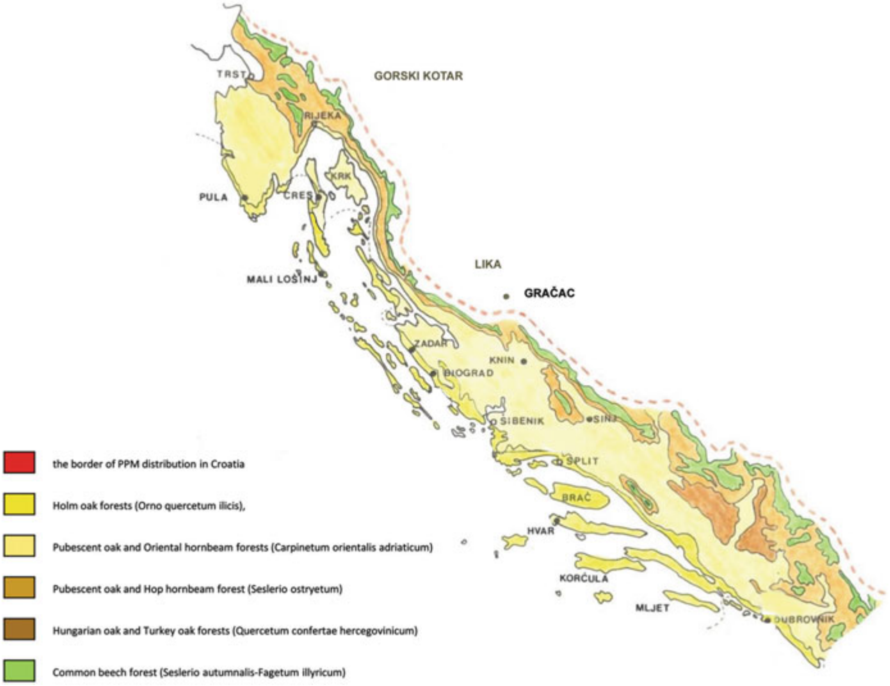


Fig. 3.18 Distribution of pine processionary moth in Croatia in 1984 (Modified from Harapin 1984)

border between the Mediterranean zone (coast and in its immediate hinterland) and the Alpine or Dinaric (Lika and Gorski Kotar) regions of Croatia.

Moth spread into the mainland thus depends on climate which is mediated by topography. Indeed, the pine processionary moth is present in the areas where the topography allows warm air currents to penetrate, giving the characteristics of Mediterranean or Sub-Mediterranean climates (eg. Gračac, Knin).

Minimal temperatures in the months when pine processionary moth is in egg or larval stages are the limiting factors for its further spread into the mountains. Laboratory trials carried out in Croatia showed that 12 °C is a limiting temperature for embryonic development, and 11 °C for the development of the first larval instar (Androić 1957).

5.2.2 Host Range

The main host plants of pine processionary moth in Croatia are *Pinus nigra*, *P. halepensis*, *P. pinea*, *P. sylvestris* and *P. pinaster*. *Cedrus* spp. are also mentioned as host plants (Beltram 1947; Harapin 1984).

5.2.3 Expansion with Global Warming

The present distribution of pine processionary moth in Croatia, shown in Fig. 3.19, is quite similar to the one previously detailed by Beltram (1947), Androić (1957) and Harapin (1984). Recent data showed that 2,000–3,000 ha of pine forests were damaged in the coastal region each year since 2001. However, the moth has not yet been found in the pine forests or plantations of the continental part of Croatia. The front edge has not moved to mainland Croatia and has not jumped across the mountain range which is the main obstacle for its moving up north. Egg masses and larval colonies are still not found in these mountains as well. Both alpine climate and the climate corresponding to the vegetation zone of silver fir and common beech forests are major limiting factors for moth expansion.

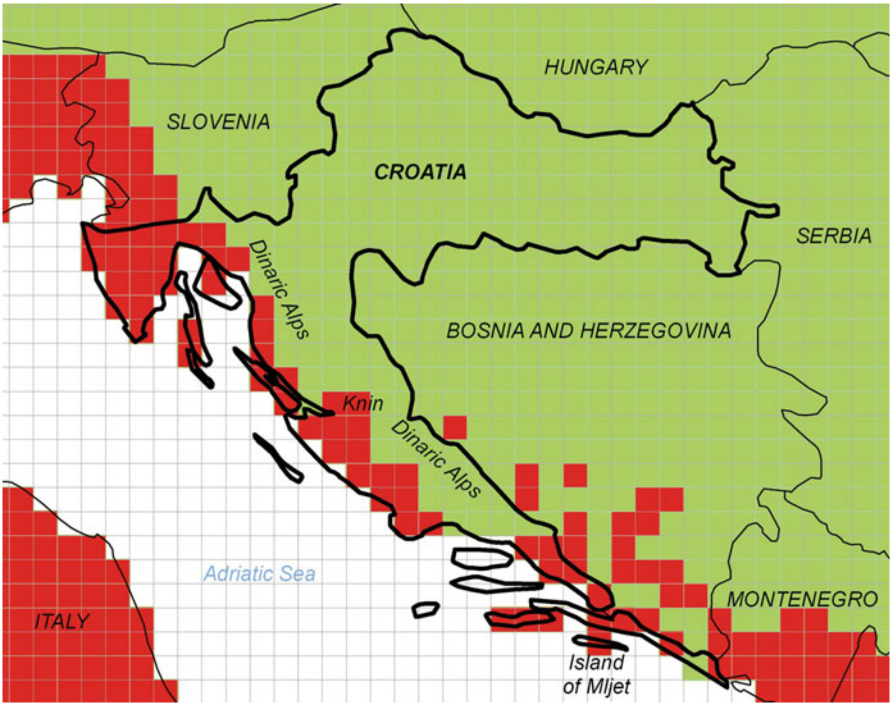


Fig. 3.19 Distribution of pine processionary moth in Croatia and neighboring countries during winter 2010–2011 on a 16 km-cell grid. *Red squares* show the presence of *T. pityocampa* whereas the moth is absent in areas figured in *green*

5.3 The Pine Processionary Moth in Bosnia and Herzegovina

Mirza Dautbašić

5.3.1 Present Biogeographical Range

From both an economic and ecological point of view, the pine processionary moth, *Thaumetopoea pityocampa*, is a very important pest of Austrian black pine (*Pinus nigra*) in the sub-Mediterranean range of Bosnia and Herzegovina. Unfortunately, moth impact was largely underestimated in the country's forestry practices during the past. The species was first mentioned in Bosnia and Herzegovina during the late 1970s where it was only recorded only in canyons of the Neretva River (Konjic, Prozor) (Androić 1978).

The occurrence of a serious moth outbreak in Herzegovina Region, near Mostar City, in 2007, led to start investigations on its distribution and infestation level in the whole country. So far, pine processionary moth was recorded in the following locations: Borci, Bosansko Grahovo, Buško jezero, Čapljina, Čitluk, Glavatičevo, Grude, Konjic, Livno, Mostar, Posušje, Prozor, Rujišta, Široki Brijeg, and Trebinje (Fig. 3.20). The high Bosnian Mountains are natural barriers for the further spreading of the moth into the central part of the country. Rather low at high elevations such as Ruište (840 m) and Borci (850 m), the infestation was very high at Mostar and Trebinje.

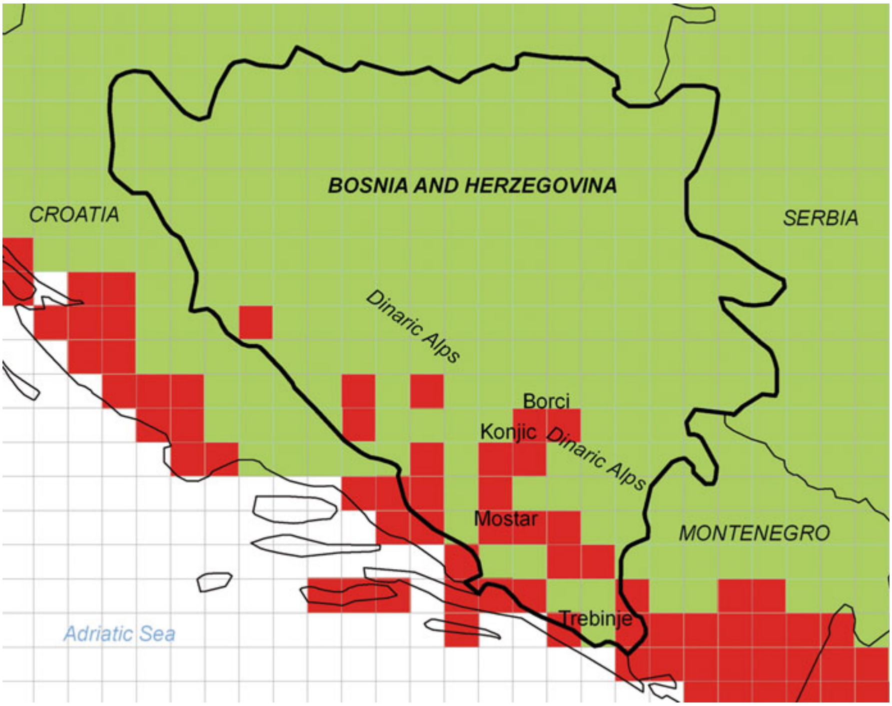


Fig. 3.20 Distribution of *Thaumetopoea pityocampa* in Bosnia and Herzegovina and neighboring countries during winter 2010–2011 on a 16 km-cell grid. *Red squares* show the presence of *T. pityocampa* whereas the moth is absent in areas figured in *green*

5.3.2 Host Range

In Bosnia and Herzegovina, pine processionary moth exclusively attacks Austrian black pine but does not infest the other pine species growing in the country (*P. sylvestris*, *P. halepensis*, *P. mugo* and the endemic species, *P. heldreichii*).

Three major egg parasitoid species have been identified: *Baryscapus servadeii, Ooencyrtus pityocampae* and *Anastatus bifasciatus*. No control methods have been applied against this pest in Bosnia and Herzegovina.

5.4 The Pine Processionary Moth in Serbia and Kosovo

Milka M. Glavendekić and Ljubodrag Mihajlović

5.4.1 Present Biogeographical Range

In the former Yugoslavia, the pine processionary moth was commonly reported from the Mediterranean and Sub-Mediterranean regions. In Serbia, it regularly occurred in the vicinity of Peć (AP Kosovo), and during the late 1970s the moth was observed at Mt. Prokletije, in the locality of Žare, at an elevation of 1,100 m. A further outbreak occurred at the same locality during 1996–1997 but was suppressed by high egg parasitism (app. 70 %) caused by the specialist eulophid parasitoid *Baryscapus servadeii* (Mihajlović and Roganović 1997).

Sex pheromone monitoring carried out during 2009–2012 revealed moth movements eastwards from Peć to Rabovce (Orahovac). In addition, moths were recorded for the first time in South-Eastern Serbia in the forest monocultures of *Pinus nigra,* which were afforested in 1988 by the Public Enterprise “Srbijašume” of the Forest Department of Bujanovac, in the localities of Trnovačka Reka, Rajince, Crnotince (near Preševo) and Rujan (near Bujanovac). Monitoring was performed in pine plantations located between 482 and 646 m (Glavendekić and Mihajlović 2012). Pheromone monitoring in 2012 confirmed these results (Table 3.1). Additional records

Table 3.1 Pheromone monitoring in Serbia in 2012

Forest unit and compartment	Coordinates	Captures
Preševo, 150a	N 42°22,866 E 21°40,944	9
Preševo, 148a	N 42°22,996 E 21°40,175	30
Preševo, 129a	N 42°21,713 E 21°42,198	8
Trnovačka reka, 19	N 42°28,631 E 21°43,224	15
Rujan, comp. 22j	N 42°25,867 E 21°47,938	11
Rujan, comp. 5a	N 42°21,671 E 21°48,070	41
Rujan, comp. 4b	N 42°21,665 E 21°48,437	22
Rujan, comp. 5a	N 42°21,584 E 21°47,825	103

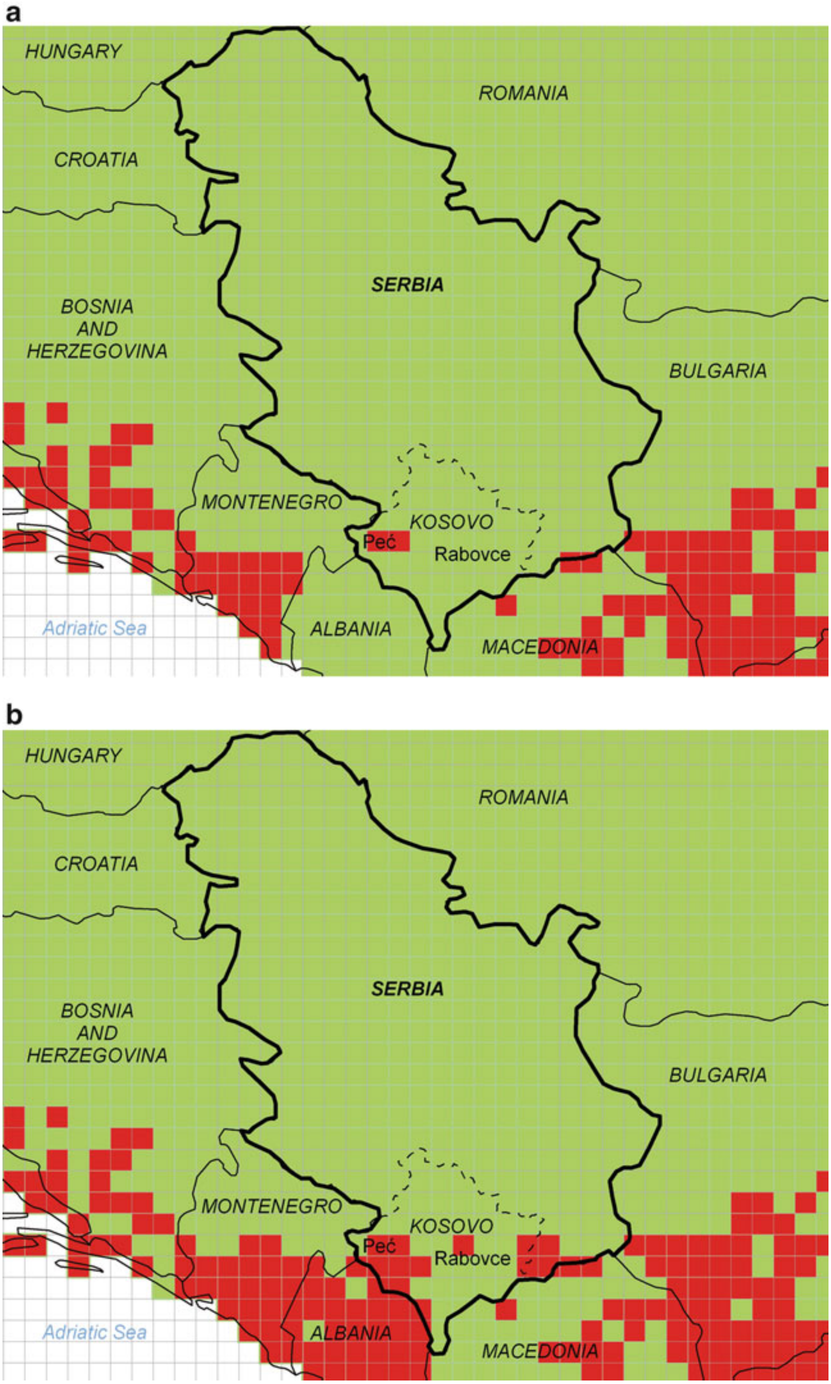


Fig. 3.21 Distribution of pine processionary moth in Serbia and Kosovo and neighboring countries on a 16 km-cell grid. *Top*: before 2008; *bottom*: winter 2010–2011. *Red squares* show the presence of *T. pityocampa* whereas the moth is absent in areas figured in *green*

from the Republic of Macedonia (see 5.7, this chapter) indicated that moth presence in the locality Rujan (forest compartment 5a) is likely to result from a northwards expansion along the valley to Serbia. In this place, larval tents were observed for the first time in December 2011 on black pine. Moth range is thus expanding eastwards from its previous distribution in Peć and northwards from Macedonia (Fig. 3.21.).

5.4.2 Particular Biological Features Observed in the Country

Adult flight period in Serbia starts in August and males are captured in pheromone traps until late September. In the expansion area at Rujan, larvae were still feeding on the top of pine crowns by late December after an extremely mild autumn. The first frosts occurred in January where some larvae proved to be capable of surviving few days with temperature below −20 °C and to resume development when then reared in insectarium in Belgrade. The encyrtid egg parasitoid *Ooencyrtus pityocampae* was found during autumn 2012 in the same locality, thus following pine processionary moth in the newly occupied pine stands

5.4.3 Expansion with Global Warming

Data covering from the period 1951–2005 revealed significant changes in temperature in Serbia. Average summer air temperature has been rising for more than 1 °C during 100 years on more than two-thirds of the Serbian territory but a slight negative trend in summer temperature is recorded in the South-East of Serbia (Popović 2007).

5.5 The Pine Processionary Moth in Montenegro

Milka M. Glavendekić

5.5.1 Present Biogeographical Range

Pine processionary moth is common along the coast of Montenegro, being observed in Bar, Petrovac, Miločer, Črvanj and Budva. In the continental part of Montenegro it has been recorded in the vicinity of the cities of Cetinje, Podgorica, Nikšić and Danilovgrad. The first outbreak of pine processionary moth in Montenegro was recorded in 1924–1925 in pine forests of Nikšić County. Then, local outbreaks were noticed after the Second World War on the Adriatic coast and in the vicinity of Cetinje, Podgorica and Nikšić. Large outbreaks were observed in pine plantations during 1957–1961, covering areas from 145 to 1,234 ha (Stamatović 1961). During winter 1959–1960, an outbreak occurred in a ca. 70 years-old pine forest with 200–300 trees in the vicinity of the capital Podgorica, where all pine trees and also planted *Cedrus atlantica* were infested (Mijušković 1961). A further outbreak occurred there during 1968–1970, and pine forests suffered a severe defoliation (Mijušković 2002). The last outbreak occurred in 2005–2006 in the Forest Enterprise of Danilovgrad, at the localities Bzo (1,024 m) and Topolovo (1,080 m). During our research, carried out from 2003 to 2012, a continuous increase in population levels of pine processionary moth has only been observed at the locality Ćemovsko Polje in plantations of *Pinus nigra* and *P. halepensis* in the suburbs of Podgorica.

5.5.2 Particular Biological Features Observed in the Country

The flight period starts from early August in the coastal area and at low elevation. At higher elevation, from 1,000 to 1,540 m, the first adults were captured in pheromone traps from the middle of July until the last decade of September. Mijušković (1961) noted that egg masses include 148–279 eggs, mainly laid in seven rows. In our observations, larvae hatched after 30–35 days. Hatching started from September 5th but extended to October 10th. On September 23rd, both first and second-instar larvae were observed. Due to mild winter temperatures, the larvae feed continuously during winter (Mijušković 2002).

The encyrtid egg parasitoid *Ooencyrtus pityocampae* has already been observed since 1959 in forests near Podgorica where it parasitized 16.9 % of the moth eggs (Mijušković 2002). *O. pityocampae* is the only egg parasitoid recorded so far in Montenegro at low elevation (Ćemovsko Polje, suburbs of Podgorica) but no egg parasitoids were observed at elevations above 1,000 m (Glavendekić 2010).

5.5.3 Host Range

Pine processionary moth attacks *Pinus nigra, P. halepensis, P. heldreichii* and *P. pinaster* in Montenegro.

5.5.4 Expansion with Global Warming

There is an evidence of climate change in Montenegro. As far as the temperature is concerned, almost all measuring places showed that the last observed decade (1999–2008) is, in average, the warmest one during the instrumental period from 1949 on (Burić 2011). Thus, during the 1951–2008 period, the number of summer days, i.e.; showing a maximum daily temperature above 25 °C, increased by 3.6 days per decade in Podgorica whilst the annual amounts of precipitation showed a growth tendency in the last two decades in Podgorica as well as in the other parts of Montenegro. Thus, it could be considered that climate change in Montenegro is favorable to the expansion of pine processionary moth, and its range effectively expanded towards higher elevation, the insect being observed at 1,024–1,540 m (Fig. 3.22). In 2005, a first outbreak of pine processionary moth was even observed

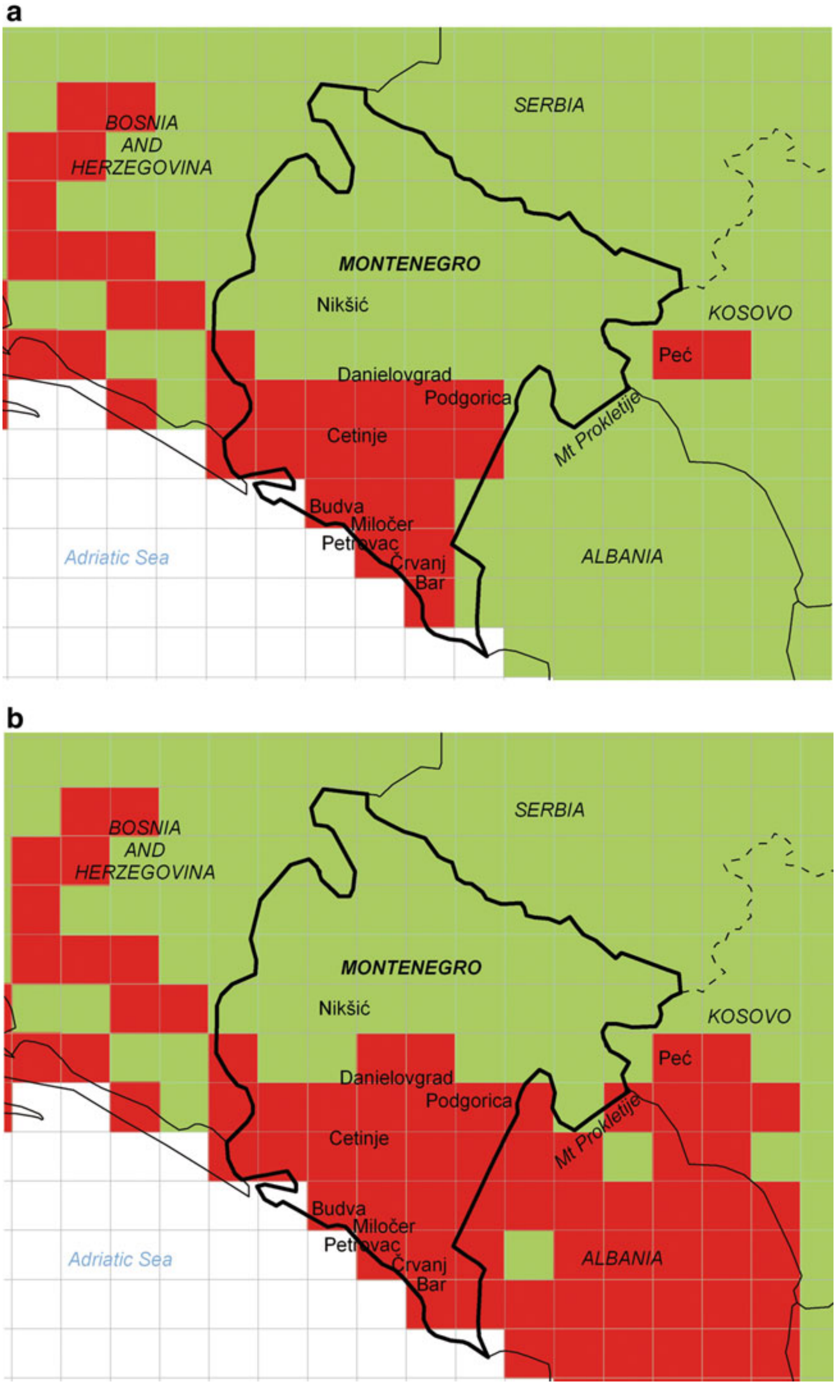


Fig. 3.22 Distribution of pine processionary moth in Montenegro and neighboring countries (**a**) before 2008; (**b**) during winter 2010–2011 on a 16 km-cell grid. *Red squares* show the presence of *T*. *pityocampa* whereas the moth is absent in areas figured in *green*

at an elevation of 1,024–1,080 m. Moreover, up to now there is no evidence that the natural enemies followed moth colonies in the newly occupied pine stands.

5.6 The Pine Processionary Moth in Albania

Ejup Çota

5.6.1 Present Biogeographical Range

Albanian forests presently cover 1,026,410 ha, i.e., 51 % of the country surface whilst agricultural lands only cover 24 %, the remaining 25 % corresponding to rocky areas, water bodies and settlements. Forests are either pure or mixed and mainly consist of beech, black pine, oak, maritime pine, fir and other broadleaves and conifers. Black pine, *Pinus nigra,* the main host of the pine processionary moth is present in the counties of Lure (Diber), Balgjaj (Mat), Llogara (Vlore), Voskopoje (Korce), Terbune (Puke), Gramsh, Erseke (Dida et al. 2001). Mountain pines occur above the beech and fir forests under conditions of hard climate and poor soils, at elevations of 1,600–2,100 m in the north and from 1,700 to 2,300 m in the south. They are represented by *Pinus leucodermis, P. peuce* and *P. heldreichii* (Dida et al. 2001).

It is likely that two periods of expansion of pine processionary moth occurred in Albania (Fig. 3.23). The first one took place before 1994. Actually, there was no relevant information about the distribution and the bioecology of the moth before the late 1980s (Llubani and Zadrima 1989). Nevertheless, it was known that the pest was present since many years ago in the country, with infestation rates ranging 25–30 % in black pine stands (Çota, unpublished data). Then, a large outbreak was observed in 1994, where about 16 % of the pine forests were heavily infested. The infested area reached about 70 000 ha (personal information of M. Dida, F. Ducci and G. Zeneli). The infestation rate ranged from 5 to 95 %.

More recently, pine processionary moth was monitored from 2009 to 2012 at the northern border of Albania, mainly in Puka and Kukës, in a region mainly dominated by black pine, which could have favored the expansion and damage caused by this species. Indeed, while the winter temperature was increasing, the moth expanded towards the northern mountainous areas of Albania. In 2009, the infestation rate in Puka region (northern frontier) was 2–4 tents/pine trees over 100 examined trees. This high infestation rate was rather stable with 2–3 tents/tree in 2010 and 3–4 in 2011.

5.6.2 Particular Biological Features Observed in the Country

At lower elevation/latitude, larval feeding ends by late winter or early spring, diapause is facultative, and moths emerge in late summer. The larvae can tolerate

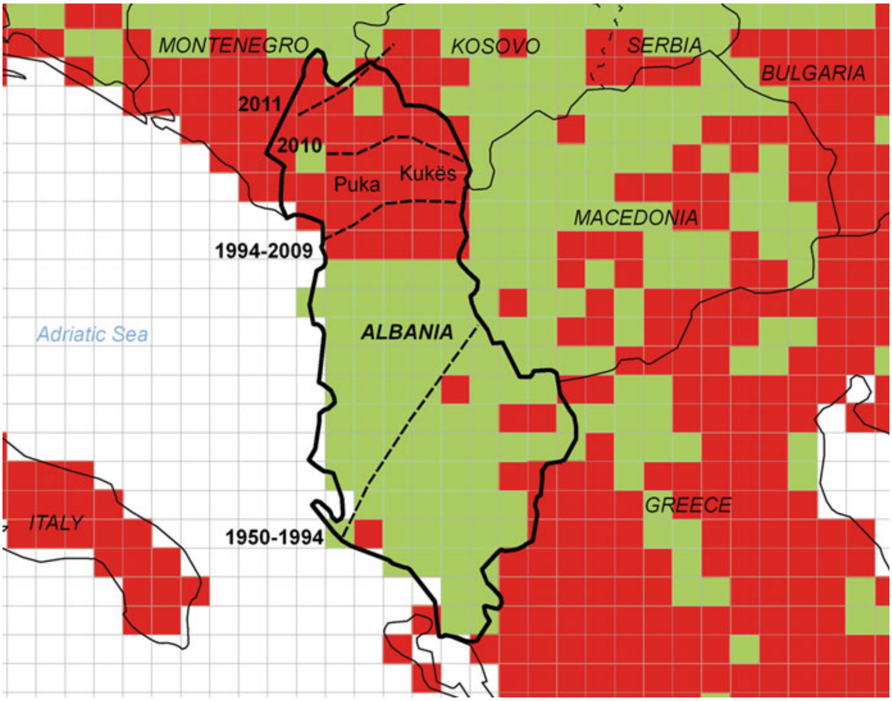


Fig. 3.23 Past and present distribution of pine processionary moth in Albania and neighboring countries on a 16 km-cell grid. *Red squares* show the presence of *T. pityocampa* whereas the moth is absent in areas figured in *green*. The lines 1950–1994, 1994–2009, 2010, 2011 show the front edge of the moth distribution at these different periods

temperatures as low as −15 °C for several days provided that the colony is numerous and the tent is well built. We observed that winter temperatures increased, reducing the number of days with frost. This is a key factor determining the outbreak capacity of pine processionary moth, as low winter temperature strongly determines the larval survival of this insect (e.g. Breuer et al. 1989; Halperin 1990).

5.7 The Pine Processionary Moth in the Republic of Macedonia

Sterja Nasceski and Irena Papazova

5.7.1 Present Biogeographical Range

Pine processionary moth was already recorded 50 years ago in nearly all the natural black pine stands of the Republic of Macedonia (Serafimovski 1959; Kusevska et al. 1978). It was observed in the southern part of the country

(Gevgelija at an elevation of 535 m a.s.l. to Visoka Čuka at 1,200 m.; Mariovski basen, where is the main focus of infestation, to Ligurasa – Tribot – Karavastina at 1,200 m a.s.l.), as well in the north (from Pusta Breznica to Skopje), the Central part (it can occasionally be found near Krusevo on 1,300 m.a.s.l), the east along the border (Malesevki Mountains, Golak, Plačkovica, Ograzden), and the west to Bitola, Resen and Ohrid Region. In these natural stands, the processionary moth did not constitute particular threat because of the natural regulation of its populations, and the resulting damage is thus reduced to a minimum.

But the pine processionary moth has extended to the man-made pine plantations which cover 160,000 ha, 95 % from them being black pine monocultures. At present it can be found nearly everywhere, from Gevgelija on south through the whole flow of Vardar River to Skopje; in the east at Kriva Palanka, Kratovo, Golak, Malesevski Mountains, Plackovica, and Sveti Nikole; in the west at Prilep, Resen, Ohrid, Struga occasionally in Krusevo and Brod; and a single presence is registered in Demir Hisar and Kičevo Region. Presently, the most jeopardized black pine cultures are those in the regions near Vinica, Delcevo, Radoviš, Kočani, Štip, Veles, Negotino, Sveti Nikole, Bitola and Prilep. (Fig. 3.24).

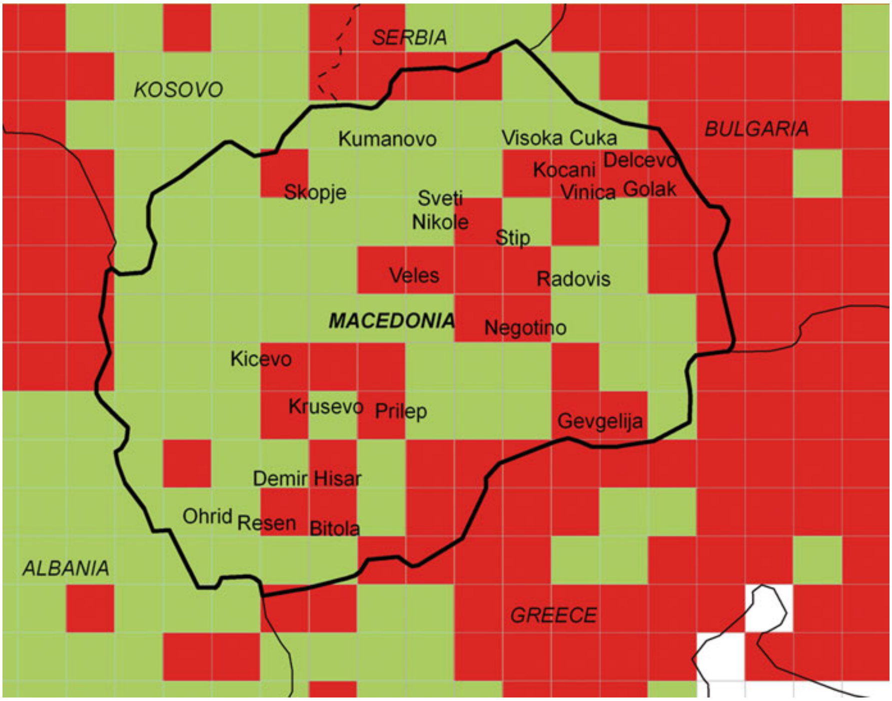


Fig. 3.24 Distribution of pine processionary moth in the Republic of Macedonia and neighboring countries during winter 2010–2011 on a 16 km-cell grid. *Red squares* show the presence of *T. pityocampa* whereas the moth is absent in areas figured in *green*

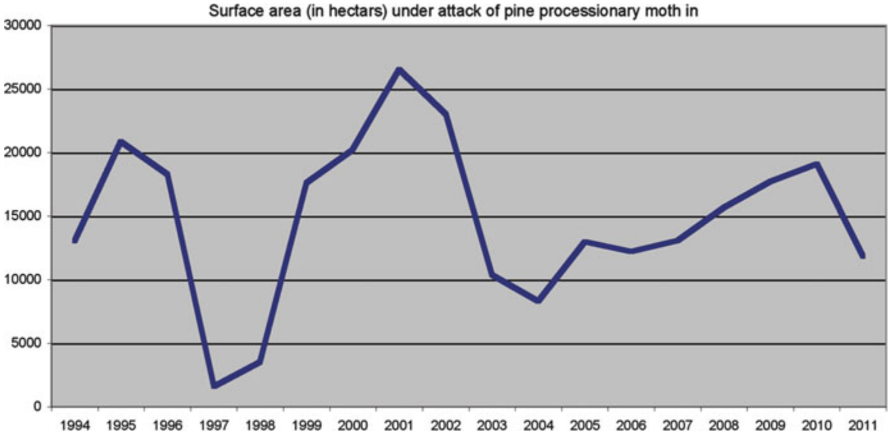


Fig. 3.25 Annual variations in the size of forest surfaces attacked by processionary moth from 1994 to 2011 in the Republic of Macedonia

5.7.2 Population Dynamics and Outbreaking Periods in the Past

Pine processionary moth showed gradations in the pine stands of the Republic of Macedonia at regular intervals of 4–5 years. Thus, moth outbreaks were registered in 1990, 1995 and 1996, when more than 20,000 ha of pine stands were attacked.

The first outbreak on the large area was noticed in 1986, when 3,000 ha of pine forests were damaged in the region of Bitola. Since then, cyclical heavy infestations occurred, increasing in intensity with changes in climatic conditions. In 1992, 4,500 ha became infested whilst the damaged area reached 20,000 ha in 1995. Control measures resulted in population collapse in the following years. However, in 1999, the level of infestation increased, and 26,500 ha subsequently became infested (Fig. 3.25).

In 2009, there was another outbreak and by May 2010 significant damage was reported. Moth monitoring using the number of larval tents revealed a critical population density in the country although annual and regional fluctuations were noticed. Moth presence was ascertained in 27 regions. During 2003–2010, the number of larval tents ranged 400–20,400 in Bitola region whilst these values varied between 460 and 19,000 in Kočani region. In 2011, nearly 8,000 ha showed very high population density, with serious threats for total defoliation, and possibly destruction. In this year, the number of larval tents varied from 3,400 per ha at Mirjanina crkva-Štip to 8,600 at Gočeva Gora – near Negotino.

5.7.3 Particular Biological Features Observed in the Country

Swarming and egg-laying of pine processionary moth starts by late July and lasts until the beginning of August in sites located at high elevation (700–900 m), in the Republic of Macedonia. However, these processes start 7–10 days later in sites at lower elevation (200–500 m). Larva development depends on the climatic conditions. In a year with mild winter (such as years 2001/2002), larval development is completed by mid-February when the larvae begin to process. By contrast, in years with cold and long winters (such as years 2011/2012), the development is delayed and only completed by mid- or late May.

Several species of egg parasitoids have been identified in Macedonia: *Ooencyrtus pityocampae*, *Tetrastichus tibialis*, *Trichogramma semblidis* and *Trichogramma embryophagum*. Natural parasitization by these egg parasitoids only reached 13.5 %, which is not enough to induce a natural regulation of moth populations in the pine plantations.

5.7.4 Hosts

Predominantly on *Pinus nigra*, but occasionally on *P. sylvestris, P. peuce, P. brutia*, *P. pinaster*, and *Pseudotsuga menziensii*.

5.7.5 Expansion with Global Warming

As a likely result of global warming, larval colonies were registered in 2009 for the first time at Zmiski Rid near Kumanovo as the most northern location in the country (Fig. 3.24). High densities of larval tents were also observed on the 500 ha of this area in 2010.

5.8 The Pine Processionary Moth in Greece

Dimitrios N. Avtzis

Conifer forests of Greece are mainly composed of pine species, with *Pinus halepensis, P. brutia, P. nigra*, *P. pinea* and *P. sylvestris* being the most abundant ones (Arabatzis 1998). The dominating needle-feeding pest of these forests, and one of the most dangerous pests in Greece in general is the Pine processionary moth, *Thaumetopoea pityocampa* (Avtzis and Avtzis 2001). This species infests each and every one of the endemic and exotic pine species in Greece; yet the larvae shows a clear preference for some specific host species (*Pinus halepensis, P. nigra* and *P. radiata*) over others (*Pinus pinea, P. pinaster*), something that has been attributed to differences in the chemical composition and ingredients of needles (Avtzis 1986; Breuer et al. 1989; Schmidt 1989). In particular, larval mortality was positively correlated with the concentration of silica in the needles and the metabolization of phenols (Schopf and Avtzis 1987). It was thus suggested that the combined effect of hardness and resin composition of

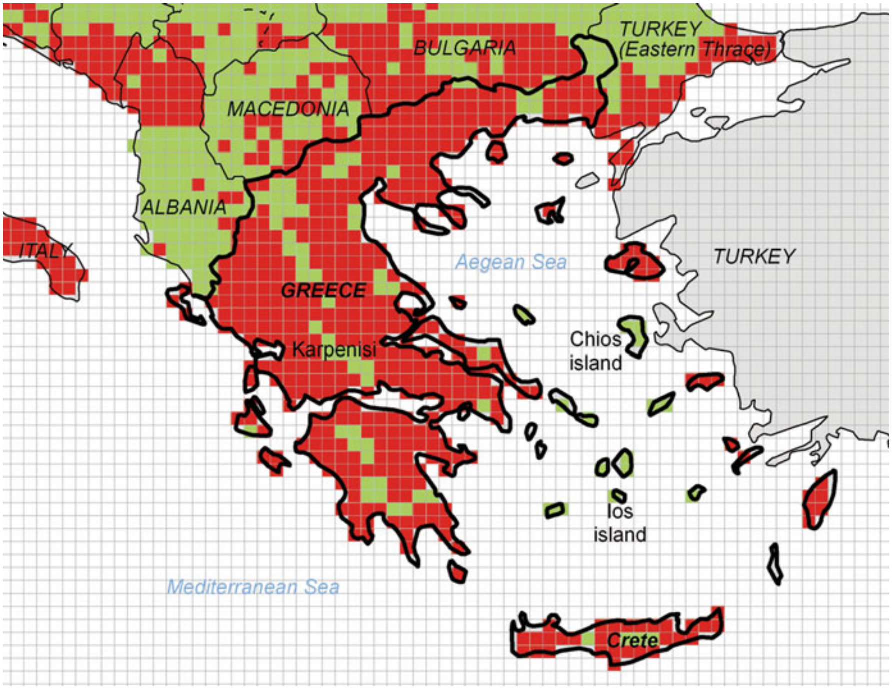


Fig. 3.26 Distribution of pine processionary moth in Greece and neighboring countries during winter 2010–2011 on a 16 km-cell grid. *Red squares* show the presence of *T. pityocampa* whereas the moth is absent in areas figured in *green*

needles determines host selection by pine processionary moth (Devkota and Schmidt 1990).

A direct consequence of the wide spectrum of host species is that pine processionary moth occurs wherever pine grows in Greece from sea level up to 1,800 m (Avtzis 1983). The occurrence of pine processionary moth in Greece (Fig. 3.26) is inhibited only either by unsuitable weather conditions (Karpenisi) or mainly due geographic isolation of the areas (e.g., some islands such as Hios where the moth has not yet been introduced or areas with an elevation higher than 1,800 m) (Avtzis 1983; Buxton 1983). However, even in the areas where it occurs, the population density of the pest in Greece varies over different areas (Avtzis 1986). As possible reasons that could account for the fluctuating population density of the moth in Greece, Kailidis (1991) suggested the exposition of the stand (associated with the general preference of the pest for warm, dry and sunny places on trees) as well as the occurrence of *Quercus coccifera* at the lower levels of vegetation (that poses an impediment during the procession of pine processionary moth).

The importance and significance of pine processionary moth in Greece is reflected on the amount of studies conducted that investigated the most effective methods to control this pest. From chemical insecticides and pyrethrinoids to the currently and most commonly used biological approach of *Bacillus thuringiensis*, Greek researchers have struggled to put pine processionary moth under control (Kailidis 1965; Georgevits 1979; Avtzis 1984). However, as pine processionary moth is a pest that constantly concerns the Greek forest services and authorities, research on control strategies is still being conducted. To that, recent advances in the science technology of pest management have facilitated the combination of different approaches (e.g. mating disruption with a mixture of pheromones and then subsequent application of *B. thuringiensis*-containing insecticides) increasing the efficacy of the methods (Michaelakis et al. 2011).

5.9 The Pine Processionary Moth in Bulgaria

Plamen Mirchev, Georgi Tsankov, and Georgi Georgiev

Pine processionary moth, *Thaumetopoea pityocampa*, was reported for the first time in Bulgaria in 1906 (Drenovsky 1923). During the first half of twentieth century, mainly faunistical studies were conducted in order to establish the species habitats and to outline its distribution. Several outbreaks were reported during this period, predominately in the Rhodopes Mountains, causing significant damage in the attacked stands. Since 1950, the areas infested by the pest were annually surveyed, providing statistics on its fluctuations in Bulgaria (Fig. 3.27).

During the period 1951–2012, a total of 1,070,246 ha of pine forests were infested, with an average of 17,262 ha per year. The changes in *T. pityocampa* damage could be separated into three steps: (a) 1951 to 1971 with the infested areas amounting 5,133 ha on the average; (b) 1972 to 1976 with an increase in moth population density and the infested areas reached up an average of 8,650 ha; and (c) 1977–2012 with the average infested areas increasing to 25,627 ha, i.e., ca. five times larger than during the 1950–1970s.

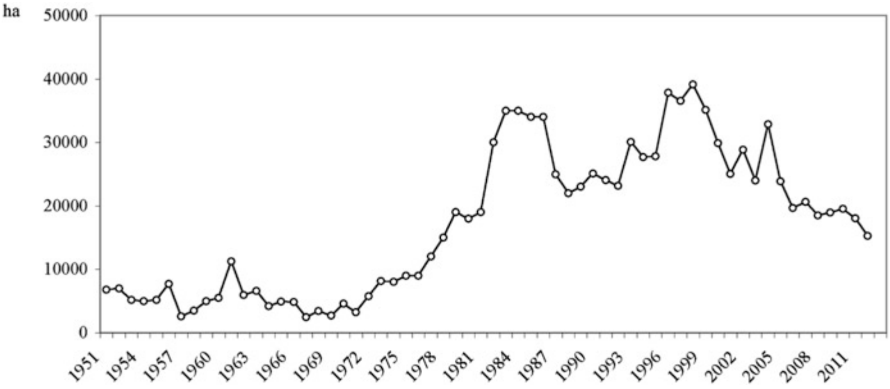


Fig. 3.27 Annual variations in the size of forest surfaces attacked by the pine processionary moth in Bulgaria from 1950 until 2011

The significant increase in the areas infested by moth since 1970 was primarily due to the massive afforestations carried out after 1960 in Bulgaria. In 25 years the plantations of *Pinus sylvestris* have increased by more than two times, and those of *P. nigra* by almost three times. These changes were particularly significant in the natural range of *T. pityocampa*. For example, in the region of Kardzhali, the areas of Scots pine increased by nearly nine times, and those with Austrian Black pine by nearly three times (Mirchev et al. 2000).

Historically, pine processionary moth is distributed in mountainous areas of South Bulgaria – Rila, Pirin, the Rhodopes, Osogovo, the Central Balkan Range and Sredna gora. Within these limits it occurs in pine stands on northern slopes at up to 1,200 m a. s. l., and on southern slopes up to 1,350 m (Fig. 3.28). However since 1999, the species extended into new areas of the country

In 1999, the moth overpassed Kalofer Hills which was the natural eastern border of its distribution in Bulgaria. With an annual velocity of 3–5 km it further colonized new habitats on the slopes of the artificial pine plantations in the Balkan Range and Sredna Gora mountains. Mirchev et al. (2011) detailed some factors which may help predicting the spread of *T. pityocampa* in Bulgaria. First, there is an available food basis, consisting in a huge reserve of untouched Scots and Austrian pine stands. Thus, in 1998, a year showing a maximum infestation, less than 5 % of

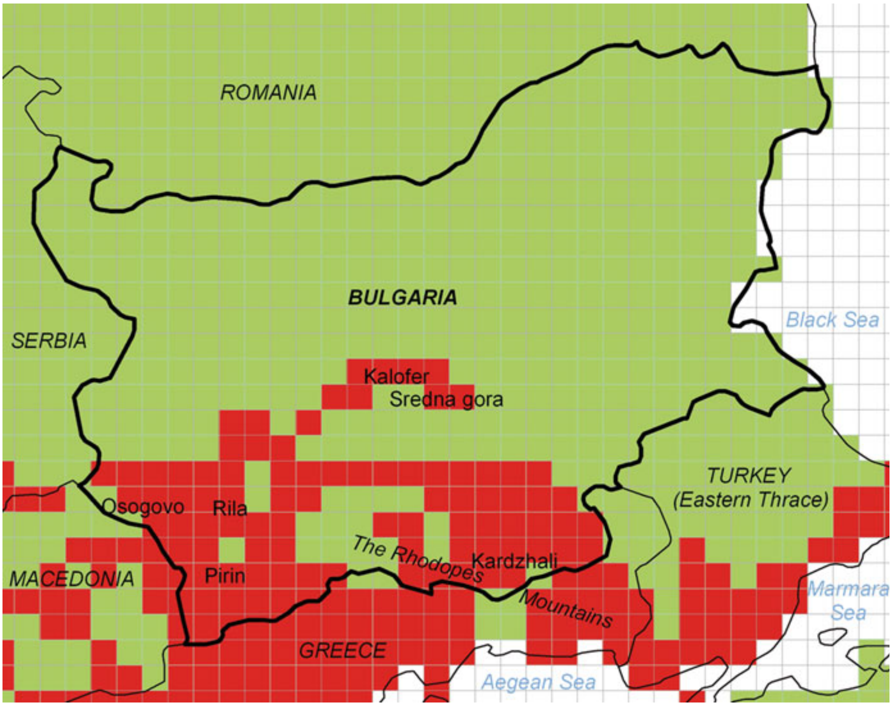


Fig. 3.28 Distribution of *Thaumetopoea pityocampa* in Bulgaria and neighboring countries during winter 2010–2011 on a 16 km-cell grid. *Red squares* show the presence of *T. pityocampa* whereas the moth is absent in areas figured in *green*

the pine forests in Bulgaria were attacked by pine processionary moth. Second, the analysis of the climatic parameters proposed by Battisti et al. (2005) to regulate moth survival and feeding during winter, i.e., survival temperature of –16 °C and day activation temperature of +9 °C in the larval tent, revealed that only the region of Central Northern Bulgaria is unsuitable for pest development due to a pronounced continental climate and critically low winter temperatures.

Actually, the expansion of *T. pityocampa* is realized mainly by an ecological form of the species that completes its larval development before cold weather and overwinters in the soil. Another biological feature also favours the expansion – pupal diapause, where a part of population can emerge up to 6 years after pupation (Démolin 1969a). Additional arguments rely on the ecological plasticity of the species, which helps it to overcome the extreme temperatures and provides an opportunity to expand its range. The third factor influencing *T. pityocampa* distribution is the topography of Bulgaria. The ridge of Western and Central Balkan Range is an insuperable barrier for pine processionary moth to north due to both its high elevation and the predominance of non-host beech forests. However, *T. pityocampa* expands its range to east and could penetrate in Northern Bulgaria through low elevation passes in the Eastern Balkan Range. *T. pityocampa* could also penetrate to the north using the corridor along the Black sea coast where many pine plantations have been settled (Mirchev et al. 2011).

6 Detail of the Past and Situation of the Pine Processionary Moths, *Thaumetopoea pityocampa* and *T. wilkinsoni*, in North Africa and Asia Minor

6.1 The Pine Processionary Moth, Thaumetopoea pityocampa, *in Algeria*

Mhamed El Mokhefi, Gahdab Chakali, Mohamed Zamoum, Atia Bensidi, and Andrea Battisti

The pine processionary moth *Thaumetopoea pityocampa* occurs everywhere there are pine (*Pinus* spp.) and cedar (*Cedrus atlantica*) forests and trees in Algeria (Fig. 3.29). Present elevation range extends to upper timberline, notably on cedar, although it is not clear whether timberline has been reached recently because of global warming or the moth was already present at low density. Certainly the outbreaks observed at high elevation are recent (Sbabdji and Kadik 2011). Definitely its expansion to the south has been facilitated by the large afforestation effort made during the twentieth century and called ‘barrage vert’, i.e. the planting of millions of hectares with Aleppo pine (*Pinus halepensis*) along the Saharian Atlas, a mountain chain dividing the Sahara desert from the coastal area (Zamoum 1998). This expansion has been associated with large-scale pest management, mainly based on *Btk* applications over hundreds thousand hectares every year in the last decades.

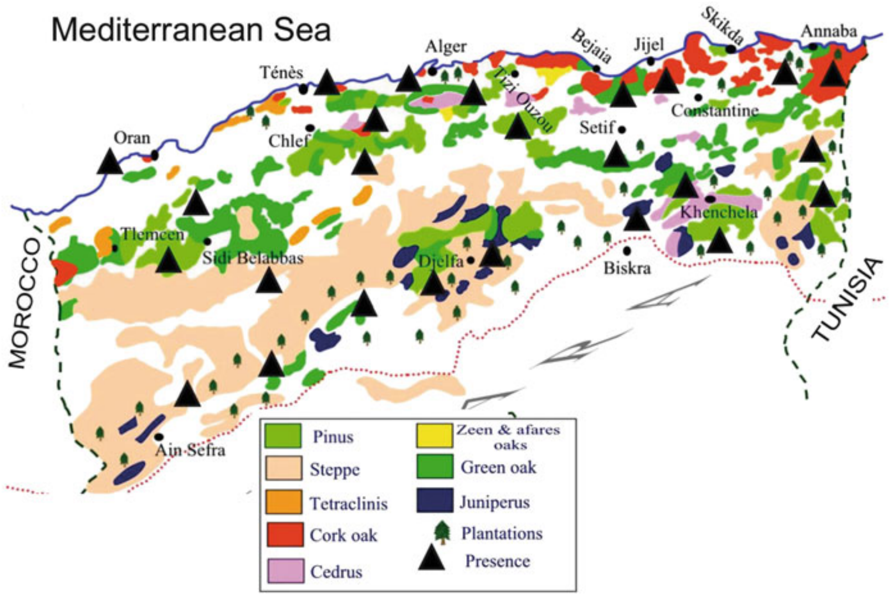


Fig. 3.29 Present distribution of *Thaumetopoea pityocampa* in Algeria in relation to the range of conifer species

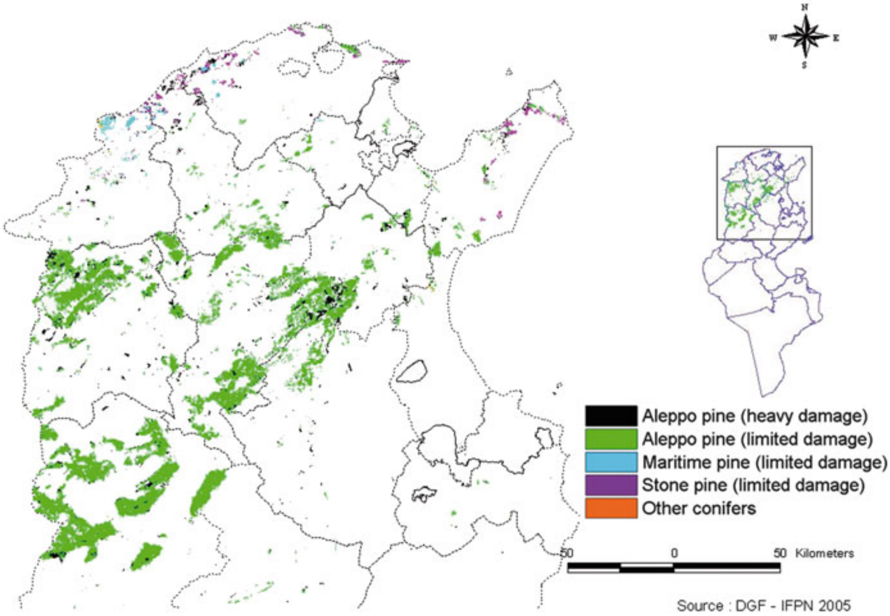
A recent genetic survey has shown that a population from this southern area belongs to the *pityocampa* clade, i.e. to the populations extending from the Balkan peninsula to the west, including the Iberian peninsula and the north-western Africa, whereas another population located closer to the coast belongs to the ENA clade of *T. pityocampa*, which is centered in Tunisia and extends to north-eastern Africa as well (Cyrenaica) (Kerdelhué et al. 2009, 2014, chapter 4 in this book). It appears likely that the contact area between the two clades is located in Algeria and a project has been started to better clarify the situation. Populations have been sampled all over the country and the results will reveal where the contact area is and the possible consequences of the occurrence of the two clades on the insect pest management.

6.2 *The Pine Processionary Moth,* Thaumetopoea pityocampa, *in Tunisia*

Mohamed Lahbib Ben Jamaa

6.2.1 Distribution Area and Preference of Pine Processionary Moth

The pine processionary moth, *Thaumetopoea pityocampa*, is one of the most important forest pests in Tunisia, present everywhere in all the Tunisian pine



Source : DGF - IFPN 2005

Fig. 3.30 Present distribution of Thaumetopoea pityocampa in Tunisia in relation to the range of conifer species

forests (Rivé 1966) (Fig. 3.30). The moth larvae feed on coniferous species, mainly *Pinus halepensis* (Aleppo pine) which covers about 360,000 ha (Selmi 2006). It may show different preferences for pine host species in the different regions of the Mediterranean basin, but in Tunisia *P. halepensis* and *P. canariensis* are more attacked than *P. pinea* and *P. pinaster* when they are growing in the same stand (Rivé 1966).

The tolerance of Aleppo pine provenances to the attack of the pine processionary moth was compared by counting the number of tents on 30 Tunisian and exotic provenances (Sghaier et al. 1999). This work was carried out between 1993 and 1995 in Arboretum of Korbous (10°35′E, 36°50′N, elevation 180 m) created in 1963 in the North-East of Tunisia. Covariance analysis was applied to compare the number of tents per tree in relation to total tree height at the age of 30 years. It appeared that, for an equal tree height, the rate of attack did not differ significantly between the provenances, suggesting that the previously observed differences in attack could not be attributed to the intrinsic genetic resistance of the provenances but to the difference in height among the surveyed trees (Sghaier et al. 1999). This result confirm those of Démolin and Rivé (1968), for whom there is a difference in preference of pine processionary moth for pines species but this difference is disappearing when the stand is nonspecific. Mendel (1988) found no relationship between the needle morphology and the host preference in *T. wilkinsoni*.

6.2.2 Natural History

In Tunisia, the life cycle of *T. pityocampa* is normally annual but may extend over 2 years at high elevation (Jebel Chaâmbi, Jebel Selloum) for a part of the population. The emergence of adults depends on elevation and climatic conditions. Early emergences are observed at high elevation (Jebel Chaâmbi, 1,544 m; Jebel Selloum, 1,373 m), from 15th July to 1st August at the southern edge of their range. At mid-elevation in Jebel Chaâmbi, Jebel Selloum and Le Kef, belonging to the upper semi-arid bioclimatic range with mild winter, the emergence of adults occurs from the 1st to 15th August (Rivé 1966; Démolin and Rivé 1968). In the mild winter zone, adult emergence is earlier but larval development is longer (6–7 months Démolin 1969a, b) whereas in other parts of Tunisia, larval development lasts 3–5 months. The first instar lasts 12 days, the 2nd 14 days and the 3rd one 30 days. However, the fourth and fifth instars duration varies from 30 days to 90 days according to the severity of the winter (Dissescu and Ceianu 1968). In the mountains, pupation takes place on February whereas it occurs in September and January-February on the littoral.

6.2.3 Effect of the Climate

Colonies of pine processionary moth can survive and resist to low temperatures (-10 °C) as well as tolerate high temperatures (<25 °C), but during the aerial phase they cannot support very high temperature (more than 25 °C) for a long time without physiological effect (weakness) (Démolin 1969a, b). The vital optimum would correspond to an average monthly temperature between 18 and 20 °C; mass effect, tent, and larval movements being susceptible to compass (or restore) variations around this average (Démolin 1969a, b).

In mild winter, tents will be well architected and the epizooties risks will be less frequent. The population is more stable (lack of prolonged fluctuations). The natural enemies (predators and parasitoids) are able to maintain large populations. The winter tents are in general, situated at the branch tips in the upper part of the crown (Démolin and Rivé 1968). In the South, where the temperature is high, the sun does not play any role for the pine processionary moth and the winter tents are less architected. The development of larvae must be at post-summer, allowing the population to avoid temperatures higher than 25 °C (Démolin 1969a, b).

6.2.4 Effect of Defoliation

The larvae feed on pine needles, though even complete defoliation of a pine does not necessarily result in death of the tree but it may dramatically delay development. Repeated defoliation causes loss of increment and may result in tree death. The effect of the defoliation on tree growth is evaluated in Tunisia since the 196 s

(Rivé 1967). This study was carried out on young Aleppo pine trees (3–4 years old) in December of 1965 in the arboretum of Mejez Elbab. In total, 54 infested trees were compared with 54 non-infested trees divided on 6 repetitions. Trees defoliated twice loose about 30–40 % on their growth in height and from 12 to 65 % on their growth in diameter (Rivé 1967).

6.3 *The Pine Processionary Moth,* **Thaumetopoea pityocampa,** *in Morocco*

Moulay Ahmed El Alaoui El Fels and Saïd El Mercht

Pines and cedar are the dominant species in the conifer forests in Morocco. Native pines include Aleppo pine (*Pinus halepensis*), maritime pine with two subspecies (*P. pinaster* subsp. *hamiltonii* var. *maghrebiana* and var. *iberica*), and north African black pine (*P. nigra* var. *mauretanica)*, with a total surface of ca. 82,115 ha. In addition, conifer afforestations using pines cover approximately 200,000 ha. Morocco is also sheltering the largest surface of Atlas Cedar (*Cedrus atlantica*) within the Mediterranean basin, with approximately 133,600 ha.

The pine processionary moth, *Thaumetopoea pityocampa*, has been recorded since a long time in Morocco (Delepiney 1939) because it constitutes a major forest defoliator capable of damaging all pine species but also Altas cedar. Thus, this species aroused much more interest from scientists than the congeneric *T. bonjeani*, which specifically attacks Atlas cedar (see Battisti et al. 2014, this volume). A number of papers detail its biological cycle, population dynamics, natural enemies, impact on productivity of host trees (among others, Benazoun 1976; Questienne and Miermont 1979; El Yousfi 1982, 1983; Messaoudi 1982; Mzibri 1991; Rattal 1991; Ben Jamâa 1992; El Hassani et al. 1994). Large outbreaks of pine processionary moth have been recorded since the beginning of the last century (1926–1932, 1937–1939, 1947–1952, 1960–1965, 1974–1979) and have not ceased until now.

From 1960 on, pine processionary moth expanded its range in new areas in relation to the large afforestations carried out in Morocco (El Hassani et al. 1994; Ghaioule et al. 1998). Moreover, the introduction in the country of exotic pine species such as Canarian pine (*Pinus canariensis*) and Monterey pine (*P. radiata*), probably contributed to its fast propagation (El Hassani et al. 1994). However, its global distribution was still limited in the late 1970s as it appeared from the map by Questienne and Miermont (1979) (Fig. 3.31). Considering the duration of annual insolation and the minimal temperatures, these authors also defined zones where the moth can further establish. Actually, most of the zones were effectively colonized in 1992, except the central part of the country (Ben Jamâa 1992).

The definition of a control program did not allow to stop moth expansion and damage and large pesticide treatments had to be carried out every year since 1980 (Fig. 3.32), with an average treated surface of approximately 20,000 ha per year (Ben Jamâa and Jerraya 1999).

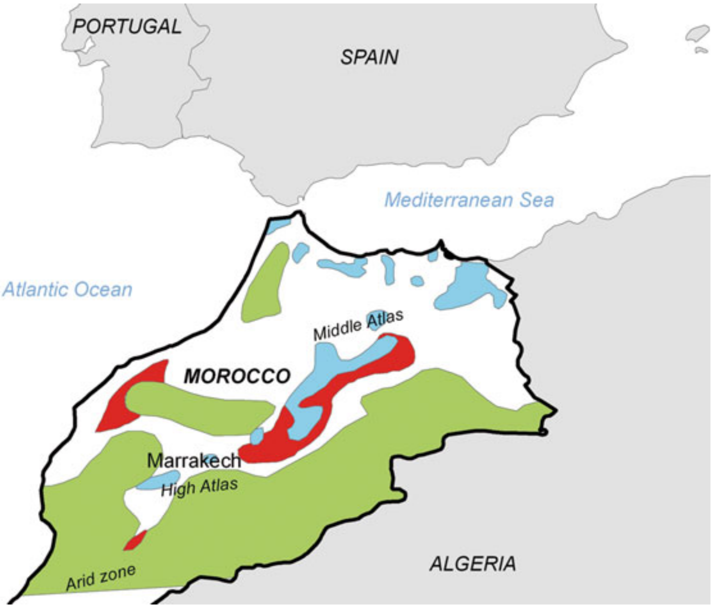


Fig. 3.31 Distribution range of the pine processionary moth in Morocco in 1979, and areas of potential moth establishment considered at that time by Questienne and Miermont (1979). Moth presence figured in *red*; moth potential presence figured in *blue*; adverse areas where moth cannot establish fig. in *green*

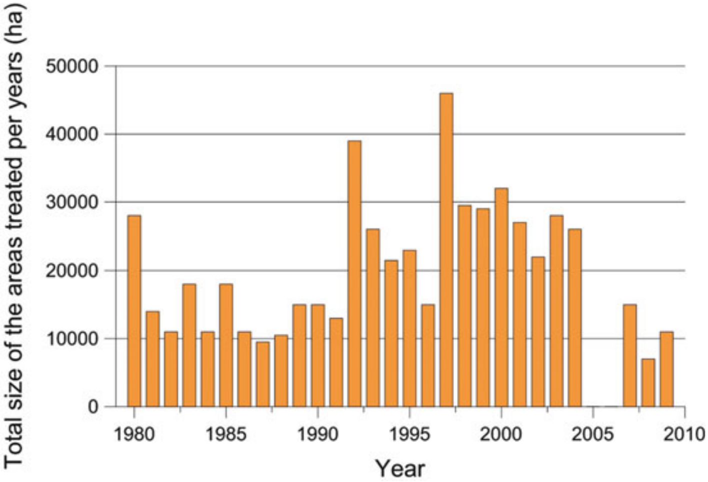


Fig. 3.32 Annual variations in the total area treated against pine processionary moth from 1980 to 2009 in Morocco

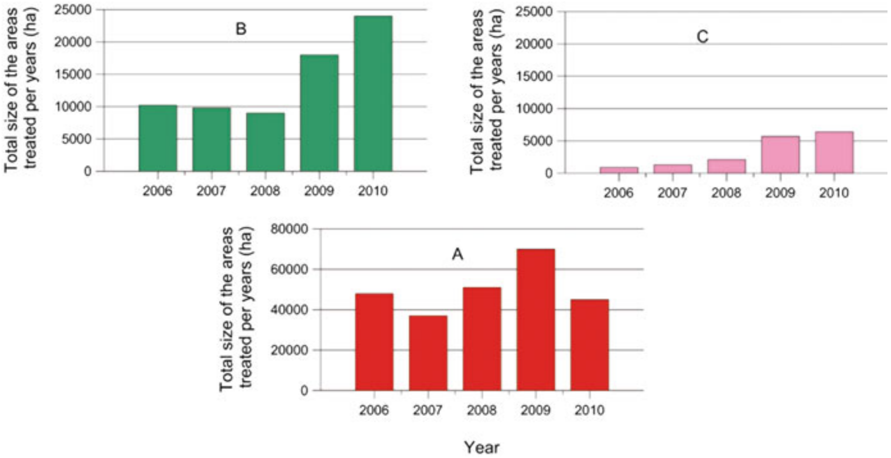


Fig. 3.33 Annual variation in forest surfaces infested by pine processionary moth in Morocco during 2006–2010. (**a**) Global damage (*data missing for 3 regions over 9 in 2010); (**b**) Middle Atlas; (**c**) North-West region

The infestation data worked out by the regional forest managers between 2006 and 2010 suggest that damage increased during the last years (Fig. 3.33a). Indeed, damage is observed in nine regions of Morocco but it especially increased in the Middle Atlas (Fig. 3.33b) and Northwestern regions (Fig. 3.33c).

No detailed, updated map of the pine processionary distribution is presently available but it can be told that the moth is probably present everywhere in Morocco except in the Saharan areas (Fig. 3.34). This expansion seems primarily due to the introduction of exotic pine species as ornamentals, especially in the urban areas, and to the continuous afforestation projects using conifers. At present, processionary colonies are observed even at high elevation in recent afforestations in the high Atlas mountains close to Oukaïmeden such as the plantations of cedar and maritime pine at Aït Lqaq (2,300 m) and those of Aleppo pine at Tachdert (2,400 m).

The great adaptive potential of the species allows to cope with the large variations in climatic conditions between regions. The lifecycle is known to depend on the climatic conditions, in particular the temperature (El Hassani et al. 1994). Thus, adult flight begins earlier at high elevations, which makes it possible the larvae to escape low temperatures during winter, while it starts later at plain areas like Marrakech in order to avoid hatching during the hot summer days (Fig. 3.35).

In addition, the duration of each larval stage is variable according to the areas. In areas with mild winter, the duration of the fourth and fifth larval instars lasts approximately 30–45 days whilst it can reach 90 days in the areas with cold winter. Processions start in February–March in cedar forests of the continental areas but can occur until the end of April in other cedar forests and on Aleppo pine in the Eastern high plateau (El Hassani et al. 1994). Finally, one should not forget the diapause, an important biological mechanism, which can be prolonged up to 6 years (Démolin 1969b).

Fig. 3.34 Present distribution range of the pine processionary moth in Morocco: area in *red*

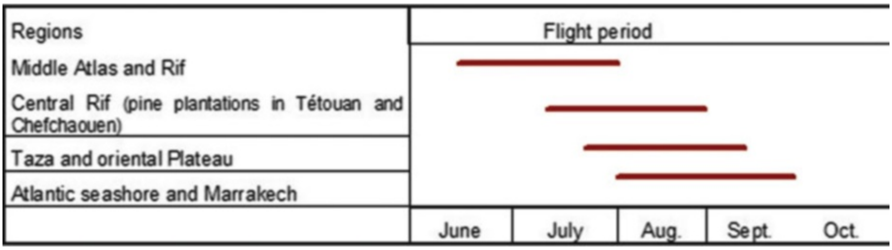


Fig. 3.35 Adult flight periods of pine processionary moth in different regions of Morocco

6.4 *The Pine Processionary Moths,* Thaumetopoea pityocampa *and* wilkinsoni*, in Turkey*

Mustafa Avcı and Kahraman İpekdal

Forests in Turkey cover 21.2 million ha. Red pine (*Pinus brutia*) is one of the most preferred host species of the pine processionary moth and it has a range of 5.4 million ha. Distribution rate of red pine is 47 % in the Mediterranean Region, 40 % in the Aegean Region, and 10 % in the Marmara Region (Taşolar 2002). Anatolian black pine (*Pinus nigra* ssp. *pallasiana*), Scots pine (*P. sylvestris*), stone pine

(*Pinus pinea*), and cedar (*Cedrus libani*) cover 4.2 million ha, 1.2 million ha, 42,000 ha, and 417,000 ha, respectively (Turkish General Directorate of Forestry 2006). The pine processionary moth distributes in 1/7 of the forests in Turkey (Mol and Küçükosmanoğlu 2002) with a higher density in regions under the Mediterranean climate. It exits totally in a region of 1,800 km long and 160 km wide on the Turkish coast line. This region includes the Mediterranean, Aegean, Marmara, and Black Sea Regions. Pine processionary moth currently affects a forested area of about 1.5 million ha in Turkey (Turkish General Directorate of Forestry 2003).

The pine processionary moth has different names in Turkish, such as "ağu böceği, çam büyüsü, gürdük, keseli tırtıl, keseli kelebek"; but its common name is "çam kese böceği" which means pine tent insect.

The oldest record that we could find about existence of pine processionary moth in Turkey goes back to 1885 when an article was published by Julius Lederer. According to this paper, Albert Kindermann, a German lepidopterist, who organized an expedition to collect butterfly in Samsun, Amasya, Tokat, Sivas, and Diyarbakır, reports that he observed many tents on the pines between Samsun and Amasya in May. This short note proves that the pine processionary moth existed in the Black Sea Region back in the nineteenth century.

Another old record was found in the Ottoman Section of the Turkish State Archives. Two Ottoman documents dated to 2 April 1904 summarize methods to control pine processionary moth populations in Istanbul. Thus we can easily say that the pine processionary moth existed in the Marmara Region back in the twentieth century. In the 1940s, serious pine processionary moth damage was reported in some of the mansion yards in Bursa (Sekendiz and Varlı 2002). A passenger train heading from Ankara to Izmir skidded due to larva processions on the railway in Çamlık station (İzmir) in 10 May 1949 (Acatay 1953). Due to an increase in afforestation actions, the pine processionary moth has become more important especially after 1960s in Turkey (Sekendiz and Varlı 2002). Figure 3.36 is showing the present distribution of pine processionary moth in Turkey and its relative importance in the different provinces.

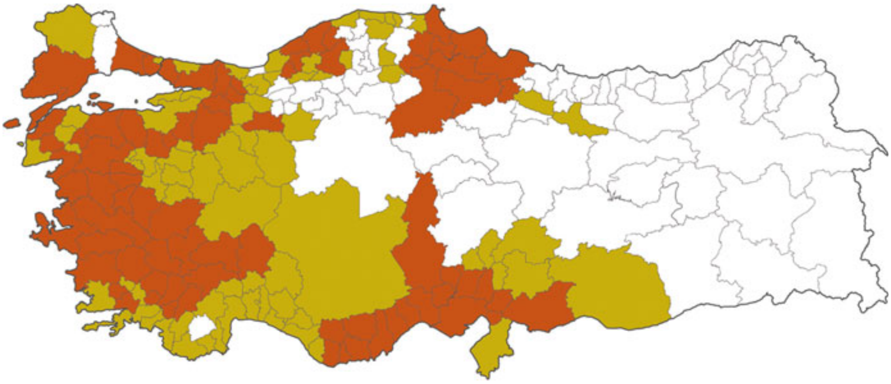


Fig. 3.36 Distribution and density of pine processionary moth in Turkey. In *red*: high density; in *orange*: low density

All these records showed that the pine processionary moth had continuous populations big enough to be recognized in the Aegean, Marmara, and Black Sea Regions at least for the last 200 years. Thus it is obvious that pine processionary moth did not invade these regions a very short time ago. However, there is a significant decrease in pine processionary moth haplotype diversity in Turkey from south to north (İpekdal 2012) which suggests a later invasion into the north.

Until recently, the common pine processionary moth species in Turkey had been thought as *T. pityocampa*. However, current studies (Simonato et al. 2007; İpekdal 2012) showed that the common species in Turkey is *T. wilkinsoni* with a smaller *T. pityocampa* range in the European Turkey (See Fig. 4.7 in Kerdelhué et al. 2014, Chap. 4, this volume).

Phenology differs significantly either latitudinally or longitudinally in Turkey (Akbulut et al. 2002; Çanakçıoğlu and Mol 1998; Schmidt 1990; Özkazanç 2002; Avcı 2011). Adults emerge between July and September, depending on the latitude and elevation. Female moths lay their eggs generally at the end of summer and larvae hatch in early fall; yet, there can be 1 month delay at lower latitudes (Özkazanç 2002).

Pine processionary moth populations in Turkey live on a land that had been used as a refugium during the ice ages. Additionally, north-western Turkey includes a contact zone for the two *Thaumetopoea* species, *T. wilkinsoni* and *T. pityocampa* (see Kerdelhué et al. 2014, Chap. 4, this volume). Therefore it is not only interesting to conduct morphology, phenology and genetic studies on Turkish populations of pine processionary moth, but also crucial to understand nature of these populations and to plan better management strategies on the region.

6.5 *The Pine Processionary Moth,* Thaumetopoea wilkinsoni, *in Israel*

Zvi Mendel

The overall geographic distribution of *T. wilkinsoni* overlaps the area of occurrence of its major pine host, *P. brutia* ssp. *brutia* (known as Brutia pine, Calabrian pine, Turkish red pine, or East Mediterranean pine). The moth colonized the *P. halepensis* forests in Transjordan and in the area of *P. brutia* ssp. *brutia* in Kurdistan (the border areas between Turkey and Iraq) during the last decade (Marwan Abdelwali, personal communication), and, it was absent until the last decade from the eastern *P. brutia* ssp. *brutia* area of the Black Sea. The moth population in the Brutia pine forests of Crete is genetically intermediate between *T. wilkinsoni* and *T. pityocampa* (Simonato et al. 2007). The moth is absent from areas of the other subspecies of Brutia pine, e.g., *eldarica, pityusa* and *stankewiczii*, and Quetta (Afghan) pine, which ranges from the Crimea to Afghanistan. In Israel it was first recorded in 1936 in the 40-ha Umm Safa forest in Samaria (25 km NNW of Jerusalem), on 10-year-old Aleppo and Brutia pines, planted near old, autochthonous Aleppo pine. This may suggest that *T. wilkinsoni* is indigenous here, and that it was found because it became conspicuous in young plantations, next to old, already infested trees. However, the absence of the moth from native *P. halepensis* forests in the Carmel and the Galilee in Israel, in the plantations on the Golan, and in native pine forests in Jordan until the twenty-first century, and also the small genetic differences between the Israeli population and those of eastern Turkey or southern Lebanon (Simonato et al. 2007) may suggest that the population in Israel is a recent introduction (Mendel 1990). It is interesting to note that *P. halepensis* in East Mediterranean is probably an outlier of the pine population in North Africa (Schiller et al. 2004) and we guess that while spreading the tree was not accompanied by the moth. Since the late 1940s of the nineteenth century, the spread of the moth at various rates paralleled the afforestation projects that covered the hilly regions with *P. halepensis* (Halperin 1968, 1990). In the late 1960s a population extending from southern Lebanon was established in the Upper Galilee. The complete coverage of the Israeli pine area was completed in 2009–2010, when the two populations (from Umm Safa and southern Lebanon) intermingled.

7 Past and Present Range of the Other Processionary Moths

7.1 The Oak Processionary Moth, Thaumetopoea processionea

Nicolas Meurisse, Axel Schopf, and Andrea Battisti

Established populations of *T. processionea* are known from almost all European countries with the noticeable exception of the northernmost ones (Fig. 3.37). There are no reports from Iceland, Ireland, Denmark, Norway, Sweden, Finland, Latvia, Estonia and Lithuania. In the Mediterranean islands, *T. processionea* is established in Cyprus, but absent from Corsica, Sardinia and Malta. Records exist from Turkey, including Anatolia (Kanat and Aknulut 2005), and the Near East. More details are provided in Groenen and Meurisse (2012).

In 2006 *T. processionea* was found in west London which was the first recorded breeding population in Great Britain (Townsend 2007; Townsend 2009). Human activity, including the commercial movements of infested nursery trees, was thus shown to be a possible source of spread over geographical barriers (Baker et al. 2009; Townsend 2013).

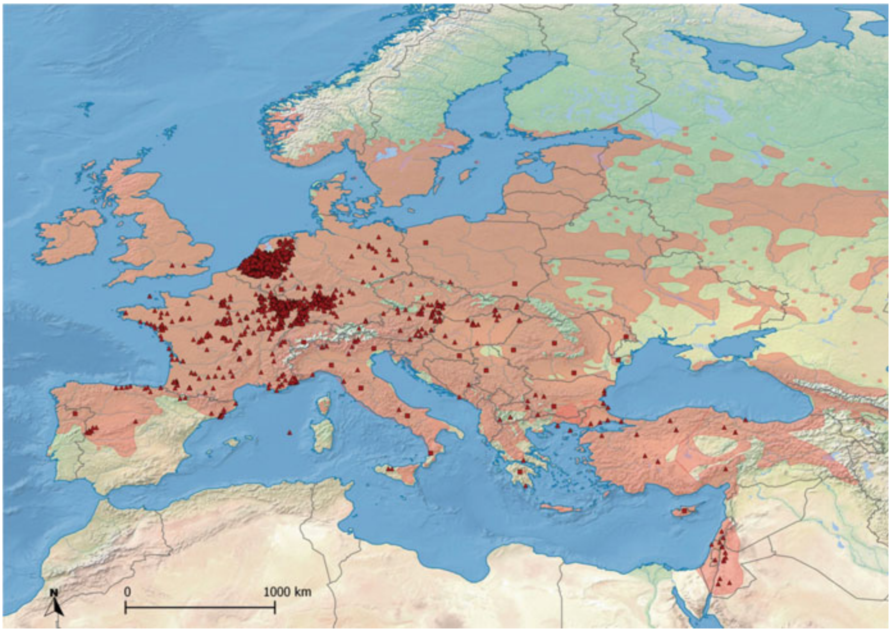


Fig. 3.37 Present and potential distribution of *Thaumetopoea processionea*. *Red triangles* indicate populations records (i.e. records that were properly dated and mapped, all during the 1750–2010 period). *Red squares* indicate records at the regional level (i.e. records that were only partially dated and mapped). The *red-shaded* area indicates the actual cumulative distribution of the host trees *Quercus boissieri, Q. calliprinos, Q. cerris, Q. frainetto, Q. petraea, Q. pubescens, Q. pyrenaica and Q. robur* (Adapted from Groenen and Meurisse 2012)

7.2 *The ‘Summer’ Processionary Moths Associated with Conifers,* Thaumetopoea bonjeani, T. ispartensis, T. libanotica, *and* T. pinivora

Andrea Basso, Andrea Battisti, and Stig Larsson

In this group there are a few species with scattered distribution in Europe, Africa, and Asia (Fig. 3.38). They are all associated with *Cedrus* spp. with the only exception of *T. pinivora* which feeds on *Pinus* (see below). As a consequence, their ranges are highly fragmented and largely overlap with those of the host plant species. *T. bonjeani* is associated with *Cedrus atlantica* in the mountains of Morocco and Algeria, while *T. ispartaensis* and *T. libanotica* occur on *Cedrus libani* in the mountains of Turkey and Lebanon, respectively. Another recently described species, *T. sedirica*, occurs in Turkey close to the site of *T. ispartaensis* and its identity needs confirmation. A further species morphologically belonging to

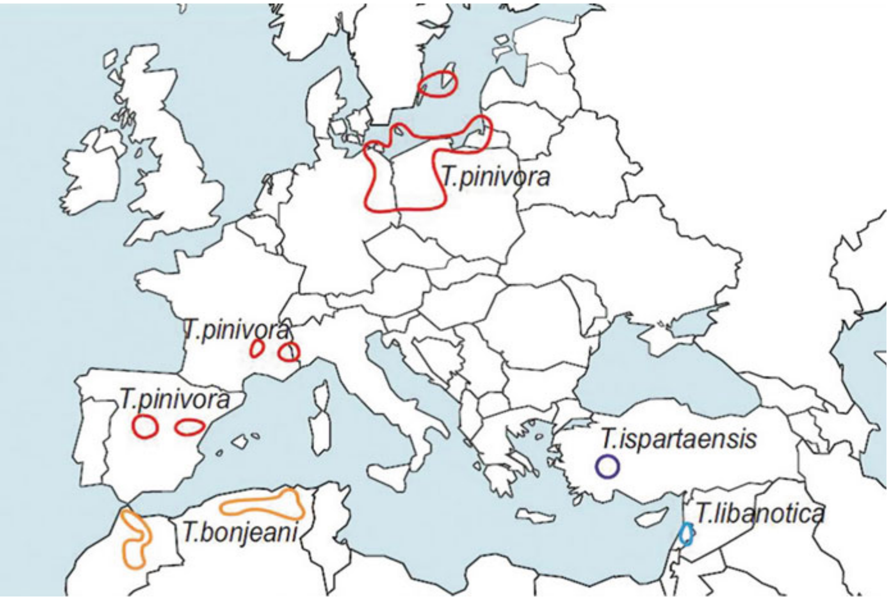


Fig. 3.38 Schematic distribution of the ‘summer’ processionary moths. *Thaumetopoea bonjeani*, *T. ispartensis*, *T. libanotica*, and *T. pinivora*

this group is *T. cheela* from India/Pakistan, where it could live on *Cedrus deodara*, although this needs to be confirmed.

The northern pine processionary moth *Thaumetopoea pinivora* has a scattered distribution with fragmented populations in two separate regions; northern and south-western Europe (Cassel-Lundhagen et al. 2013; Fig. 3.39). In the north the distribution seems to be concentrated around the Baltic Sea in Germany, Lithuania, Poland, and Russia (Kaliningrad). *T. pinivora* is established at least since the 1930s on the Danish island Bornholm (Per Stadel Nielsen, personal communication). In Sweden, the population on Gotland is by far the biggest. A small population is established on the island of Öland, also in the Baltic Sea. There is no reliable information on how long the populations have been on Gotland and Öland, but at least on Gotland there are reports from local residents that larvae were present at least in the 1930s. Lepidopterologists have caught flying individuals also along the Swedish east coast for at least 20 years (Palmqvist 1984; Franzen 2004); in these cases it is likely that it was males originating from the populations at Gotland, Öland or Bornholm. No established populations are known from the Swedish mainland. In south-western Europe, the species in known from several sites in Spain and from a few in France.

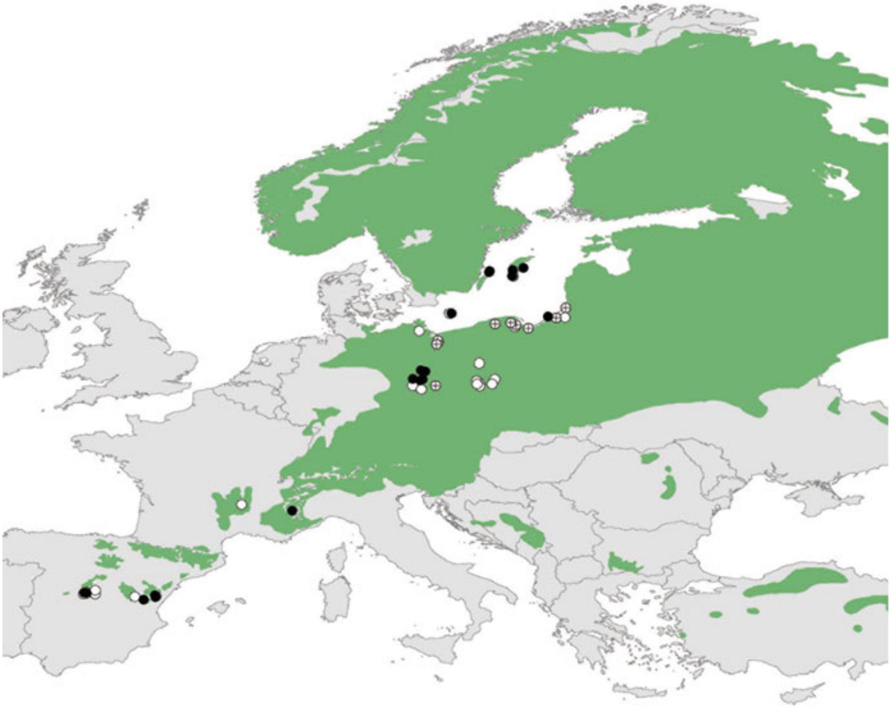


Fig. 3.39 Known records of *Thaumetopoea pinivora*. *Black circles* figure populations sampled in Cassel-Lundhagen et al. (2013); *open circles* correspond to records in literature; *crossed circles* to outbreaks noticed in literature. The range of *Pinus sylvestris* is figured in *green*

7.3 *The Pistachio Processionary Moth*, Thaumetopoea solitaria

Zvi Mendel and Alex Protasov

Figure 3.40 displays the natural range of *T. solitaria*, based on several sources cited in the chapter on the natural history of the pistachio processionary moth (see Battisti et al. 2014, Chap. 2, this volume); the displayed borders of the natural range of the main hosts of the moth are based on various sources, but mainly Schmuker (1942). The moth is distributed from Macedonia and the eastern Mediterranean region to Afghanistan.

The common host trees of *T. solitaria* are *Pistacia* spp., belonging to the *Pistacia* group, and comprise *P. palaestina, P. terebinthus, P. atlantica* and *P. vera.* All are deciduous, growing in rather harsh sites or semidesert areas. *Pistacia paleastina* is probably a twin species of *P. terebinthus* that occurs in the eastern areas, including Greece and the Near East, usually at lower elevations. *Pistacia atlantica* occurs from the Atlantic coast of North Africa to Central Asia; the eastern population is

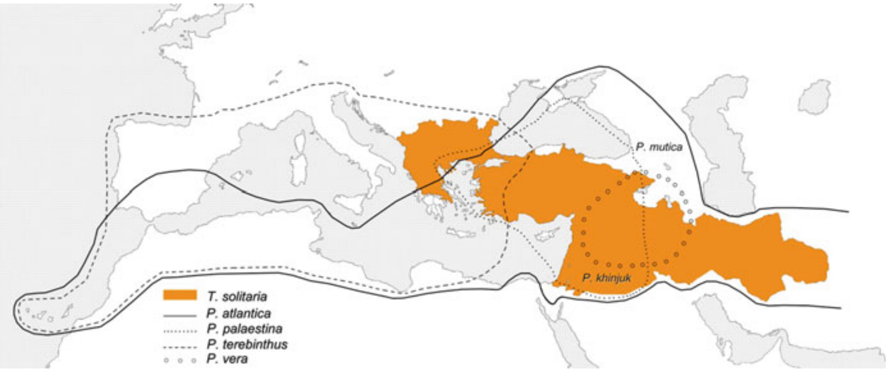


Fig. 3.40 Natural range of *Thaumetopoea solitaria* and the borders of the natural range of *Pistacia* spp., its main host trees

known as *P. mutica* or as *P. atlantica* subsp. *mutica* and occurs mainly between the Black Sea and the Caspian Sea; the natural range of *P. vera* is in western Central Asia (Zohary 1973). Another tree species that falls in the same groups and occurs within the range of *T. solitaria* is *P. khinjuk*. These six tree species belong to a monophyletic group that comprises three pairs of species: *palaestina* – *terebinthus*, *atlantica* – *mutica*, and *vera* – *khinjuk*. The species of each pair are genetically similar (e.g., Kafkas and Perl-Treves 2002; Al-Saghir and Porter 2012), therefore we assume that *T. solitaria* may be found also on *P. mutica* and *P. khinjuk*. The absence of *T. solitaria* from large areas of *P. terebinthus* and *P. atlantica* in the central and western Mediterranean regions suggests that, similarly to other *Thaumetopoea* species, *T. solitaria* colonized the present-day landscapes much later than its principal hosts.

7.4 *Thaumetopoea herculeana*

Mauro Simonato, Laura Berardi, Juan Pino, and Andrea Battisti

The moth has an almost continuous distribution in the Iberian peninsula, Spain and Canary Islands and Portugal (Agenjo 1941; Gómez-Bustillo 1979; Gomez de Aizpurua 1986; Bacallado Aránega and Hernández Pacheco 1990) (Fig. 3.41). Isolated findings exist from Morocco, Algeria, Tunisia, Libya Cyrenaica, and Palestine, although most of the material is old (Agenjo 1941) and would need reconfirmation.

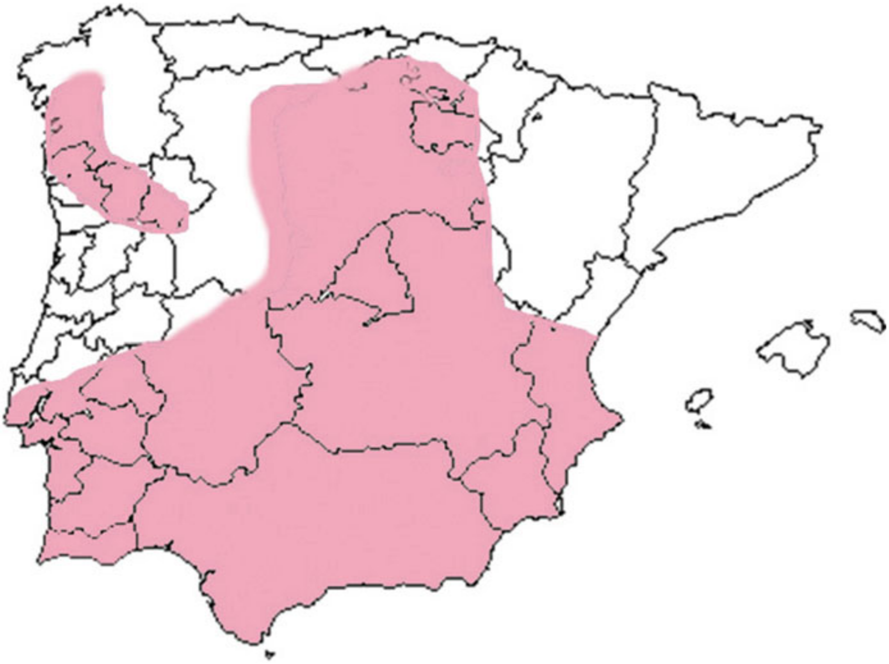


Fig. 3.41 Distribution map of *Thaumetopoea herculeana* in the Iberian Peninsula according to Gómez-Bustillo (1979)

7.5 Thaumetopoea jordana

Andrea Battisti and Zvi Mendel

The moth is known from a small area situated in the lower part of the Jordan valley river, between Jordan and Israel (Trougth 1954; Furth and Halperin 1979; Halperin 1990). It has been also recorded from Asir mountains in Saudi Arabia (one male and one female collected by Abdul Mun'im S. Talhouk on 20.XI.1981, in Wiltshire 1982). *R. tripartita* is a semi-deciduous shrub; it is the only known host of *T. jordana*. The plant is distributed in rather isolated populations across North Africa into the Middle East in relict desert or refuge Mediterranean habitats (Furth 1985). *R. tripartita* is related to Afro-tropical *Rhus sensu lato* (Quezel 1979).

7.6 Thaumetopoea apologetica, T. cheela *and* T. dhofarensis

Andrea Battisti

These species are known only as adults from Lepidoptera collections. *T. apologetica* is known from the Eastern African region (Ethiopia) (Seitz 1930) and there is no information about precise occurrence and host plants. *T. cheela* is a species living in the Indian region (Seitz 1933), present between Pakistan and India, and feeding on *Rhus cotinus*, a species of the Anacardiaceae family (Furth and Halperin 1979). Precise data about the geographical occurrence are missing. *T. dhofarensis* is known from Arabic region (Dhofar Oman) and the host plant is unknown (Wiltshire 1980).

8 The Unexpected Importance of Man-Mediated Introductions of Processionary Moths Outside the Natural Range

Alain Roques, Christelle Robinet, and Jérôme Rousselet

Until recently, the expansion of the pine processionary moth, *Thaumetopoea pityocampa*, from its Mediterranean original range, was considered to correspond simply to a natural dispersal process jointly mediated by the positive insect response to winter warming up and by the plantations of susceptible pine hosts in previously non-forested or deforested areas (Battisti et al. 2005). For example, the moth naturally progressed by more than 100 km in the Paris basin between 1972 and 2012, with a significant acceleration during the last 10 years when increasing temperatures allowed it to cross previously unfavorable areas in the south of the Paris basin (Robinet et al. 2007; this chapter). Up to recently, man-mediated movements seemed completely incongruous because of the urticating characteristics of the larvae (Battisti et al. 2011; Moneo et al. 2014, Chap. 8, this volume).

However, the survey of the northern front edge of the moth in France revealed the occurrence of an unexpectedly large number of isolated larval colonies located far beyond the limits of the main range of the species (Robinet et al. 2012; Figs. 3.7 d, e, f; 3.8 b, c). A total of 12 colonies were thus detected since 2003, 10 of which around downtown Paris (Fig. 3.42), one in Alsace, near the German border (Obernai, detected in 2008; cf. Sect. 4.6 above and Figs. 3.6 and 3.8c), and one in northern France (Chamouille, detected in 2011; cf. Figs. 3.6 and 3.8c). At the time of their detection, the colonies in the vicinity of Paris were located between 30 and 55 km to the nearest point of the front edge (except the colonies at Palaiseau) whereas those in northern France and Alsace were 120 and 190 km far from the front, respectively. It is likely that these colonies remained undetected for several years before they were recorded.

The combined use of genetic markers, measurement of female flight capabilities, and comparative analyses of the natural enemy complexes revealed that most of the pioneer colonies located near Paris likely resulted from long-distance translocations as a result of human activities rather than from a natural expansion of the moth (Robinet et al. 2012). Indeed, flight mill experiments confirmed that the limited flight capabilities of the female moths, even if larger than previously considered (see Battisti et al. 2014; Chap. 2, this volume) would not have allowed the insects to

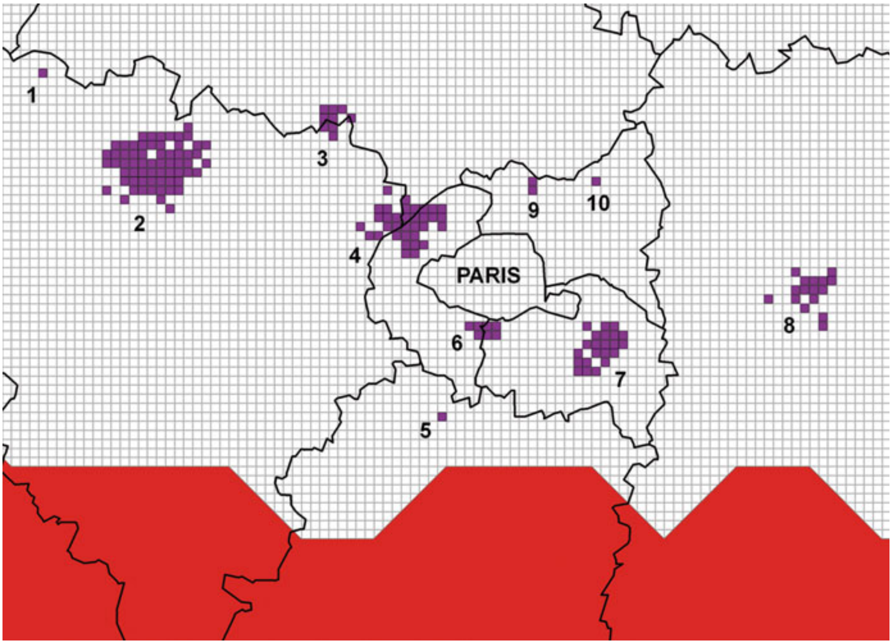


Fig. 3.42 Areas colonized during winter 2011–2012 by the pioneer colonies of pine processionary moth observed in the vicinity of downtown Paris. The grid corresponds to 1 km × 1 km cells. Each *purple* square indicates the presence of one colony at least in the cell. The natural front edge in 2010–2011 over the 8 km resolution grid is figured in *red*. Locations of the colonies and date of first detection: *1* – Moisson/Mousseaux sur Seine (2012); *2* – Flins-Aubergenville (2008); *3* – Eragny-Conflans Sainte Honorine (2008); *4* – Nanterre (2007); *5* – Palaiseau (2012); *6* – Bagneux-Arcueil (2010); *7* – Saint-Maur-des-Fossés (2008); *8* – Disneyland-Bailly-Romainvilliers (2003); *9* – La Courneuve (2012); *10* – Aulnay-sous-bois (2012)

fly over the distance to the nearest established colonies at more than 25 km. It is even more obvious for the colonies located in northern France and Alsace, at more than 100 km from the front of natural expansion. In addition, congruent mitochondrial and DNA microsatellite analyses excluded that most colonies originated from closeby populations. Five over the 7 pioneer colonies of the Paris basin submitted to genetic analyses were assigned either to Italy and south-eastern France or to Spain and south-western France, the two others being possibly related to the nearby populations of north-western France (see Fig. 4.10, Kerdelhué et al. 2014; Chap. 4, this volume). Looking at the parasitoid complexes of pine processionary moth in the same pioneer colonies, Robinet et al. (2012) did not notice the presence of any egg parasitoids but observed that 15–30 % of the tents hosted a specific larval-pupal parasitoid, *Phryxe caudata*. This tachinid fly presents two generations, the first one developing inside the processionary larvae from second to fourth instar while the second one parasitizes the last instar larvae, and emerges from the pupae developing in the soil (Biliotti 1956; Géri 1980; Buxton 1990). Taking into account that the white silk tents are easy to spot on small pines and that pine trees are usually not planted in summer during the egg stage, Robinet et al. (2012) suggested that the likely pathway for these long-distance jumps is the trade of mature pine trees transplanted for ornament from nurseries located in the southern area, the moth being moved as pupae with the accompanying soil. A similar pathway has been hypothesized for the introduction of oak processionary moth in England (Evans 2008). The capacity of the moth pupae to enter prolonged diapause, and to stay inactive for several years in the soil, also increases the probability of accidental translocations of the insect at this stage (Géri 1980).

The location of all of the pioneer colonies in man-made habitats constituted of recent plantations of large pine trees near human dwellings supports this hypothesis. Thus, these colonies were first detected in such plantations along highways (Arcueil), in runabouts (Obernai), around urban buildings (Bagneux, Saint-Maur-des-Fossés), around swimming pools (Eragny), in parks of university (Nanterre) and factory (Flins-Aubergenville), and in recreative parks (Disneyland Paris at Bailly-Romainvilliers; Parc de La Courneuve; Chamouille). Moreover, once the moth is introduced with plantations in urban and semi-urban areas, the combination of global warming and urban microclimate is favoring its survival and establishment. A comparative survey of the colony survival during two recent, severe cold periods having occurred during winter 2009 and 2010 in the Paris basin revealed that the larvae survived significantly better in urban areas, which behave like heated islands, than in the main range (Robinet et al. 2012). These processes also led the moths to establish in highly-populated areas, thus constituting a serious threat for human health.

Such transportations may have existed for a long time although they probably increased recently with the 'green' fashion. However, if pupae were transported before the late 1990s, it is likely that the moth offspring did survive the harsh winter conditions in northern areas. A random simulation of translocations over France clearly revealed an increase in the probability of establishment since 1995 (see Figs. 5.8 and 5.9; Roques et al. 2014, Chap. 5, this volume; Robinet et al. 2014), which is the congruent with the discovery of an increasing number of pioneer colonies after the 2000s.

Indeed, climate models based on the survival constraints of the moth (see Sect, 2; this chapter) show that a large part of Western, Central and Eastern Europe is becoming increasing favourable to the establishment of larval colonies if the moth is accidentally introduced (see Fig. 5.2, Roques et al. 2014, Chap. 5, this volume). Thus, human-mediated dispersal creating satellite populations is likely to accelerate significantly the spread of the pine processionary moth in the future (Robinet et al. 2014).

Actually, there is no reason that such man-mediated translocations of moth populations with the trade of large trees would be restricted to areas beyond the front edge and do not occur from one region to another of the main natural range. This would explain, at least partly, some genetic admixtures observed in some part of the natural range (see Kerdelhué et al. 2014; Chap. 4, this volume). Roques et al. (2011) also hypothesized that long-distance jumps may be involved in the relatively high rate of spread of the moth in the Paris basin between 2007 and 2009.

9 Conclusion

In conclusion, although a large part of western and central Europe is at present climatically favorable to establishment, pine processionary moth is colonizing it slowly, at ca. 5 km per year in the western part, due to the limited flight capabilities of females. However, the expansion appears at present to result from a combination of natural spread and long-distance jumps mediated by the human trade of large trees. Accidentally-introduced colonies are thus likely to establish and create satellite populations in a large part of the yet non-infested regions of Europe, especially near urban areas, and to accelerate the colonization of Europe by the moth (Robinet et al. 2014). For this reason, it would be important to quantify this chance of accidental transportation in order to be capable of predicting these long-distance jumps and the expansion of the species' distribution. However, the genetic admixture resulting from the combination of naturally-expanding and introduced populations would become increasingly difficult to be disentangled with continued climate change (Walther et al. 2009).

If the moth expansion has been deeply studied in the western part of the range, it remains to be characterized in the eastern part in order to appreciate whether the processes are similar, and especially if the man-mediated movements play the same role there. Another great challenge is the precise delimitation and the survey of the southern front edge in northern Africa in order to understand whether climate change may led to a retraction of this southern range as it has been observed in other lepidopteran species (Parmesan et al. 1999).

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