Department for Environment Food & Rural Affairs

Rapid Pest Risk Analysis (PRA) for:

Thaumetopoea pityocampa

September 2015

Summary and conclusions of the rapid PRA

Pine processionary moth (PPM), *Thaumetopoea pityocampa*, is found in Europe including parts of France. The caterpillars build nests where they live communally, feeding throughout the winter on pine trees and occasionally some other conifer species. However, one population of larvae in a limited part Portugal has larvae which develop rapidly during the summer months, and overwinters as pupae. Like other processionary moths, older caterpillars have urticating hairs which can cause rashes and other unpleasant reactions in humans and other animals. During the last 25 years, the pine processionary moth has been increasing its range, spreading northwards in France, and is now found in the area around Paris as well as parts of Brittany. This northwards expansion in range has meant that this moth is of increasing concern to the UK. This PRA is an update of the PRA written in 2012, and includes detailed climate mapping for the southern part of the UK, in order to help assess the risk *T. pityocampa* poses to this area.

Risk of entry

The likelihood of entry is considered moderately likely for pupae transported with soil attached to the host plants or plants growing in the vicinity, or eggs on trees imported in the summer directly from the country of origin (as the egg stage is short, transport via an intermediate country is thought to give the egg masses time to hatch, and larvae will be more detectable). Other life stages are considered less likely to be associated with this commodity, as larvae live gregariously in conspicuous silken nests, and thus are likely to be detected. As well as hosts such as *Pinus* spp., *T. pityocampa* pupae could also be associated with soil of other plants grown in the vicinity of hosts. The uncertainties around the volume of imports of non-host plants contribute to the low confidence rating for this pathway. The risk of entry on the other pathways assessed, namely wood, hitchhiking and

natural spread, is considered to be very low. Natural spread has a medium confidence rating, as the pest is now spreading in parts of Brittany, while the other two pathways have high confidence.

Risk of establishment

This is considered to be likely outdoors, in limited parts of England. Cornwall appears to be most at risk, as are other parts of the South Coast, coastal Pembrokeshire and London. However, confidence in this judgement is only medium as, despite the climate modelling and mapping carried out here, there are remaining uncertainties as few thresholds are available to aid in interpretation of the models. Establishment under protection is considered very unlikely, with high confidence, as suitable hosts are not commonly grown in such environments.

Economic, environmental and social impact

In the current area, impacts are considered to be large, with medium confidence. In the UK, only low population densities are likely and it is considered that these will cause only small levels of economic and environmental damage. However, even small populations can cause severe skin rashes and ocular damage from the larval hairs, and thus the social impacts are assessed as large. All three assessments of potential impacts in the UK are made with medium confidence.

Endangered area

The south coast of England, particularly western areas such as Cornwall, and parts of Pembrokeshire.

Risk management options

Eggs and adults are unlikely to be present on imports and larvae can be readily detected by inspection. However, the only measures likely to be effective in preventing pupae from being transported in soil attached to plants for planting, such as place of production, area freedom or a requirement for bare roots, are likely to have significant impacts on trade.

Key uncertainties and topics that would benefit from further investigation

The volume of non-host plants with soil imported from regions known to contain *T. pityocampa*, and better quantification of the risk of association of *T. pityocampa* pupae with such plants.

There are remaining uncertainties about the suitability of the UK for establishment. These are outlined in more detail in Appendix 2, but the most important of these is that there are very few published thresholds for the development requirements of the larvae, as used in the models examined here.

There is a population of larvae in a small area of Portugal whose larvae develop very rapidly in the summer, instead of more slowly over the winter. This PRA focuses on the populations with overwintering larvae, as they have been extensively studied and form the vast majority of the populations of *T. pityocampa* including those spreading northwards in France. It is assumed that the Portuguese summer-developing populations of larvae require much higher temperatures to complete development than those available in the UK.

Is there a need for a detailed PRA or for a more detailed analysis of particular sections of the PRA? If yes, select the PRA area (UK or EU) and the PRA scheme (UK or EPPO) to be used.

(For completion by the Plant Health Risk Group) ✓ (put a tick in the box)

<table>
<tr><td colspan="4">No</td><td>✓</td><td colspan="2"></td></tr>
<tr><td>Yes</td><td></td><td>PRA area: UK or EU</td><td></td><td colspan="2">PRA scheme: UK or EPPO</td><td></td></tr>
</table>

A more detailed PRA would not help to address the uncertainty over potential establishment and UK impacts, as these are limitations of the climate models available. Data on intra-EU trade in rooted plants with soil is very hard to find, and, again, it is unlikely that significant new sources of data would be located in a more detailed PRA.

Given the information assembled within the time scale required, is statutory action considered appropriate / justified?

For completion by the Plant Health Risk Group] *(put a tick in the box)*

Yes Statutory action	✓	No Statutory action	

This is a damaging pest that is not currently present in the UK. If an introduction was to occur, parts of southern England and a small part of Wales seem suitable for establishment.

Images of the pest

Fig. 1 *Thaumetopoea pityocampa* larvae on the outside of the silk larval nest © John H. Ghent, USDA Forest Service, Bugwood.org

Fig. 2 *Thaumetopoea pityocampa* larval nest © IZRF INRA Orleans

Stage 1: Initiation

1. What is the name of the pest?

Thaumetopoea pityocampa (Denis & Schiffermüller) (Lepidoptera, Thaumetopoeidae). Pine processionary moth (PPM). The name pine processionary moth may also be applied to *Thaumetopoea wilkinsoni*, which is now generally considered to be a separate species on molecular evidence (Erkan, 2011).

2. What initiated this rapid PRA?

A previous PRA on *T. pityocampa* was published by Baker *et al.* in 2012 in response to the northward expansion of *T. pityocampa* in France, which had raised concerns for the UK (Jordan, 2011). The 2012 rapid PRA identified the need for a more detailed climate analysis to fully assess the potential risk that *T. pityocampa* poses to the UK. This detailed climate analysis has now been carried out (Appendix 2), and the 2012 PRA is accordingly updated here. It should be noted that this update has focussed on the reassessment of establishment potential using the new climatic data available. Any new information relating to other areas of the PRA has also been included, but these were not the primary objective of this update.

3. What is the PRA area?

The PRA area is the United Kingdom of Great Britain and Northern Ireland, with a particular focus on the southern areas of England and Wales, as these areas were identified in the previous PRA in 2012 as climatically most at risk for the potential establishment of *T. pityocampa*.

Stage 2: Risk Assessment

4. What is the pest's status in the EC Plant Health Directive (Council Directive 2000/29/EC[1]) and in the lists of EPPO[2]?

The pest is no longer listed in the EC Plant Health Directive (in 2008, *T. pityocampa* was removed from Section II, part B: for the protected zone of the island of Ibiza only, it was formerly listed on plants of *Pinus* intended for planting). It is not listed by EPPO, although detailed information is available in the EPPO Global Database[3].

5. What is the pest's current geographical distribution?

Until recently it was only found in the Mediterranean region, North Africa and some areas of the Middle East and southern Europe. The full list of countries from which it has been recorded is presented in Table 1 (compiled from the EPPO Global Database and Roques (2015)). Responding to climate change, since the 1990s the pest has been moving north through France and is now breeding near Paris (Robinet *et al.*, 2011).

Table 1: Distribution of *Thaumetopoea pityocampa*	
North America:	No records
Central America:	No records
South America:	No records
Europe:	Albania, Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, France (including Corsica), Greece (including Crete), Hungary, Italy (including Sardinia and Sicily), Macedonia, Montenegro, Portugal, Serbia, Slovenia, Spain (including the Balearic Islands), Switzerland and European areas of Turkey.
Africa:	Algeria, Libya, Morocco and Tunisia
Asia:	See text on *T. wilkinsoni* below
Oceania:	No records

Thaumetopoea wilkinsoni is now generally considered to be a separate species on morphological and molecular evidence, and its range partially overlaps with *T. pityocampa* in Turkey. İpekdal *et al*. (2015) provide information on the distribution of the two species in

[1] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0029:20100113:EN:PDF

[2] https://www.eppo.int/QUARANTINE/quarantine.htm

3 https://gd.eppo.int/taxon/THAUPI

Turkey (based on molecular evidence), showing that the ranges of the two species come into contact in the northwestern part of Turkey (Anatolia). As well as Turkey, *T. wilkinsoni* is found in the Middle East (Erkan, 2011) as well as Cyprus. Records of *T. pityocampa* from Lebanon, Israel, Syria and Turkey thus appear likely to be *T. wilkinsoni* (CABI, 2011).

6. Is the pest established or transient, or suspected to be established/transient in the UK/PRA Area?

The pest is not established in the UK. There have been several reports and findings over the last 150 years, involving both adults and larvae, and each of these is discussed further below.

A colony in Kent survived from 1872-74 and then died out (Heath & Emmett, 1979). However, there is a likelihood that this is fictitious, since it was reported during a period of rivalry between unscrupulous collectors (Allan, 1943) and subsequent authors treat records of this colony as dubious.

One transient population of larvae was found in a UK nursery in 1995 on *Pinus sylvestris* imported from Italy in 1994. The affected trees and soil were treated, and subsequent monitoring did not detect the pest (Starzewski, 1998).

Reports of larvae and nests in Sherwood Forest in Nottinghamshire dating from 2010 were communicated to Fera in 2012 by a member of the public. An article was subsequently published in the Sunday Times in May 2013, reporting the presence of *T. pityocampa* in Sherwood Forest (Leake, 2013). Seven hours of survey work in November 2012 around the reported sighting location failed to detect any signs of the pest, and no sightings were recalled by staff involved in actively managing the woodland. A follow up survey in April 2013 took place over three days, and again, no evidence of *T. pityocampa* nests, larvae or other signs were found. Pheromone traps were deployed in the area from July to September 2013, and once again no *T. pityocampa* were detected. It is unclear if the original report of *T. pityocampa* at the site was mistaken, or if there had been a small population which had subsequently died out, but in either case, following the intensive surveys in 2012-13, *T. pityocampa* was considered unlikely to be present at the site (M. Townsend, unpublished report, 2013).

Two adults have been caught in light traps, many years apart. In 1966 an adult was caught in a light trap in Berkshire, but the origin of the moth is unclear and the sex was not reported (Jones, 1968; Waring & Townsend, 2003). A single male moth was caught in a light trap at Ordfordness nature reserve in Suffolk in August 2013 (Higgot & Marsh, 2014), and again the origin is unclear.

7. What are the pest's natural and experimental host plants; of these, which are of economic and/or environmental importance in the UK/PRA area?

The genus *Pinus* is most susceptible to attack and the following species are particularly susceptible: *P. nigra* (Austrian pine), *P. sylvestris* (Scots pine), *P. pinea* (stone pine), *P. halepensis* (Jerusalem pine), *P. pinaster* (cluster pine), *P. contorta* (lodgepole pine), *P. radiata* (Monterey pine) and *P. canariensis* (Canary Island pine) (EPPO, 2004). Other recorded hosts include the conifers *Cedrus atlantica* (atlas cedar), *Larix decidua* (European larch) (EPPO, 2004) and *Pseudotsuga menziesii* (Douglas fir) (Battisti *et al.,* 2005). CABI (2011) also states that *Crateagus laevigata* (midland hawthorn) is a host, though no other sources can be found that record non-coniferous trees as hosts.

Pinus sylvestris grows very widely in the UK, as do other *Pinus* host species (see Appendix 1). In 2011 there was a total of 1,406,000 hectares of coniferous woodland in Great Britain including 227,000 ha of *P. sylvestris*, 135,000 ha of *P. contorta* and 47,000 ha of *P. nigra*[4]. Maps showing the distribution of the key hosts are provided in Appendix 1, though it should be noted that most of the *P. nigra* in the UK is *P. nigra* subsp *laricio* (Corsican pine). All the known hosts may be bought commercially from nurseries in the UK (RHS Plant Finder, 2012).

8. What pathways provide opportunities for the pest to enter and transfer to a suitable host and what is the likelihood of entering the UK/PRA area?

Plants for planting

Eggs are laid in a flat mass and are relatively cryptic. However, eggs hatch quickly and comparatively little of the life cycle is spent as eggs. Egg masses are considered to be a low risk by Robinet *et al.* (2011) due to pine trees not usually being planted in the summer months when adult moths lay their eggs. However, *Pinus* trees for the horticultural trade are also imported in late summer when eggs may be present. This trade can be quantified since such imports are subject to notification. Imports that come directly from areas where *T. pityocampa* is present provide the greatest risk since by the time those that have come via other countries, e.g. the Netherlands, arrive in the UK, the eggs are likely to have hatched and the larval tents will be more detectable. As such only the imports from Italy provide the greatest risk. Peak egg-laying is likely to be between July and August in the Pestoia areas west of Florence where large numbers of trees are exported from Italy but data from June to September have been analysed as a precaution. From the notifications reported, 113 *Pinus* plants were imported in 19 consignments from Italy in June-

[4] http://www.forestry.gov.uk/website/forstats2011.nsf/0/BF32BD6C9B18DD3680257360004FE23E

September 2014 and 2015. Although this trade is small, there has been a significant increase in consignments in 2015 compared to 2014.

Larvae of *T. pityocampa* were found on a UK nursery in 1995 on pot grown pine saplings, which had been imported from Italy the previous year (Starzewski, 1998). There is therefore a potential danger for caterpillars associated with plants for planting being brought into the UK. However, these caterpillars are gregarious, forming white silken nests up to the size of a football on host plants, in which they overwinter, occasionally coming out to feed (Starzewski, 1998). In the majority of cases, these nests (see Fig. 2) and the associated caterpillars would be clearly visible prior to, or at import, greatly lowering the risk of movement.

Adults are short lived and unlikely to remain with planting material being moved, and it is not considered that this life stage presents a significant threat on this pathway, either.

Undetected pupae could be brought into the UK in the soil of plants for planting – most likely with hosts, but potentially with any plants which have been growing in the vicinity of infested host trees prior to export. Although this is considered a low risk, pupae are unlikely to be detected by inspection and may remain in the soil for up to three years before the moths emerge (Starzewski, 1998). This is the pathway by which it is believed that *T. pityocampa* moved to the Paris area in France (Robinet *et al*., 2011). Although plants for planting of a wide range of genera enter the UK annually and there are no requirements for plants to be free of this pest, the volume of imports of host plants with soil from areas where *T. pityocampa* is present is not large. According to the Forest Reproductive Material Database, the UK only imported hosts (*Pinus sylvestris*, *P. pinaster* and *Larix eurolepis*) in containers (which are thus assumed to have a significant quantity of soil) from countries with *T. pityocampa* on six occasions between 2003 and 2012. Greater quantities of bare-rooted trees are imported (both hosts and non-hosts), but due to the lack of soil for pupae, and the visibility of the other life stages, these are not considered to be a high risk. The total amount of trade of ornamental pine and containerised non-host species growing in vicinity of infested pine trees is not known. Data for containerised tree imports is given in Table 2, and the number of pines reported through the pre-notification scheme is given in Table 3; of the latter, it is unknown how many of the trees included significant quantities of soil.

Overall, based on this evidence, the pathway has been assessed as moderately likely with medium confidence.

Table 2. Imports of containerised trees (both host and non-host species) from within the EU between 2003 and 2012. Source: Forestry Reproductive Material Database.

Tree species	Origin	Quantity	Year
Fagus sylvatica	Unknown	40,000	2005
Larix eurolepis	Unknown	5,000	2007
Picea abies	Czech Republic	40,000	2005
Pinus pinaster	Belgium, France	15,584[5]	2012 (3 consignments)
Pinus sylvestris	Czech Republic, unknown	30,000	2007 (2 consignments)
Quercus rubra	Unknown	1,080	2005

Table 3. Imports of *Pinus* spp. under the pre-notification scheme from European countries where *Thaumetopoea pityocampa* is present, January 2013 to January 2015. Source: https://www.gov.uk/government/publications/pre-notification-for-tree-species-imported-from-europe

Origin	Number of notifications	Number of trees
France	11	114
Italy	44	1825
Spain	2	30
Unknown	*50*	*1404*

Wood

Association of this pest with wood or wood products is considered very unlikely, with high confidence. There is potential that larvae may be incidentally associated with wood, but the likelihood of them being associated with this pathway is very low and they would need to locate a suitable host to complete their development.

Hitchhiking on vehicles / containers

Again, association of any life stage with this pathway is considered very unlikely with high confidence.

[5] The actual figures contributing to this total are 4.2, 5.621 and 5.763. As fractions of a tree are unlikely to be imported, it has been assumed here that a decimal point was used in error, instead of a comma delimiting thousands.

Natural spread

Adults have wings and both sexes can fly. Reports have been made of possible migrants to the UK (Waring & Townsend, 2003; Starzewski, 1998; Higgot & Marsh, 2014). However, natural dispersal is dependent on the flight capacity of female moths (as males are unable to found a new population), and female dispersal distances are lower than that of males. Robinet *et al*. (2011) conducted experiments to estimate the females' flight capacity in laboratory conditions. The average flying distance recorded was 1.7 km, with the maximum being 10.5 km. This experimental data is consistent with the rate of spread of this moth in the south of the Paris Basin, which has been reported as 5.6 km per year (Battisti *et al.*, 2005; Robinet *et al*., 2007). Based on the moth's current known distribution, the risk of natural spread is still low compared to the movement with plants for planting, however, *T. pityocampa* is now present in parts of Brittany (Boutte, 2014). The females' maximum recorded flight capacity is considerably less than the width of the English Channel at this point, meaning that this pathway is considered very unlikely. However, the northward expansion in range means there is only medium confidence in this judgement. If significant populations of this pest were to build up in costal Brittany, this would increase the chances of natural spread.

Plants for planting	Very unlikely ☐	Unlikely ☐	Moderately likely ☑	Likely ☐	Very likely ☐
Confidence	High Confidence ☐	Medium Confidence ☐	Low Confidence ☑		

Wood	Very unlikely ☑	Unlikely ☐	Moderately likely ☐	Likely ☐	Very likely ☐
Confidence	High Confidence ☑	Medium Confidence ☐	Low Confidence ☐		

Hitchhiking	Very unlikely ☑	Unlikely ☐	Moderately likely ☐	Likely ☐	Very likely ☐
Confidence	High Confidence ☑	Medium Confidence ☐	Low Confidence ☐		

Natural spread	Very unlikely ☑	Unlikely ☐	Moderately likely ☐	Likely ☐	Very likely ☐
Confidence	High Confidence ☐	Medium Confidence ☑	Low Confidence ☐		

9. If the pest needs a vector, is it present in the UK/PRA area?

No vector is needed. This is a free-living insect.

10. How likely is the pest to establish outdoors or under protection in the UK/PRA area?

Appendix 1 shows that the *Pinus* host species of *T. pityocampa*, particularly *P. sylvestris*, are widespread in the UK. The greatest diversity is found near the coast in Southern England between Bournemouth and Southampton where non-native *Pinus* host species, such as *P. nigra, P. radiata* and *P. pinaster*, are grown. Appendix 2 details the investigations that were carried out into the climatic suitability of the UK for *T. pityocampa*. The outcome of this climate mapping is that parts of Cornwall appear to be most at risk, with the South Coast, parts of Pembrokeshire and London also at least partially suitable. However, few thresholds were available for the models, and as a result the maps need to be interpreted with some caution. The approaches taken in response to the lack of thresholds, as well as other limitations and caveats around these models are discussed more fully in Appendix 2. Overall, establishment in parts of southern England is assessed as likely, but with only medium confidence due to the uncertainties and unknowns in the interpretation of the model outputs.

The geographically restricted population of summer-developing larvae in Portugal has not been considered in the current analysis, and is not included in the establishment ratings given here. However, given these larvae have a rapid rate of development, descending to the soil by the early autumn to pupate (Pimentel *et al.*, 2006), it is assumed that the UK will not have summers that are warm enough to enable this faster growth to occur and hence allow this population to establish.

Suitable hosts are not generally grown under protected cultivation, and if infestation was to occur, the nests and larvae are very noticeable and it seems likely that the population would be controlled. Therefore, establishment under protection is considered very unlikely, with high confidence.

Outdoors	Very unlikely	☐	Unlikely	☐	Moderately likely	☐	Likely	☑	Very likely	☐
Confidence	High Confidence	☐	Medium Confidence	☑	Low Confidence	☐				

Under Protection	Very unlikely	☑	Unlikely	☐	Moderately likely	☐	Likely	☐	Very likely	☐
Confidence	High Confidence	☑	Medium Confidence	☐	Low Confidence	☐				

11. How quickly could the pest spread in the UK/PRA area?

The natural rate of dispersal appears to be quite low, with records from France indicating a range of expansion of around 5.6 km per year (Robinet et al., 2007). In a flight mill, the average flying distance of 47 females was 1.7 km with a maximum of 10.5 km. This suggests that natural spread would be slow. While males have a higher dispersal capacity, and at least one individual that might have been a migrant appears to have reached the UK (e.g., Higgot & Marsh, 2014), males cannot found a new population and thus the rate of spread is dependent on the flight capacity of the females. Overall, the rate of natural spread is considered to be slow, with high confidence as there are good data available from France.

However, as found in France, the spread of pupae in plants with soil can produce satellite populations greatly increasing the speed of spread (Robinet *et al*., 2007, 2011). The pest could establish over a wide area if infested consignments were split between a number of different locations, although slow natural spread would mean that these remain quite isolated. Spread with trade is assessed as occurring quickly, and, once again, based on data from France, the confidence in this judgement is high.

Natural Spread	Very slowly	☐	Slowly	✓	Moderate pace	☐	Quickly	☐	Very quickly	☐
Confidence	High Confidence	✓	Medium Confidence	☐	Low Confidence	☐				

With trade	Very slowly	☐	Slowly	☐	Moderate pace	☐	Quickly	✓	Very quickly	☐
Confidence	High Confidence	✓	Medium Confidence	☐	Low Confidence	☐				

12. What is the pest's economic, environmental and social impact within its existing distribution?

The pest can be a serious defoliator of *Pinus* species in Mediterranean Europe where it occurs in high densities. Controlling for the effects of climate, Laurent-Hervouët (1986) found that defoliation could in severely infested years affect the trees to such an extent that visible growth rings were absent in southern France. However, in Corsica, the pattern of infestation was different, and only affected tree growth in 2 of the 28 years studied (Laurent-Hervouët, 1986). Impacts on *Pinus sylvestris nevadensis* in the Sierra Nevada mountains in southern Spain included reduced tree growth, but severely affected trees also produced fewer and lighter seeds, thus potentially affecting regeneration of the forest for years to come (Hódar *et al.* 2003). In north-eastern Portugal, the pest was calculated to cause an economic loss of around €100 per hectare in *Pinus pinaster* after heavy defoliation (Arnaldo *et al.,* 2010). In Portugal there is some evidence that trees weakened by *T. pityocampa* become more vulnerable to attack by other biotic agents, particularly bark beetles. There is a population of summer-developing larvae in Portugal, which has caused high levels of defoliation in the limited area in which they occur (Pimentel *et al.*, 2006).

In the majority of regions in France where *T. pityocampa* is present, the populations are cyclical, with a periodicity of 7–11 years (Li *et al.,* 2015). This means that while impacts in many years may be relatively low, in outbreak years, damage can be much more severe. For example, there were less than 5 nests per 100 trees in the network of Départment la Santé des Forêts surveillance plots in the Paris Basin in 1989: by 1993, there were over 100; but in 1994, the levels were back down to around 10 nests (Boutte, 2014). Over a similar period, the populations in the Brittany area went from under 20 nests per 100 trees in 1989, to 60 by 1992, to less than 5 in 1994. The average number of nests per 100 trees in different zones of France does appear to differ geographically, with Corsica routinely showing higher numbers of nests than many other areas. Due to the cyclical nature of the populations, it is rather difficult to compare other areas, as they are more similar to each other and any differences that do exist are partially masked by the fluctuations in the populations of *T. pityocampa*. However, overall, the surveillance plots in Brittany and the Paris Basin do not seem to show fewer nests than areas further south, such as the two areas ("Massif landais" and "Zone sous influence méditerranéenne, these being in the southern half of France) regarded as most suitable for *T. pityocampa* by Boutte (2014) (using the Huchon and Demolin (1970) model – see Appendix 2). Data for the Paris Basin shows that in the winter of 2012-13, isolated reports of damage were recorded for the second year running, in the area between Orleans and Paris (Boutte, 2013). Li *et al.* (2015) showed that, for the region containing Orleans ("Centre"), there were areas that showed distinctly cyclical populations, but also areas that did not. They hypothesised that the lack of periodicity may be linked to this being an expansion area for the pest, and thus the limiting factors on the populations may be different to those responsible for the cyclical pattern elsewhere.

But when reports of defoliation instead of the number of nests are considered, lower levels of damage have been recorded in Brittany and the Paris Basin, compared to areas further south, though Boutte (2014) does note that, while the colonisation of Brittany by *T. pityocampa* is limited by lack of sunshine, the mild winter temperatures are favourable for defoliation. In these more northern regions, significant defoliation at the edges of the pine stands have been reported only in a small area north-east of Orleans around Nemours in 2013-13 (Boutte, 2013) and in an area south-east of Orleans in the winter of 2013-14 (Boutte, 2014). In contrast, areas around the Massif Landais (identified as more suitable for *T. pityocampa*) had records of over 50% of the marginal trees in pine stands with visible defoliation in 2012-13 (Boutte, 2013), and by the winter of 2013-14, there was a rise in the number of sites within the Massif that had high levels of defoliation (Boutte, 2014).

In addition to impacts on the health of the trees by defoliation, social impacts are caused by the urticating hairs of the older larvae which become detached from the larvae and contaminate the environment more widely. If they come into contact with skin, these setae cause severe rashes in both humans and other mammals (including dogs (e.g. Niza *et al.,* 2012)) due to a toxic protein they contain. If airborne setae are inhaled, they may cause breathing difficulties, e.g., asthma. If the setae enter the eye, severe corneal inflammation can occur (Portero *et al*., 2012). The larval nest also contains shed hairs that continue to pose a risk to those that handle it for months or even years afterwards.

Impacts	Very small	☐	Small	☐	Medium	☐	Large	✓	Very large	☐
Confidence	High Confidence	☐	Medium Confidence	✓	Low Confidence	☐				

13. What is the pest's potential to cause economic, environmental and social impacts in the UK/PRA area?

Establishment in parts of Cornwall and along other parts of the south coast of England is judged to be possible, but it is likely that the pest would be at the edge of its range – though it should be noted that some parts of the UK appear to be as climatically favourable for the larvae as the area around Orleans, where *T. pityocampa* has been present since the early 1990s. Preliminary results from the first winter of experimental work on the effect of colony size indicates that larger colonies have higher survival rates, possibly due to higher numbers of larvae being better able to regulate the humidity levels inside the nest (Laparie *et al.,* 2015). It might be expected that any colonies in England would be smaller, due to the marginally favourable climate, and thus overall survival would also be lower. High levels of defoliation over large areas only appear to be reported from more southerly parts of France, and thus it is expected that, in the UK, economic and environmental damage through tree defoliation will be minimal apart from in exceptionally mild sunny winters when higher levels of damage could be sustained. However, as the pest is still increasing in range in France, and is now in Brittany, confidence in this judgement is only medium, as almost 5% defoliation was reported in Brittany in 2012 (Boutte, 2014). Potential UK impacts of the Portuguese summer-developing population of larvae are unclear. It is assumed that these larvae would not be capable of completing their development in the UK, given the cooler summers here, and so this population was not included in the assessments of impacts.

Social impacts are judged to be higher, as even low population densities could cause major health problems due to the urticating setae of the larvae. As the larvae favour isolated trees, and urban heat islands will favour establishment, the potential for social impacts may also be increased as these conditions are most likely to occur in populated areas. Confidence in this judgement is also medium.

Economic Impacts	Very small	☐	Small	✓	Medium	☐	Large	☐	Very large	☐

Confidence	High Confidence	☐	Medium Confidence	☑	Low Confidence	☐				

Environ - mental Impacts	Very small	☐	Small	☑	Medium	☐	Large	☐	Very large	☐
Confidence	High Confidence	☐	Medium Confidence	☑	Low Confidence	☐				

Social Impacts	Very small	☐	Small	☐	Medium	☐	Large	☑	Very large	☐
Confidence	High Confidence	☐	Medium Confidence	☑	Low Confidence	☐				

14. What is the pest's potential as a vector of plant pathogens?

Thaumetopoea pityocampa is not a known vector of any plant pathogen.

15. What is the area endangered by the pest?

Appendices 1 and 2 show that parts of Cornwall and parts of the south coast of England have (a) a high density and diversity of host *Pinus* species and (b) climatic conditions for the larvae, modelled in a variety of ways, that are similar to those in Orleans where *T. pityocampa* is established and occasionally damaging. Urban areas including London and other parts of the coastal fringe such as Pembrokeshire also have some climatic similarity to Orleans, though the density of *Pinus* spp. in these areas is less.

Stage 3: Pest Risk Management

16. What are the risk management options for the UK/PRA area?

Exclusion

This pest is currently absent from the UK. However, it is present and spreading naturally in other EU Member States. Currently the major hosts of *T. pityocampa*, *Pinus, Cedrus* and *Larix* spp., are prohibited from all non-European third countries. However as *T. pityocampa* is present in much of southern and central Europe including a number of EU Member States this prohibition provides little protection against *T. pityocampa*. *Thaumetopoea* *pityocampa* is not a regulated pest within the EU and, therefore, there are no existing phytosanitary measures against this pest. Exclusion of this pest would be an effective means of preventing establishment in the UK. This would require the adoption of new legislation which would impose requirements to ensure that plants for planting arriving in the UK from EU Member States and European third countries were free from *T. pityocampa*. However the measures which would be required to ensure that *T. pityocampa* does not enter the UK are likely to be very difficult for infested countries to meet and therefore unacceptable to other EU Member States.

It is possible that egg masses and larvae could be imported with plants for planting of host species and that pupae could be imported with soil associated with plants for planting of any species from an infested area.

Appropriate measures for the exclusion of *T. pityocampa* egg masses and larvae from the UK would be a requirement for careful visual examination of host plants on places of production and in the immediate vicinity of places of production to ensure freedom from egg masses, larvae and nests either on the trees themselves or the surrounding area.

Detection of pupae in the soil associated with plants for planting would not be possible and it is likely that pupae could be associated with any plant for planting from an infested area, not just the host species. This adds a significant complication to any measure aimed at excluding the pest, as any plant with soil attached from an infested area carries the risk of introducing *T. pityocampa* pupae which could potentially complete their life cycle and emerge as adult moths which could infest hosts plants. In order to prevent movement of pupae, restrictions would have to be placed on the movement of all plants for planting with soil attached from infested areas. In France it is thought that *T. pityocampa* has made jumps in its distribution associated with human activity and it is considered most likely that pupae of *T. pityocampa* have been moved long distances associated with soil attached to plants.

Appropriate measures would be a requirement for all known hosts to have come from a place of production which has been subject to an official inspection at an appropriate time and has been found free from signs of *T. pityocampa*. The immediate vicinity of the nursery would also need to be inspected and found free from *T. pityocampa*. The immediate vicinity around the nursery would have to be defined and would need to be further than the average flight distance of the female moth, which was considered by Robinet *et al.* (2011) to be 1.7 km (although it should be noted that there will be female moths which can fly significantly further, up to 10.5 km was recorded by Robinet *et al*. 2011). To ensure freedom from *T. pityocampa* pupae all plants for planting from infested areas should either have come from a place of production within an immediate vicinity which has been inspected and found free from *T. pityocampa* or should be moved without soil (bare roots) which would have huge implications for the movement of plants for planting within the EU.

Eradication or Containment

If *T. pityocampa* was identified at an early stage, i.e. in imported plants for planting and before any further spread to the wider environment, it may be possible to eradicate. As has been the case with *T. processionea* (oak processionary moth: OPM), if *T. pityocampa* was to infest trees in the wider environment (either forest or amenity trees) eradication would be unlikely. The difficultly associated with eradication of *T. pityocampa* makes the best option the exclusion of the pest from the UK. However, if *T. pityocampa* was to enter and establish in the UK, the measures employed against OPM could be used in an attempt to eradicate or at least contain *T. pityocampa*.

There are a number of insecticides which are highly effective against OPM and therefore would be expected to be effective against *T. pityocampa*. However a major limitation to the effectiveness of insecticides used against OPM has been the methods of application, due to the size of trees it has not always been possible to deliver insecticides to the site of infestations. *Bacillus thuringiensis* (BT) (DiPel DF), deltamethrin (e.g. Decis) and diflubenzuron (Dimilin Flo), which are all approved for use on amenity vegetation in the UK, are highly effective against OPM if applied early enough to the whole canopy. However, once the larvae have passed the third instar, BT and diflubenzuron are less effective and better control is obtained using deltamethrin. It should be noted that this broad-spectrum insecticide is highly toxic to aquatic life (as is diflubenzuron) and cannot be used near water. It should also be noted that these products are only approved for use on amenity vegetation, none are approved for use in woodland, and only Dimilin is approved for use in forestry plantations.

In situations where larvae cannot be killed with insecticides, then larvae and nests can be removed manually, either by hand or by using vacuum equipment. This can be very effective in reducing populations of OPM, but it is very costly and labour intensive and experience in the UK and on the continent shows that removing by hand or vacuum equipment does not eliminate OPM completely. It appears that some larvae or nests always remain undetected, or are found to be in positions that cannot be reached.

References

Allan, P.B.M. 1943. Talking of Moths. pp.240-244. Newtown, Montgomery.

Arnaldo PS, Chacim S, Lopes D, 2010. Effects of defoliation by the pine processionary moth *Thaumetopoea pityocampa* on biomass growth of young stands of *Pinus pinaster* in northern Portugal. *iForest* **3**: 159-162.

Baker CRB. 1980. Some problems in using meteorological data to forecast the timing of insect life cycles. *EPPO Bulletin* **10** (2) 83-91.

Baker R., Anderson H., Matthews-Berry S. & Korycinska A. 2012. Rapid Pest Risk Analysis for *Thaumetopoea pityocampa* (the Pine Processionary Moth). 20 pp.

Battisti, A. Stastny, M., Netherer, S. Robinet, C., Schopf, A., Roques, A. & Larsson, S.2005. Expansion of geographic range in the pine processionary moth caused by increased winter temperatures. *Ecological Applications,* **15**: 2084-2096.

Biavetti I, Karetsos S, Ceglar A, Toreti A & Panagos P (2014) European meteorological data: contribution to research, development, and policy support. In *Second International Conference on Remote Sensing and Geoinformation of the Environment* (Hadjimitsis D, Themistocleous K, Michaelides S & Papadavid G eds.), pp. 1-9.
Boutte B. 2013. Bilan de la surveillance de la chenille processionnaire du pin en forêt. Cycle biologique 2012-13. Available at*:* http://agriculture.gouv.fr/sites/minagri/files/documents/pdf/bilanpp_cle0149a1.pdf [Accessed 21 August 2015].
Boutte B. 2014. Bilan de la surveillance de la chenille processionnaire du pin en forêt. Cycle biologique 2013-14. Available at: http://agriculture.gouv.fr/sites/minagri/files/documents/pdf/Bilan_PP_2014_cle8ad32e.pdf [Accessed 7 August 2015].
CAB International. 2012. *Thaumetopoea pityocampa* datasheet. In: Crop Protection Compendium. Wallingford, UK: CAB International.
EPPO (Gomboc S & Germain J-F). 2004. Diagnostic protocols for regulated pests: *Thaumetopoea pityocampa*. *EPPO Bulletin* **34**: 295–297.
Erkan N. 2011. Impact of pine processionary moth (*Thaumetopoea wilkinsoni* Tams) on growth of Turkish red pine (*Pinus brutia* Ten.). *African Journal of Agricultural Research* **6**(21): 4983-4988.
Evans (2008) Increasing global trade and climate change: co-factors increasing the international movement and establishment of forest pests. In: Alien invasive species and international trade, 2nd meeting of IUFRO working unit 7.03.12, 26-30 May 2008. National conservation training center, Shepherdstown, WV, USA. Available from http://www.forestry.gov.uk/pdf/IUFRO_Shepherdstown_Evans_Trade_and_Climate_Change.pdf/$FILE/IUFRO_Shepherdstown_Evans_Trade_and_Climate_Change.pdf [Accessed 30 July 2015].
Forestry Facts & Figures. 2011. Available from http://www.forestry.gov.uk/forestry/infd-7aqf6j [accessed 25 July 2012].
Heath J. & Emmett JM. 1979. Moths and Butterflies of the British Isles Vol. 9. Harley Books London.
Higgot J.B. & March M. 2014. A Suffolk record of pine processionary *Thaumetopoea pityocampa* ([D. & S.]). *Atropos* **51**: 36–38.
Hoch, G., Toffolo, E.P., Netherer, S., Battisti, A & Schopf, A. 2009. Survival at low temperature of larvae of the pine processionary moth *Thaumetopoea pityocampa* from an area of range expansion. *Agricultural and Forest Entomology*, **11**: 313-320.
Hódar JA, Castro J & Zamora R. 2003. Pine processionary caterpillar *Thaumetopoea pityocampa* as a new threat for relict Mediterranean Scots pine forests under climatic warming. *Biological Conservation* **110**: 123–129.
Huchon, H & Demolin G. 1970. La bioécologie de la processionnaire du pin dispersion potentielle – dispersion actuelle. *Revue Forestière Française* **22** (Spécial “La lutte biologique en foret”), 220–234.
İpekdal, K., Burban, C., Kerdelhué, C. & Çağlar, S.S. 2015. Distribution of two pine processionary moth species in Turkey evidences a contact zone. *Turkish Journal of Zoology* **39**: 868-876.
Jones JR. 1968. *Theumetopoca pityocampa* in Berkshire. *The Entomologist* **101**: 10.

Jordan H, 2011. Pine processionary moth - its progress and threats. *Horticulture Week*, 11th November 2011.
Laparie M., Robinet C., Rousselet J., Bernard A., Pineau P., Garcia J. & Roques A. 2015. Report in progress: preliminary results only available September 2015.
Kriticos, D.J., Leriche, A., Palmer, D.J., Cook, D.C., Brockeroff, E.G., Stephens, A.E,A. & Watt, M.S. 2013. Linking climate suitability, spread rates and host-patterns when estimating the potential costs of invasive pests. *PLoS One* **8**(2): e54861.
Laurent-Hervouët N. 1986. Mesure des pertes de croissance radiale sur quelques espèces de *Pinus* dues à deux défoliateurs forestiers. I - Cas de la processionnaire du pin en région méditerranéenne. *Annales des Sciences Forestières* **43**(2): 239–262.
Leake, J. 2013. Oaks at risk from killer caterpillars. *Sunday Times*, 5 May 2013.
Li S, Daudin JJ, Piou D, Robinet C & Jactel H. 2015. Periodicity and synchrony of pine processionary moth outbreaks in France. *Forest Ecology and Management* **354**: 309–317.
MARS-AGRI4CAST (2014) Gridded meteorological data in Europe. Available at: http://agri4cast.jrc.ec.europa.eu/DataPortal/ [Accessed March 2015].
Niza ME, Ferreira RL, Coimbra IV, Guerreiro HM, Felix NM, Matos JM, de Brito TV & Vilela CL. 2012. Effects of pine processionary caterpillar *Thaumetopoea pityocampa* contact in dogs: 41 Cases (2002-2006). *Zoonoses and Public Health* **59**(1): 35-38.
Pimentel C, Calvão T, Santos M, Ferreira C, Neves M & Nilsson J-A. 2006. Establishment and expansion of a *Thaumetopoea pityocampa* (Den. & Schiff.) (Lep. Notodontidae) population with a shifted life cycle in a production pine forest, Central-Costal Portugal. *Forest Ecology and Management* **233**: 108–115.
Portero, A., Carreño, E., Galarreta, D., Herreras, J.M. 2012. Corneal Inflammation From Pine Processionary Caterpillar Hairs. *Cornea*, June 5 http://www.ncbi.nlm.nih.gov/pubmed/22673853 [Accessed 30 July 2015].
RHS Plant Finder (2012) Available at https://www.rhs.org.uk/Plants/Search-Form [Accessed 30 July 2015].
Robinet, C., Baier, P., Pennerstorfer, J., Schopf, A & Roques, A. 2007. Modelling the effects of climate change on the potential feeding activity of *Thaumetopoea pityocampa* (Den & Schiff.) (Lep., Notodontidae) in France. *Global Ecology and Biogeography, 16: 460-471.*
Robinet C, Imbert C-E, Rousselet J, Sauvard D, Garcia J, Goussard F & Roques A. 2011. Human-mediated long-distance jumps of the pine processionary moth in Europe. *Biological Invasions* **14:** 1557–1569.
Robinet C, Rousselet J, Goussard F, Garcia J & Roques, A. 2010. *Modelling the range expansion with global warming of an urticating moth: a case study from France. Chapter 3: Climate change impacts on biodiversity.* In: Josef Settele, Lyubomir Penev, Teodor Georgiev, Ralf Grabaum, Vesna Grobelnik, Volker Hammen, Stefan Klotz, Mladen Kotarac, Ingolf Kühn, Atlas of Biodiversity Risk (p. 86-87). Sofia, BGR: Pensoft Publishers.
Roques, A (ed). 2015. *Processionary Moths and Climate Change: an update.* Springer. 427 pp.

Starzewski J. 1998. Caterpillars of the pine processionary moth *Thaumetopoeapityocampa* ([Denis & Schiffermüller], 1775) (Lepidoptera: Thaumetopeidae) overwintering in Britain on imported *Pinus sylvestris* L. *Entomologist's Gazette* **49**: 247–248.
Waring P & Townsend M. 2003. *Field Guide to the Moths of Great Britain and Ireland.* British Wildlife Publishing, 432 pp.

Name of Pest Risk Analysts(s)

Anastasia Korycinska, Richard Baker, Helen Anderson and Sharon Matthews-Berry (Defra), reviewed by Joan Webber and colleagues at Forest Research and the Forestry Commission.

Appendix 1. Pine Processionary Moth: *Pinus* Host Distribution in the UK

Figures 4 and 5 show that many of the principal *Pinus* host species for *T. pityocampa* (see section 7) are widespread in the UK. The highest diversity of pine species is found near the coast in central southern England, particularly between Bournemouth and Southampton.

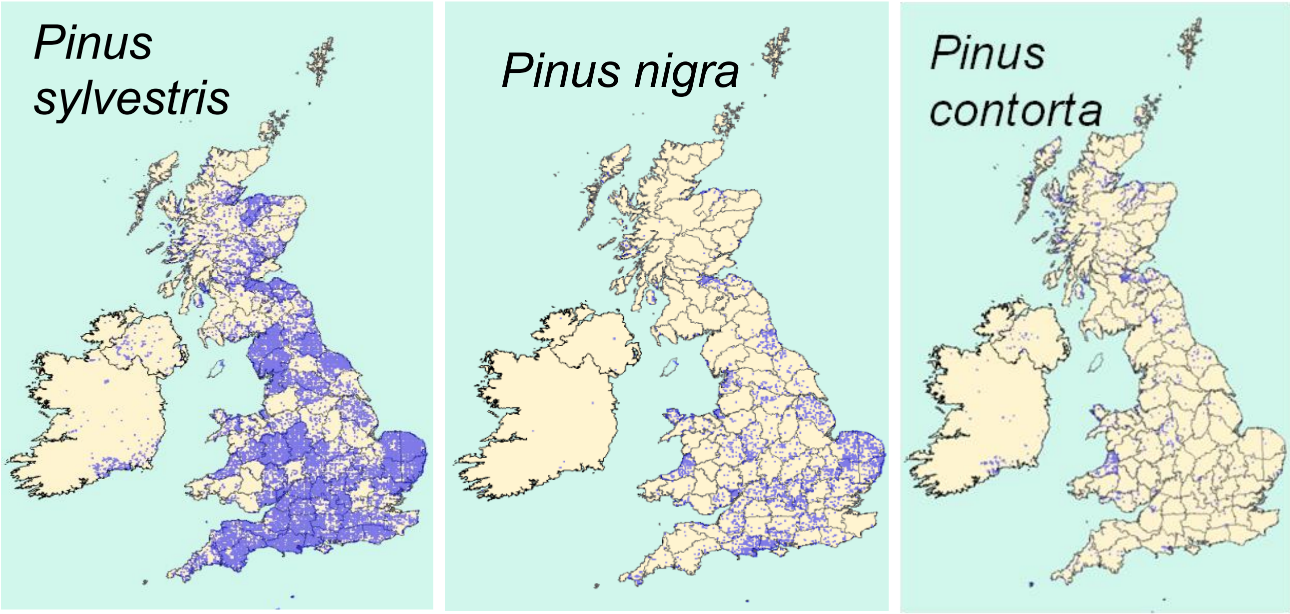

Fig. 4. Species distribution maps for *Pinus sylvestris*, *P. nigra* and *P. contorta*, reproduced from the Botanic Society of the British Isles Atlas Tetrad (2 km x 2 km) maps. Note that most of the *P. nigra* grown in the UK is *P. nigra* ssp. *larico*. *http://www.bsbimaps.org.uk/mstetrads/main.php*

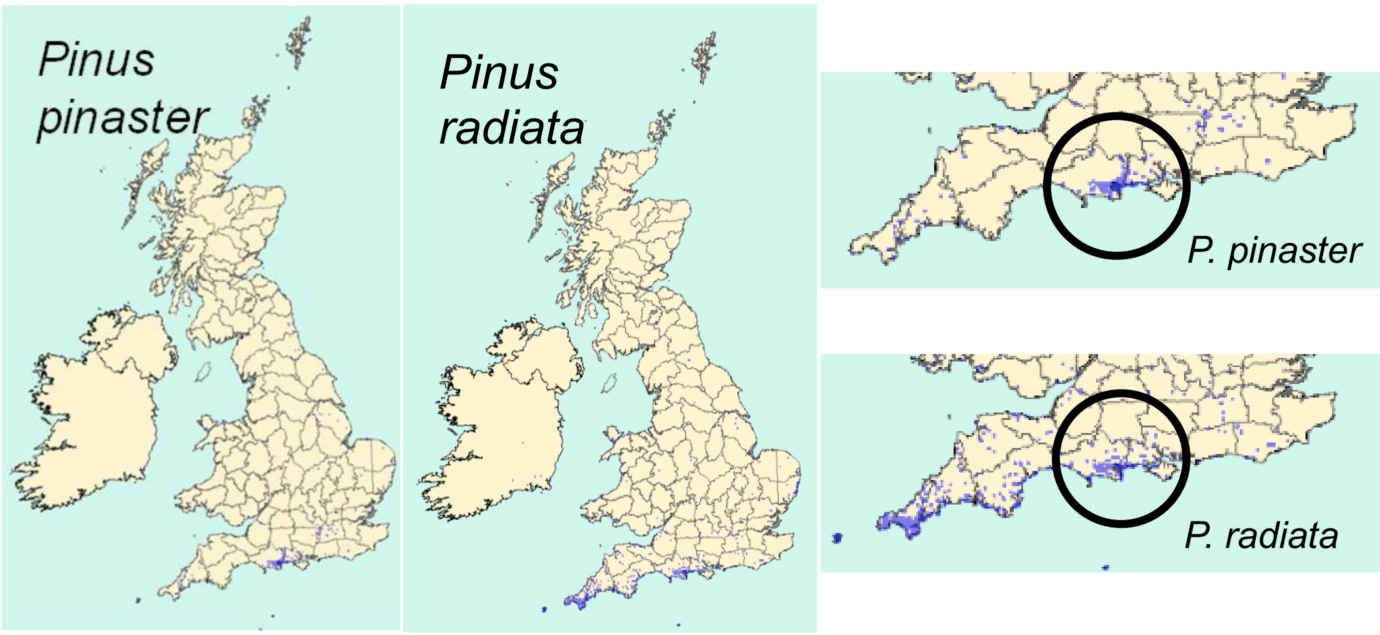

Fig. 5. Species distribution maps for *Pinus pinaster* and *P. radiata,* both at the national level and for southern England only, where the black circles are centred around Bournemouth, where there is a high diversity of *Pinus* species. All maps reproduced from the Botanic Society of the British Isles Atlas Tetrad (2 km x 2 km) maps *http://www.bsbimaps.org.uk/mstetrads/main.php*

Introduction

The 2012 PRA included a preliminary analysis of the suitability of the UK climate for *T. pityocampa*, and this identified a need for more detailed climate mapping (Baker *et al.*, 2012). *Thaumetopoea pityocampa* is relatively unusual among insects, in that the eggs hatch in the late summer or autumn, and most populations of larvae actively feed throughout the winter. The larvae live in silken tents, emerging to feed at night and returning to the nest by day, where they digest their food. During sunny days, temperatures inside the nest can be raised considerably above the surroundings, due to the effect of sunlight on the nest. Thus, when modelling the potential risk posed by *T. pityocampa* to the UK, in addition to temperature data, the amount of solar radiation is important as this influences the local temperature within the nest experienced by the larvae. The situation is also complicated by the fact that the distribution of *T. pityocampa* is no longer stable in France, with the species spreading northwards: the range has expanded north by 87 km in the 32 years between 1972 and 2004 (Robinet *et al.*, 2010). Expansion of the range in Italy is also occurring, where in the Alps, the height at which *T. pityocampa* is found is increasing (Battisti *et al.,* 2005). The expansion in range is considered to be due to the warming winter climate to which this species, because of its life history, is unusually sensitive (e.g., Robinet *et al.* 2007, 2010, 2011; Battisti *et al.*, 2005). Robinet *et al*. (2011) particularly highlight that *T. pityocampa* is highly sensitive to small changes in temperature, and that enhanced winter feeding activity (due to higher winter temperatures) enhances the winter survival rate of the larvae.

Climate data

Daily minimum temperatures, maximum temperatures and solar radiation between 1990 and 2013, interpolated to 25 km grid squares, were obtained for France and the UK (dataset described in Biavetti et al., 2014; from the EU Joint Research Centre (Ispra, Italy): MARS-AGRI4CAST, 2014). The data were then filtered to exclude the UK north of 53° and France south of 47°, in order to focus on the areas of interest, namely the south of the UK (considered most at risk) and the Orleans and Paris basin area of France (where the range is expanding). The data were manipulated and analysed in Microsoft Excel 2010®, with the relevant summary values mapped using ArcGIS 10.2.2®.

Models analysed

Over time, a number of models have attempted to explain the distribution of *T. pityocampa*. All the models considered here rely on the input of solar radiation in addition to temperature data. The more recent models also build upon previous work, and thus share common elements. Two models were considered here in their entirety: Robinet *et al.* (2007) and Huchon and Demolin (1970). The work of Battisti *et al.* (2005) provided parameters for a third approach, though only elements of this work were used here, as much of the data from Battisti *et al.* has been incorporated into the Robinet *et al.* (2007) model. Each approach used here is discussed in more detail below.

1. Robinet *et al.* (2007) model

This model uses daily min/max temperatures and solar radiation to calculate the temperatures experienced by the larvae in the nest over winter. A winter season was defined as being from October 1st in one year through to March 31st in the next (inclusive). The nest maximum temperature is calculated by: 0.552 + (0.902 * maximum air temperature) + 0.003 * solar radiation. The nest minimum temperature is equal to the minimum air temperature. A feeding day is defined as having occurred if the nest maximum temperature the previous day was >9°C and the minimum nest temperature that day is > 0°C. If neither of the above conditions for a feeding day are met, it is classed as a starvation day. In an experiment where colony size was manipulated to be between 40 and 160 larvae, preliminary work based on the first winter of the experiment (2013-14: data for 2014-15 are still being collected and analysed) indicates that larger colonies have higher maximum nest temperatures, but that the minimum and mean nest temperatures were similar across all colony sizes (Laparie *et al.* 2015).
Two outputs of this model were considered:

1. a) The total number of feeding days in each grid square in each winter season (Figs. 6 and 7)
1. b) The maximum number of consecutive starvation days in each winter season for each grid square (Figs. 8 and 9)

There are no thresholds available for either outcome, i.e. how many feeding days are required for a colony to survive to pupation, or how many consecutive starvation days will kill the larvae. Robinet *et al.* (2007) provided maps that indicate that the total feeding days in the areas where the insect was colonising (in the area between Orleans and Paris), was somewhere between 110-116 days during 1992-96, and between 120-126 days during 2001-04. The maximum starvation days during the same time periods were in the range of 14-16 and 13-15 days respectively. Battisti *et al.* (2005) noted that in northern Italy, some colonies survived an almost complete starvation period of just under three months, with only one period of 27 hours that was suitable for feeding during this time. Battisti *et al.* (2005) also noted a starvation period of almost two months in the Paris Basin, again broken by a single period of feeding.

2. Autumn degree day accumulation (after Battisti *et al.* (2005))

Thaumetopoea pityocampa larvae hatch in late summer or early autumn and feed throughout the winter. Thus, the larvae are youngest and most vulnerable in autumn and adverse conditions at this time may disproportionately affect their survival. In an ongoing experiment on the effect of colony size upon survival, preliminary results from the first winter of the experiment suggest that colonies with fewer larvae have lower survival rates, this being linked to the smaller colonies being less able to construct winter nests (Laparie *et al.,* 2015). Theoretical nest temperatures were used in the calculations, as generated by the model of Robinet *et al.* (2007), i.e. allowing for the effect of solar radiation on the maximum temperature. The degree day calculations used were those provided by Baker

(1980), who included a correction for days when the mean temperature is below the threshold, but the maximum is over the threshold and thus some development can still take place. Threshold temperatures of both 6°C and 9°C were used, as Battisti *et al.* (2005) calculated the actual feeding threshold temperature as 6°C, but used a precautionary value of 9°C to ensure that at least some time in excess of the actual threshold occurred. Kriticos *et al.* (2013), using CLIMEX to model *T. pityocampa*, used a lower temperature limit for development of 5.6°C, in order to allow sufficient development in the northern part of the species range. Within the stress parameters, day degree cold stress required 15 degree days over a threshold of 5.6°C per week, in order to fit their model to the northern limits of the distribution in Europe.

It should be noted that the degree day calculations carried out in here were not used to model any aspect of the biology of the larvae, such as calculating days suitable for feeding. Instead, the degree day accumulations were used purely to compare grid squares, with those squares accumulating a higher number of degree days considered more favourable for the larvae. As such, no thresholds were considered to apply to this model. Six outputs were produced:

- 2. a) The month of October with a threshold of 6°C
- 2. b) The month of November with a threshold of 6°C
- 2. c) Both October and November with a threshold of 6°C
- 2. d) The month of October with a threshold of 9°C (Fig. 10)
- 2. e) The month of November with a threshold of 9°C (Fig. 11)
- 2. f) Both October and November with a threshold of 9°C

The actual model of Battisti *et al.* (2005) was investigated but not used, because the temperature thresholds are the same as those in the Robinet *et al.* (2007) model. While the influence of solar radiation on nest temperature is noted in the Battisti *et al.* (2005) paper, all temperatures were obtained using probes in the nest. Therefore, this model has been supplanted by the later model from Robinet *et al.*, which included solar input.

3. Huchon and Demolin (1970) model

The earliest of the three models by Huchon & Demolin (1970) uses mean minimum January temperatures combined with total yearly solar radiation. Three outputs were produced:

- 3. a) Mean minimum January temperature (data not illustrated)
- 3. b) Total yearly solar radiation (data not illustrated)
- 3. c) Combining a) and b) (Fig. 12)

The absolute thresholds for *T. pityocampa* survival are areas where solar radiation is ≥1800 hours per year and mean minimum January temperature is ≥ -4°C, though for long term persistence, the mean minimum January temperature is higher, at 0°C. However, colder January temperatures can be compensated for by increased solar radiation, with every degree less of heat being compensated for by an increase of 100 hours in annual solar radiation (Huchon & Demolin, 1970). However, the minimum threshold for solar radiation is not met by any of the grid squares examined here, whether in northern France or southern England, based on the interpolated data from MARS-AGRI4CAST. The maps produced by Huchon and Demolin (1970) do show that the isocline for 1800 hours of yearly solar radiation runs through the area of northern France examined here, i.e. some parts of the maps generated here would be expected to have values in excess of 1800 hours according to Huchon and Demolin's data. Unlike temperatures, which are warming in recent years, solar radiation is likely to have remained reasonably constant over the time period (Robinet *et al.*, 2007) and thus the disagreement over levels of solar radiation may be due to differences between the datasets used. Robinet *et al.* (2007) note that the Huchon & Demolin (1970) model incorrectly predicted presence or absence of *T. pityocampa* in about 11% of sites from 1970-80, and the error rate increased to around 22% for the time period 1995-2005. The incorrect classifications were approximately evenly split between errors in absence and presence in the earlier period, but in the later period, the rate for incorrectly predicting absence was much higher.

Mapping outputs

Analysis: general considerations

For every model, maps were generated for each of the 24 years or 23 winter feeding seasons, as appropriate. However, analysis of yearly data is difficult as there is a great deal of variation from year to year. Additionally, the only published thresholds are those for the Huchon & Demolin (1970) model, and none of the grid squares for any year in the area studied here meet the minimum level of annual solar radiation, as calculated using the MARS-AGRI4CAST dataset. Two main options for summarising the data over the whole time period were considered:

(i) Averaging the data over the time period studied and mapping the mean values. This option does not help with assigning thresholds required for development, and thus assessing which areas are actually at risk from establishment. Additionally, the temporal resolution is lost, i.e. a location with varying climate such that some years are suitable and some years not, could have the same mean value as a location that is marginally unsuitable every year, though the risks associated with the two locations are likely to be different.

(ii) For each year or winter season, comparing the output for each grid square with a grid square where *T. pityocampa* is known to be established.
This option assigns thresholds to the data by default, as whatever values are required by the larvae, they are assumed to be met in the comparison square (as the larvae are established there). It is important to note that the "threshold" will vary from year to year, as a comparison of one grid square with all the others on a year-by-year basis is being used, rather than a fixed value. Therefore, the comparison grid square needs to be chosen carefully. However, this option does still retain an element of temporal variation within the analysis, albeit one dependent on the relative changes between grid squares, rather than variation against an absolute measure.

Both approaches detailed above have limitations, but in view of the lack of data for thresholds, it was decided that the approach detailed in (ii) was more likely to generate maps and data that provided comparisons of use when assessing the risk to the UK.

Analysis: choice of comparison square

In the early 1990s, *T. pityocampa* began to expand its range northwards in France. By 1992, it had reached just a location just north of Orleans, and has continued to spread north towards Paris at an increasing rate in subsequent years (Battisti *et al.,* 2005; Robinet *et al.*, 2007), with pioneer colonies (almost certainly accidentally introduced to these locations) to the north and east of Paris detected from 2003 on (Robinet *et al.* 2011). As Orleans is at the northern edge of a 25 km grid square (Fig. 6), climatic conditions are considered to have been suitable in this grid square for initial colonisation and subsequent establishment during the period studied here (1990-2013 inclusive). Accordingly, the 25 km grid square containing Orleans was chosen as the comparison square, as the presence of *T. pityocampa* in and around the city has been well documented throughout the time period of interest. Data from Boutte (2013, 2014) for the Paris Basin shows that the percentage of trees attacked varies considerably over time, and thus comparing levels of damage from the early 1990s to the present day in Orleans is difficult, though in the winter of 2012-13, isolated reports of damage were recorded for the second year running, in the area between Orleans and Paris (Boutte, 2013). Li *et al.* (2015) showed that, for the region containing Orleans ("Centre"), there were areas that showed distinctly cyclical populations, but also areas that did not. They hypothesised that the lack of periodicity may be linked to this being an expansion area for the pest, and thus the limiting factors on the populations may be different to those responsible for the cyclical pattern elsewhere.

Summary maps were generated for each of the outputs detailed in 1a to 3c, where for every time period, the variable in question was compared to the value obtained for the Orleans square for each year studied. If the variable was equal to, or more favourable than, the Orleans value, the square was scored 1; otherwise, 0. There was no buffering, i.e. for a value less than that for Orleans, the score was always 0, and no attempt was made to distinguish between values substantially less than the Orleans value, and a value only slightly lower. It is important to note that the comparison was always year to year, i.e., the value for any given square in 1991 was always compared with the Orleans square in 1991; the value for Orleans in 1992 was compared with values from all the other squares in 1992. The score for each of the 24 years (or 23 winter seasons) was then calculated and the resulting maps (Figs 6, 8 and 10–12) show for how many years of the time period each grid square was equally favourable to, or more favourable than, the Orleans square. Thus the Orleans square, as calculated here, is always maximally favourable to the development of *T. pityocampa*, as it is always equal to itself. Other squares will vary in their suitability and can be discriminated accordingly.

Further analysis: temporal considerations

When interpreting the maps, it should be noted that *T. pityocampa* has moved northwards towards Paris and beyond within the time period studied here. As such, several of the grid squares may have become more suitable for *T. pityocampa* in recent years than in the early 1990s. Accordingly, a second series of comparisons were made between Orleans and other grid squares for each of most recent ten years or winter seasons (i.e., 2004-2013). Ten-season maps are presented in Figs 7 and 9 for both outputs in the Robinet *et al.* (2007) model (note that these map legends are not to the same scale as the maps for the longer time period). Data for the other model outputs are discussed below, but the 10-year maps are not presented.

The maximum number of cumulative starvation days shows a similar pattern between time periods in the south of the UK and Brittany, though the Paris basin does show some differences in the ten-season period, with a greater number of squares being more similar to Orleans compared to the full time period of 23 winter seasons (Fig. 9). The total winter feeding days show a similar pattern between the two time periods (Fig. 7), as do the maps for all six categories of degree day accumulations, and all three components of the Huchon & Demolin model (data not shown).

Limitations, key additional questions, and potential further work

The lack of thresholds and the resultant difficulties in interpreting and analysing the data and maps generated has already been covered in some detail earlier (in the section “Mapping outputs – analysis: general considerations”).

Thaumetopoea pityocampa larvae are dependent on winter sunshine to increase the daytime temperatures they experience inside their nests. The amount of sunshine an individual nest receives will be dependent on many factors, such as aspect and shading from neighbouring trees and other structures. This analysis is using a coarse spatial resolution of 25 km squares, and therefore can only provide an overview of the general suitability of a particular area for establishment. Individual areas within any one grid square will have differing levels of suitability which will be dependent on many micro-factors, such as the availability of suitable hosts in a south-facing, unshaded position.

The role of sunlight has been used here in combination with temperature. However, if solar radiation in and of itself is important (rather than merely as a means of raising the nest temperature above ambient, as used here), then most parts of the UK receive less yearly sunlight than most parts of France, particularly in the critical winter months (Fig 13).

A species which is undergoing range expansion is not usually considered a good candidate for climate modelling. However, the work in this appendix was carried out because previous studies (e.g., Robinet *et al.,* 2011) indicate that the expansion in range is due to warming in the winter temperatures, and thus the climatic limitations are still thought to apply to this species.

Modelling *T. pityocampa* using CLIMEX has already been investigated by Kriticos *et al.* (2013), with the results showing that no part of the UK was suitable for establishment. This model is not necessarily in conflict with the risks presented here. The climatic temperature data used in CLIMEX are based on the period 1961-1990. This time period is outside that in which *T. pityocampa* has undergone the majority of its range expansion in France. The climate data used here was based around the time period in which *T. pityocampa* has undergone this range expansion, namely, 1990-2013. Previous work modelling *Popillia japonica* (Japanese beetle) showed a considerable increase in the northern limits of the range when modelled with the MARS AGRI4CAST data set (using mean values for 2000-2014), compared to a 1961-1990 global climate series (Defra PRA, 2015). Future work on modelling the risk of *T. pityocampa* to the UK could include importing the MARS AGRI4CAST temperature data into CLIMEX, using the parameters set by Kriticos *et al.* (2013), as these were set on the basis of the species distribution during the date range covered by the CLIMEX source data.

Conclusions

Parts of the south coast of England, including areas of Cornwall, are depicted as most at risk. This is consistent with these being the warmest, sunniest areas of the UK. Due to the urban heat island effect, London is also at a higher risk than surrounding areas. From Appendix 1, the south coast and Cornwall are areas of the UK with a high diversity of *Pinus* species, and it is expected that there will be a range of ornamental hosts grown in London, too. Pembrokeshire in Wales is another area that would seem to be climatically suitable for establishment, though the density of *Pinus* spp. in this region is much lower (Appendix1).

- In terms of the number of feeding and starvation days calculated by the Robinet *et al.* model (2007), parts of Cornwall are at highest risk for the establishment of *T. pityocampa* as they are most similar to Orleans values. The areas around Pembrokeshire, the Bristol Channel, parts of the South Coast and London are also considered to be at risk.
- Using autumn day degree accumulations, there is no major difference in pattern dependent on whether the threshold selected was 6 or 9°C, though fewer areas are identified as similar to Orleans using the 9°C threshold.
    - If temperatures in October are most limiting, then no part of the southern UK is as suitable as Orleans (with the possible exception of a very small area around Weymouth).
    - Day degree accumulations in November show that a greater area (costal parts of southern England and Wales plus London) is similar to Orleans.
    - The results for both October and November are, unsurprisingly, intermediate between the values for the individual months.

Appendix 2. Pine Processionary Moth: Climate suitability of southern parts of the UK

- The oldest model examined from Huchon & Demolin (1970), which uses total yearly insolation combined with mean minimum January temperatures, shows that only the areas around Plymouth and Weymouth are partially similar to Orleans.

However, it should be noted that there are few thresholds available to help analyse the data and different models do show differing levels of risk.

Appendix 2. Pine Processionary Moth: Climate suitability of southern parts of the UK

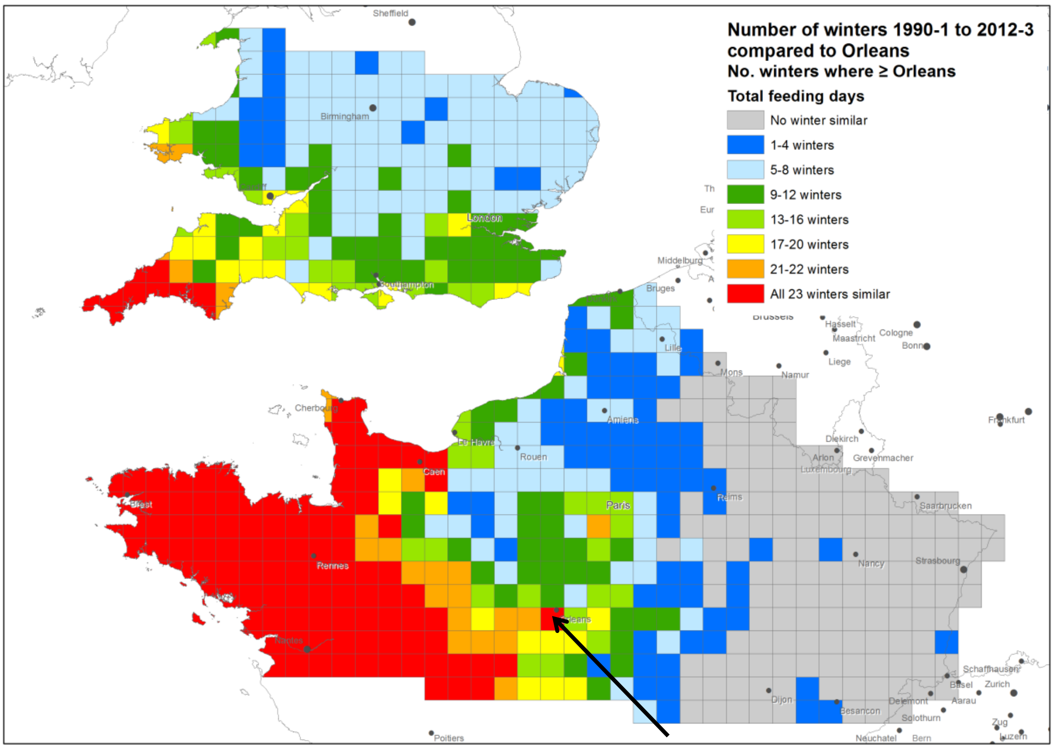

Figure 6. Comparison of the total winter feeding days (October to March) between Orleans (marked with an arrow) and the rest of northern France and southern UK for the winters of 1990-91 to 2012-13. Data are at a resolution of 25 km, and sourced from MARS AGRI4CAST.

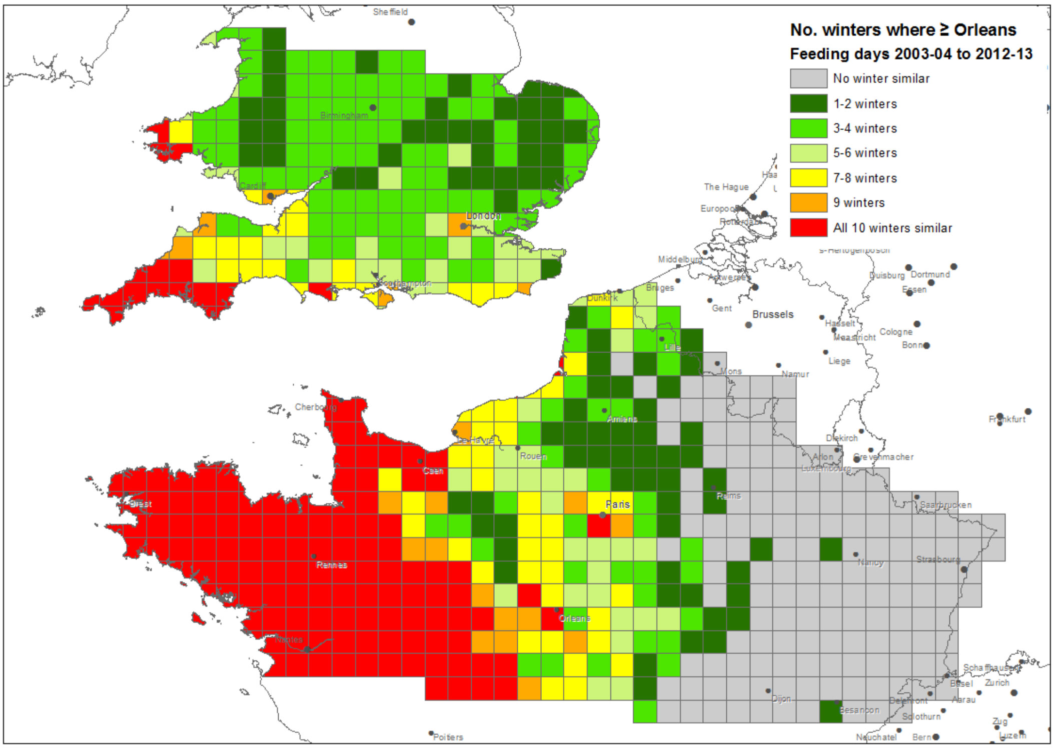

Figure 7. Comparison of the total winter feeding days (October to March) between Orleans and the rest of northern France and southern UK for the winters of 2003-4 to 2012-13. Data are at a resolution of 25 km, and sourced from MARS AGRI4CAST.

Appendix 2. Pine Processionary Moth: Climate suitability of southern parts of the UK

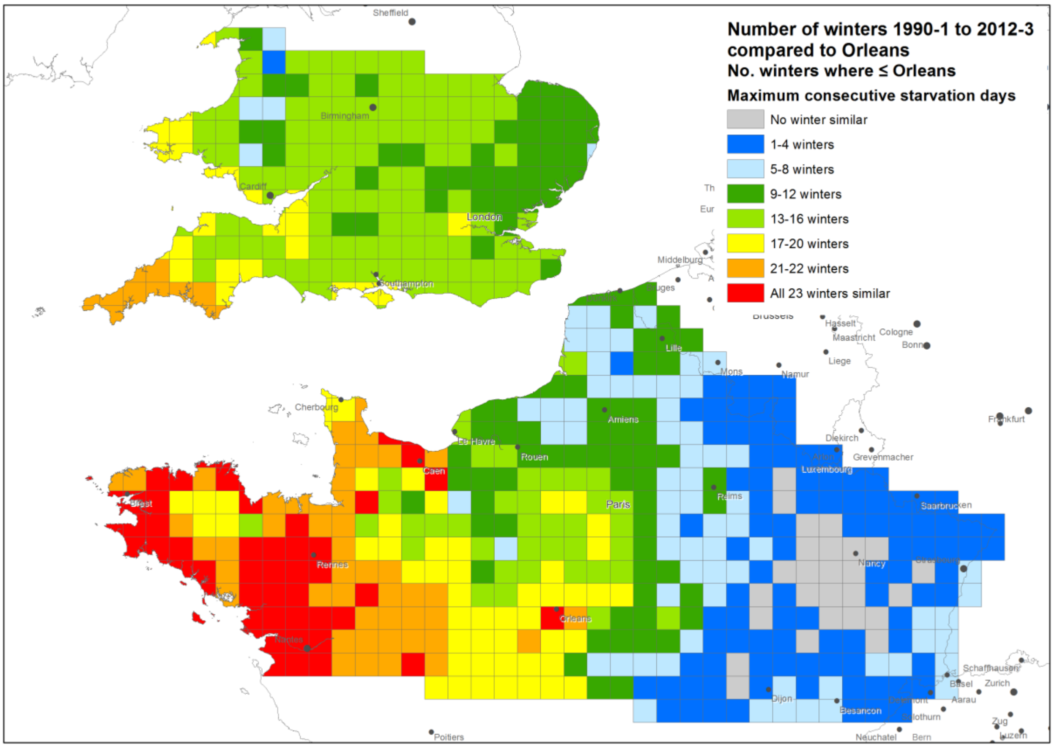

Figure 8. Comparison of the maximum number of cumulative starvation days (October to March) between Orleans and the rest of northern France and southern UK for the winters of 1990-91 to 2012-13. Data are at a resolution of 25 km, and sourced from MARS AGRI4CAST.

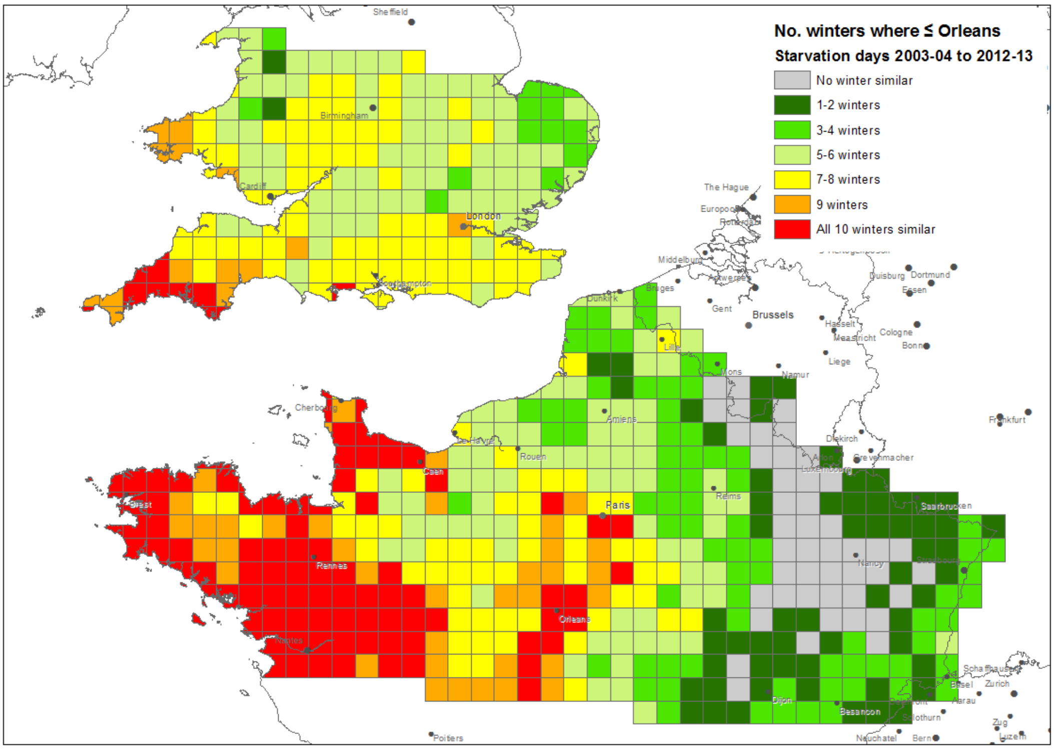

Figure 9. Comparison of maximum cumulative starvation days (October to March) between Orleans and the rest of northern France and southern UK for the winters of 2003-4 to 2012-13. Data are at a resolution of 25 km, and sourced from MARS AGRI4CAST.

Appendix 2. Pine Processionary Moth: Climate suitability of southern parts of the UK

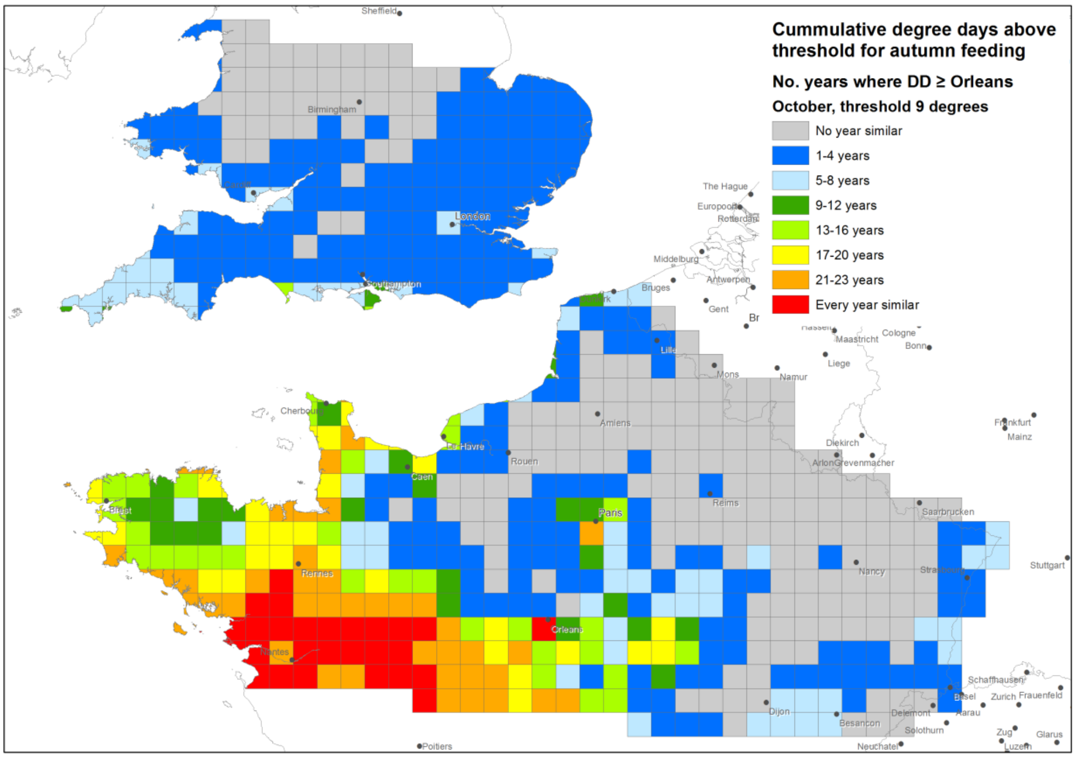

Figure 10. Comparison of the accumulated day degrees in October (threshold temperature 9°C) between Orleans and the rest of northern France and southern UK, 1990 to 2013. Data are at a resolution of 25 km, and sourced from MARS AGRI4CAST.

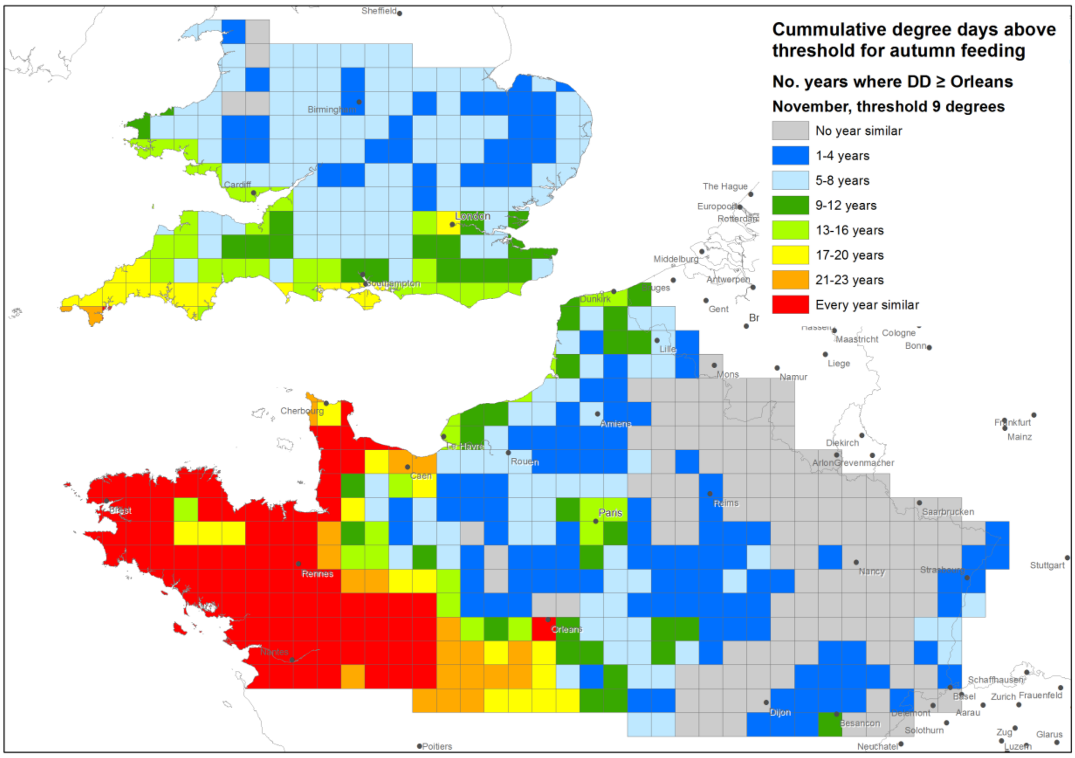

Figure 11. Comparison of the accumulated day degrees in November (threshold temperature 9°C) between Orleans and the rest of northern France and southern UK, 1990 to 2013. Data are at a resolution of 25 km, and sourced from MARS AGRI4CAST.

Appendix 2. Pine Processionary Moth: Climate suitability of southern parts of the UK

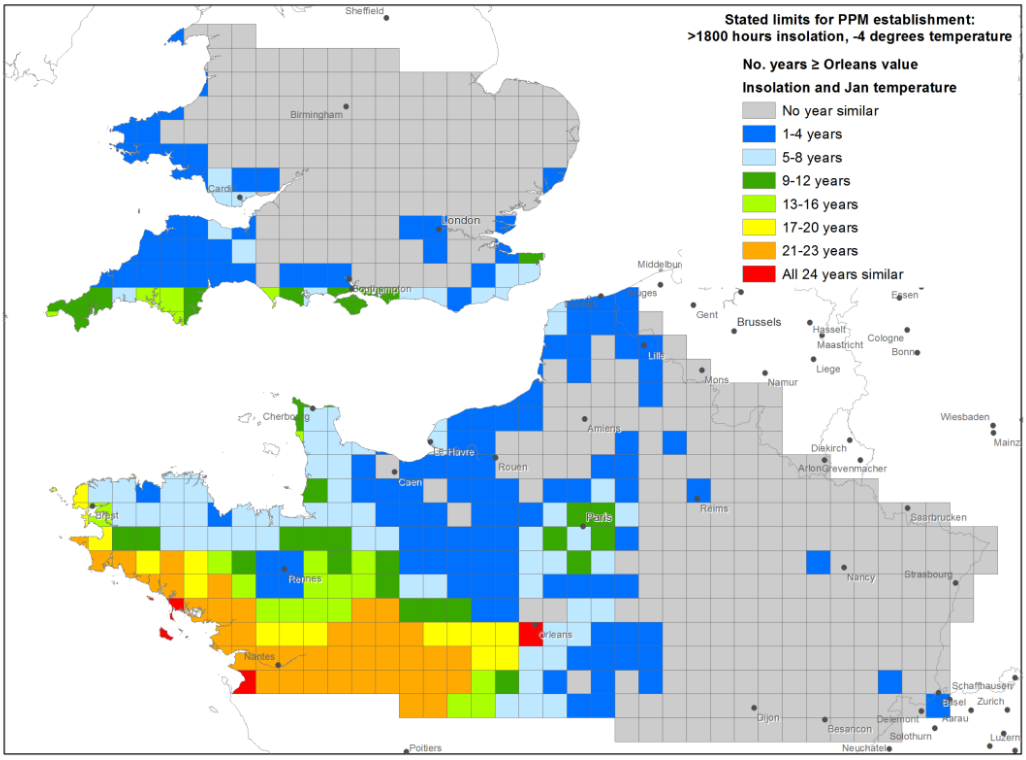

Figure 12. Comparison of mean minimum January temperature and total yearly solar radiation between Orleans and the rest of northern France and southern UK, 1990 to 2013. Data are at a resolution of 25 km, and sourced from MARS AGRI4CAST.

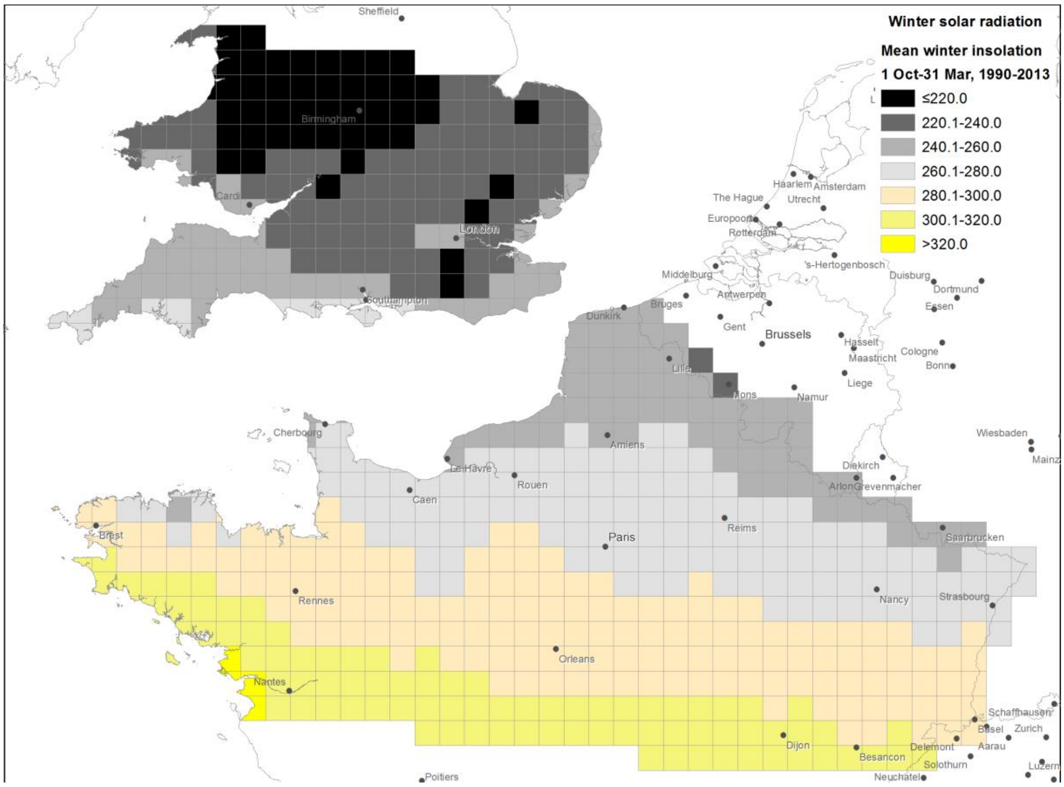

Figure 13. Winter solar radiation (sum of watt hours m^{-2} from 1 Oct to 31 March), mean 1990-91 to 2012-13 inclusive. Data are at a resolution of 25 km, and sourced from MARS AGRI4CAST.

This publication is available via the UK Plant Health Information portal https://planthealthportal.defra.gov.uk/

This PRA has been undertaken following IPPC International Standards for Phytosanitary Measures (ISPMs 2 and 11) and it provides technical evidence relating to the risk assessment and risk management of this pest.

Any enquiries regarding this publication should be sent to us at:

The Chief Plant Health Officer

Department for Environment, Food and Rural Affairs

Room 11G32

Sand Hutton

York

YO41 1LZ

Email: plantpestrisks@defra.gsi.gov.uk