**The relationship between pheromone trap catch and local population density of the oak processionary moth *Thaumetopoea processionea* (Lepidoptera: Thaumetopoeidae)**

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**Abstract**

1. Oak processionary moth (OPM) was introduced into the U.K. in 2004–2005 and pheromone traps have been used to monitor its spread and provide early warning of the colonisation of new areas.
2. The traps capture adult male OPM, but catches are highly variable and it has proved difficult to establish a relationship between the numbers of males caught and local population densities.
3. Surveys carried out around 260 pheromone traps as part of the UK OPM control programme, however, reveal a consistent linear relationship between square-root transformed adult males per trap and cube-root (or log10) transformed numbers of larval nests (R2 = 0.47; *P*<0.001)
4. In 91% of cases where traps captured no adult males, there were no OPM nests within 250m and where nests were present the numbers of nests were low. Traps that captured more than 10–20 males were associated with counts of 50+ larval nests.
5. Defoliation and risks to human health from OPM are more closely related to nest density, i.e. the numbers of nests per tree. Consequently, identifying trap catches that might initiate a management response also requires information on the numbers of oak trees in the surrounding area.

(196 words)

**Keywords:** monitoring, oak processionary moth, pheromone traps, pest management, population density, *Thaumetopoea processionea*

**Running title:**  Pheromone trapping of *T. processionea*

**Introduction**

Oak processionary moth (OPM) *Thaumetopoea processionea* (L.) is native to continental Europe, but was introduced into in the U.K. in 2004-2005 on imported oak trees (*Quercus robur* var*. fastigiata*) (Mindlin et al., 2012; Tomlinson et al., 2015). The imported trees were planted at two sites in west London, in north Ealing and at Kew Riverside, and from these initial centres of infestation the population has spread to occupy an area that now exceeds 1280 km2. In 2018, the characteristic larval nests of OPM were found on oak trees up to 30–42 km from the original sites of introduction (Forestry Commission, 2019).

The establishment of OPM in the U.K. has raised concerns, because high populations can cause severe defoliation of oak, which may be a contributing factor in oak decline. The combination of defoliation and other adverse factors, such as drought and attack by secondary insect pests and pathogens, can also lead to significant tree mortality (Thomas et al., 2002; EFSA, 2009; Battisti et al., 2015). However, OPM also poses a risk to human and animal health. Older larvae possess large numbers of urticating hairs that are easily detached and which, on contact, cause a skin rash, eye and throat irritation, and sometimes more severe medical problems (Maier et al., 2003; Jans & Franssen, 2008; Mindlin et al., 2012).

In response to these risks, an OPM control programme was established soon after the moth was discovered in the U.K., initially to contain and eradicate the pest, but subsequently to reduce the rate of spread and minimise the impact on human, animal and tree health (Williams et al., 2013; Tomlinson et al., 2015). The programme includes annual surveys to locate OPM nests, manual nest removal and spraying infested trees with the biological insecticide *Bacillus thuringiensis* var. *kurstaki* (Dipel-DF). In addition, large numbers of pheromone traps have been used to monitor spread and to identify outlying, previously undetected infestations.

The pheromone traps have been deployed using a standard procedure and they have proved useful for indicating the presence or absence of OPM in the expansion zone around the main infested area. The traps are baited with lures containing the female sex pheromone (Z,Z-11,13-hexadecadienyl acetate; Quero et al., 2003) and they attract the adult male moths, which are retained in the trap and can be counted. In the longer term, in areas where OPM has become established, the objective is to develop pheromone traps as a management tool, to provide an indication of local population numbers and whether control measures need to be applied. Similar pheromone trap-based monitoring systems have been developed for a wide range of forestry, orchard and crop pests, and they are an essential component of many integrated pest management systems (Howse et al., 1998; Myers & Hosking 2002; Jactel et al., 2006; Tobin et al., 2007; Witzgall et al., 2010).

One of the first requirements when using pheromone traps as part of a management system is to establish the relationship between trap catches and local population densities (Barbour, 1987; Howse et al., 1998; Morewood et al., 2000; Jactel et al., 2006). Establishing this relationship for OPM has proved elusive, but the large numbers of pheromone traps deployed as part of the London control programme, and the capacity to carry out surveys around many of these traps, has an enabled a larger dataset to be assembled, and from these data it is possible to demonstrate a consistent relationship between trap catches and local populations.

 This paper describes this relationship and provides some explanation for the wide variation in trap catches that has hampered analysis in the past, and discusses the prospects and limitations of using pheromone trapping for OPM as part of a management system.

**Materials and methods**

Pheromone traps have been used in London to monitor OPM since 2007. The trapping programme has been funded by the Department for Environment and Rural Affairs (Defra) and has been organised and managed by Forestry Commission England. In 2016 and 2017, a total of 1597 and 436 pheromone traps, respectively, were deployed across the Greater London area. All of the traps were standard green funnel traps (Oecos, Kimpton, U.K.) and contained 250ml of saturated salt solution to kill and preserve the adult male moths, and they were baited with OPM-specific pheromone lures obtained from Pherobank BV (The Netherlands). The lures consisted of a natural rubber septum coated with 1.1 mg of the synthetic pheromone components, and under summer conditions in the UK the lures release the pheromone at a rate of approximately 0.005 mg.day-1 (Williams et al., 2003).

The pheromone traps were placed at a height of 10–15m above the ground in the canopy of oak trees (*Q. robur*), and they were emptied and recharged every 2 weeks from the second week of July to the second week of September, which covered the whole of the OPM flight period (Straw et al., 2013; Williams et al., 2013). The lures were replaced after 4 weeks. Positioning the traps in the upper canopy was achieved by passing a line over a higher branch and pulling the trap up to the desired height (Williams et al., 2013).

In 2016, pheromone traps were distributed across a 61 km x 70 km area covering all but the central part of the known infestation. The trapping area was divided into 2 x 2 km (4 km2) squares and two traps were located in each square. In 2017, traps were located in the centre of the outbreak on a similar 2 x 2 km grid and along eight transects leading outwards in cardinal directions from the outbreak centre into the surrounding uninfested areas. The transects were 40 km in length and traps were placed at roughly 1 km intervals. The primary purpose of the trapping programme in both years was to identify the outer limits of the OPM distribution and new infestations in the peripheral zone.

Larvae of OPM hatch from overwintering eggs during late April or early May and feed on the leaves of oak during May, June and July. The older larvae spin up characteristic silk nests on the main stem and larger branches of the tree, and they hide inside the nest during the day and return to the canopy to feed at night. Pupation takes place inside the nest and the adult moths emerge from mid-July (Stigter et al., 1997; Sobczyk, 2014). The larval nests remain on the tree long after the adults have emerged and can be counted and recorded during the autumn and winter months.

After the end of the OPM flight period, when the total number of adult males caught per trap was known, a subset of the traps was selected for follow-up survey work. A total of 94 traps were surveyed in 2016 and 173 traps were surveyed in 2017. These were the maximum numbers of traps that could be surveyed given the resources available and they were not selected entirely at random, but were selected from across the range of trap captures to maximise the chances of detecting a relationship with nest numbers. In 2016, the traps selected consisted of the 34 traps with the highest numbers of adult male OPM and 30 traps, chosen at random, from traps that caught 5–10 and 11–49 adult males. In 2017, the 30 traps with the highest numbers of adult males were selected, along with 50 traps chosen at random from those that caught 0–5 adult males and 30–32 traps chosen at random from those that caught 6–15, 16–50 and 51–100 adult males. Apart from the traps with the highest numbers of captures, traps were excluded if they were within 500 m of a previously selected trap.

Nest surveys were carried out between January and March 2017 (for comparison with trap captures in 2016) and between October 2017 and February 2018 (for comparison with trap captures in 2017). The surveys were completed by contract surveyors and involved finding and inspecting all oak trees within 250m of the selected traps and recording the numbers of OPM nests per tree. The trees were inspected visually from the ground, using binoculars if necessary, and the location of each oak tree, and the tree with the trap, was recorded using GPS. The numbers of oak trees that could not be surveyed, because of difficulties with access, were also recorded. Data were logged using a mobile phone App designed specifically for the surveys, and were downloaded into a central GIS database maintained by GeoData at Southampton University.

Once the data had been checked and verified, the numbers of OPM nests, infested trees, total trees surveyed and trees not surveyed occurring within 50, 100, 150, 200 and 250m of each pheromone trap were extracted from the GIS database. Satellite images of the area around each trap (Google maps©) were also viewed and the traps allocated to one of the following land use categories: commercial or industrial, houses and gardens, public open space, farmland or woodland, and whether the trap was in an isolated oak tree, a group of trees, in open woodland or on the edge or within closed woodland. The distance (km) of each trap from the centre of the outbreak, designated as Barnes (OS Grid Ref. TQ225761), which accounted for a slight eastward shift in population density, was also calculated.

*Statistical analysis*

Nest numbers in both years were adjusted in proportion to the percentage of oak trees around the trap that could not be surveyed. In the case of 6 traps in 2016, more than 50% of the surrounding oak trees were not surveyed and these traps were removed from the analysis. One trap in 2017, which was located next to a public play area and showed signs of having been emptied unofficially, was also excluded from the analysis.

The total numbers of adult male OPM caught per trap over the season and the numbers of larval nests in the surrounding area were over-dispersed. A square-root transformation of trap catches and cube-root transformation of nest numbers stabilised the variances and produced a linear relationship, which is illustrated by regressing trap catch on nests numbers. A log10(X+1) transformation of nest numbers also produced a linear relationship and stabilised the variances, but was avoided because of the bias introduced by adding a value of 1 to the zero counts (O’Hara & Kotze, 2010). Regressions were based on trap catch plotted against nest numbers, even though the ultimate aim was to use trap catch to predict the numbers of nests (see below), because during the summer it is the nests that produce the adult moths.

Separate regressions, using the square-root and cube-root transformed data, were calculated for the accumulated numbers of nests recorded within 50, 100, 150, 200 and 250m, representing survey areas of different sizes. The significance of the regressions was confirmed using a negative binomial generalised linear model (GLM) applied to the untransformed data, and R2 values and Akaike Information Criteria (AIC) from the GLM were used to determine which survey area produced the best fit model in each year.

The influence of other potential explanatory variables on trap catches was identified, in the first instance, by determining whether there was a significant difference between the regressions of trap catch against nest numbers for different land use categories, or for isolated trees, trees in groups, or trees in open woodland or on the edge or within closed woodland and, secondly, by looking for correlations between the residuals from the overall trap catch and nest numbers regression and land use category or whether the trees were growing in isolation or in a group or in woodland. Additional variables that had a significant individual effect on trap catch were included in a generalised linear mixed model (GLMM), in which nest numbers and the additional variable were included as fixed effects and year was included as a random effect. The contribution of the additional explanatory variable in explaining the variation in trap catches was identified from the difference in R2 value between the single-factor model, based just on nest numbers, and the two-factor model containing nest numbers and the additional variable. Analyses were carried out using GenStat© (ver. 16.0, Payne et al., 2013) and R (ver. 3.5.1, R Core Team, 2018).

**Results**

The 88 pheromone traps used for calibration in 2016 caught 3,297 adult male OPM. A total of 32,221 oak trees were located and searched for larval nests within 250m of the traps, and 567 nests were found on 318 infested trees (included in the total number of trees surveyed). In 2017, the 172 traps used for calibration caught 8,017 adult male OPM and 54,828 oak trees were surveyed, and 5535 larval nests were found on 3883 trees.

The relationship between trap catch and the numbers of larval nests within 250m is illustrated in Fig. 1. Regression relationships were significant in both years (*P* < 0.001) and although the regression coefficients did not differ significantly (*P* > 0.05), the intercepts of the regressions for 2016 and 2017 were significantly different (*P* < 0.01). The regression relationship obtained by combining the data for both years was *y* = 1.55*x* + 2.91 (R² = 0.47, P<0.001, N=260).

Fig. 1

*Increasing the size of the survey area*

Regressions of trap catch against nest numbers were significant (*P* < 0.001) for smaller and larger survey areas, although R2 increased with the size of the survey area (Table 1). The best relationship (highest R2 and lowest AIC value) was obtained using the total numbers of nests recorded out to a distance of 250m. There was no indication that R2 had reached a maximum, however, even with a survey radius of 250m, suggesting that surveys beyond 250m might have improved the relationship even further.

Table 1

Regressions of trap catch against nest density on an area basis (nests per km2) produced the same basic relationship, whereas regressions of trap catch against nest density on a per tree basis, calculated as the number of nests divided by the total number of trees surveyed, were poor (R2 = 0.08-0.16). As might have been expected, it was the total number of adult male moths produced in the area around the trap that was important in determining trap catch, and not the numbers of adult males relative to the numbers of trees.

*Other factors influencing trap catch*

Trap catches were not related to the total numbers of oak trees in the surrounding area, or whether the trap was located in a commercial or industrial area or was surrounded by houses and gardens, public green space or farmland or woodland, or whether the trap was in an isolated oak tree, a group of trees, in open woodland or on the edge or interior of closed woodland. The only other factor that was correlated significantly with the numbers of adult males caught per trap was the distance of the trap from the outbreak centre (*P*<0.001). Traps closer to the outbreak centre captured higher numbers of adult males (Fig. 2). This was the result primarily of there being greater numbers of nests towards the centre of the outbreak, but in addition, traps towards the centre caught slightly more adult males than expected and traps towards the periphery of the outbreak caught slightly fewer adult males than expected. However, the effect was small. Even though distance from the outbreak centre was significant in the GLMM analysis (F1,255=21.0, *P*<0.001), its inclusion increased R2 only marginally from 47% to 50%.

Fig. 2

*Predicting nest numbers from trap catches*

The wide variation around the regression of trap catch against nest numbers meant that using the regressions to predict nest numbers was subject to considerable error. A simpler summary of the data, however, provides a more practical tool for gauging nest densities from the numbers of adult males caught in the traps (Table 2). Where a trap caught no adult males, then in 90.5% of cases, there were no larval nests within 250m, and in those cases where there were larval nests, the numbers of nests were relatively small (<15 nests) (Table 2). The majority of traps that caught 1–5 adult males also, in 87% of cases, did not have larval nests within 250m.

Table 2

The percentage of traps around which there were no larval nests decreased as the numbers of adult male OPM in the traps increased and, conversely, the percentage of traps where there were larval nests in the vicinity increased (Fig. 3). The highest numbers of larval nests (>50 within 250m) were generally associated with traps that caught more than 20 adult males (Table 2).

Fig. 3

**Discussion**

The numbers of adult male OPM caught in the pheromone traps and the numbers of nests were over-dispersed and trap catches generally increased exponentially with nest numbers. The over-dispersion in trap catches likely reflects the non-random behaviour of adult male OPM when orientating to a trap, trap catch being very dependent on position in the canopy and aspect (Williams et al., 2013; Williams and Jonusas, 2019). The tendency for trap catches to increase exponentially with nest numbers may result also, at least partly, from an increase in average nest size with nest density. At higher densities, OPM larvae tend to aggregate and form communal nests, and some of these nests can attain a considerable size and may produce several thousands of adults (Stigter et al., 1997; Sobczyk et al., 2014).

Despite transforming the data, there remained considerable variation in trap catches relative to nest numbers. The relationship improved as the size of the survey area increased, but there was no sign that the total variance explained by regression had reached a maximum even with a survey radius of 250m, which suggests that nests beyond 250m and ingress of adult males flying into the survey area from outside were at least partly responsible for the variation in trap catches.

Individual adult male OPM can fly long distances (Stigter et al., 1997; Battisti et al., 2015), and it is well within the capacity of adult males to have reached the pheromone traps from beyond 250m. However, given that the relationship with local nest density diminishes with distance travelled, adult males flying in from distances further away from the pheromone traps will have contributed increasingly just to the general background numbers of adult males. This probably explains why traps in the centre of the outbreak caught more adult males than expected compared with traps towards the periphery. Nest numbers were higher towards the outbreak centre and, consequently, there was probably a higher background number of adult males in this area compared with areas towards the edge of the outbreak.

Several other factors were investigated that might have influenced the number of adult males caught in the traps, but none were significant. There were no significant differences between the regressions of trap catch against nest numbers for traps allocated to different land use categories, including commercial and industrial areas compared with traps surrounded by houses and gardens or farmland and woodland. Consequently, there was no correlation with the presence of roads and buildings and therefore no apparent effect of general light levels or point light sources that might have attracted males away from the traps. The numbers of adult males caught in the traps may have been influenced by the presence of other tree species, or whether the traps were placed on the windward or leeward side of woodlands (Jactel et al., 2011; Williams & Jonusas, 2019), but data on other tree species was not collected and only 32 of the 267 traps were on the edge of a woodland block, which was too few to explain the wide variation in catches.

The relationship between trap catches and nest numbers could have been disrupted if nests were removed after the adult flight period before the surveys were carried out. However, only limited numbers of nests were removed as part of the OPM control programme in 2016 and 2017, and generally not from the central areas where most of the traps were located. Consequently, nest removal is unlikely to explain the variation in trap catches relative to nest numbers, and ingress of adult males from outside the survey area remains the most likely factor responsible for the unexplained variation in trap catches.

*Variation between years*

Higher numbers of adult males were caught in 2016 relative to the numbers of nests compared with 2017. This variation between years probably reflects different weather conditions during the flight periods. The weather in London during July and August 2016 was warmer and drier than in the same period in 2017, and these conditions will have favoured adult dispersal and survival (Bonsignore & Manti, 2013). At Kew Gardens, in West London, daily mean and daily maximum temperatures between 16 July and 31 August 2016 averaged 19.4 oC and 24.6 oC, respectively, and total rainfall was 26mm (Met Office, 2018). In 2017, in contrast, average daily mean and daily maximum temperatures over the same period were 17.5 oC and 22.1 oC, respectively, and there was 141mm of rainfall. The cooler and wetter conditions in 2017 are likely to have disrupted flight and the ability of adult males to orientate towards the traps, and may have reduced adult survival, with the result that fewer males were caught compared with the numbers that emerged.

It is not surprising that weather conditions in a particular year should influence the relationship between trap catch and nest numbers, and a slightly different relationship would be expected when comparing data from different years. Over a number of years, however, a general relationship ought to emerge that, on average, is a better predictor of nest numbers from trap catches. At the present time, therefore, even though there was a significant difference in the background numbers of adult males in 2016 and 2017, the relationship obtained using the combined dataset should provide the best predictive model.

 *Application to management*

Pheromone traps have been deployed in and around London ever since OPM first became established, to monitor spread and to determine, in areas outside the known distribution, whether OPM might have arrived and nests could be present. In this context, it is important to know whether a trap that catches no adult males is a reliable indicator of the absence of larval nests. In other words, if no adult males are caught, what are the chances that nests are actually present in the surrounding area?

The data collected over two years indicates that in 90.5% of cases where the trap did not catch any adult male OPM, there were no larval nests within 250m, and where nests were present, these were generally in low numbers (7-14 nests). Therefore, nests are likely to be missed in about 9–10% of cases, but this need not be a significant problem. The chances of capturing an adult male and detecting nests could be increased by deploying several pheromone traps rather than just one trap, and even if nests were not detected, OPM populations take 2–3 years to build up from low densities to significant numbers (unpubl. data). Consequently, there would still be time to act even if nests were not known to be present until the following year.

The opposite problem, of capturing adult males when nests are not present within 250m, is less of an issue, because at least nests are not being missed and the trap catch may prompt a survey that would confirm that nests were not present in the area (Straw et al., 2013).

The longer term objective, where OPM has become established, is to use pheromone trap catches as a guide to local population density and therefore whether intervention, either spraying or nest removal, may be required to prevent defoliation or adverse effects on human or animal health. The capture of 1–5 adult males in a trap, like a zero catch, was also associated with low numbers of larval nests, and probably wouldn’t prompt a management response, whereas the capture of 20 adult males or more was associated increasingly with finding upwards of 50 nests within the surrounding area (Table 2). This number of nests is more likely to raise concerns. The significance of capturing a particular number of adult males, however, and determining at what stage trap catches should initiate a management response, is not straight forward and depends on the number of oak trees in the vicinity of the trap.

Trap catches were related to the total number of nests, i.e. the total number of adult males produced in the area around the trap. Trap catches were not related to the total number of oak trees within the 250m survey area and they were only weakly related to nest density, the average number of nests per tree. This is not unsurprising, because trap catch ought to reflect the total numbers of adult males active in the area. The issue though, is that the impact of OPM on tree health, through defoliation, or the risks to human and animal health, through the concentration of infestation, are related to nest density, the numbers of nests per tree. In commercial forestry plantations and orchards, and in agriculture, trees and crops are planted in a regular manner and are grown at standard densities, and in these situations there is a close relationship between the total population size of an insect pest and the densities of the pest on the plants (Howse et al., 1998; Jactel et al., 2006). Consequently, in these situations, pheromone trap catches, which are related to total population size, are also a good guide to the degree of infestation per plant, and it is relatively straight forward to identify a trap catch above which the pest may need to be controlled.

The urban and mixed habitats in which OPM has become established, however, represent a very different situation. There could be just one oak tree near the pheromone trap or there could be a large number of oak trees, and 50 larval nests, for example, could all be concentrated on just the one tree or they could be spread amongst a large number of trees. A high density of nests on a single tree would probably require some form of intervention, whereas a low density of nests spread across a much larger number of trees would probably not raise any immediate concerns.

Consequently, it is the density of OPM nests on the oak trees that is significant in terms of whether any management intervention is required, and the significance of a particular pheromone trap catch and the associated number of nests, can only be determined using local knowledge of the numbers of oak trees, the likely distribution of nests between trees, and information on how many OPM nests per tree might represent a risk to human or animal health, or might result in defoliation.

**Acknowledgments**

We thank Simon Levy and Gordon Purdie and their teams of contractors for setting up and maintaining the pheromone traps and carrying out the nest surveys, and Jack Forster for advice on statistics, Paul Taylor for abstracting the meteorological data and three anonymous reviewers for helpful comments on the manuscript. The pheromone trapping programme and survey work were funded by Defra as part of the OPM Control Programme.

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**Table 1** R2 and AIC valuesfrom the regression of thenumber of adult males per trap against the number of larval nests within 250m for increasing survey areas around each trap in 2016 and 2017. All regressions were significant (GLM, *P*<0.001\*\*\*).

|  |  |  |
| --- | --- | --- |
| **Survey radius****(m)** |  **2016** |  **2017** |
|  **R2** |  **AIC** |  **R2** |  **AIC** |
| 50 | 0.21 | 808.6 | 0.35 | 1583.5 |
| 100 | 0.22 | 807.9 | 0.44 | 1582.6 |
| 150 | 0.33 | 811.1 | 0.44 | 1584.6 |
| 200 | 0.35 | 809.4 | 0.50 | 1581.0 |
| 250 | 0.40 | 807.5 | 0.53 | 1580.1 |

**Table 2** The numbers of larval nests within 250m of pheromone traps that caught different numbers of adult male OPM. Data for 2016 and 2017 combined.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Moths per trap** | **No. of traps** |  **Number of nests with 250m:** | **% traps with no nests** | **% traps with ≥ 1 nest** |
| **0** | **1-5** | **6-10** | **11-20** | **21-50** | **>50** |
| 0 | 21 | 19 | 0 | 1 | 1 | 0 | 0 | 90.5 | 9.5 |
| 1-5 | 38 | 33 | 3 | 2 | 0 | 0 | 0 | 86.8 | 13.2 |
| 6-10 | 44 | 29 | 9 | 1 | 3 | 0 | 2 | 65.9 | 34.1 |
| 11-20 | 36 | 15 | 9 | 8 | 2 | 2 | 0 | 41.7 | 58.3 |
| 21-50 | 34 | 9 | 5 | 6 | 4 | 8 | 2 | 26.5 | 73.5 |
| 51-100 | 57 | 8 | 12 | 7 | 14 | 8 | 8 | 14.0 | 86.0 |
| >100 | 36 | 1 | 2 | 4 | 5 | 11 | 13 | 2.8 | 97.2 |

**Figure captions**

**Figure 1** Relationship between pheromone trap catch and the number of OPM nests within 250m. *Open symbols*, 2016, y = 1.67x + 3.69 (R² = 0.40, *P*<0.001, N= 88); *closed symbols*, 2017, y = 1.64x + 2.29 (R² = 0.53, *P*<0.001, N=172).

**Figure 2** Relationship between pheromone trap catch and distance from the centre of the outbreak. *Open symbols*, 2016, y=16.16-3.89.ln(x) (R² = 0.40, *P*<0.001); *closed symbols*, 2017, y = 11.71-2.68.ln(x) (R² = 0.24, *P*<0.001).

**Figure 3** Percentage of the pheromone traps that captured different numbers of adult male OPM, which had at least one larval nest within 250m. Data for 2016 and 2017 combined.

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