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Approaches and experiences of deploying nature-based solutions to control the oak processionary moth in the UK and the Netherlands

Guidance Report

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Summary

A range of nature-based solutions (NbS) for controlling the pest oak processionary moth (*Thaumetopoea processionea* L.) (OPM) are being deployed across the Netherlands, but similar practices have not yet been adopted at OPM affected sites in the UK.

In the Netherlands, NbS are increasingly popular with government and local authorities as serious alternatives to chemical biocides and pesticides. However, scientifically robust trials are at an early stage and are yet to provide evidence of the efficacy of different control options.

For instance, a €2 million LIFE-program funded project that aims to reduce the amount of biocides used across trial locations in the Netherlands and Belgium began in 2020/21 (LIFE19 ENV/BE/000102). The project will investigate three ecological management techniques, i) attracting birds as natural predators; ii) attracting parasitoid wasps and flies by means of adapted road verge management; and iii) breeding and releasing the predatory beetle, *Calosoma sycophanta*. In addition, the project will provide training and feedback to interested parties on ecologically focussed management techniques.

Further, there have been several investigations conducted by local authorities, environmental groups, independent researchers, and local communities using a variety of techniques to enhance the environment for natural enemies of OPM. The overall picture from these trials were positive. However, the ad hoc nature of the investigations has resulted in patchy reporting of the efficacy of the methods and often a lack robust experimental protocols.

In contrast, the UK is only beginning to consider natural alternatives to chemical spraying and nest removal. A few local authorities have begun to monitor the parasitoid fly, *Carcelia iliaca*, but there were no reports of efforts to encourage natural predators by other means.

The main message from the Netherlands was that NbS can be effective means of control, but they may take multiple years before reductions in pressure are seen, and multiple simultaneous interventions are likely to be required to achieve results. This multi-year, multi-solution approach may lead to challenges in monitoring efficacy.

Contents

1 Introduction

In this brief assessment we present an overview of the approaches and experiences of deploying nature-based solutions (NbS) to control oak processionary moth (*Thaumetopoea processionea* L.) (OPM). We define NbS as ecologically focussed OPM control measures aimed at reducing OPM, which excludes nematodes and other “biocontrols”, for instance. This assessment will inform workshop discussions on potential NbS to trial in the UK as part of the Future Proofing Plant Health Program funded ‘Alternative control strategies for oak processionary moth’ project.

OPM is an alien invasive species that poses a threat to native oak trees and to human and animal health in the UK. It was accidently introduced in 2004/2005 in the greater London area and has since spread across greater London and into the surrounding counties (Forest Research 2021).

In the UK, regulation exists to reduce the risk of new introductions and control the spread of OPM. The Forestry Commission coordinates the Oak Processionary Moth Control Program which delivers control measures across three zones spreading outward from the Greater London area (Forest Research 2021; Marzano *et al.* 2020).

In the ‘Core Zone’, where OPM are already established, no government funded control takes place beyond offering support and advice to affected oak tree owners. Surrounding the Core Zone is the ‘Control Zone’ where action aims to slow the spread of OPM via surveying to identify infected oaks and spraying infected trees with foliar applications of insecticide sprays. Beyond these zones is the ‘Protected Zone’, where control takes place when necessary to eradicate any infestations.

Concerns exist around potential environmental and non-target impacts of spraying insecticides into the canopy of oak trees. It is therefore necessary to develop alternative methods to manage OPM populations with fewer undesirable non-target and environmental consequences. Here, we assess the approaches and experiences of deploying a variety of NbS currently in use for managing OPM in the Netherlands and UK, including:

i) the type of NbS

ii) the environment(s) in which deployed

iii) efficacy of approach on control of OPM

iv) monitoring and baseline data

2 Methods

We sought to find individuals or organisations that have actively engaged in research or applied OPM control measures that could be considered nature-based solutions. Our search focussed on the UK and the Netherlands as it was known that several NbS had been trialled in the Netherlands.

We consulted with networks of scientific professionals engaged with the OPM community in the UK to identify relevant individuals and projects. Additionally, we reviewed the available online literature using keywords in English and Dutch and followed quoted references within to identify further suitable projects.

Information sheets describing the known efficacy, side-effects, and any existing protocols for current and potential measures for controlling OPM provided the basis for investigating NbS in the Netherlands. The Oak Processionary Knowledge Platform (https://processierups.nu/) to date has published 22 information sheets written in collaboration with independent experts and expert organisations. The online platform is organised by a partnership of Dutch government departments, academic researchers, and nature organisations, and is led by the Netherlands Ministry of Agriculture, Nature and Food Quality.

Following identification of relevant people and projects, we extensively reviewed all related published reports, online news articles, and any other published literature. We additionally conducted informal interviews via video call or email to ask follow-up questions to enhance our understanding of the approaches taken.

3 Results

We found no evidence of land managers in the UK engaging in trials for natural control of OPM. However, one local authority has been conducting surveys of the OPM associated parasitoid fly, *Carcelia iliaca*, and several other authorities have been engaged in ad-hoc monitoring of the fly and predation by birds.

In contrast, forms of natural control appear to be widespread in the Netherlands. For instance, a Dutch OPM expert and consultant reported that she has advised multiple local authorities and other organisations about installing natural control measures (S. Hellingman 2021, pers. comm.), and believes that some form of natural control has been deployed in more than one-hundred locations.

Even though natural control measures appear to be widely deployed in the Netherlands, there are few published reports providing evidence on the efficacy of interventions. Two projects that have reported results were conducted in the municipality of **Westerveld** and Province of **Gelderland.** Each of these medium-scale trials have been ongoing for 4-5 years and include both test and control locations for monitoring of interventions efficacy. Additionally, a larger scale €2 million **EU-LIFE project** began in 2020/21, initiating the trial of multiple natural control measures in the **Netherlands** and **Belgium**.

Between them, these three projects have or will trial all the natural control measures described in this report. Each project is detailed in the appendix. The outputs produced thus far across the three form the following assessment of nature-based solutions: i) increasing floristic diversity and vegetation management, ii) encouraging natural populations of parasites, iii) attracting birds and bats, and iv) releasing natural predators. However, the LIFE project has only begun to monitor efficacy of interventions in the summer of 2021 and therefore results were not available for this assessment.

3.1 Increasing floristic diversity and vegetation management

A variety of predators and parasites are associated with each life-stage of OPM including ladybirds, lacewing larvae, ground beetles, spiders, and parasitic wasps and flies (Klein *et al.* 2020a; Spijker *et al.* 2019). Stimulating growth of native plants and flowers through planting, and vegetation management can create habitat suitable to sustain their populations. Flower rich habitats provide nectar as food for adult insects while their larvae can feed on the oak processionary caterpillars (Klein *et al.* 2020a). Further, increases in insect populations can help to support populations of birds and bats which also predate on OPM.

Management to reduce the density of oak trees could also reduce pest pressure by reducing the food available for OPM larvae (Klein *et al.* 2020a). Dutch Guidance on controlling oak processionary caterpillars recommends following the 10-20-30 rule for tree diversity in urban forests (Spijker *et al.* 2019). This rule recommends an urban tree population should include no more than 10% of any one species, 20% of any one genus, or 30% of any one family (Santamour 1990). This could be achieved by diluting the existing stock through planting of other oak species or other tree species. The guidelines recommend that new planting should follow a stricter 5-10-20 rule (Spijker *et al.* 2019).

3.1.1 Deployment approaches

To our knowledge, this method has not been trialled in the UK, but has been a major component of the projects reviewed in the Netherlands. Each of the three reviewed Dutch projects have trialled or plan to trial planting and vegetation management to stimulate populations of natural enemies. In the Gelderland and Westerveld projects, native flower mixtures were sown, and mowing management undertaken on roadside verges on infected oak-lined avenues (Stichting Boermarke 2019a; van Deijk 2019, 2020). The EU-LIFE project in Netherlands-Belgium plans to instigate a variety of verge management techniques with the aim of attracting parasitic wasps and flies (LIFE Oak Processionary Project 2020).

3.1.2 Deployment environment

In each of the three Dutch projects, this control measure has been deployed in oak-lined roadsides, which are common in the Netherlands. In the Gelderland and Westerveld trials the roadsides were in rural/agricultural areas within or close to residential areas. This method may not be suitable for roadsides where many people pass such as along bicycle paths and next to houses, as stricter verge management to ensure visibility would likely be required (Klein *et al.* 2020a).

3.1.3 Monitoring methods

Monitoring methods were similar between the Dutch projects. The effect of verge management and sowing flowers was or will be monitored yearly by surveying flower species diversity as well as calculating a nectar index to indicate habitat quality for natural enemies (Hellingman 2020; LIFE Oak Processionary Project 2020; van Deijk 2020). The effect of verge management on insect populations was or will be monitored by surveying insect species diversity around the verges and trees. The effect on the OPM population was or will be measured by monitoring the number and size of nests, and pheromone trapping for OPM moths (Hellingman 2020; LIFE Oak Processionary Project 2020; van Deijk 2020).

3.1.4 Efficacy of approach on control of OPM

In the Gelderland trial, it was only in the fifth year (2020) that differences were found between sown verges and control locations. Fewer nests per tree, more insects, and more potential enemies including parasitic wasps and flies, particularly *Carcelia iliaca*, were found in the trial location compared to the controls (van Deijk 2020). The results were not clear cut, however. Differences between the test and control locations were only apparent after controlling for the effect of the orientation of the roads (van Deijk 2020). The project determined that orientation of nests in relation to sun, wind, and rain was likely to affect the development of the caterpillars. And while more insects in general and more parasites were found in the trial location, there was little difference in the nectar index compared to control locations. The project concluded that the difference in number of insects was likely to be the result of the management regime rather than the result of planting, as control verges were mown in mid-summer.

In the Westerveld trial, a higher nectar index, more insects, and more potential enemies including parasitic wasps and flies were found in the test verge compared to the controls

(Hellingman 2020). However, multiple simultaneous control measures were deployed in this location, so it was not possible to determine the effect of planting and vegetation management alone.

This control measure is likely to take a number of years before any effects are seen (Klein *et al.* 2020a; Hellingman 2020; van Deijk 2020). Additionally, as vegetation influences the ecosystem in many ways, the effect on reducing the pressure of OPM will not be easily measurable and attributable to the intervention (Klein *et al.* 2020a).

3.2 Encouraging natural populations of parasitic organisms

The practice of encouraging parasitic organisms aims to increase parasitism rates and consequently reduce the number of fledged OPM adults. This may be achieved by breeding and releasing parasitic organisms or encouraging natural populations in-situ through habitat manipulation and management including utilising old OPM nests. Here we focus on encouraging natural populations of parasitic organisms.

A wide variety of parasitoids use OPM eggs, pupa, and larvae as hosts (de Boer & Harvey 2020; Kitson *et al.* 2019). Understanding which parasitoids utilise OPM and quantifying parasitism rates is an essential first step towards incorporating these natural enemies within a control management plan (Kitson *et al.* 2019).

Little is known about the relationships between OPM and its specific parasites, however tachinid flies *Carcelia iliaca* and *Pales processionea*, chalcid wasps, and ichneumonids *Pimpla processionea*, *Pimpla rufipes*, *Coccygomimus turionellae*, and *Theronia atalantae* are known to be associated with OPM at different life stages (Sands 2017).

C. iliaca was found in the UK for the first time in 2014, only a few years after OPM was first introduced (Sands *et al.* 2015). It is not known how the parasitoid flies arrived at the UK, however several OPM parasitoids have demonstrated an ability to track their hosts as OPM expand their range. For example, *C. iliaca, Pales processionea* and *Pimpla processionea* were all found in the Netherlands only a few years after OPM had re-established itself there (de Boer & Harvey 2020). However, it has been suggested that *C. iliaca* may have been present in the UK pre-establishment of OPM (J. Meares 2021, pers. comm.).

It is currently unknown what impact parasitoids have on the regulation of populations of OPM (de Boer & Harvey 2020; Klein *et al.* 2020b). However, it is thought that parasitism rates of up to 90% are required before changes in the host population are seen (J. Kitson 2021, pers. comm.). In the UK, parasitism rates of ~46% were reported for *C. iliaca* in late larval stage OPM caterpillars collected in Croydon, with a further 0.4% parasitised by a rare generalist tachinid species, *Compsilura concinnata* (Kitson *et al.* 2019). In Richmond Park, parasitism rates by *C. iliaca* have steadily increased from 36% to 68% between 2014 and 2018 (J Kitson 2021, pers. com.). Whereas, high rates of parasitism of up to 76% have been reported for Belgium, France, and the Netherlands (Sands 2017).

Some highly specialised parasitic wasps and flies are closely associated with OPM nests, for example *C. iliaca*, are thought to overwinter inside the nests (Klein *et al.* 2020b; Hellingman *et al.* 2020; Sands 2017). Therefore, some methods of OPM control, such as removing nests from trees and incinerating them risk destroying the new generation of parasites before they can infect and kill OPM larvae. Whereas leaving nests in-situ or placing removed nests inside specially made boxes may help to encourage natural populations of parasitoids to build up in the environment (Klein *et al.* 2020b).

Placing nests in boxes has the advantage of preventing the stinging hairs dispersing into the environment, however there is a health and safety risk associated with removal from the tree and putting in the box. The boxes can be engineered such that holes or slits are large enough that the parasitic flies and wasps and other insect natural enemies can leave or enter but small enough that any surviving OPM moths are unable to leave and complete their lifecycle (Figure 1). Boxes may be affixed to the affected trees, or placed within the vegetation below the trees (Hellingman 2020; Hellingman *et al.* 2020). Alternatively, boxes may be moved to areas without parasitoid populations to encourage the build-up of new populations (Klein *et al.* 2020b). However, moving the parasitic organisms to new places may not be allowed under current regulations in the UK (J. Kitson 2021, pers. comm.).

Habitat management including planting and mowing regimes should be practiced to provide nectar for the adult parasitic wasps and flies (Klein *et al.* 2020b). Particularly, umbellifers were found to be regularly visited by *C. iliaca* during summer in the Netherlands and bulbous plants were important in spring (Hellingman 2020).

A standard protocol has not yet been developed and further research is required to determine whether an OPM nest is sufficiently parasitised to increase the chance of multiplying the *C. iliaca* population and the optimal composition and management of vegetation to provide parasitoids with the necessary habitat (Klein *et al.* 2020b).

3.2.1 Deployment approaches

UK

Interest in the effect of parasitic flies and wasps on regulating OPM populations appears to be growing among researchers and local authorities in the UK. For instance, scientists from Forest Research, Hull University and Newcastle University have been monitoring parasitoids in Richmond Park since 2014 (J. Kitson 2021, pers. comm). The City of London Corporation, which manages Highgate Woods and Hampstead Heath, have monitored *C. iliaca* for the last three years by harvesting OPM nests at the end of the summer to observe emergence the following spring (J. Meares 2021, pers. comm.). They also practice non-removal of nests in low-use areas, in part due to costs associated with removal, but also as a passive method to encourage natural populations of parasitoids (J. Meares 2021, pers. comm.). The borough councils of Elmbridge and Epsom and Ewell have engaged in ad-hoc monitoring of *C. iliaca* for several years but lack the funding and time to commit to a full monitoring program (H. White 2021, pers. comm. & S. Cocker 2021, pers. comm.).

Figure 1. Left: Secure box containing parasitised OPM nest as used by the Municipality of Westerveld. Right: Secure box attached to tree containing parasitised nests which have been used within the municipality for more than 10 years. Images from (Hellingman 2020).

Netherlands

Over the last 10 years, several municipalities and other organisations in the Netherlands have engaged in encouraging parasitic wasps and flies through overwintering parasitised nests in secure boxes at an estimated more than one-hundred locations (S. Hellingman 2021, pers. comm.). Both the Westerveld and Gelderland projects trialled this method, as well as vegetation planting and management, in part, to attract and feed adult parasitic wasps and flies (detailed in the above section on increasing floristic diversity and vegetation management) (Hellingman 2019, 2020; van Deijk 2019).

The EU-LIFE project will also test the efficacy of encouraging parasitic wasps and flies through storing OPM nests in boxes. However, no details of how they plan to do this were provided on the project website. In contrast to the Gelderland and Westerveld trials, the LIFE project will implement vegetation management specifically to encourage parasitic wasps and flies rather than insect natural enemies in general (detailed in the above section on increasing floristic diversity and vegetation management).

3.2.2 Deployment environment

In the UK, Hampstead Heath and Highgate Woods practice non-removal of OPM nests from trees in areas that are less frequently visited by the public, and therefore less likely to impact public health (J. Meares 2021, pers. comm.).

In the Westerveld and Gelderland trials, boxes containing OPM nests were secured to infected trees or placed on the ground in trial locations with warning notices attached (Figures 1 & 2) (Hellingman 2020; van Deijk 2019). All trial locations were in rural areas with little walking or cycling traffic, and projects had the backing of local people. There are greater health and safety risks associated with leaving boxes in areas of heavy use as they will be a potential source of the stinging hairs (Klein *et al.* 2020b).

3.2.3 Monitoring methods

Both the Gelderland and Westerveld projects monitored insect biodiversity including parasitic wasps and flies in trial and control locations. The Westerveld trial additionally monitored all removed nests at the test location to determine if the nest was parasitised, fledged, or attacked by birds (Hellingman 2020). However, neither reported on the numbers of nests stored per box or per area or related nest storage to changes in populations of observed parasitic wasps and flies (Hellingman 2019, 2020; van Deijk 2019).

3.2.4 Efficacy of approach on control of OPM

The extent to which encouraging natural populations of parasitic organisms affects numbers of OPM is still currently unknown, and more substantiated research is required to determine the effectiveness of this method (Klein *et al.* 2020b). (Klein *et al.* 2020b)

Interventions carried out in Westerveld were successful in reducing OPM nests compared to control locations (Hellingman 2020). However, multiple control options were trialled simultaneously, therefore it is not possible to isolate the effect of encouraging parasites specifically, or the effect of overwintering nest boxes on increasing the number of parasitic flies and wasps.

3.3 Attracting birds and bats as predators

This method aims to encourage populations of birds and bats as natural predators of oak processionary caterpillars by providing nest boxes in and around infected trees (Klein *et al.* 2020c). Hanging bird or bat nesting boxes in affected areas provides more opportunity for nesting space which may stimulate localised populations.

Many bird species are natural predators of oak processionary caterpillars. Great tits are particularly adept at predating on OPM as they eat all larval stages as well as the pupae and moths, whereas blue tits have been observed to eat only the 1st and 2nd instar stages (Hellingman 2020; LIFE Oak Processionary Project 2020). It is estimated that over two weeks one great tit chick can eat up to 800 caterpillars and broods can number between 8-14 chicks (LIFE Oak Processionary Project 2020). Wrens, robins, nuthatches, treecreepers, starlings, jackdaws, cuckoos, orioles, woodpeckers, and blackbirds are also known to predate on the caterpillars in the Netherlands (Spijker *et al.* 2019). Additionally, late-flying bats such as long-eared bats are known to predate on the flying moths (Klein *et al.* 2020c; Spijker *et al.* 2019).

The negative effects of encouraging localised bird and bat populations are unknown. However, it is possible that increased predation could affect population numbers of rarer lepidoptera and other insect species (Klein *et al.* 2020c).

3.3.1 Deployment approaches

UK

No evidence was found of efforts to encourage bird or bat populations as a control measure for OPM. However, there were incidental reports of great tits eating OPM caterpillars (J. Meares 2021, pers. comm.), and of great tits predating on OPM nests with evidence of golf-ball sized holes in the sides of multiple nests (S. Cocker 2021, pers. comm.).

Netherlands

In the Netherlands, hanging bird or bat boxes to encourage predation on OPM is popular as there is a perceived positive effect and it is easy for residents to hang nest boxes in their gardens (Klein *et al.* 2020c). Private residents are encouraged by local authorities to control OPM on their property by hanging bird boxes and increasing floristic diversity. For instance, the Municipality of Amersfoort's webpage on OPM provides this advice with a link to information on how best to hang the boxes (Municipality of Amersfoort 2021).

The Westerveld project installed bird and bat boxes as part of the trial and additionally distributed a further 250 bird boxes to local residents (Vree Egberts, 2018). Whereas, the EU-LIFE project will test on a large scale the effects of installing tit nest boxes on the number and size of OPM nests by comparing between infected trees with and without nest boxes (LIFE Oak Processionary Project 2020).

3.3.2 Deployment environment

Following the success of the project in Westerveld, the organisations involved provided guidelines on the methods they used and advised that some locations are unsuitable for installing nest boxes, such as high traffic roads, roads without shelter or water for birds, places where there is lots of spraying with pesticides, or paved gardens with few plants and hiding places (Stichting Boermarke 2019b).

3.3.3 Monitoring methods

In Westerveld, trial and control locations were monitored daily when the birds had young to monitor if they were taking caterpillars (Hellingman 2019). Monitoring also took place to note which species had nested in the boxes, and the success of fledging young. Evidence of predation on OPM nests was also noted.

The EU-LIFE project plans to monitor the number of inhabited nest boxes and the number of young annually during April-May (LIFE Oak Processionary Project 2020). Additionally, the size and number of OPM nests will be monitored.

3.3.4 Efficacy of approach on control of OPM

It is unknown to what extent installing bird and bat boxes may lead to reduced OPM pressure. Additionally, this method is considered to take longer to be effective than most other methods as the bird and bat density near the outbreak needs to build substantially (Klein *et al.* 2020c). It is also likely that vegetation management will be required to provide a year-round supply of adequate food and shelter for fledging young to achieve greater nesting success and greater OPM control (Klein *et al.* 2020c).

Overall results from the Westerveld project indicated decreased OPM nest numbers in the test location compared to the controls, but it was unclear to what extent the bird and bat boxes contributed to the overall result (Hellingman 2019, 2020). Almost 80% of OPM nests in the trial location were determined to have been predated upon by birds in the fourth year of the trial, but no comparable numbers were reported for the control locations (Hellingman 2020).

3.4 Releasing natural predators

This method aims to reduce OPM pest pressure by releasing organisms that are known to feed on OPM larvae (Klein *et al.* 2020d). The logic being that by releasing large quantities of predatory organisms there will be an increase in the number of OPM taken. Releasing natural predators is a widely used method to supress pest pressure, for instance ladybirds are commonly used to control aphids in agriculture (Klein *et al.* 2020e).

The Dutch Knowledge Centre on OPM have written two information sheets detailing the known information on controlling OPM using lacewing larvae (Klein *et al.* 2020d), and ladybirds (Klein *et al.* 2020e). Both organisms are considered likely to exert some controlling effect on OPM caterpillars, however because they are generalist predators, they will also affect other insects which may be undesirable.

Both lacewing larvae and two-spotted ladybirds are known to predate on the 1st and 2nd larval stages of OPM caterpillars and occur naturally in the range and habitat of OPM in the Netherlands (Klein *et al.* 2020d). Lacewing larvae have been trialled in experiments to test their efficacy on controlling OPM (Klein *et al.* 2020d), but there were no reports of trialling the effect of ladybirds (Klein *et al.* 2020e).

3.4.1 Deployment approaches

UK

There were no reports of this control method being employed in the UK.

Netherlands

The Westerveld project released lacewing larvae (*Chrysoperla carnea*) into infected oak trees in the test location each year for the first three years of the project (Hellingman 2018, 2019). While the EU-LIFE project plans to release the ground beetle, *Calosoma sycophanta*, in test areas in Belgium and the Netherlands (LIFE Oak Processionary Project 2020).

3.4.2 Deployment environment

Successful release of natural predators requires knowledge of the habitat requirements of the organism. For instance, lacewing larvae are naturally found in oak trees, but the adults also require sources of nectar for feeding, and shelter for hibernation over winter (Klein *et al.* 2020d). In the Westerveld trial, drought and high temperatures hampered the establishment of wildflowers in verges underneath infected oak trees, which decreased the availability of nectar and therefore restricted establishment of the lacewing population (Hellingman 2018). In the EU-LIFE project, suitable locations for releasing *Calosoma sycophanta* will be determined based on habitat modelling.

3.4.3 Monitoring methods

The Westerveld project monitored insect food sources for the lacewing larvae through the general monitoring of insect diversity at the test location (Hellingman 2018, 2019, 2020). However, the direct effect of lacewing larvae on pest suppression was never measurable because it was one of a suite of methods deployed simultaneously (Hellingman 2020).

The EU-LIFE project plans to monitor the movements of the released beetles using lightweight transmitters attached to beetles, as well as monitoring beetle emergence from the soil, and population monitoring using light traps in addition to monitoring OPM nest numbers and size (LIFE Oak Processionary Project 2020).

3.4.4 Efficacy of approach on control of OPM

Lacewing larvae reportedly reduced OPM pest pressure in the short-term by approximately 20% in a small 2016 trial in the Netherlands (Klein *et al.* 2020d). The longer-term effect was determined to be negligible however because once the lacewing larvae become adults, they descend from the oak trees into the verges to feed and lay eggs. The new generation of larvae therefore remain in the verge and have no further effect on OPM caterpillars in the trees (Klein *et al.* 2020d).

4 Discussion

We found some evidence NbS that encourage populations of natural enemies have the potential to control OPM. However, the evidence base was limited, and many questions remain. For instance, it was not clear to what extent the reviewed NbS may reduce OPM, which NbS are better or less suited to different environments, or non-target consequences of encouraging generalist predators on rare insects. It was clear however that interventions are likely to take several years before measurable controlling effects are seen.

Aspects of implementing the reviewed NbS are likely to be relatively simple. Increasing floristic diversity through planting and seeding, and vegetation management is a common ecological intervention and installing bird boxes or simply leaving OPM nests in-situ would take up little time. However, collating sufficient baseline and monitoring data to detect and quantify the efficacy of the intervention will likely be time consuming and require good study design.

Consideration of the optimal spatial and temporal scale over which to deploy interventions will be required to achieve measurable effects that can be attributed to interventions while remaining economically and practically viable. As OPM are an outbreaking species with highly variable population densities in space and time (Csóka *et al.* 2018; de Boer & Harvey 2020; Sands 2017), multiple years of monitoring and large sample sizes may be required to robustly distinguish background population variation. Future results from the LIFE project will provide key evidence in this respect.

Careful site selection will also be required to determine suitable comparable locations to minimise uncontrolled variation between sites. This may require working with multiple public and private landowners across the complex urban green infrastructure landscape of Greater London where oak trees form an important part of woodlands, parks, and linear green spaces such as railway embankments and road verges (Cowley *et al.* 2015). A related consideration is to determine which type of site is most suitable for NbS interventions. As the Dutch trials we reviewed all took place along oak-lined avenues in semi-rural locations, it will be necessary to look beyond existing OPM research to determine which environments within the urban/peri-urban Greater London landscape are likely to benefit most from NbS.

The Dutch experience suggests that multiple simultaneous interventions are likely to be required to achieve pest pressure reduction. This approach will make it difficult to determine efficacy of any one intervention. Therefore, future studies may need to consider trade-offs between achieving greater success in reducing OPM pressure vs determining the effect of any one NbS.

Likely suitability of Dutch approaches within the UK context is variable. Planting, seeding or vegetation management to increase floristic diversity and encourage natural enemies would require knowledge of native UK natural enemies and their nectar sources and habitat needs. There is a wide body of knowledge available describing management practices to encourage insect predators and parasitoids to supress crop pests in UK agriculture which could be utilised in this respect (for instance, Ellis *et al.* 2014).

Both England’s tree health resilience strategy 2018 and the England Tree Action Plan 2021-2024 have an aim to improve the genetic and structural diversity of England’s trees and woodlands to resist, recover from, and adapt to the impact of pests and diseases (Defra 2021, 2018). Investigations of the degree to which OPM pest pressure varies with oak tree density could identify favoured ratios of community assemblages that resist high pest pressure, and therefore inform planting schemes and mitigation efforts.

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6 Appendix

6.1 Overview of the three main Dutch projects reviewed

6.1.1 Westerveld

A four-year trial held between 2016 to 2020 in Wapserveen, Westerveld, combined multiple control measures simultaneously. These were installing bird and bat boxes, releasing lacewing larvae, planting to increase floristic diversity and vegetation management, and overwintering OPM nests in boxes in-situ (Hellingman 2020; Hellingman *et al.* 2020; Vree Egberts 2017, 2018).

This project was led by Stichting Boermarke Wapserveen (Boermarke foundation Wapserveen), with support from Agrarische Natuur Drenthe (Agricultural Nature Drenthe), Hellingman Onderzoek en Advies BV (Hellingman Research and Advice), and the local community (Stichting Boermarke 2019a).

6.1.2 Gelderland

This study is led by De Vlinderstichting (The Butterfly Foundation) in collaboration with the Province of Gelderland, Hellingman Research and Advice, and others, and has been ongoing since 2015 (van Deijk 2019, 2020). They have been trialling increasing floristic diversity through planting and vegetation management as well as overwintering OPM nests in boxes.

6.1.3 EU-LIFE project Netherlands-Belgium

A recently initiated project funded by the LIFE program beginning in 2020/2021 plans to manage vegetation specifically to encourage parasitic organisms, install bird boxes to encourage predation, breed and release the predatory beetle *Calosoma sycophanta*, and overwinter OPM nests in boxes (LIFE Oak Processionary Project 2020). The aim of this large project is to reduce usage of biocides in trial areas in the Netherlands and Belgium. The project is backed by the multiple municipal and provisional authorities involved and the Belgian Institute for Nature and Forest Research (INBO).