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Theory of Change for Controlling Oak Processionary Moth Using Nature-Based Solutions

Guidance Report

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Summary

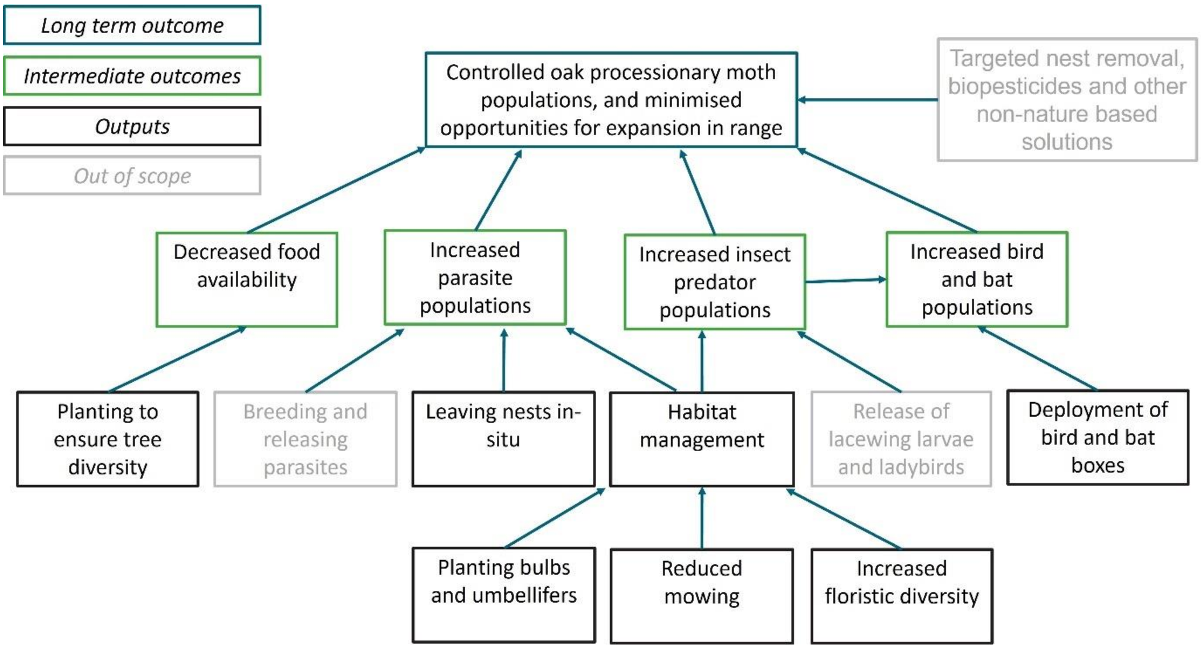

Figure 1: A summary of the components of the theory of change presented in this report.

Nature-based solutions, such as those outlined in Figure 1, have potential to control (reduce and maintain low levels of) populations of oak processionary moth (OPM) and reduce its spread. Oak processionary moth is an invasive pest posing a fairly low but not insignificant risk to human health and oak trees. There is therefore a need for control, but as the impacts are fairly minor there is also a clear need for any control implemented to be associated with minimal risks and non-target effects. Whilst there is little direct evidence of nature-based solutions controlling OPM populations, the indirect evidence, strong co-benefits, low risks and relatively low costs of their use, support their implementation while further data and evidence are gathered. This theory of change explores the nature-based solutions outlined in the diagram, detailing the evidence and wider context associated with each intermediate outcome.

Contents

1 Introduction

1.1 How was this theory of change developed?

This theory of change was developed by the JNCC as part of the Future Proofing Plant Health project. It was put together following an assessment of the approaches and experiences of deploying nature-based solutions to control the oak processionary moth in the UK and the Netherlands (Deasey *et al.* 2022). Additional time-limited literature reviews were carried out to fill evidence gaps where possible. Input from stakeholders was incorporated through consultation at a workshop focusing on acceptability of different OPM intervention types. Further stakeholder engagement would be required during the implementation phase, to understand more fully the implications for these stakeholders in terms of encouraging uptake and engagement, awareness raising, training, skills and learning needs, building landowner networks to facilitate landscape scale approaches, communication with the public and establishing who would undertake the monitoring and evaluation proposed.

1.2 Aims and intended impact

The overall aim of this theory of change is to provide guidance for those planning work that seeks to control (reduce and maintain to acceptably low levels of) oak processionary moth (OPM) populations and minimise opportunities for expansion in range, using nature-based solutions. Nature-based solutions are “actions which enlist elements of nature or natural processes to address a particular problem, or suite of problems, faced by society and which deliver multiple benefits in the form of public goods” (JNCC 2021). They include, for example, habitat restoration and management. It is hoped that environmental practitioners, landowners and land managers in areas affected by OPM could make use of the nature-based solutions outlined in this document to complement current solutions for controlling OPM populations.

1.3 Need and context for interventions

OPM (*Thaumetopoea processionea*) is a non-native species that was first reported breeding in the UK in 2006, in west London. It was believed to have been introduced by two separate imports of infested oak trees (Mindlin *et al.* 2012; Tomlinson *et al.* 2015). Despite initial eradication efforts, the moth has since spread and become established in a wider range, including throughout Greater London and some of the surrounding counties (Godefroid *et al*. 2020; Suprunenko *et al*. 2021). Strategy has now shifted from eradicating OPM to slowing its spread (Forest Research 2021; Suprunenko *et al.* 2021). OPM presence raises concerns in terms of both human and tree health.

OPM larvae produce urticating hairs which can be harmful when they come into contact with humans (or other animals), causing skin rashes and eye irritation, as well as sore throats and breathing difficulties in some cases (Forest Research 2021; Gottschling & Meyer 2006; Maier *et al.* 2003; Public Health England 2015). The severity of the symptoms generally increases the more times the same individual is exposed to the hairs (Marzano *et al*. 2020; Public Health England 2015). Hairs can be transported by the wind, meaning direct contact is not necessary for symptoms to occur (Gottschling & Meyer 2006; Maier *et al.* 2003; Marzano *et al.* 2020). There is also one reported incidence in the literature of a possible anaphylactic reaction in the Netherlands, although it was not possible to distinguish whether this was attributable to OPM or a type of pesticide being used as a control measure (Bosma & Jans 1998, in Public Health England 2015). Public Health England (2015) consider the threat to human health of OPM to be low, as the vast majority of those exposed present either no symptoms or dermal symptoms that are minor enough to be treated with over-the-counter medicines from a pharmacy.

OPM larvae feed on the leaves of oak (*Quercus*) species, which may lead to partial or complete defoliation (Forest Research 2021; Wagenhoff & Veit 2011). Whilst evidence suggests that the trees usually recover, there are concerns that following defoliation trees are more vulnerable to other stressors, such as drought or attack from other insect species (Forest Research 2021; Tomlinson *et al.* 2015). It is thought that the effects of OPM on tree health are highly variable across its range, with feeding damage not considered substantial in most areas, but significant in certain locations (European Food Safety Authority 2009). Healthy oak are valued not only for their timber (Urquhart *et al.* 2017), but also for their biodiversity, amenity, cultural and historical value (Marzano *et al.* 2020).

The impacts of OPM on both human and tree health have led to efforts to control of OPM populations. However, the moderate nature of both impact types highlights the importance of any intervention mechanisms used being relatively cheap and not to lead to additional negative impacts themselves. This is largely not the case for current interventions, which generally involve a combination of physical nest removal and spraying of pesticides such as Deltamethrin and *Bacillus thuringiensis* (Bt) on infected trees. These interventions are costly, requiring specialist contractors with personal protective equipment (Mindlin *et al.* 2012), and lead to further concerns around the potential environmental and health implications of contact with biopesticides (Urquhart *et al.* 2017). Whilst they will likely remain the most appropriate interventions in certain cases, for example in areas with particularly high OPM populations, areas that present a particularly high risk to humans (e.g., nests over a path in a popular park) or new OPM populations away from the established zone, there is a need for the development of a wider range of strategies that can be more readily deployed in other contexts. This theory of change aims to provide a pathway to fulfil this need through the use of nature-based solutions to control OPM populations in the UK.

2 Outcomes and outputs to achieve intended impact

In order to achieve the intended long-term outcome of using nature-based solutions (to reduce OPM populations, maintain them at acceptably low levels, and minimise opportunities for expansion in range), this theory of change focuses on four main intermediate outcomes or pre-conditions:

- Decreased availability and ease of access to food for OPM larvae
- Increased populations of natural insect predators of OPM
- Increased populations of natural bird and bat predators of OPM
- Increased populations of OPM parasites

The following sections explore the outputs required to reach these outcomes, the strength of the evidence for each mechanism suggested and wider context that would need to be considered during implementation (risks, trade-offs, geographic context, etc). It is assumed that these solutions would be adopted alongside current solutions (which are out of scope for consideration within this document). Land managers and advisers would be expected to take a decision on the measures most appropriate for their unique context. Alternative strategies that are not nature-based (e.g. gene silencing, tree injections) are also out of scope for consideration within this document.

2.1 Decreased availability and ease of access to food for OPM larvae

2.1.1 Outputs

OPM larvae feed on the leaves from several species of oak (Forest Research 2021). When planning the planting of a new area, it is important to ensure tree species diversity rather than planting a single species of oak. This would decrease food availability and the ease of locating the food source among other tree species. This should lead to reduced OPM populations through a decrease in the number of larvae able to consume enough food to survive and breed. This could be achieved by planting to ensure relevant tree populations include no more than 10% of any one species, 20% of any one genus, or 30% of any one family (Santamour 1990; Spijker *et al.* 2019).

2.1.2 Evidence

Minimal direct evidence is available to link decreased oak proportions within stand compositions to decreased OPM populations explicitly. One French study found significantly higher rates of defoliation in stands in which at least 75% of trees consist of a single oak species than in mixed stands (Damestoy 2019). However, the same study found no correlation between nest location and stand composition.

Official Dutch recommendations for controlling OPM also suggest controlling the proportion of oak that make up a tree population (Klein *et al.* 2020a; Spijker *et al.* 2019). However, this recommendation is based on a source that refers to controlling pest and pathogen species more broadly rather than providing evidence for a link with OPM specifically (Santamour 1990). Increasing tree diversity is a common solution backed up by evidence for controlling a wide range of other specialist pest species (Jactel *et al.* 2021; Muiruri & Koricheva 2017; Sholes 2008). However, it is not a universal solution. For example, one study focusing on pine processionary moth (a species of the same genus as OPM) showed decreased pest occurrence but increased rates of pest attack as host density was reduced (Damien *et al.* 2016). Some studies found the relationship between tree diversity and pest impacts to be context dependent, for example changing under drought conditions (Jactel *et al.* 2019), with time since planting (Castagneyrol *et al.* 2020) or even with extent of diversity (with greatest protection apparent at mid-levels of diversity, not very high or very low diversity; Guo *et al.* 2018).

While OPM caterpillars can occasionally be found feeding on other broadleaved trees, this typically only happens when they have run out of oak leaves, and generally they cannot complete their life cycle in such situations (Forest Research 2021). Whilst they are also known for 'processing' between oak trees, these processions are generally found "close" to oak trees ("OPM Manual 12 - Pictures," n.d.).

There is therefore a high likelihood of this approach having some effect, although little direct evidence. Monitoring and evaluation as the intervention is rolled out will help to provide more robust evidence for a subsequent assessment and decision around its continuation.

2.1.3 Geographic context

Tree diversity in London as a whole is already fairly high, with oak making up only 3% of trees in Inner London and 7-8% in Outer and Greater London (Treeconomics 2015) – or 5% overall ("London Tree Map" 2016). Therefore, in many areas no action would be required for this intervention. Rather, the importance would be on ensuring that any new planting follows a similar pattern.

2.1.4 Risks, trade-offs and non-target effects

Interviews conducted by Marzano *et al.* (2020) highlighted that people place a high cultural value on oak trees. Oak also has high biodiversity value. For example, it has found to be associated with 2300 species within the UK, 326 of which are only found on oak (Mitchell *et al.* 2019). It would therefore be important to take this into account by ensuring the solution is not over-implemented (e.g. ensuring the overall proportion of oak in any larger area should not decline) and that trade-offs are assessed on a case by case basis. It would also be important to ensure that a high proportion of the other trees planted, or present, are also native and of importance to biodiversity.

2.1.5 Co-benefits

In addition to its potential for controlling OPM populations, tree species diversity has a number of potential co-benefits. Firstly, it could also help to reduce the likelihood of other pests and pathogens affecting any tree species within the area (Guyot *et al.* 2016; Hantsch *et al.* 2014; Jactel *et al.* 2019). Secondly, greater diversity is able to support more overall biodiversity and multi-trophic interactions, through providing a greater variety of ecological niches (Ampoorter *et al.* 2020; Fornoff *et al.* 2019). This effect extends below ground, where tree diversity has been shown to have important effects on the diversity of soil biota (Korboulewsky *et al.* 2016; Thoms *et al.* 2010). In urban systems, increased tree diversity has been shown to have positive effects on air quality through pollution removal (Manes *et al.* 2012) and urban heat island mitigation (Wang *et al.* 2021).

2.1.6 Costs

As the intervention is mainly about ensuring appropriate ratios in new planting, it would likely have a low cost; oak seedlings are similarly priced to other large trees (Woodland Trust 2021), and so changing their ratio within planned planting should not cost extra, nor take any additional time to implement. Costs for monitoring and evaluation would also need to be considered.

2.1.7 Timelines

It would be an ongoing task to ensure recommended ratios are maintained over time and trees planted reach maturity with the same composition.

2.1.8 Monitoring and evaluation

- **Action indicator:** Ratio of tree species planted on an area of land. Average distance between oak trees planted on an area of land.
- **Outcome indicator:** Ratio of trees present on an area of land (would require tree identification skills or eSurveyor and depending on the size of land may require a sampling technique, such as walking a transect). In some cases, this information may be possible to obtain from existing databases.
- **Evaluation:** Counting the number and size of OPM nests present on the area of land (could be used in combination with data on the ratio of mature trees present to feed into a wider scale analysis evaluating the effectiveness of the intervention as a whole, with some areas left as controls).

2.1.9 Summary

- Evidence: Low
- Geographic relevance: Medium
- Risks, trade-offs and non-target effects: Medium
- Co-benefits: High
- Costs: Variable, but low in most cases

2.2 Increased populations of natural arthropod predators of OPM

2.2.1 Outputs

A variety of natural predators are associated with each life-stage of OPM including ladybirds, lacewing larvae, ground beetles and spiders (Klein *et al.* 2020a; Spijker *et al.* 2019). Increasing their populations should lead to reduced OPM populations through lower survival rates due to predation. Predator populations can be encouraged through conservation biological control (an ecologically based approach aiming to improve habitats to favour natural enemies of a pest species), such as increasing the floristic diversity and the presence of understory vegetation. Such actions provide necessities such as larval development sites, food for different life cycle stages, and shelter (Landis *et al.* 2000), and can be achieved through vegetation management (e.g. reduced mowing regimes under and around oak trees or fencing off areas around oak stands to reduce trampling and compaction) and the planting of flower rich habitats (Klein *et al.* 2020a). Increased arthropod populations may also lead to increased populations of natural bird and bat predators (see next section).

2.2.2 Evidence

Dutch studies have provided preliminary evidence that planting and management of flower rich habitats lead to higher populations of natural enemies and fewer OPM nests per tree (Hellingman *et al.* 2020; Van Deijk 2020), but more conclusive evidence would be required to fully justify the approach.

Increasing predator populations has been found to reduce prey populations both in the context of insects (Lang *et al.* 1999; Riechert & Lawrence 2003) and wider taxonomic groups (Lindström *et al.* 1994). This can occur both through direct consumption and inducing behavioural changes (Nelson *et al.* 2004). Whilst predation plays an important role in limiting prey populations, it is not the only factor; for example, resource availability is also important (highlighting the need for combination with the intervention described in the previous section), as well as wider food web dynamics such as higher-order predators (Rosenheim, 1998). Habitat management and increased floral diversity has been linked to decreased pest populations via predation in other species (Hogg *et al.* 2011; Landis *et al.* 2000; Ramsden *et al.* 2015; Werling *et al.* 2011).

A wide range of arthropods are known to predate on OPM during at least one life cycle stage, including grasshoppers, the lesser searcher beetle (*Calosoma inquisitor),* *Dendroxena quadrimaculata,* rove beetles, earwigs, *Malachius* spp., ants, lacewing larvae (*Chrysoperla carnea*), harlequin ladybirds (*Harmonia axyridis*), two-spot ladybirds (*Adalia bipuntacta*), *Rhabdomiris striatellus,* dung flies, spiders, hoverflies and wasps (Spijker *et al.* 2019). For some of these species, the larvae feed on insects such as OPM, while the adults visit flowers to feed on nectar (e.g. *Dendroxena quadrimaculata* visit umbels and rowan flowers; *Malachius* adults feed on both insects and nectar, mainly from plants in the Asteraceae, Apiaceae and Rosaceae families; lacewing adults feed on nectar, pollen and aphid honeydew). For other species, it is the adults that feed on OPM and the larvae that require other plants for food (e.g. *Rhabdomiris striatellus,* the larvae of which feed on unripe catkins, flowers and fruits). Others still (e.g. earwigs, lacewing larvae) are omnivores, requiring both insects and plants as food. Many of the species also rely on leaf litter (e.g. *Dendroxena quadrimaculata,* rove beetles) or low vegetation (e.g. nettles and docks for two-spot ladybirds) to live in. Lacewing larvae are commonly used as a generalist biocontrol agent for a range of pest species, and it has been shown that the presence and type of additional food sources impact their effectiveness (Jacometti *et al.* 2010; Messelink *et al.* 2016; Robinson 2009). This supports the idea of the intervention but suggests that more species-specific research would be required to understand factors such as which floral mixes to use in order to ensure its effectiveness.

As with the previous intervention, there is little direct evidence that this intervention would work. However, the indirect evidence suggests it would be worth carrying out, at the very least to gather more information for a more robust subsequent evaluation.

2.2.3 Geographic context

The arthropod predators listed in the previous section are from a Dutch study (Spijker *et al.* 2019). A tailored study identifying predators in a UK context would help to ensure a more geographically appropriate understanding. While some of the species listed are commonly found within southern England (e.g. *Dendroxena quadrimaculata*, *Malachius* spp., *Rhabdomiris striatellus*), others are much rarer in this geographic context (e.g. *Calosoma inquisitor*) or have experienced dramatic recent declines (e.g. two-spot ladybirds). One of the species listed (the harlequin ladybird) is invasive to the UK and its arrival has been linked to recent population declines in seven of the eight native UK ladybird species, including the two-spot (Roy *et al.* 2012), so encouraging its population would not be desirable.

At a more local geographic scale, the potential for additive effects must be considered. Further research would be required in order to gain a better understanding of the scale of relative benefits of performing this intervention in a small area compared to a larger area to provide optimal recommendations for its implementation. For example, many studies have demonstrated the importance (both positive and negative) of edge effects on arthropod species (Bolger *et al.* 2000; Caitano *et al.* 2020; Chacoff & Aizen 2006; González *et al.* 2015).

2.2.4 Risks, trade-offs and non-target effects

Many of the species listed above as predators of OPM are generalists, also feeding on a range of other species (e.g. *Calosoma inquisitor* and *Dendroxena quadrimaculata* feed on insects more widely, in particular lepidoptera larvae; lacewings are known to have seventy different prey species across five insect orders). This raises a potential risk that any intervention to increase their populations could inadvertently affect other prey species and the wider food web. The harlequin ladybird in particular is a threat to native biodiversity through both competition and predation (Roy *et al.* 2016). However, by using the proposed intervention, the habitat would also likely be improved for prey species, leading to a healthier ecosystem overall if implemented successfully. Nevertheless, carrying out insect surveys to monitor for unintended knock-on effects would be important evidence to gather alongside implementation. This risk would need to be considered more strongly if combining this intervention with alternative approaches such as direct release of biocontrol agents into the environment.

The flower mix must be selected carefully to avoid the risk of introducing non-native flowers that would be of low benefit to biodiversity. Similarly, it would be important that a range of different flower mixes are used, because if the same combination were prescribed for everywhere, it could reduce overall diversity rather than increase it. There is also a risk that any given selection will support only a narrow range of species. For example, an assessment of the effectiveness of typical flower-rich agri-environment schemes has shown improvements in honeybee and bumblebee populations, but not in flower and pollinator diversity more widely (Wood *et al.* 2015). Additional evidence would need to be gathered on the most effective mixes to use and how best to implement them spatially.

In terms of reducing mowing regimes, safety risks must be considered where this takes place on road verges, as visibility is important.

2.2.5 Co-benefits

By improving the habitat through reduced mowing and increased native floral diversity, other native biodiversity will also benefit. For example, reduced mowing has been shown to increase both the abundance (Garbuzov *et al.* 2015) and diversity (Sehrt *et al.* 2020; Wastian *et al.* 2016) of plants and insects. Increased floral diversity has been linked to increased arthropod diversity in general (Bennett & Gratton 2013). This includes increased diversity of bees and flower-visiting insects (Blaauw & Isaacs 2014; Klein *et al.* 2020a) which support an increase in pollination as an ecosystem service (Blaauw & Isaacs 2014; Ghazoul 2006).

Some of the predators this approach aims to encourage also predate on other pest species. For example, lacewing are also used as biocontrol agents of mealybugs (Messelink *et al.* 2016) and aphids (Jacometti *et al.* 2010).

2.2.6 Costs

Some aspects of the intervention, such as reduced mowing, may actually reduce costs for landowners compared to current practices. Other aspects, such as planting flower rich mixes, would involve a cost. It is important to avoid buying the cheapest seed mix possible, but rather to ensure the seeds are native and have been selected on ecological rather than solely visual merits. Typical costs range from ~£10.00-30.00 per 100g, with recommendations of sowing seeds at about 1.5g per square metre ("100% Wildflower Mixtures," n.d.; "British Wildflower Seeds | Wildflower Meadow Seed Packets," n.d.; "Meadow and Grassland | Mixtures | Emorsgate Seeds – (01553) 829 028," n.d.; "Mixes," n.d.; "Native British Wildflower Perennial Seed Mixes - Meadow Mania," n.d.; "Wild Flower Meadow | Wild Meadow Seeds | Wild Flower Seed Mixes," n.d.). Labour costs for planting the seed mixes should also be considered, although the time required for this type of planting is minimal. Costs associated with research to identify the correct floral mix for the particular location (urban, next to road, countryside, garden, soil type, wetness etc) and the flowers most likely to attract the desired arthropods in relation to the location could also be considered. Costs for monitoring and evaluation would also need to be considered.

2.2.7 Timelines

It is likely to take a number of years before any effects from this intervention are noticeable (Klein *et al.* 2020; Hellingman 2020; Van Deijk 2020).

2.2.8 Monitoring and evaluation

As vegetation influences the ecosystem in many ways, the effect of this intervention on reducing the pressure of OPM will not be easily measurable or clearly attributable (Klein *et al.* 2020).

- **Action indicators:**
  - Area planted.
  - Area with reduced mowing regimes.
- **Outcome indicators:**
  - Floral diversity and nectar index on site (e.g. species richness, Shannon index).
  - Population and diversity of relevant arthropod predator species.
- **Evaluation:**
  - Counting the number and size of OPM nests present on the area of land (could be used in combination with data on floral diversity and arthropod predator populations in order to feed into a wider scale analysis evaluating the effectiveness of the intervention as a whole, with some areas left as controls).

2.2.9 Summary

- Evidence: Low
- Geographic relevance: Medium
- Risks, trade-offs and non-target effects: Low, if mitigation advice followed
- Co-benefits: High
- Costs: Variable, but low in most cases

2.3 Increased populations of natural bird and bat predators of OPM

2.3.1 Outputs

A number of species of bird and bat predate on OPM. Providing bird and bat boxes in and around infected trees can lead to increased populations of natural bird and bat predators in the vicinity, through providing more opportunity for nesting space (Klein *et al.* 2020b). This intervention is linked to the previous one, as improved vegetation management also supports fledgling survival (they rely on it for shelter) and increases food sources for the rest of the year (through increasing arthropod prey populations).

2.3.2 Evidence

A wide range of bird species are natural predators of OPM, including wrens, robins, blue tits, great tits, nuthatch, treecreepers, starlings, jackdaws, cuckoos, orioles, woodpeckers, jays, magpies, sparrows and blackbirds (Spijker *et al.* 2019). Great tit chicks in particular are estimated to each consume up to 800 caterpillars over two weeks, with broods of 8-14 (LIFE Oak Processionary Project, 2020). Long-eared bats (*Plecotus auritus*) and serotine bats (*Eptesicus serotinus*) also feed on adult OPM (Klein *et al.* 2020b).

One trial that made use of this intervention in Westerveld in the Netherlands reported that bird predation was present in nearly 80% of OPM nests in the trial location in its fourth year, but no comparable data were reported for control sites (Hellingman *et al.* 2020). Overall results showed a decrease in the number of OPM nests at test sites compared to controls, but the significance of bird and bat boxes contributing to the overall result was not clear

(Hellingman *et al.* 2020). Initial results from another trial in the Netherlands and Belgium show that the largest and greatest number of OPM nests were found in locations where there were no nest boxes (LIFE Oak Processionary Project 2021).

The previous section outlines evidence for the theory that increased predator populations will control prey populations. Studies focusing specifically on the effects of birds (Holmes *et al.* 1979) and bats (Riccucci & Lanza 2018) on Lepidoptera have also shown population regulation, and reductions in larval densities.

Bird boxes are generally considered to support bird populations, with one review finding that 63 of 66 studies across a range of songbird taxa globally showed high levels of occupancy rates (Williams *et al.* 2020). Five of these also looked at population densities or growth rates and found these to be higher in areas with nest boxes than without nest boxes (Williams *et al.* 2020). One study showed that great tits (one of the species listed as a significant predator of OPM) showed increased populations densities in areas where nest boxes were provided (Mänd *et al.* 2009). However, other factors, such as food supply (both over the winter and during the breeding season), predation and behavioural factors, are also known to have significantly contributed to great tit population densities (Källander 1981; Krebs 1970).

In the case of bats, providing nest boxes is a popular management option to improve or maintain populations, particularly in cases aiming to mitigate the loss of roost sites such as tree cavities (Boyd & Stebbings 1989; Brittingham & Williams 2000; López-Baucells *et al.* 2017; Rueegger 2016). Long-eared bats in particular are noted as common users of bat boxes (e.g. Garland *et al.* 2017), while serotine bats are known to make use of bat boxes as well, but less frequently (e.g. Wojtaszyn *et al.* 2021). 'Conservation Evidence' consider the provision of bat boxes as 'likely to be beneficial' (Berthinussen *et al.* 2021). However, as with birds, other factors also significantly contribute to population levels. This includes structural connectivity of tree networks and urbanisation (Border *et al.* 2017; Hale *et al.* 2012), although the topic remains understudied and poorly understood (Browning *et al.* 2021).

2.3.3 Geographic context

All bird species listed in the Dutch study as predators of OPM are present and fairly common within the UK, with the exception of orioles. Of the two bat species noted in the Dutch studies as feeding on OPM, brown long eared bats are one of the most common bat species in the UK, whilst serotine bats are much rarer and less widespread in a UK context (Bat Conservation Trust 2020).

It is also important to consider the geographic context at a more local scale. Studies have shown that the success of bat boxes is largely dependent on the surrounding habitat. For example, boxes surrounded by pine forest or wetland have greater uptake than those surrounded by urban areas or deciduous forest, potentially due to the current number of possible nesting sites in each of these situations (Ciechanowski 2005; Flaquer *et al.* 2006; López-Baucells *et al.* 2017). Similarly, factors relating to the local geographic placement of bird boxes, such as edge effects (Wilkin *et al.* 2007) and surrounding habitat type (Mänd *et al.* 2005), have also been shown to impact nesting success.

Similarly, scale and boundary effects must be considered, with the intervention likely more effective through collaborative community action or via larger landowners to ensure consistent implementation. For example, one bird box is unlikely to make a significant contribution to local populations as a whole whereas many bird boxes throughout the area surrounding an OPM infestation are likely to have greater success.

2.3.4 Risks, trade-offs and non-target effects

The negative effects of encouraging localised bird and bat populations are unknown. However, there is some risk that higher populations could impact population numbers of rarer species of moth or other insect (Klein *et al.* 2020b). Monitoring for rare species in addition to monitoring OPM populations and combining this intervention with the previous intervention to support greater numbers of insects more generally would therefore be ideal where possible (but may not be feasible in many cases). Comparing current species distributions with recent species distribution for any unexpected risks would also be useful if feasible.

Concerns have been raised that the use of bat boxes can be dominated by certain bat species, leading to less diverse bat community structures overall. However, the evidence for this is conflicted, with field studies both supporting (Griffiths *et al.* 2018) and contradicting the hypothesis (Griffiths *et al.* 2020).

Another risk is the potential for use of bird or bat boxes by OPM themselves. Dutch guidance therefore recommends avoiding placing bird or bat boxes in oak trees and instead selecting other tree species or buildings (Klein *et al.* 2020b).

2.3.5 Co-benefits

Provision of bird and bat boxes will also support native bird and bat populations. Bats in particular are protected under legislation and are thought to have suffered significant population declines throughout the 20th Century (although trends are now stable), so benefitting their survival would be an important co-benefit of this intervention (Bat Conservation Trust 2020).

2.3.6 Costs

Basic bird boxes can be bought for £5-10 (Amazon 2021a; The Range 2021), and basic bat boxes for £10-20 (Amazon 2021b; Garden Nature 2021). Costs would likely decrease if buying in bulk. Rueegger (2016) highlights the importance of factoring in long term maintenance costs to a box programme; it is recommended that old nests are removed and boxes cleaned each autumn (RSPB, n.d.). It would be important to use the right type of bird and bat box for the species being targeted, as studies have shown this has a significant effect on box selection (Dodds & Bilston 2013; Sarà *et al.* 2005). Costs for monitoring and evaluation would also need to be considered.

2.3.7 Timelines

This intervention is likely to take a long time for effects to take place. Bird and bat populations must build at the site substantially for the intervention to be effective (Klein *et al.* 2020b). One study investigating long eared bat population change associated with installation of bat boxes reported a population doubling time of around 10 years (Boyd & Stebbings 1989). In addition, bats feed on the moths rather than the caterpillars, meaning any change in bat population would only be reflected in caterpillar populations the following year.

2.3.8 Monitoring and evaluation

- **Action indicators:**
    - Number of bird and bat boxes installed.
- **Outcome indicators:**
    - Number of boxes occupied;
    - Nesting success;
    - Number of chicks fledged from nest boxes;
    - Populations of relevant bird and bat species.
- **Evaluation:**
    - Counting the number and size of OPM nests present on the area of land (could be used in combination with data on bird / bat population change in order to feed into a wider scale analysis evaluating the effectiveness of the intervention as a whole, with some areas left as controls).

2.3.9 Summary

- 🟥 Evidence: Low
- 🟧 Geographic relevance: Medium
- 🟩 Risks, trade-offs and non-target effects: Low
- 🟩 Co-benefits: High
- 🟩 Costs: Fairly low

2.4 Increased populations of OPM parasites

2.4.1 Outputs

Encouraging populations of OPM parasites can be achieved by both leaving nests in-situ and managing habitat. Leaving nests in situ over winter allows parasite species to complete their life cycles, infecting and killing OPM. Sometimes nests are left within specially made boxes that let parasites enter, but do not let OPM leave. Managing habitat in a similar way to that described in the 'increased populations of natural insect predators' section (planting flower rich habitats and reduced mowing regimes) can also support parasite populations, for example by providing nectar for adult parasitic wasps and flies. In particular, parasites associated with OPM are known to frequently visit umbellifers and bulbous plants, so these should be included in planting mixes (Hellingman 2020).

2.4.2 Evidence

OPM are thought to be hosts to a number of parasites, including *Carcelia iliaca, Pales processionea,* chalcid wasps*, Pimpla processionea, Pimpla rufipes, Coccygomimus turionellae, Theronia atalantae* and *Compsilura concinnata*, some of which overwinter in OPM nests (Sands 2017). However, little is known about parasitism rates of OPM (particularly in the UK), and little is known of their impact on OPM populations (Kitson *et al.* 2019; Sands 2017). Although there is little evidence on the parasitism rates required for changes in OPM populations to be seen, one expert believes that it may be as high as 90% based on cases in other species (J. Kitson 2021, pers. comm. in Deasey *et al.* 2022). Interventions carried out in Westerveld (which included leaving OPM nests in situ in specially made boxes) were successful in reducing OPM nests compared to control locations (Hellingman *et al.* 2020). However, several control options were trialled at the same time, meaning that isolating the impact of encouraging parasites specifically (or understanding the effect of the boxes on parasite populations) was not possible.

More generally however, many studies have suggested that increased parasite rates can reduce host populations (Albon *et al.* 2002; Anderson 1978; Holmstad *et al.* 2005), again providing indirect support to the intervention. However, studies highlight that this is not the case for all parasite-host interactions (Ebert *et al.* 2000), nor in all contexts (Washburn *et al.* 1991), meaning further evidence directly related to OPM is required. Additionally, parasitoids are commonly used to control insect pest populations in the context of classical biological control, where parasitoids are bred and released (e.g., Boivin *et al.* 2012).

Other studies have also shown that managing floral habitat and increasing floral diversity can lead to population rises of many parasite species (Araj *et al.* 2008; Fern & Didham 2002) but highlight the importance of context specific evidence to avoid the potential for cascading trophic effects (Araj *et al.* 2009).

2.4.3 Geographic context

The parasites listed vary in terms of UK prevalence. For example, *P. rufipes* is fairly common and widespread in England and Wales ("*Pimpla rufipes* | NatureSpot," n.d.), whereas *P. processioneae* is not present (CABI, n.d.). *Carcelia iliaca* was first recorded in the UK in 2014, several years after OPM first became established (Sands *et al.* 2015), and in one study was found to parasitise 47.5% of a sample of UK OPM larvae (Kitson *et al.* 2019).

2.4.4 Risks, trade-offs and non-target effects

Leaving nests in situ also leaves the risk posed by the caterpillar's urticating hairs, which may last for many months. There will therefore be some areas (e.g. school grounds, busy parks) where this would not be an appropriate solution. Boxes reduce but do not eliminate this risk. Landowners will need to weigh up the situation in their particular context before taking a decision.

Carcelia iliaca is a parasite specific to OPM, so is unlikely to have non-target effects (Sands *et al.* 2015). However, some of the other parasites listed also affect other Lepidoptera species.

Additional risks and trade-offs relating to increasing floral diversity and managing floral habitat are explored in the 'Increased populations of natural arthropod predators of OPM' section.

It is also important to note that leaving nests in situ would only currently be possible within the 'established area' as defined by the government; in the 'pest free area' and 'buffer zone' requirements for nest removal may be issued by the Forestry Commission (Forestry Commission 2022).

2.4.5 Co-benefits

None identified.

2.4.6 Costs

Leaving nests in situ would be low cost, as no action would be required. It may even save money compared to contracting people to remove nests if this was the norm previously. Putting nests in boxes would be fairly expensive, as it would require boxes to be specially made and the labour to install the boxes would require personal protective equipment and involve risk of repeated exposure to the caterpillars' urticating hairs (symptoms worsen with repeated exposure; Public Health England 2015). Costs involved with habitat management and increased floral diversity in general are discussed in the section on 'Increased populations of natural arthropod predators of OPM.' Umbellifers are included in many wildflower mixes anyway, so ensuring that this is the case for the mix selected would be important but would not add additional cost. However, adding bulbous plants to this mix would be a little more expensive than using standard wildflower mixes alone. Bulbs are typically sold individually or in sets of ten instead of as mixed packets containing hundreds of seeds. Typical prices (although with variation per species) are £0.40-2.00 per bulb ("Native British Wild Flower Bulbs In the Green," n.d.; "Wildflower Bulbs In The Green (Spring Planting)," n.d.). Labour costs would also be slightly higher, as bulbs require individual burying. Costs for monitoring and evaluation would also need to be considered.

2.4.7 Timelines

The immediate effects of this intervention would largely affect OPM in the year following the intervention. It would likely take many years for parasite populations to build up to a high enough level that they impact population levels.

2.4.8 Monitoring and evaluation

- **Action indicators**:
    - Proportion of nests left in situ;
    - proportion of nests left in situ in specially made boxes;
    - area planted;
    - area with reduced mowing regimes.
- **Outcome indicators:**
    - Parasitism rates of OPM nests;
    - Number of species of parasitic wasps and flies from nests and parasitism rates of OPM larvae (measured by taking a proportion of nests and keeping in a secured box to monitor over time to see what parasites come out of it the following spring, then dissecting the nests to investigate the parasitism rates of the larvae);
    - Populations of relevant parasite species.
- **Evaluation**:
    - Counting the number and size of OPM nests present on the area of land (could be used in combination with data on parasite population change in order to feed into a wider scale analysis evaluating the effectiveness of the intervention as a whole, with some areas left as controls).

2.4.9 Summary

- Evidence: Low
- Geographic relevance: Medium
- Risks, trade-offs and non-target effects: Medium
- Co-benefits: Low
- Costs: Medium

3 Actors and stakeholders

Actors and stakeholders of relevance to this theory of change will largely consist of landowners in areas at risk of OPM. They may also include tree surgeons, conservationists, public health practitioners, local councils, and Government departments relating to health or the environment. It may also be of interest to the general public in areas affected by OPM, for example to better understand why changes are being made. As this theory of change is designed to be generic and high level, it will require adaptation by each actor for their unique context.

4 Acceptability

A workshop held in February 2022 showed strong support from stakeholders for trialling nature-based solutions. Stakeholders attending the workshop included land managers across a range of different contexts.

The workshop included a poll which asked stakeholders what their preferred options for OPM control, the options they would consider to be priorities for future trials, and their least preferred control options were. The choice was between; nature-based solutions, augmentation of natural enemies, classical biological control, mating disruption, mass trapping, trail pheromones, botanical bio-pesticides, and trunk injections. Nature-based solutions received the highest number of votes as preferred options (17 out of 20 respondents), and the least number of votes as least preferred options (1 person out of 19 respondents). Nature-based solutions received the second highest number of votes to be a trial priority (15 out of 19 respondents), after mating disruption (17 out of 19 respondents). In all cases respondents could vote for more than one option.

Advantages of nature-based solutions over other alternative control strategies included the co-benefits they can provide to the wider ecosystem, the fact that it would be a long-term solution (that could last for decades), the belief that they could increase the resilience of the wider treescape, and the belief that it would be received positively by other stakeholders and the public. The support for nature-based solutions also came in part from a strong desire to steer clear of other solutions where unknown secondary effects were seen as more likely to be negative (e.g., trunk injections, botanical bio-pesticides), even where such potential negative secondary effects were not proven.

Disadvantages included the uncertainty around the evidence base linking them to control of OPM populations and the fact that it would only be a long-term solution with sustained effort. There were also worries that it could be challenging to communicate nature-based solutions where the goal is on control rather than eradication. Specific cases where they may not be appropriate, such as the limited options for installing bird boxes on highway trees, were also flagged. Stakeholders wished to know more about the efficacy of nature-based solutions and the timeframes over which they can begin to be effective.

5 Conclusions

Overall, there is little direct evidence that nature-based solutions will effectively control OPM populations, although indirect evidence does support this theory. However, the high co-benefits, low risks and low costs associated with several of these solutions (decreased food for OPM larvae, managing habitat to increase populations of natural predators and parasites, and providing nest boxes to increase populations of bird and bat predators) provide a strong argument for supporting their implementation whilst further data are gathered. Monitoring and evaluation will therefore be particularly key in the context of this theory of change, and it will require re-evaluation in subsequent years as more evidence becomes available. Conversely, the solution based on increasing parasite populations by leaving nests in situ does not provide adequately high co-benefits and low risks to be able to recommend implementing it universally until more conclusive evidence about its effects on controlling OPM populations is available; although it may be suitable (and is already used in some places) in areas away from people.

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