Are there viable chemical and non-chemical alternatives to the use of conventional insecticides for the protection of young trees from damage by the large pine weevil Hylobius abietis L. in UK forestry?

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In UK forestry, the synthetic pyrethroid insecticides alpha-cypermethrin and cypermethrin have been used for many years to provide protection for young trees planted on restock sites from damage by the large pine weevil, Hylobius abietis L. However, concerns over the toxicity of these insecticides to aquatic life if misused have led to a search for alternative forms of protection. This paper describes a detailed programme of efficacy experiments undertaken between 2009 and 2015 to find replacements for these products. Over 50 combinations of chemical and non-chemical approaches were tested on 16 different sites. Of the alternative synthetic insecticides tested, applications of 0.037 g a.i. stem\(^{-1}\) acetamiprid provided high levels of protection from Hylobius browsing damage on young Sitka spruce (Picea sitchensis (Bong.) Carrière) trees, without causing any phytotoxic symptoms, and gave comparable levels of protection to those achievable using alpha-cypermethrin or cypermethrin. Acetamiprid is less toxic to aquatic life than alpha-cypermethrin or cypermethrin and has not been linked to bee decline. Applications of 0.0129 g a.i. stem\(^{-1}\) chlorantraniliprole also showed promise, and this relatively low toxicity non-neonicotinoid insecticide merits further study. Although imidacloprid and thiacloprid also provided good levels of protection, their use in forests is not now permitted due to concerns over their potential impacts on bees and drinking water, respectively. Whilst the natural product insecticide spinosad, and the entomopathogenic fungal control agent Metarhizium anisopliae (Metschn.) Sorokin, gave only limited protection in our work, they may have some future potential if methods of deployment can be improved. Other chemical and non-chemical approaches tested, but found to be largely ineffective in UK conditions, included the natural product insecticides azadirachtin, maltodextrin and pyrethrins, the synthetic insecticides lambda-cyhalothrin and spirotetramat and a wide range of repellents, flexible stem coatings and physical barrier products. However, we conclude that physical barrier sleeves such as MultiPro\textsuperscript{®} and BioSleeve\textsuperscript{®} may have a limited role as a partial substitute for the use of insecticides in the UK in some circumstances, but only if on-site populations of Hylobius are predicted to be low.

Introduction

The large pine weevil (Hylobius abietis L., hereafter referred to as “Hylobius”) is a major pest of young trees planted to restock recently clearfelled forest sites in the UK and the rest of Europe (Långström and Day, 2007; Willoughby et al., 2017). In the UK, preventing Hylobius damage has been estimated to cost the forest industry at least £4 million per year (Leather et al., 1999) (nearly £7 million in 2019, adjusted for inflation), but if indirect impacts such as delays to revenue received are included, total losses are estimated to be ~£40 million per year (Moore, E. Wilson, I.H. Willoughby, T. Connolly, I. Sayyed, K. Leslie, et al., in preparation). An even-aged high forest silvicultural system encourages high populations of Hylobius to develop in coniferous forests, as large volumes of fresh woody material left on site after cutting, especially the stump and root systems of harvested trees, attract the insect to breed in large numbers (Eidmann, 1985). Adults mate and lay their eggs in cut stumps, roots and other debris,
Alternatives to conventional insecticides for protecting trees from *Hylobius abietis*

with larvae hatching soon afterwards. Depending on resource quality, available habitat and climate, larval development in the UK takes from 1 to 3 years before adults emerge to feed on the bark of any newly planted trees (Moore, 2004; Moore et al., 2004). The combination of the periodic emergence of large numbers of adults from stumps and their persistence on site results in significant damage to newly planted trees, with browsing occurring repeatedly during the first 5 years after felling. Without effective remedial control measures, death of seedlings due to *Hylobius* browsing averages ∼50 per cent in the first 2 years, but mortality rates often reach 100 per cent (Heritage et al., 1989; Leather et al., 1999). Replacing dead plants and delays in achieving successful restocking can result in uneven crop establishment, whilst sublethal damage can result in poor growth and stem defects on surviving plants (Willoughby et al., 2004).

Traditionally, trees across Europe have been protected from *Hylobius* damage by using insecticides (Långström and Day, 2007). However, concerns over pesticides and their impact, if misused, on human health, environmental condition and ecological functioning have led to the exploration and adoption of a range of other approaches. In the UK, it is recommended that an integrated approach to the management of this pest is adopted (Willoughby et al., 2004, 2017). This includes predicting the likely impacts of *Hylobius* attack using the *Hylobius* Management Support System, based on a scientifically rigorous model of the *Hylobius* life cycle (Moore, 2018). This then enables forest managers to consider the full range of chemical and non-chemical approaches available to prevent the insect damaging young trees if necessary by using different techniques in combination with each other. Although research into non-chemical approaches is ongoing, currently on many sites in the UK and Ireland insecticides still need to be used as part of the integrated management of *Hylobius* (Willoughby et al., 2017).

Synthetic pyrethroid insecticides such as alpha-cypermethrin, cypermethrin and lambda-cyhalothrin have been widely used since the 1980s to control chewing and sucking insect pests in agricultural and horticultural crops, on sheep, as well as in domestic woodworm treatment and garden products. They are non-systemic and act by preventing transmission of impulses along nerves of insects, brought about by cloaking the passage of sodium ions through sodium channels in nerve membranes. This intoxication results in rapid knockdown followed by insect death (MacBean, 2012). Pre-treatment of young trees in an off-site plant nursery with alpha-cypermethrin generally provides 3–7 months of near complete protection from *Hylobius* damage when these trees are subsequently planted in the forest. Because the pre-treated trees are dry, with the insecticide having been absorbed onto the bark when they arrive at the forest, there is almost no risk of exposure to bees and very little risk of any other environmental contamination so long as the treated trees are not inadvertently put into watercourses. Post-planting sprays of cypermethrin, often called ‘top-up sprays’, give ∼1–3 months additional protection depending on the size of the local *Hylobius* population. Lambda-cyhalothrin has not been used for *Hylobius* management in the UK, but bioassay work has suggested it may be effective (Lurenan and Viri, 2005; Rose et al., 2005). Concerns about the use of cypermethrin centre around its use as a top-up spray, due to its extreme toxicity to aquatic life if watercourses are accidentally contaminated through spray drift, runoff or poor mixing and filling practices (Willoughby et al., 2017). Alpha-cypermethrin, cypermethrin and lambda-cyhalothrin are also now classified as ‘highly hazardous – highly restricted’ by the Forest Stewardship Council, the presumption being that they should not normally be used for post-planting top-up spraying on estates voluntarily certified to FSC standards via the UK Woodland Assurance Standard where less hazardous alternatives are available (UKWAS, 2012; FSC, 2019). In addition, cypermethrin is classified as a priority substance under the European Commission Water Framework Directive (European Commission, 2013), meaning its usage must be progressively reduced.

The environmental concerns over the continued use of synthetic pyrethroid insecticides as top-up sprays on forestry restock sites, together with the legal and policy challenges identified above, have led to research across Europe to search for less hazardous alternatives (e.g. Långström and Day, 2007; Harvey et al., 2016). In the UK, a large collaborative research programme took place during 2009–2015 involving public forestry administrations across Great Britain, private forestry companies and Forest Research scientists. This paper describes experiments from this programme that trialled a wide range of alternative chemical and non-chemical approaches as potential replacements for alpha-cypermethrin and cypermethrin use in plantation forestry. The results of 5 different efficacy experiments, involving 16 experimental sites located in Scotland, Wales and northern England, are described and discussed. A brief rationale for including each of the alternative treatments is given below.

Acetamiprid, imidacloprid and thiacloprid are broad-spectrum, systemic, synthetic neonicotinoid insecticides that affect or kill insects by contact or ingestion (see Table 1 for insecticide product names). They act as antagonists by binding to postsynaptic nicotinic receptors in the insect central nervous system, leading to rapid death of affected insects (MacBean, 2012). They have been widely used since the 1990s to control sucking, biting and soil-living insect pests in agricultural and horticultural crops, on home garden plants and in the case of imidacloprid also on domestic pets as well as in household fly and ant killers. In a laboratory study (Olenici et al., 2014), they were all shown to be effective at reducing weevil damage to excised twigs, but could not prevent damage altogether. Nevertheless, given their broad spectrum of control, the fact that they are readily taken up and translocated by plants and the fact that acetamiprid is ∼500 times less toxic to aquatic life (Willoughby et al., 2017), it was thought that the synthetic pesticides acetamiprid, imidacloprid and thiacloprid would be good candidates for investigation as potential replacements for cypermethrin.

A further low toxicity synthetic pesticide tested was chlorantraniliprole. This is a selective, translaminar, synthetic diamide insecticide that acts by contact and ingestion. It activates insect ryanodine receptors, leading to loss of internal calcium stores, muscle paralysis and death in a range of agricultural and horticultural pests including Lepidoptera and some Coleoptera, Diptera and Isoptera species (MacBean, 2012). The final low toxicity synthetic insecticide tested was spiromesifen, a tetramic acid insecticide that affects lipid biosynthesis in sucking insects such as aphids, mainly through ingestion (MacBean, 2012).

Bioinsecticides contain naturally occurring microorganisms, normally have a low toxicity to non-target organisms and are increasingly of interest as forest managers look to move away...
from reliance on synthetic pesticides. The entomopathogenic fungal control agent *Metarhizium anisopliae* var. *anisopliae* (Metschn.) Sorokin strain F52 attacks insects by penetrating the cuticle and invading the haemolymph. It has been shown to infect a high percentage of *Hylobius* in laboratory-based experiments, with all life stages susceptible to the fungus (Ansari et al., 2012), but prior to our work it had not been widely tested in the forest.

Natural product insecticides are chemicals that are derived from natural organisms such as plants, or as by-products of microorganisms, rather than being produced synthetically. They are often viewed as more acceptable than synthetically produced insecticides, although they are not necessarily inherently any less toxic (Clay et al., 2005). Several natural product insecticides, which previously had not been tested against *Hylobius* in UK conditions, were included in our work. Azadirachtin extracts from neem (*Azadirachta indica* A. Juss.) trees have been used for plant protection in agriculture and forestry for several decades (Schmutterer, 1990; Benelli et al., 2017) and are thought to have multiple modes of action against phytophagous insects including repellency and moulting and mating disruption (Copping, 2009). Pyrethrins, extracted from the Dalmatian chrysanthemum (*Tanacetum cinerariifolium* (Trev.) Schultz-Bip.), have been used as a broad-spectrum insecticide since ancient times. They are non-systemic, act by binding sodium channels in insects and are also thought to have some repellent effect (Copping, 2009).

*Spinosad* is an insecticide obtained from fermentation of the soil bacterial species *Saccharopolyspora spinosa* Mertz and Yao and acts on the nicotinic receptors in the insect central nervous system, controlling a range of insects including foliage feeding beetles. *Maldodextrin* is a widely used food additive produced by enzymes from starch. It can also be used as an insecticide and acts by physically blocking the spiracles of insects it is sprayed onto, leading to suffocation.

A range of other natural product pesticides are available that primarily act as repellents. Products containing blood meal, capcicum (chilli pepper) and sheep fat were included in our work to determine whether a single product developed for plant protection against mammals that are often also a problem on clearfell sites could provide a dual function and also act as a deterrent against feeding by *Hylobius*. We also included naturally occurring essential oils such as eucalyptus, limonene, garlic and geraniol, all of which have been proposed as possible insect repellents or insecticides in an agricultural or forestry context (Nordlander, 1990; Ibrahim et al., 2001; Batish et al., 2008; Wilson et al., 2014; Mossa, 2016).

Finally, we included a range of physical barrier systems following Swedish research which demonstrated their potential for

### Table 1 List of products tested.

| Active ingredient(s) | Product name | Supplier company | Product type | Experiment number |
|-----------------------|--------------|------------------|--------------|------------------|
| Acetamiprid, 20% w/w | Gazzelle SC® | Certis, www.certiseurope.co.uk | Synthetic insecticide | 1, 2, 3, 4, 5 |
| Acetamiprid, 20% w/w | Trees Please treated trees | Trees Please, www.treesplease.co.uk | Synthetic insecticide | 4 |
| Acetamiprid, 60% w/w | Flexcode® | Bayer, www.bayer.com | Synthetic insecticide | 5 |
| Acciflora® | | | Marker dye | 5 |
| Alpha-cypermethrin, 60 g l⁻¹ | | | Flexible barrier film | 1, 2, 3 |
| Alpha-cypermethrin, 15% w/w | Contest® | BASF, www.agricentre.basf.co.uk | Synthetic insecticide | 1, 2, 3, 4 |
| Azadirachtin, 10% w/w | NeemAzal® | www.neemazal.com | Natural product insecticide | 2 |
| Azadirachtin (+ other a.i.) | | | Natural product insecticide mixture | 1 |
| Blood meal, 99.8% w/w | Plantkyd® | www.plantkyd.com | Natural product mammal repellent | 4 |
| Cardboard waxed | Rainbow Professional, www.rainboweu.com | Physical barrier sleeve | 4 |
| Cardboard waxed | MultiPre® | Svenska Skogsplantor, www.svenskaskogsplantor.se | Physical barrier sleeve | 3, 4 |
| Capsicum extract, 3 g kg⁻¹ | Repellex® | Repellex, www.repellex.com | Natural product insect/mammal repellent | 4 |
| Chlorantranilate, 200 g l⁻¹ | Gorgon® | FMC Syngenta, www.fmc-agro.co.uk | Synthetic insecticide | 4 |
| Cypermethrin, 100 g l⁻¹ | Forest® | Arysta, www.arysta.eu | Synthetic insecticide | 5 |
| Eucalyptus oil, 82.5% w/w | Eucalyptol oil | Sigma-Alrich, www.sigmalrich.com | Natural product insect repellent/insecticide | 3 |
| Garlic, 82.5% w/w | Garlic metabolic solution | Neem Biotech, www.neembiotech.com | Natural product insect repellent/insecticide | 3 |
| Genisol | Sigma-Alrich | Sigma-Alrich | Natural product insect repellent | 3 |
| Mentine Forest® | Bayer, www.cropsence.bayer.co.uk | Synthetic insecticide | 2, 3, 5 |
| Lambda-cyhalothrin, 10% w/w | Hallmark® | Syngenta | Natural product insect repellent | 3 |
| Limonene, 95% w/w | (S⁻)−(−)−limonene | Fargro, www.fargro.co.uk | Natural product insecticide | 1 |
| Maltodextrin, 598 g l⁻¹ | Majestix® | Fargro, www.fargro.co.uk | Biological insecticide | 2, 3 |
| Metarhizium anisopliae, 2% w/w | Met52® | Alba Trees, www.albatrees.co.uk | Physical barrier netting | 1 |
| Plastic netting | Wannen® | Certis | Natural product insecticide | 1 |
| Pyrethrins, 4.5 g l⁻¹ | Spruz® | Kwikia Agro, www.kwikia-agro.at | Natural product mammal repellent | 4 |
| Sheep fat, 64.6 g l⁻¹ | Trico® | Fargro | Natural product insecticide | 2, 3, 5 |
| Spinosad, 120 g l⁻¹ | Conserve® | Bayer CropScience | Synthetic insecticide | 4 |
| Spinetoram, 150 g l⁻¹ | Movant® | AgraVista Reggae | Synthetic insecticide | 4 |
| Thiialdradip, 480 g l⁻¹ | Agrovista® | | | |
| Wax | Kvalo® wax | Norsk Wax AS, www.kvaae.com | Flexible barrier film | 3, 4, 5 |

1 Rigel M contains Margosa 1–10% (an extract derived from seeds of the neem tree (*Azadirachta indica*)), garlic oleoresin NR1718 1–10% (derived from garlic, *Allium sativum* L., bulbs), salicylaldehyde 40–50% (salicylaldehyde occurs in the larval defensive secretions of several leaf beetles), alkylpolyoxypolyethyleneoxyethanol 30–40% (to control ticks and other insect pests), polyether 1–10%, tetraethyl silicates 10–20%, ethanol 0–0.5% and polysiloxanes 0.5–0.5%.
tree protection against weevil browsing, usually in combination with other silvicultural measures (e.g. Petersson and Örlander, 2003; Nordlander et al., 2009). Flexcoat® is a Swedish polysaccharide flexible stem coating product available in solution, which can be applied to seedlings using single or multiple coatings before planting. Kvaae® wax is a flexible protective wax product developed in Norway which is applied to the tree stem. MultiPro® and BioSleeve® are custom-made short cardboard sleeves, fitted around trees either at the nursery or after planting, and Weenet® is a protective netting normally fitted at the nursery. We also investigated the use of flexible coating systems in combination with other synthetic, natural product or bioinsecticide treatments.

Materials and methods

All experiments were established on sites due to be restocked with Sitka spruce (Picea sitchensis (Bong.) Carrière), as this represents the most significant commercial conifer species in Great Britain, covering 51 per cent of all coniferous forests (Forestry Commission, 2019). The species is also important in Ireland and other north-western Europe countries (Houston Durrant et al., 2016). Table 1 lists the different treatments tested. Effectiveness of the treatments was determined by comparing the amounts of damage to planted trees. Therefore, based on their location and timing of felling, 16 sites (Table 2) were selected so that predicted over-wintering adult populations of Hylobius would be relatively low during the first 3 months after planting in April, but numbers would increase to form a substantial population likely to cause significant damage following the emergence of new adults from stumps of the previous crop from August onwards (Moore, 2004). Thus it was intended that damage would develop gradually over the first 3 months after planting to provide a clear comparison of differences in efficacy between individual treatments and then for damage to accumulate more rapidly during the following 3 months of emergence to provide a representative test of the efficacy of the insecticide treatments under the type of severe feeding pressure likely to be regularly faced on more challenging restocking sites in the UK.

All sites had previously had a standing crop of at least 70 per cent Sitka spruce and had been typically harvested 7–18 months before the start of the experiment. After clearfelling, the sites were prepared for restocking by cultivation through excavator mounding (Patterson and Mason, 1999), producing a settled mound size of ∼50 × 50 × 20 cm. This provided an elevated planting position clear of any competing vegetation, to facilitate successful establishment and to minimize as far as possible confounding effects of alternative food resources for the adult weevils. Planting was carried out during April to June depending on site (see Table 2). Two-year-old bare-root Sitka spruce transplants, ranging from 20 to 40 cm in height, were planted. Nursery stock were not treated with any insecticides in 3 months prior to experimental treatment and then planting, and none, apart from the experimental treatments, were applied after planting. Each site had four replicate blocks of the experimental treatments. The transplants were planted 2 m spacing, with 25 plants per treatment plot. This resulted in a 5 × 5 tree grid and a plot area of roughly 8 m². Where possible, plots in the same block were separated by a 4-m-wide unplanted buffer, whilst those in different replicate blocks were separated by an 8-m-wide unplanted buffer. All transplants in a plot were assigned the same plot treatment. A 10-m-wide unplanted buffer strip was established around the perimeter of each experimental area to eliminate unwanted effects from off-site operations (e.g. chemical spray drift, leaching). The synthetic pyrethroid insecticide alpha-cypermethrin (as Alpha C 6ED®, applied to plants in the forest nursery after lifting via the Electrodyn® system), which is a commonly used standard treatment to protect trees against Hylobius damage, was included as an active control at each site for comparison purposes. In addition, an untreated control was also included on all sites as an indicator of Hylobius population size and damage pressure, as well as to evaluate the efficacy of the experimental treatments. Unless noted otherwise, experimental treatments were applied by spot gun or knapsack sprayer in the nursery before planting, usually between 10 and 20 ml per plant, to achieve complete and even coverage of the stem.

Transplant damage was measured twice in the first year after planting: a mid-season assessment in June to July, during the main period of adult Hylobius activity, and an end of growing season in October to November, after the cessation of adult Hylobius seasonal activity. For Experiment 4, assessments also took place in the second growing season after planting. A standard Hylobius damage scoring system developed for assessing rates of Hylobius damage at restock sites was used in the field experiments (Heritage et al., 1989). Under this system, transplants were scored as:

- (A) Alive, undamaged by Hylobius
- (B) Alive, but with signs of sublethal Hylobius damage (without cambial girdling)
- (C) Dead, killed by Hylobius action (usually with cambial girdling)
- (D) Dead, killed by means other than Hylobius (e.g. transplant failure, mammal browsing)
- (X) Transplant missing

Data analysis

Data analyses were based on the number of transplants assigned to each damage category as described above. This procedure was carried out for each experimental forest site, on an experiment-by-experiment basis. Descriptive summary data were calculated for each treatment by site. Percentage transplant survival, which is used in this paper as a measure of efficacy, was calculated as the number of trees still alive (A + B) divided by the number of trees available to Hylobius (A + B + C). For descriptive outputs, survival was multiplied by 100 to obtain percentages. Data for each experimental forest site were then analysed using R (ver. 3.5.2) (R Core Team, 2018). Analysis was based on comparisons of the proportions of trees killed by Hylobius vs all live trees (alive (A) or alive (damaged) (B) vs dead (due to Hylobius) (C)). Missing trees (X) and other dead trees not killed by Hylobius (D) were excluded from the analyses.

Data were analysed using a generalized linear model with logit link and quasibinomial errors (to account for overdispersion).
The various treatments are detailed in Table 3. The insecticide and Flexcoat® treatments were carried out, and the Weenet® alpha-cypermethrin, untreated control and also against the single active control, using Tukey's HSD. Plot survival data were tested against the contrasts between treatments corrected for multiple comparisons using the emmeans package (Lenth site, where the interaction was significant) at specific time points.

Experiment 2 investigated the efficacy of various alternative and bioinsecticides. Many of the insecticide treatments were applied, depending on treatments, were applied in the nursery using a wax fountain machine. Spinosad was applied to the stem in the nursery, with a soil drench on site by adding the product to the planting holes. Spinosad was applied to the stem and as a root drench on site by adding the product to the planting holes.

Post hoc marginal means were calculated by treatment (and site, where the interaction was significant) at specific time points using the emmeans package (Lenth et al., 2019), with contrasts between treatments corrected for multiple comparisons using Tukey's HSD. Plot survival data were tested against the untreated control and also against the single active control, alpha-cypermethrin.

### Experiment 1 – efficacy of synthetic and natural product insecticides and physical plant protection

The principal objectives of this experiment were to compare the efficacy of various synthetic and natural product insecticides, and physical plant protection products, for protecting Sitka spruce transplants from damage by *Hylobius* at four forest sites (Table 2). The various treatments are detailed in Table 3. The insecticide and Flexcoat® treatments were carried out, and the Weenet® sleeves fitted, at Maelor Forest Nurseries before the trees were transplanted from damage by physical plant protection products, for protecting *Sitka spruce*.

### Experiment 2 – efficacy of synthetic, natural product and bioinsecticides

Experiment 2 investigated the efficacy of various alternative insecticide types for protecting trees from *Hylobius* damage on a further four forest sites (Table 2). Survival and damage suffered by transplants pre-treated with the neonicotinoids acetamiprid and imidacloprid, or with azadirachtin, spinosad, or the biological agent *Metarhizium anisopliae*, were tested.

Azadirachtin was applied directly to the stem and as a root dip in the nursery prior to planting. It was also applied as a soil drench on site by adding the product to the planting holes. Spinosad was applied to the stem in the nursery, with and without Flexcoat®. *Metarhizium anisopliae* was applied alone and in combination with other products. Flexcoat® was applied on its own and in combination with the active chemical products; the latter was applied either as a mix in a single application or as a two-stage application of each of the individual products. More details of the treatments are given in Table 4.

### Experiment 3 – efficacy of synthetic, natural product and bioinsecticides and physical plant protection

A third experiment investigated the efficacy of a range of insecticide, physical and repellent-based products in protecting trees from *Hylobius* damage on two further restock sites in south-west and south Scotland (Table 2). Many of the insecticide treatments (Table 5) were common to Experiment 2. In addition, Flexcoat®, wax and wax + repellent mixtures were also tested. Flexcoat® was applied on its own or in combination with other active products. Either a single (‘mix’) or double coating (‘two-stage’ process) of Flexcoat® and other products was applied, depending on treatment. *Kvaea*® wax treatments, including wax + repellent mixtures, were applied in the nursery using a wax fountain machine (Heco-V-450NW, ZetaEcotech). Where required, repellents were incorporated into the liquid wax to create the appropriate solution. Solutions were applied to the lower stem of the

### Table 2 Experiment site details.

| Site name                      | National grid reference | Elevation (metres above sea level) | Annual rainfall (mm) | Accumulated temperature (growing degree days >5°C) | Soil type                  | Felling date             | Experiment planting date |
|-------------------------------|-------------------------|-----------------------------------|----------------------|---------------------------------------------------|----------------------------|--------------------------|--------------------------|
| **Experiment 1**              |                         |                                   |                      |                                                   |                            |                          |                          |
| Llandegla, Wales              | SJ205500                | 450                               | 1063                 | 1006                                              | Stagnapodzol              | 10/2008–3/2009           | 4/2010                   |
| Watermeetings, Scotland       | NS863095                | 330                               | 1812                 | 1083                                              | Dystrophic blanket peat   | 10/2008–3/2009           | 4/2010                   |
| Glasgow, Scotland             | NK896649                | 190                               | 1465                 | 1312                                              | Peaty gley                | 10/2008–3/2009           | 4/2010                   |
| Westwood, Scotland           | NT218016                | 295                               | 1816                 | 1140                                              | Non-calcareous gley       | 10/2008–3/2009           | 4/2010                   |
| **Experiment 2**              |                         |                                   |                      |                                                   |                            |                          |                          |
| Bogowie, Scotland             | NX800859                | 280                               | 1364                 | 1190                                              | Peaty gleyed podzol       | 11/2011–3/2012           | 4/2012                   |
| Myldykes, England            | NT603011                | 365                               | 1333                 | 983                                               | Peaty gley                | Winter 2011–12            | 4/2012                   |
| Ramsayglen, Scotland         | NT342027                | 365                               | 1426                 | 1025                                              | Dystrophic blanket peat   | Winter 2011–12            | 4/2012                   |
| Ruegill, Scotland            | NY157998                | 445                               | 1852                 | 881                                               | Peaty gleyed podzol       | 11/2011–2/2012           | 4/2012                   |
| Glengetmet, Scotland         | NX269978                | 225                               | 1221                 | 1178                                              | Peaty gley                | Spring–summer 2012       | 5/2013                   |
| Raeburn, Scotland            | NT266007                | 235                               | 1619                 | 1222                                              | Non-calcareous gley       | Summer 2012              | 5/2013                   |
| **Experiment 4**              |                         |                                   |                      |                                                   |                            |                          |                          |
| Cornis, Wales                 | SH712077                | 380                               | 2558                 | 1249                                              | Surface water gley        | Winter 2013–2014         | 4/2014                   |
| Whey Knowe, Scotland          | NT274059                | 360                               | 1633                 | 1013                                              | Peaty gleyed podzol       | 11/2012–8/2013           | 4/2014                   |
| Lambaughy, Scotland          | NK270897                | 275                               | 1617                 | 1193                                              | Dystrophic blanket peat   | 3/2013–12/2014           | 4/2014                   |
| Smittons, Scotland            | NK23927                | 300                               | 1973                 | 1141                                              | Dystrophic blanket peat   | 4/2013–9/2013             | 4/2014                   |
| **Experiment 5**              |                         |                                   |                      |                                                   |                            |                          |                          |
| Black Fell, Scotland          | NY607934                | 390                               | 1450                 | 983                                               | Raw oligo-fibrous peat    | Summer 2011–winter 2012  | 5–6/2013                 |
| Dunn’s Sike, England          | NY771935                | 330                               | 1146                 | 1076                                              | Cambic stagnohumic gley   | Autumn 2010–summer 2011  | 5–6/2013                 |

1From: Met Office; Hollis and McCarthy (2013).
transplant, except in the full-plant treatment (FP), where wax was applied to the whole length of the transplant, up to the base of the terminal bud (Table 5).

**Experiment 4 – efficacy of physical barriers and synthetic and natural product insecticides**

This experiment was established on four sites (Table 2) and sought to extend the range of physical barriers, repellents and novel pesticide plant protection products tested. Kvaoe® wax, MultiPro® and BioSleeve® were applied as solo treatments, without the addition of chemical insecticides. Kvaoe® wax was applied to 50, 80 or 100 per cent of the length of the stem before the transplants were planted. Protective sleeves were fitted to the plants before planting.

The repellent products (blood meal, sheep fat and capsicum) were tested as solo treatments and when combined with acetamiprid. Separate treatments tested the efficacy of spraying acetamiprid to single trees or batches of 10 or 25 trees, to examine if this systemic insecticide could be translocated sufficiently around each tree in the bundle without having to treat every individual stem, to reduce application costs. Thiacloprid, spirotetramat and chlorantraniliprole were tested at low and high concentrations (Table 6). Treatments were applied in spring 2014, and assessments of transplant damage for both autumn 2014, and assessments of transplant damage for both autumn 2014 (representing the effects after one growing season) and 2015 (representing the cumulative effects after two growing seasons) are reported below.

**Experiment 5 – effect of marker dye (Acid Blue 9) and wax barriers on the efficacy of insecticide treatment**

The fifth experiment was carried out on two sites in northern England (Table 2) to assess the protection to trees provided by acetamiprid, imidacloprid and spinosad, each at a range of effective concentrations. The food dye Acid Blue 9 (Colour Index 42 090) is often used in mixture with insecticides when applied as a top-up spray on transplants to increase the visibility of the spray
### Table 4 | Experimental treatments at Bogrie, Myredykes, Ramsaygrain and Ruegill forests – Experiment 2.

| Treatment no. | Active ingredient(s) (or coating) | Product dosage (g ha\(^{-1}\)) | Product dosage (g stem\(^{-1}\)) | A.i dosage (g stem\(^{-1}\)) | A.i dosage (g ha\(^{-1}\)) | Flexcoat (mix) | Flexcoat (T/S) |
|---------------|----------------------------------|-------------------------------|-------------------------------|-----------------|-----------------|---------------|---------------|
| 1             | Untreated                        | –                             | –                             | –                | –                | –             | –             |
| 2            | Alpha-cypermethrin               | 270 (ml ha\(^{-1}\))         | 0.100 (ml stem\(^{-1}\))     | 0.006            | 16.2             | –             | –             |
| 3            | Acetamiprid                      | 100                           | 0.037                         | 0.008            | 20               | –             | –             |
| 4            | Metarhizium                      | 5400 (ml ha\(^{-1}\))        | 2 (ml stem\(^{-1}\))         | 0.200            | 540              | –             | –             |
| 5            | Azadirachtin                     | 5400 (ml ha\(^{-1}\))        | 2 (ml stem\(^{-1}\))         | 0.200            | 540              | –             | –             |
| 6            | Azadirachtin (soil drench)       | 5400 (ml ha\(^{-1}\))        | 2 (ml stem\(^{-1}\))         | 0.200            | 540              | –             | –             |
| 7            | Imidacloprid                     | 60                            | 0.022                         | 0.016            | 42               | –             | –             |
| 8            | Spinosad                         | 750 (ml ha\(^{-1}\))         | 0.277 (ml stem\(^{-1}\))     | 0.033            | 90               | +             | +             |
| 9            | Spinosad                         | 750 (ml ha\(^{-1}\))         | 0.277 (ml stem\(^{-1}\))     | 0.033            | 90               | +             | +             |
| 10           | Imidacloprid                     | 60                            | 0.022                         | 0.016            | 42               | –             | –             |
| 11           | Imidacloprid                     | 60                            | 0.022                         | 0.016            | 42               | +             | +             |
| 12           | Imidacloprid                     | 500                           | 0.037                         | 100              | –                | –             | –             |
| 13           | Acetamiprid                      | 175                           | 0.045                         | 122.5            | –                | –             | –             |
| 14           | Spinosad                         | 750 (ml ha\(^{-1}\))         | 0.033                         | 90               | –                | –             | –             |
| 15           | Spinosad                         | 750 (ml ha\(^{-1}\))         | 0.033                         | 90               | –                | –             | –             |
| 16           | [Flexcoat](B)                    | –                             | –                             | –                | –                | –             | –             |
| 17           | [Flexcoat](B)                    | –                             | –                             | –                | –                | –             | –             |
| 18           | Acetamiprid                      | 75 (ml ha\(^{-1}\))          | 0.003                         | 9                | –                | –             | –             |
| 19           | Spinosad                         | 500                           | 0.037                         | 100              | –                | –             | –             |
| 20           | Spinosad                         | 75 (ml ha\(^{-1}\))          | 0.033                         | 90               | –                | –             | –             |
| 21           | Spinosad                         | 75 (ml ha\(^{-1}\))          | 0.033                         | 90               | –                | –             | –             |
| 22           | [Flexcoat](B)                    | –                             | –                             | –                | –                | –             | –             |
| 23           | [Flexcoat](B)                    | –                             | –                             | –                | –                | –             | –             |
| 24           | Acetamiprid                      | 500                           | 0.037                         | 100              | –                | –             | –             |
| 25           | Spinosad                         | 75 (ml ha\(^{-1}\))          | 0.033                         | 90               | –                | –             | –             |

Dosages g ha\(^{-1}\) or g stem\(^{-1}\) unless other units stated in parentheses. Tree dosages calculated assuming a restocking density of 2700 stems ha\(^{-1}\).

Insecticide treatments show whether a Flexcoat® physical barrier or Flexcoat® two-stage (T/S) combination was used (+/-). Flexcoat® solution was one part product in four parts water, applied in an insecticide mix, or applied, then followed by insecticide application in a two-stage process. The active control.

### Table 5 | Experimental treatments at Glengennet and Raeburn forests – Experiment 3.

| Treatment no. | Active ingredient(s) (or physical product) | Product dosage (g ha\(^{-1}\)) | A.i dosage (g stem\(^{-1}\)) | A.i dosage (g ha\(^{-1}\)) | Flexcoat (mix) | Flexcoat (T/S) | Wax | Wax (T/S) |
|---------------|--------------------------------------------|-------------------------------|-----------------|-----------------|---------------|---------------|-----|-----------|
| 1             | Untreated                                   | –                             | –                | –                | –             | –             | –   | –         |
| 2            | Alpha-cypermethrin                           | 270 (ml ha\(^{-1}\))         | 0.006            | 16.2             | –             | –             | –   | –         |
| 3            | Acetamiprid                                 | 500                           | 0.037            | 100              | –             | –             | –   | –         |
| 4            | Spinosad                                    | 750 (ml ha\(^{-1}\))         | 0.033            | 90               | –             | –             | –   | –         |
| 5            | Spinosad                                    | 750 (ml ha\(^{-1}\))         | 0.033            | 90               | –             | –             | –   | –         |
| 6            | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 7            | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 8            | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 9            | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 10           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 11           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 12           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 13           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 14           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 15           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 16           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 17           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 18           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 19           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 20           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 21           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 22           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 23           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 24           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |
| 25           | [Flexcoat](B)                               | –                             | –                | –                | –             | –             | –   | –         |

Dosages g ha\(^{-1}\) or g stem\(^{-1}\) unless other units stated in parentheses. Tree dosages calculated assuming a restocking density of 2700 stems ha\(^{-1}\).

The active control.

Mix and hence help in improving targeting and efficacy and in reducing the risk of non-target drift and worker contamination (Brown et al., 2003; Willoughby, 2007). This marker dye was included in Experiment 5 to determine whether its use affected the efficacy of the insecticide treatments. Alpha-cypermethrin and wax treatments were applied in the nursery according to the
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**Table 6** Experimental treatments at Corris, Lambdoughty, Smittons and Whey Knowe – Experiment 4.

| Treatment no. | Active ingredient(s) and physical product | Product dosage (g ha\(^{-1}\)) | Product dosage (g stem\(^{-1}\)) | A.i dosage (g stem\(^{-1}\)) | A.i dosage (g ha\(^{-1}\)) |
|---------------|------------------------------------------|----------------------------------|----------------------------------|-------------------------------|-----------------------------|
| 1             | Untreated                                | –                                | –                                | –                             | –                           |
| 2\(^1\)       | Alpha-cypermethrin 270 (ml ha\(^{-1}\))  | 0.100 (ml stem\(^{-1}\))         | 0.006                            | 16.2                          |
| 3             | Acetamiprid 500                          | 0.185                            | 0.037                            | 100                           |
| 4             | Wax 100% cover                           | –                                | –                                | –                             | –                           |
| 5             | Wax 80% cover                            | –                                | –                                | –                             | –                           |
| 6             | Wax 50% cover                            | –                                | –                                | –                             | –                           |
| 7             | MultiPro\(^\circ\)                       | –                                | –                                | –                             | –                           |
| 8             | BioSleeve\(^\circ\)                      | –                                | –                                | –                             | –                           |
| 9             | Blood meal 2700                          | 1.000                            | 0.990                            | 2694                          |
| 10            | Blood meal + acetamiprid 8100 (ml ha\(^{-1}\)) 3 (ml stem\(^{-1}\)) + 0.185 | 0.194                            | 0.037                            | 523.3                         |
| 11            | Sheep fat + acetamiprid 8100 (ml ha\(^{-1}\)) 3 (ml stem\(^{-1}\)) + 0.185 | 0.194                            | 0.037                            | 523.3                         |
| 12            | Sheep fat + acetamiprid 500              | 0.185                            | 0.037                            | 100                           |
| 13            | Capsicum 12 420                          | 4.600                            | 0.0138                           | 37.26                         |
| 14            | Capsicum + acetamiprid 12 420 + 500      | 0.185                            | 0.0138 + 0.037                   | 37.26 + 100                   |
| 15            | Acetamiprid batch of 1 tree 500          | 0.185                            | 0.037                            | 100                           |
| 16            | Acetamiprid batch of 10 trees 500        | 0.185                            | 0.037                            | 100                           |
| 17            | Acetamiprid batch of 25 trees 500        | 0.185                            | 0.037                            | 100                           |
| 18            | Trees Please acetamiprid 500             | 0.185                            | 0.037                            | 100                           |
| 19            | Thioccloprid 375 (ml ha\(^{-1}\))        | 0.139                            | 0.067                            | 180                           |
| 20            | Thioccloprid 750 (ml ha\(^{-1}\))        | 0.278                            | 0.133                            | 360                           |
| 21            | Spirotetramat 500 (ml ha\(^{-1}\))       | 0.185                            | 0.028                            | 75                            |
| 22            | Spirotetramat 1000 (ml ha\(^{-1}\))      | 0.370                            | 0.056                            | 150                           |
| 23            | Chlorantraniliprole 175 (ml ha\(^{-1}\)) | 0.065                            | 0.013                            | 35                            |
| 24            | Chlorantraniliprole 350 (ml ha\(^{-1}\)) | 0.130                            | 0.026                            | 70                            |

Dosages g ha\(^{-1}\) or g stem\(^{-1}\) unless other units stated in parentheses. Tree dosages calculated assuming a restocking density of 2700 stems ha\(^{-1}\).

\(^1\) The active control.

The methodology described for Experiment 3. All other treatments were carried out by spraying the young trees in the forest immediately post-planting in April 2012. In addition, the potential additional protection that might be provided by making ‘top-up’ spray applications in July 2012 was tested for six insecticide treatments and in addition for the barrier wax + insecticide treatments (Table 7).

**Results**

**Experiment 1**

The size of *Hylobius* populations, and hence potential damage pressure, is indicated by the survival of the trees in the control (untreated) treatments at each of the four sites. The data for Plascow and Westwood forests suggests that populations of *Hylobius* were intermediate and high there, respectively (Figure 1). At Llandegla and Watermeetings, tree survival was high, suggesting that *Hylobius* pressure was lower; at these sites, survival of the controls was not significantly different from those treated with alpha-cypermethrin (Figure 1), and the only significant differences in survival were the lower survival in the azadirachtin natural product insecticide mix treatments at Llandegla. Thus, only the intermediate and high populations at Plascow and Westwood (Figure 1), typical of the damage pressure found on the majority of forest sites in the UK, provide a sufficiently rigorous test of the alternative plant protection treatments, and the following description focusses on these sites.

Neonicotinoid products (acetamiprid and imidacloprid) generally provided strong protection, with no difference in survival to alpha-cypermethrin observed at any site (all \(P > 0.05\)), with >75 per cent of transplants (excluding those affected by factors other than *Hylobius*) surviving after one season (Figure 1).

In the azadirachtin plots with a higher rate of application (0.370 g Rigel M\(^\circ\) stem\(^{-1}\)), mortality caused by factors other than *Hylobius* was high for treatments, with and without Flexcoat\(^\circ\), across all sites (Figure 1). This suggests a high phytotoxicity of the natural product insecticide mix to Sitka spruce transplants. At Plascow at the lower rate of application, phytotoxicity was lower, but the insecticide mix provided very little protection against *Hylobius*, and survival was significantly less than that of plants treated with alpha-cypermethrin (\(P < 0.05\)). Survival of transplants treated with lambda-cyhalothrin was significantly lower at Plascow compared with plants treated with alpha-cypermethrin (\(P < 0.05\)). However at Westwood, survival was too low in both the alpha-cypermethrin active control and lambda-cyhalothrin treatments to yield a statistically significant difference. The same
Table 7  Experimental treatments at Black Fell and Dunn’s Sike in Kielder forests – Experiment 5.

| Treatment no. | Active ingredient(s) and physical products | Product dosage (g ha\(^{-1}\)) | A.i dosage (g stem\(^{-1}\)) | Product July dosage (g ha\(^{-1}\)) | A.i July dosage (g stem\(^{-1}\)) | A.i July dosage (g ha\(^{-1}\))^2 | Dye applied |
|---------------|-------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|
| 1 | Untreated | – | – | – | – | – | – |
| 2 | Alpha-cypermethrin | 270 (ml ha\(^{-1}\)) | 0.006 | 16.2 | – | – | – |
| 3 | Cypermethrin | 1080 (ml ha\(^{-1}\)) | 0.040 | 108 | – | – | – |
| 4 | Acetamiprid | 500 | 0.037 | 100 | – | – | – |
| 5 | Acetamiprid | 405 | 0.030 | 81 | – | – | – |
| 6 | Acetamiprid | 405 | 0.030 | 81 | – | – | – |
| 7 | Acetamiprid | 297 | 0.022 | 59.4 | – | – | – |
| 8 | Acetamiprid | 297 | 0.022 | 59.4 | – | – | – |
| 9 | Acetamiprid | 297 | 0.022 | 59.4 | – | – | – |
| 10 | Imidacloprid | 120 | 0.031 | 84 | – | – | – |
| 11 | Imidacloprid | 120 | 0.031 | 84 | – | – | – |
| 12 | Imidacloprid | 96 | 0.025 | 67.2 | – | – | – |
| 13 | Imidacloprid | 96 | 0.025 | 67.2 | – | – | – |
| 14 | Imidacloprid | 73.3 | 0.019 | 51.3 | – | – | – |
| 15 | Imidacloprid | 73.3 | 0.019 | 51.3 | – | – | – |
| 16 | Spinosad | 1500 | 0.067 | 180 | – | – | – |
| 17 | Spinosad | 1500 | 0.067 | 180 | – | – | – |
| 18 | Spinosad | 900 | 0.040 | 108 | – | – | – |
| 19 | Spinosad | 900 | 0.040 | 108 | – | – | – |
| 20 | Spinosad | 750 | 0.033 | 90 | – | – | – |
| 21 | Spinosad | 750 | 0.033 | 90 | – | – | – |
| 22 | Spinosad | 600 | 0.027 | 72 | – | – | – |
| 23 | Spinosad | 600 | 0.027 | 72 | – | – | – |
| 24 | Spinosad | 450 | 0.020 | 54 | – | – | – |
| 25 | Spinosad | 450 | 0.020 | 54 | – | – | – |
| 26 | Acetamiprid | 405 | 0.030 | 81 | 405 | 0.030 | 81 |
| 27 | Acetamiprid | 405 | 0.030 | 81 | 405 | 0.030 | 81 |
| 28 | Imidacloprid | 96 | 0.025 | 67.2 | 96 | 0.025 | 67.2 |
| 29 | Imidacloprid | 96 | 0.025 | 67.2 | 96 | 0.025 | 67.2 |
| 30 | Spinosad | 750 | 0.033 | 90 | 750 | 0.033 | 90 |
| 31 | Spinosad | 750 | 0.033 | 90 | 750 | 0.033 | 90 |
| 32 | Wax | – | – | – | – | – | – |
| 33 | Wax + acetamiprid | – | – | – | – | – | – |
| 34 | Wax + imidacloprid | – | – | – | – | – | – |
| 35 | Wax + spinosad | – | – | – | – | – | – |
| 36 | Wax + cypermethrin | – | – | – | 1080 (ml ha\(^{-1}\)) | 0.040 | 108 |

Dosages g ha\(^{-1}\) or g stem\(^{-1}\) unless other units stated in parentheses. Tree dosages calculated assuming a restocking density of 2700 stems ha\(^{-1}\).

The active control.

was true of the pyrethrins treatment in which protection was significantly poorer than alpha-cypermethrin at Plascow (P < 0.05) and survival was not significantly better than untreated control trees at any site. Survival of transplants treated with maltodextrin was significantly (P < 0.05) worse than for trees treated with alpha-cypermethrin at both Plascow and Westwood, with no significant difference in survival from trees in the control plots.

When applied on their own, Flexcoat® and Weenet® barriers resulted in significantly (P < 0.05) poorer survival at Plascow compared with trees treated with alpha-cypermethrin. Otherwise, treatment differences were non-significant.

Experiment 2

In this experiment, due to the lack of alternative sites being available, the planting date was closer to the felling date than would have been ideal to maximize the chances of large on-site Hylobius populations. Nevertheless, populations of Hylobius and corresponding Hylobius-induced mortality were classed as intermediate at Myredykes, Ramsaygrain and Ruegill, and low at Bogrie, but there was no statistically significant interaction of treatment and site, and data were amalgamated across all sites (Figure 2). Overall, tree survival was above 50 per cent in untreated control plots and considerably and significantly (P < 0.05) higher in plots treated with alpha-cypermethrin.

The survival of transplants treated with the neonicotinoids imidacloprid and acetamiprid was up to 100 per cent, and not statistically different from those treated with alpha-cypermethrin. Spinosad resulted in slightly lower levels of survival than the pyrethroid and neonicotinoid treatments, but these differences were not significant.

Survival rates were similar across all azadirachtin-based treatments, were always significantly (P < 0.05) lower than those in the alpha-cypermethrin treatments and were in only in one instance significantly different from the untreated control. On its own, Flexcoat® provided no additional protection compared with the untreated control plots, and associated with other treatments, it also provided no significant additional protection.
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The biological agent *Metarhizium anisopliae* provided a significant ($P < 0.05$) but only small amount of additional protection when applied with Flexcoat®, compared with the untreated control treatment, but provided no significant additional benefit when added in mixture to the insecticides (Figure 2).

**Experiment 3**

Tree survival in untreated control plots was low at both Glen-gennet and Raeburn, and thus it was inferred that populations of *Hylobius* were intermediate to high at these sites (Figure 3). Alpha-cypermethrin resulted in 100 per cent protection from *Hylobius* at Raeburn, despite the high rate of damage in the untreated plots (Figure 3), and the difference in protection compared with control plots was statistically significant at both sites. Acetamiprid- and imidacloprid-only treatments provided 100 per cent protection of transplants across both sites. Combinations of acetamiprid with wax, Flexcoat® or *Metarhizium anisopliae* also resulted in very high transplant survival, as did combinations of imidacloprid with wax, Flexcoat® or *Metarhizium*. This was true

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**Figure 1** Transplant status after one growing season at Llandegla, Plascow, Watermeetings and Westwood in 2010, Experiment 1. Notes: Lettering indicates a statistical difference in the proportion of treatment survival (alive/alive (damaged) vs dead (due to *Hylobius*)) within-site; ($P < 0.05$; > 3 consecutive letters truncated with ‘–’ (e.g. ‘abcde’ = ‘a–e’)); ∗ = within-site significant difference to active control (3. alpha-cypermethrin); † = within-site significant difference to untreated control (P < 0.05). Other mortality and missing transplants were excluded from the statistical analysis. Treatment details are given in Tables 1 and 3.
Figure 2 Transplant status after one growing season at Bogrie, Myredykes, Ramsaygrain and Ruegill in 2012, Experiment 2. Notes: Lettering indicates a statistical difference in the proportion of treatment survival (alive/alive (damaged) vs dead (due to Hylobius); P < 0.05); * = significant difference to active control (3. alpha-cypermethrin); † = significant difference to untreated control (P < 0.05). Other mortality and missing transplants were excluded from the statistical analysis. Treatment details are given in Tables 1 and 4.

Despite lower concentrations of acetamiprid and imidacloprid being used in the treatments with Flexcoat® and Metarhizium anisopliae. Survival in these treatments was not significantly different to alpha-cypermethrin-treated plots.

Spinosad performed strongly, resulting in only marginally and non-significantly lower survival than alpha-cypermethrin, acetamiprid and imidacloprid. However, the number of sub-lethally damaged trees was always higher. Additions of Flexcoat® and wax did not significantly increase the protection provided by Spinosad.

When the biological agent Metarhizium anisopliae was applied in combination with Flexcoat®, but without any synthetic insecticide, the result was generally poor survival, which at both sites was significantly lower than the protection provided by alpha-cypermethrin (P < 0.05). The Flexcoat®/Metarhizium combination was not significantly better than the protection provided by Flexcoat® alone at Raeburn but was significantly better at Glengennet (P < 0.05). Adding Metarhizium anisopliae to other insecticides gave no significant additional benefit to the already good protection they provided (Figure 3).

The Kvaoe® wax treatment by itself gave only intermediate protection, but this was not significantly poorer than alpha-cypermethrin (P < 0.05). Full-plant (FP) applications of protective wax, with wax applied to the whole length of the stem but avoiding the foliage, did not significantly improve this protection. MultiPro also resulted in >90 per cent transplant survival at both sites (Figure 3).

When wax was combined with various insecticides, it provided little additional benefit to that already provided by the insecticides themselves. The garlic plus wax treatment resulted in only moderate transplant survival, and this was significantly poorer than the alpha-cypermethrin treatment at Raeburn. In contrast, the (S)-(-)-limonene and wax treatment resulted in considerable Hylobius-induced tree mortality, not significantly different from the untreated control at Raeburn. Strikingly, there was almost complete non-Hylobius transplant mortality when trees were treated with eucalyptus oil or geraniol, indicating severe phytotoxicity from these two compounds (Figure 3).

Experiment 4

Mean transplant survival in untreated control plots after one growing season was almost 75 per cent at Whey Knower, and Corris, inferring low Hylobius populations at these sites. In contrast, survival was very low at Lambsoudy and Smittons, inferring Hylobius populations were high, and these sites therefore provided the better test of efficacy of the various treatments in protecting against Hylobius damage (Figure 4). For all sites apart from Corris, losses in the untreated plots were significantly greater (P < 0.05) than in the alpha-cypermethrin treatment.

Conventional applications of 0.037 g a.i. stem⁻¹ acetamiprid resulted in nearly 100 per cent transplant survival after one growing season, even at Lambdoughty and Smittons. Batch applications, applied to 10 and 25 tree bundles in the nursery, resulted in statistically similar rates of survival after one growing season, but the level of protection dropped significantly below the conventional application on high population pressure sites after
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Figure 3  Transplant status after one growing season at Glengennet and Raeburn in 2013, Experiment 3. Notes: Lettering indicates a statistical difference in the proportion of treatment survival (alive/alive (damaged) vs dead (due to *Hylobius*) within-site (*P* < 0.05; >3 consecutive letters truncated with ‘–’ (e.g. ‘abcede’ = ’a–e’)); † = within-site significant difference to active control (2. alpha-cypermethrin); †† = within-site significant difference to untreated control (*P* < 0.05). Other mortality and missing transplants were excluded from the statistical analysis. Treatment details are given in Tables 1 and 5.

2 years (Figure 5). The ‘Trees Please’ acetamiprid-treated trees had significantly (*P* < 0.05) poorer survival than the conventional acetamiprid treatment (Figure 4). After 2 years, mortality due to *Hylobius* in the conventional acetamiprid treatment appeared to be smaller than that in alpha-cypermethrin-treated plots at three of the four sites, although this difference was only statistically significant at Smittons (Figure 5).

Treatment with thiacloprid or chlorantraniliprole resulted in high rates of survival at Lambdoughty and Smittons. At Smittons, survival in the chlorantraniliprole-treated plots was significantly better than that in alpha-cypermethrin-treated plots at three of the four sites, although this difference was only statistically significant at Smittons (Figure 5).

The organic repellents based on blood meal, sheep fat and capsicum generally had a negligible effect and consistently resulted in statistically lower survival than alpha-cypermethrin (all *P* < 0.05) at high population pressure sites. Survival was not significantly different to that observed in untreated controls. In general, when acetamiprid was combined with the repellents, survival only increased to the same level as was seen in the conventional acetamiprid treatment by itself (Figure 4).

In contrast to the results from Experiment 3, treating the whole stem with Kvaae® wax had a negative effect on transplant development and growth, resulting in high rates of mortality not attributable to *Hylobius*, but as the wax cover was reduced, the numbers of trees killed by *Hylobius* increased. At Smittons, survival in the wax treatments was not significantly different (*P* > 0.05) to that observed in the untreated controls. MultiPro® and BioSleeve® physical barriers gave some protection, with survival at Lambdoughty and Smittons at the end of the first
growing season being sometimes marginally and occasionally significantly ($P < 0.05$) better than the untreated control, and no different to the alpha-cypermethrin treated trees. Even so, survival of MultiPro® and BioSleeve® trees on the higher population pressure sites was unacceptably poor, even more so at the end of second growing season (Figure 5), and was significantly ($P < 0.05$) worse than in the acetamiprid-treated trees (Figures 4 and 5). For BioSleeve®, survival was also higher than the untreated control at the low population pressure site at Whey Knowe at the end of both the first and second growing seasons, but after 2 years non-lethal damage was high (Figure 5).

**Experiment 5**

Transplant survival in the untreated control treatments at Black Fell and Dunn’s Sike did not exceed 30 per cent at either location, and hence it was inferred that Hylolbus populations were high. Amongst the insecticide-treated plots, survival rates often differed markedly between the two sites, with an overall trend for lower survival at Dunn’s Sike (Figure 6). Pre-planting applications of cyberperthrin resulted in large and significant improvement in survival at Black Fell, but only for cyberperthrin at Dunn’s Sike, compared with untreated controls. Post-plant spraying of acetamiprid and imidacloprid resulted in statistically similar levels of protection to alpha-cypermethrin and cyberperthrin. However, at Dunn’s Sike, protection afforded by imidacloprid decreased at lower concentrations (Figure 6).

Spinosad provided less protection than alpha-cypermethrin, cyberperthrin, acetamiprid or imidacloprid, and it was usually not significantly different to the untreated control plots. Mid-year field top-ups of imidacloprid, acetamiprid and spinosad provided little additional benefit compared with using single post-planting sprays only of these insecticides.

The addition of a wax barrier to plants treated with cyberperthrin, acetamiprid, imidacloprid or spinosad had little effect on the overall level of protection. Likewise, the marker dye Acid Blue 9 had no consistent significant effects on transplant survival rates for any of the insecticide treatments indicating that it does not affect insecticide activity, and there was no evidence of any phytotoxic effects.

![Figure 4](https://academic.oup.com/forestry/article/93/5/694/5850434)

**Figure 4** Transplant status after one growing season at Corris, Lambdoughty, Smittons and Whey Knowe in 2014, Experiment 4. Notes: For Figure 3.

Treatment details are given in Tables 1 and 6.
Alternatives to conventional insecticides for protecting trees from *Hylobius abietis*

**Discussion**

**Synthetic pesticides**

The experiments reported here provide further evidence of high efficacy rates amongst the neonicotinoid class of insecticides in protecting young trees from attack by *Hylobius*, without causing phytotoxic effects on plants. Acetamiprid and imidacloprid were included as both pre- and post-planting spray treatments and performed consistently as well as, or better than, the industry standard, alpha-cypermethrin. Transplants treated with acetamiprid or imidacloprid regularly survived the first season on site, irrespective of whether the products were applied singly, on their own, in combination with physical products (e.g. Flexcoat®) or as part of top-up spray operations. Survival was often 100 per cent, even on sites where *Hylobius* populations were high and feeding pressure was intense (e.g. in Experiments 1 and 3). A further neonicotinoid insecticide, thiacloprid, was tested in Experiment 4. However, although it appeared to be equally as effective as acetamiprid, thiacloprid has subsequently been identified as a possible carcinogen (European Food Safety Authority, 2019), and its use is no longer permitted in the European Union (European Commission, 2020). Therefore thiacloprid was not pursued further in our work. Top-up applications of acetamiprid and imidacloprid in July of the first growing season did not further improve first year transplant survival in areas of high *Hylobius* damage pressure, e.g. at Dunn's Sike (Experiment 5). However, on the sites that were monitored over 2 years, survival in all treatments continued to deteriorate, indicating that on high population sites for trees initially pre-treated with 0.037 g a.i. stem⁻¹ acetamiprid, as the protection provided by the initial treatment starts to reduce, top-up sprays of 0.037 g a.i. stem⁻¹ acetamiprid are likely to be required in the spring of the second year after planting. To protect trees against *Hylobius* damage, insecticides are normally applied to the stems of individual trees as a nursery pre-treatment or using targeted spot guns or knapsack sprayers in the field (Willoughby et al., 2017). The alternative approach tested in Experiment 4 of treating batches of trees with acetamiprid using a knapsack sprayer produced mixed results, which suggest that this method should not be adopted without further investigation into its effectiveness. The marker dye Acid Blue 9 did not reduce the efficacy of any of the treatments; therefore it can be used in...
spray mixes as recommended by Willoughby (2007) to assist in targeting insecticide sprays, in minimizing drift and in reducing the risk of operator contamination.

Overall, the results from this study support those from complementary research reported by R. Moore, E. Wilson, I.H. Willoughby, T. Connolly, I. Sayyed, K. Leslie, et al. (in preparation) and demonstrate that the neonicotinoid insecticides tested are effective alternatives to synthetic pyrethroids in preventing *Hylobius* damage to young trees. However, neonicotinoid insecticides have attracted considerable attention from the scientific community and policy-makers in recent years because of their potential links to pollinator decline, most notably amongst bees, and potential wider impacts on ecosystem health (e.g. Lundin et al., 2015; Pisa et al., 2015). As a result, in 2018 the use of imidacloprid for protection of outdoor crops was banned in the European Union (European Commission, 2018). Nevertheless, unlike other neonicotinoid insecticides, acetamiprid has not been linked to bee decline. Given this, and because research showed acetamiprid to be as effective as alpha-cypermethrin or cypermethrin in protecting young transplants from damage by *Hylobius*, whilst being at least 500 times less toxic to aquatic life (based on Predicted No Effect Concentrations (PNEC) of 500 ng l$^{-1}$ for acetamiprid and 1 ng l$^{-1}$ for cypermethrin) (European Commission, 2004, 2005), the forest industry applied to the Chemicals Regulation Division of the UK Health and Safety Executive for an Extension of Authorisation for Minor Use (often abbreviated to ‘EAMU’) to use Gazelle SG® (containing acetamiprid) in forests. The Health and Safety Executive judged that this new use did not pose any additional risk to operators, bystanders and the wider environment, and hence they granted an approval (Health and Safety Executive, 2012). As a result, acetamiprid is now increasingly being phased in across the forest industry in the UK as an alternative to the use of conventional synthetic pyrethroid pesticides.

Chlorantraniliprole is a non-neonicotinoid synthetic insecticide that has a relatively low mammalian toxicity, is $\sim$100 times less toxic to aquatic life than alpha-cypermethrin or cypermethrin (MacBean, 2012) and has not been linked to bee decline. It was tested on four sites (Experiment 4) where it displayed promising rates of efficacy, similar to that of acetamiprid, with no obvious phytotoxic effects on plants. Further investigations into the efficacy of chlorantraniliprole are therefore recommended. Another non-neonicotinoid insecticide, lambda-cyhalothrin, was tested in

Figure 6 Transplant status after one growing season at Black Fell and Dunn’s Sike in 2013, Experiment 5. Notes: As for Figure 3. Treatment details are given in Tables 1 and 7.
one experiment, but the results were inconclusive. It provided poor protection at high pressure sites, but the level of protection was not significantly different from alpha-cypermethrin at low pressure sites. In addition, compared with chlorantraniliprole or acetamiprid, UK products containing lambda-cyhalothrin are also more toxic to mammals and bees. Further investigation into the efficacy of this active ingredient is therefore probably not a high priority at this stage. A further synthetic insecticide, spirotetramat, was tested in Experiment 4, but it provided very poor transplant protection and did not warrant further study.

**Bioinsecticides**

In our work, when the entomopathogenic biological control agent *Metarhizium anisopliae* was tested across six forest restock sites (in Experiments 2 and 3), it gave generally poor levels of transplant protection where *Hylobius* populations were intermediate to high, and mixing it with synthetic or natural product insecticides provided little additional benefit. However, given its demonstrated efficacy in laboratory conditions (Ansari and Butt, 2012), it would be worth investigating improved methods of deploying the pathogen and maintaining its stability and efficacy for protecting young trees in forest environments, for example, through its use in pheromone baited ‘lure and kill’ insect traps (El-Sayed et al., 2009).

**Natural product insecticides**

Spinosad was tested in Experiments 2, 3 and 5 across a total of eight restock sites, and whilst it showed some promise, the levels of protection it provided were very variable, and therefore ultimately unsatisfactory. Spinosad is primarily used on protected crops where good spray coverage is known to be key to achieving the best results. Applications made in the more challenging environmental conditions found on forest restock sites, coupled with potentially incomplete spray coverage, might have contributed to the poor results in Experiment 5, and it may be that spinosad is better suited to use only as a pre-planting application in carefully controlled conditions in a forest nursery. Although on the basis of our work spinosad could not currently be recommended as a potential alternative to conventional insecticides, further investigations aimed at retesting its efficacy as a potential pre-treatment for trees subsequently planted out on high population pressure sites would be worthwhile. Compared with chlorantraniliprole which is also recommended for further trials, spinosad has a similar, very low mammalian toxicity but is somewhat more toxic to bees (MacBean, 2012).

Neem is a plant-derived oil product that can have lethal and sublethal effects on non-target insects and therefore currently does not have a licence for outdoor use in the UK. None of the neem-based products we tested gave acceptable levels of protection from *Hylobius*. The azadirachtin natural product insecticide mix (Rigel M®) also performed poorly. Furthermore, transplants treated with azadirachtin showed severe phytotoxic effects, especially at higher concentrations. Others have reported similar phytotoxic effects (Thacker and Bryan, 2003; Thacker et al., 2003; Olenici and Olenici, 2006; Ivar et al., 2009).

The performance of pyrethrins was also poor. They provided adequate protection on sites with low populations of *Hylobius* but provided inadequate protection on sites where *Hylobius* pressure was high.

Maltodextrin was tested in Experiment 1 but gave very poor results. This is probably in part because unlike the other insecticides tested, it needs to be sprayed over the insects themselves to have any effect and therefore will not offer any protection if it is sprayed, as in our work, pre-emptively over plants before the insects start to forage. Making repeated, well-timed, reactive sprays to target actively browsing *Hylobius* is unlikely to be cost-effective or practical on most forestry restock sites; therefore at this stage further investigation into the use of maltodextrin is probably not warranted.

None of the repellents tested in our work – blood meal, sheep fat or the essential plant oils eucalyptus, geraniol, limonene, garlic or capsicum – provided any worthwhile protection against *Hylobius*, and in many cases they were also phytotoxic to young trees. Although it is possible that other as yet untested compounds might prove to be more effective, our evidence suggests that repellents are unlikely to have a major role in the protection of young trees from *Hylobius* damage.

**Physical barrier products**

The flexible barrier film Flexcoat® was tested in Experiments 1, 2 and 3, mostly in combination with other insecticides and biological agents, but provided no tangible benefit. The other flexible barrier film tested, the Kvaae® wax system, provided variable results. On higher *Hylobius* population sites, protection was poor, with survival levels comparable to those of the physical sleeve products. Increased stem coverage of wax was phytotoxic and reduced tree survival at several sites. Where damage was caused by *Hylobius*, it is likely to have been due to wax flaking off in cold weather to expose bare stem, weevils walking over the coating, or brash and other detritus on site allowing the insect to access and feed on untreated areas of the stem. However, the protection provided on low to intermediate population sites was sufficiently promising for further experiments involving wax to be established (work not reported here).

Weenet® provided a similar level of protection to alpha-cypermethrin on two of the low population sites in Experiment 1, although this result was not statistically significant from the untreated control, but non-lethal stem damage was still high on one of these sites which would probably have led to further deaths in later years. Where population levels were higher, the barrier was ineffective. On three of the four sites in Experiment 4, the MultiPro® and BioSleeve® barriers provided insufficient protection, but on a single, low population site (Whey Knowe), they were more effective, with BioSleeve® guards giving adequate protection for 2 years. MultiPro® barriers also provided adequate protection on two intermediate to high population sites in Experiment 3. Where failure of physical protection did occur, it is likely to have been due to insects accessing the tree stems via any gaps left between the base of the sleeves and the stem, or ‘bridging’ caused by brash or vegetation providing access to the upper parts of the transplants where they emerge from the protective barriers.

Overall, the physical barrier products Weenet®, MultiPro® and BioSleeve® did not consistently provide sufficient protection on most of the sites we tested them on. This result is contrary to other research, primarily in Sweden, where barriers have been found to be relatively effective in tree protection against *Hylobius* (e.g. Petersson et al., 2004; Eriksson et al., 2018). One explanation...
for the variable effectiveness of physical barriers is likely to be the comparative size of the *Hylobius* population and the resulting feeding damage pressure from site to site and possibly country to country (Kudela, 1983; Långström and Day, 2007). Studies on the continent have estimated overall stump populations of larvae to be in the range of 27 000 and 66 000 ha⁻¹ (Kudela, 1983), and other research has found weevil density on a typical clearfell site in southern Sweden to be in the region of 14 000 adult *Hylobius* ha⁻¹ (Nordlander et al., 2003). Recent studies indicate that larval stump populations in the UK are generally higher, ranging from 81 000 to 324 000 ha⁻¹. They also show that above-ground adult populations vary widely due to migrations to and from the site, as well as protracted periods of emergence and mortality, but there are typically between 2000 and 30 000 adult *Hylobius* ha⁻¹ at any point in time (Moore et al., 2004). It is probable therefore that many of the locations chosen for our work suffered from larger *Hylobius* populations than those found on most Swedish sites. In addition, Petersson and Örlander (2003) observed that unless suitable silvicultural practices such as scarification are also adopted, physical barriers by themselves do not give sufficient protection.

Anecdotal reports from user trials have suggested that physical barrier sleeves can be prone to being dislodged on wet and windy sites and their increased ‘sail area’ may cause trees to be blown over. It has also been reported that if the soil is very friable, it can sometimes be washed away from the base of sleeves, leaving stems unprotected, and that the sleeves do not always fit well on conifer species with low or heavy branches, leading to poor protection, although they are easier to fit on broadleaves. Barriers are also relatively expensive, being ~20 times the cost of pre-treating with alpha-cypermethrin and ~8 times the cost of pre-treating with acetamiprid. In addition, it has been reported that if barriers start to fail after 2–3 years and a top-up insecticide application is required because the on-site population pressure turns out to be higher than expected, then it would prove prohibitively expensive to remove the barriers to allow spraying to take place. The high initial cost, difficulty in use and lack of effectiveness on sites with typical, intermediate to larger *Hylobius* populations have reportedly limited the uptake of physical barriers to date in the UK, although conversely some users view them as being a practical and effective protection method, on what we assume must be low population pressure sites.

Based on the work reported here, we conclude that physical barrier sleeves, such as MultiPro®, BioSleeve® and to a lesser extent Weenets®, may have a limited role in UK forestry in preventing unacceptable levels of *Hylobius* damage to newly planted trees on sheltered sites, but only if the *Hylobius* Management Support System (Moore, 2018) or an alternative, reliable method of estimating population levels is used, and the onsite population is predicted to be low (i.e. <25 per cent untreated tree loss). Even then the barriers would need to be combined with the use of good-quality planting stock, possessing large root collar diameters and an appropriate balance between the dry weight of their roots and shoots (Morgan, 1999) and with suitable site preparation to create a weed and brash free site around the planted tree (Patterson and Mason, 1999; Willoughby et al., 2004). In these limited circumstances, physical barriers, as part of an integrated approach, may be worth considering as a potentially suitable, if more expensive, substitute for the use of insecticides in the UK (Willoughby et al., 2017).

Conclusions

The efficacy experiments reported here have identified the effectiveness of neonicotinoid insecticides as part of the integrated pest management of *Hylobius*, confirming other recent reports (Olenici et al., 2018; R. Moore, E. Wilson, I.H. Willoughby, T. Connolly, I. Sayyed, K. Leslie, et al., in preparation). Our results indicate that 0.037 g a.i. stem⁻¹ acetamiprid can provide a very similar, if not better, level of protection than the synthetic pyrethroids alpha-cypermethrin or cypermethrin, at least over the first year after tree planting. Of the other products and systems tested in our experiments, the insecticide chiorantraniliprole and natural product insecticide spinosad showed the greatest promise, at some sites offering levels of protection comparable to that of traditional synthetic pyrethroid pesticides. Nevertheless, our results are based in the main on surveillance over one season only, and we suggest that further targeted research should be undertaken to understand better how the use of these two insecticides, and in addition the bioinsecticide *Metarhizium anisopliae*, can be optimized before they can be recommended for use more widely. Regrettably, almost all of the other protection options tested fell short of providing satisfactory levels of tree protection on typical UK restock sites. The study suggests that the physical barrier methods we tested currently do not provide sufficient protection under typical UK conditions and should not be relied upon as a non-chemical control option, unless as part of an integrated approach where on-site *Hylobius* populations are predicted to be low.

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**Conflict of interest statement**

None declared.

**References**

Ansari, M.A. and Butt, T.M. 2012 Susceptibility of different developmental stages of large pine weevil *Hylobius abietis* (Coleoptera: Curculionidae) to entomopathogenic fungi and effect of fungal infection to adult weevils by formulation and application methods. *J. Invertebr. Pathol.* **111**, 33–40.

Batish, D.R., Singh, H.P., Kohli, R.K. and Kaur, S. 2008 Eucalyptus essential oil as a natural pesticide. *For. Ecol. Manage.* **256**, 2166–2174.

Benelli, G., Canale, A., Toniolo, C., Higuchi, A., Murugan, K., Pavela, R., et al. 2017 Neem (*Azadirachta indica*): Towards the ideal insecticide? *Nat. Prod. Res.* **31**, 369–386.

Brown, A., Willoughby, I., Clay, D.V., Moore, R and Dixon, F.L. 2003 The use of dye markers as a method of reducing herbicide use and potential environmental impacts. *Forestry* **76** (4), 371–384.

Clay, D.V., Dixon, F.L. and Willoughby, I. 2005 Natural products as herbicides for tree establishment. *Forestry* **78** (1), 1–9.

Copping, L.G. (ed.) 2009 *The Manual of Biocontrol Agents: A World Compendium*. 4th edn. British Crop Production Council.

Eidmann, H.H. 1985 Silviculture and insect problems. *Z Angew Entomol.* **99**, 105–112.

El-Sayed, A.M., Suckling, D.M., Byers, J.A., Jong, E.B. and Wearking, C.H. 2009 Potential of “lure and kill” in long term pest management and eradication of invasive species. *J. Econ. Entomol.* **102** (3), 815–835. doi: 10.1603/029.102.0301.

Eriksson, S., Wallertz, K. and Karlsson, A-B. 2018 Test av mekaniska plantskydd mot snytbaggar i omarkberedd och markberedd mark, anlagt våren 2015. Sveriges Lantbruksuniversitet Rapport **16**, 22 p. https://pub.epison.slu.se/15698/1/eriksson_s_et_al_181010.pdf.

European Commission. 2004 Review report for the active substance acetamiprid, *European Commission Working Document SANCO/1392/2001 – Final*. www.ec.europa.eu/food/plant/pesticides_en.

European Commission. 2005 Review report for the active substance cypermethrin. *European Commission Document SANCO/4333/2000*. www.ec.europa.eu/food/plant/pesticides_en.

European Commission 2013 Directive 2013/39/EU of the European Parliament and of the council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy. *Off. J. Eur. Union L 226*. www.ec.europa.eu.

European Commission 2018 Commission Implementing Regulation (EU) 2018/783 of 29 May 2018 amending Implementing Regulation (EU) no 540/2011 as regards the conditions of approval of the active substance imidacloprid. *Off. J. Eur. Union L132 61*, 31–34. www.ec.europa.eu.

European Commission 2020 Commission Implementing Regulation (EU) 2020/23 of 13 January 2020 concerning the non-renewal of the approval of the active substance thiacloprid, in accordance with Regulation (EC) no 1107/2009 of the European Parliament and of the Council concerning the placing of plant protection products on the market, and amending the annex to Commission Implementing Regulation (EU) no 540/2011. *Off. J. Eur. Union L88–8/11*, 14/1/2020. www.ec.europa.eu.

European Food Safety Authority. 2019 Peer review of the pesticide risk assessment of the active substance thiacloprid. *EFSA J.* **17** (2): 5595. doi: 10.2903/j.efsa.2019.5595.

Forestry Commission. 2019 Forestry Statistics 2018. https://www.forestrysearch.gov.uk/documents/5471/Complete_FS2018_74CYDs1.pdf.

FSC. 2019 Forest Stewardship Council Pesticides Policy. FSC-POL-30-001 V3–0. The Forest Stewardship Council. www.fsc.org.

Holmis, D. and McCarthy, M. 2013 UKCPO9: Met Office Gridded and Regional Land Surface Climate Observation Datasets. Centre for Environmental Data Analysis, (accessed on 18 October 2019).

Harvey, C.D., Williams, C.D., Dillon, A.B. and Griffin, C.T. 2016 Inundative pest control: how risky is it? A case study using entomopathogenic nematodes in a forest ecosystem. *Forest. Ecol. Manag.* **380**, 242–251.

Health and Safety Executive. 2012 Extension of authorisation for a minor use of the plant protection product Gazzelle SG. Extension of Authorisation Number 1068 of 2012. www.hse.gov.uk/pesticides.

Heritage, S., Collins, S.A. and Evans, H.F. 1989 A survey of damage by *Hylobius abietis* and *Hylophilus spp*. in Britain. In *Proceedings of the Eighteenth IUFRO International Conference of Entomology: Insects Affecting Reforestation: Biology and Damage*, pp. 36–42.

Houston Durrant, T., Mauri, A., de Rigo, D. and Caudullo, G. 2016 *Picea schischkin* in Europe: distribution, habitat, usage and threats. In *European Atlas of Forest Tree Species*. J., San-Miguel-Ayanz, D., de Rigo, G., Caudullo, T., Houston Durrant, A., Mauri (eds.). Publ. Off. EU. p. e013701+.

Ibrahim, M.A., Kainulainen, P., Aflatoni, A., Tiilikkala, K. and Holopainen, J.K. 2001 Insecticidal, repellent, antimicrobial activity and phytotoxicity of essential oils: with special reference to limonene and its suitability for control of insect pests. *Agric. Food Sci.* **10**, 243–259.

Ivan, S., Poomf, A. and Voolma, K. 2009 Influence of neem oil on the large pine weevil, *Hylobius abietis* L. (Coleoptera, Curculionidae). *Baltic For.* **15**, 255–261.

Kudela, M. 1983 Influence of site temperature conditions on large pine weevil (*Hylobius abietis*) population density. *Sborník Ustávů Aplikované Ekologie a Ekotechniky Vysoko Školy Zemědělské Praze* **1**, 129–148.

Långström, B. and Day, K.R. 2007 Damage, control and management of *Hylobius abietis*. In *Bark and Wood Boring Insects in Living Trees in Europe, a Synthesis*. F., Lieutier, K.R., Day, A., Battisti, J.-C., Grégoire, H.F., Evans (eds.). Springer, pp. 415–444.

Leather, S.R., Day, K.R. and Salisbury, A.N. 1999 The biology and ecology of the large pine weevil, *Hylobius abietis* (Coleoptera: Curculionidae): a problem of dispersal? *Bull. Entomol. Res.* **89**, 3–16.

Lenth, R., Singmann, H., Love, J., Buerkner, P. and Herve, M. 2019 emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.3.3. https://CRAN.R-project.org/package=emmeans.

Lundin, O., Rudloff, M., Smith, H.G., Fries, I. and Bommarco, R. 2015 Neonicotinoid insecticides and their impact on bees: a systematic review of research approaches and identification of knowledge gaps. *PLoS One* **10**, e0136928. doi: 10.1371/journal.pone.0136928.
Luoranen, J. and Viiri, H. 2005 Insecticides sprayed on seedlings of Picea abies during active growth: damage to plants and effect on pine weevils in bioassay. Scand. J. Forest Res. 20, 47–53.

MacBean, C. (ed.) 2012 The Pesticide Manual: A World Compendium. 6th edn. British Crop Protection Council.

Moore, R. 2004 Managing the threat to restocking posed by the large pine weevil, Hylobius abietis: the importance of time of felling of spruce stands. Forestry Commission Information Note. 61. Forestry Commission.

Moore, R. 2018 Hylobius Management Support System (MSS). https://www.forestresearch.gov.uk/tools-and-resources/tree-health-and-protection-services/hylobius-management-support-system/.

Moore, R., Brixy, J.M. and Milner, A.D. 2004 Effect of time of year on the development of immature stages of the large pine weevil (Hylobius abietis L.) in stumps of Sitka spruce (Picea sitchensis Carr.) and influence of felling date on their growth, density and distribution. J. Appl. Entomol. 128, 167–176.

Moore, R., Wilson, E., Willoughby, I.H., Connolly, T., Sayyed, I., Leslie, K., et al. in preparation. The insecticides acetamiprid and imidacloprid can effectively protect Sitka spruce transplants from damage by the large pine weevil Hylobius abietis.

Morgan, J.L. 1999 Forest tree seedlings – best practice in supply, treatment and planting. Forestry Commission Bulletin. 121. Forestry Commission.

Mossa, A.-T.H. 2016 Green pesticides: essential oils as biopesticides in coating (Conniflex) for the protection of conifer seedlings against damage. J. Chem. Ecol. 42, 1307–1320.

Nordlander, G. 1990 Limonene inhibits attraction to α-pinene in the pine weevils Hylobius abietis and H. pinastri. J. Chem. Ecol. 16, 1307–1320.

Nordlander, G., Bylund, H., Örlander, G. and Wallertz, K. 2003 Pine weevil population density and damage to coniferous seedlings in a regeneration area with and without shelterwood. Scand. J. Forest Res. 18, 438–448.

Nordlander, G., Nordenhem, H. and Hellqvist, C. 2009 A flexible sand coating (Conniflex) for the protection of conifer seedlings against damage by the large pine weevil Hylobius abietis. Agr. Forest Entomol. 11, 91–100.

Olenici, N. and Olenici, V. 2006 Antifeedant effect of Neemazal-T/S on the large pine weevil Hylobius abietis L. Analele ICAS 49, 107–118.

Olenici, N., Manea, I.A., Olenici, V. and Tomescu, R. 2014 Efficacy of conifer seedling protection against pine weevil damage using neonicotinoids and metalflumizone insecticides. Bulletin of the Transylvania University of Brasov, Series II: Forestry, Wood Industry, Agricultural Food Engineering 7, 29–36.

Olenici, N., Bouriaud, O. and Manea, I.A. 2018 Efficient conifer seedling protection against pine weevil damage using neonicotinoids. Baltic For. 24 (2): 201–209.

Patterson, D.B. and Mason, W.L. 1999 Cultivation of soils for forestry. Forestry Commission Bulletin. 119. Forestry Commission.

Petersson, M. and Örlander, G. 2003 Effectiveness of combinations of shelterwood, scarification, and feeding barriers to reduce pine weevil damage. Can. J. For. Res. 33, 64–73.

Petersson, M., Örlander, G. and Nilsson, U. 2004 Feeding barriers to reduce damage by pine weevil (Hylobius abietis). Scand. J. Forest Res. 19, 48–59.

Pisa, L.W., Amaral-Rogers, V., Belzunces, L.P., Bonmatin, J.M., Downs, C.A., Goulson, D., et al. 2015 Effects of neonicotinoids and fipronil on non-target invertebrates. Environ. Sci. Pollut. Res. 22, 68–102.

Rose, D., Leather, S.R. and Matthews, D.A. 2005 Recognition and avoidance of insecticide-treated scots pine (Pinus sylvestris) by Hylobius abietis (Coleoptera: Curculionidae): implications for pest management strategies. Agr. Forest Entomol. 7, 187–191.

R Core Team. 2018 R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. https://www.R-project.org/.

Schmutterer, H. 1990 Properties and potential of natural pesticides from the neem tree, Azadirachta Indica. Annu. Rev. Entomol. 35, 271–297.

Thacker, J.R.M. and Bryan, W.J. 2003 Use of neem in plant protection in temperate forestry. In The Science and Application of Neem. M., Cole, R., Strang (eds.). Bioforce Research, pp. 15–18.

Thacker, J.R.M., Bryan, W.J., McInley, C., Heritage, S. and Strang, R.H.C. 2003 Field and laboratory studies on the effects of neem (Azadirachta indica) oil on the feeding activity of the large pine weevil (Hylobius abietis L.) and implications for pest control in commercial conifer plantations. Crop Prot. 22, 753–760.

UKWAS. 2012 The UK Woodland Assurance Standard. 3rd edn, version 3.1. UKWAS. www.ukwas.org.uk.

Willoughby, I. 2007 Using dye markers to reduce pesticide use. Forestry Commission Technical Note. 16. Forestry Commission.

Willoughby, I., Evans, H., Gibbs, J., Pepper, H., Gregory, S. and Dewar, J. 2004 Reducing pesticide use in forestry. Forestry Commission Practice Guide. 15. Forestry Commission.

Willoughby, I., Moore, R. and Nisbet, T. 2017 Interim guidance on the integrated management of Hylobius abietis in UK forestry. Forest Research Research Note, https://www.forestresearch.gov.uk/documents/607/FR_InterimguidanceonmanagementHylobiusabietis_2017.pdf.

Wilson, R.P., Richards, R., Hartnell, A., King, A.J., Piasceka, J., Gaihre, Y.K., et al. 2014 A new approach to quantify semiochemical effects on insects based on energy landscapes. PLoS One 9, e106276. doi: 10.1371/journal.pone.0106276.