INTEGRATED PEST MANAGEMENT OF THE LARGE PINE WEEVIL *HYLOBIUS ABIETIS*:

REVIEW AND PERSPECTIVES FOR IRELAND

Integrated pest management of the large pine weevil *Hylobius abietis*: review and perspectives for Ireland

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EXECTIVE SUMMARY

The large pine weevil *Hylobius abietis* is a serious pest of reforestation in Ireland. Adult weevils cause damage by feeding on the bark of young trees, both coniferous and deciduous. By eating around the stem, or “ring-barking”, they can kill up to 100% of unprotected trees. Conifer stumps remaining on clear-felled sites are ideal breeding material for this weevil and adult weevils emerging from these stumps attack the newly planted trees. Thus, pine weevil is a pest wherever conifer plantations are clearfelled and sites replanted with any trees.

Nearly 11% of the land of Ireland is afforested and national policy is to encourage afforestation to reach a target of 17% by 2030. In Ireland, the vast majority of forest stands are managed under the clearfell and replant system and it is a condition of felling licences that sites must be replanted. Most of the State forests which were established since the 1920s are in the reforestation phase. Increasingly, plantations in the private and farm forestry sector are coming up to felling and restocking in the next ten years. Approximately 10,000 ha of forests are felled and restocked annually, of which about 80% is Coillte and 20% is in the private sector. This is expected to increase to 16,000 ha per annum (50% state and 50% private). An increase in felling and replanting will increase the pine weevil problem. This increase in the scale of the pine weevil problem comes at a time when practices are changing with regard to chemical pesticides- the main weapon in the fight against pine weevil.

Seedlings on sites judged to be at risk from pine weevil are routinely treated with chemical insecticides. Products available for this purpose are subject to constant revision by the regulatory authorities and by bodies responsible for the certification of forests as according with the principles of Sustainable Forest Management (SFM). Moreover, in line with the EU Sustainable Use of Pesticides Directive (and national policy), reliance on chemical pesticides should be reduced, while Integrated Pest Management (IPM) should be promoted. In IPM, insecticides should be used in combination with other approaches, including cultural practices, physical barriers and biological control, together with some form of decision support system to select the most appropriate strategy or strategies for use at a particular site. This report reviews practices currently in use against pine weevil in Ireland (primarily in Coillte estate, where the pest is an established problem) as well as practices used or trialled elsewhere in Europe.

Coillte uses a weevil management decision chart in which risk from pine weevil on a site is assessed by a combination of “stump hacking”, which gives a measure of the pine weevil population developing on site, along with consideration of other site factors such as species of previous crop and proximity to other clearfells. Non-pesticide options that are used include early planting, use of more vigorous planting stock, mounding and feeding barriers. The measures adopted by Coillte are also recommended by Teagasc for use by private forestry. This report reviews methods that have been tested both in Ireland and in Europe. Measures that are successful elsewhere may not work as well in Ireland, due to differences in weevil population size and behaviour, and to differing silvicultural practices.

Recommendations

1. Ensure effective supports (financial/other) for field trials of promising products or approaches in Ireland
2. Support for novel alternatives from fundamental research to commercial development, especially where novel solution may have export market (DAFM/other state funding including Enterprise Ireland)
3. Validate and refine Coillte’s existing decision support system, and evaluate for use in the private sector
4. Consolidate knowledge of pine weevil population dynamics in Ireland, including regional trends and patterns, taking into account future climates; probability and distance of weevil flight is a key concern
5. Revisit the UK HMMs system or develop a predictive model for pine weevil in Ireland. Stump hacking should be incorporated as a base-line
6. Ensure knowledge transfer to the private sector, including one-day training sessions for private forestry consultants and updating the Teagasc booklet (produced in 2020) as required
7. Establish a national *Hylobius* interest group with representatives of key stakeholders such as ITGA, Coillte, Teagasc and DAFM (including Forest Service and PCS)
8. Consolidate information on *Hylobius* populations, risk factors and mitigation strategies (such as biomass removal) from end-users. The value of anecdotal reports could be enhanced by incorporation into a centralised system. Feeding user experience back into a national management/forecasting system would validate and improve the system.

1.INTRODUCTION

1.1 Pine weevil as a pest

The large pine weevil *Hylobius abietis* is a **serious pest of reforestation** in Ireland. Adult weevils cause damage by feeding on the bark of young trees, both coniferous and deciduous. By eating around the stem, or “ring-barking”, they can kill up to 90% (average 50%) of unprotected seedlings (Heritage & Moore, 2001). Conifer stumps remaining on clear-felled sites are ideal breeding material for this weevil and adult weevils emerging from these stumps attack the newly planted trees. Thus, pine weevil is a pest wherever conifer plantations are clear-felled and sites replanted with any trees.

1.2 Biology of the pine weevil

The large pine weevil (Figure 1) **occurs naturally** in coniferous and mixed forests over much of Europe and Asia (Leather et al., 1999). In standing forests, adult weevils feed on branches and roots, but damage is minor relative to the size of mature trees and is therefore not considered a problem. Larvae feed on the roots of dying or recently dead trees. When a standing forest is clear-felled, adult pine weevils are attracted by the smell of recently felled conifer stumps, and colonise the clear-felled site from nearby standing forests or older clearfells. Here, adults feed on any fresh woody material available including any newly planted seedlings, and lay eggs into or close to the stumps and roots of the felled trees (Nordlander et al., 1997).

The oviposition (egg laying) period is mostly from mid-May to early June, but can extend until September (Leather et al., 1999). Larvae feed under the bark, both above ground and at depths of up to a metre underground. The duration of weevil development from egg to adult ranges from one to four years, depending mainly on temperature but also on the species of the stump. In most parts of its distribution including Ireland, the **life cycle** from egg to egg takes two years (Inward et al., 2012). On the other hand, in warmer conditions (such as the south-east of England), the life cycle can be completed within a year (univoltine). It is expected that with climate change, the regions in which the pine weevil is univoltine will increase (Wainhouse et al., 2014).

Most adults eclose (develop from pupae) in the late summer following the year in which the egg was laid (Leather et al., 1999). Some adults make their way to the surface directly after eclosion and feed (autumn feeding) before overwintering, whereas some stay underground and overwinter directly. Adult pine weevils overwinter in the soil and resume activity in the spring when temperatures reach 8-9°C. During spring, the adults have a period of maturation feeding (spring feeding). It is also during or just before this time that long distance migration by walking or flight takes place. Conifer stumps on clear-fell sites are ideal breeding material - a stump can contain up to 300 larvae (Dillon and Griffin, unpublished data) - and the quantity of accessible material leads to high population densities. Stumps can remain suitable for weevil development for up to 5 years. Once established on a breeding site, adult weevils feed through the warm parts of the year, which can be from March until November. Due to periods of migration and emergence during the weevil's life cycle, the main damage periods are in spring and autumn (Figure 2).

Figure 1. Stages of the pine weevil life cycle. Upper: adult; lower (left to right): larva, pupa, newly developed adult, adult). Adults are 8-14 mm long and are black or brown-black with yellow spots and bands on the elytra and pronotum. In older adults the yellow "hairs" can be worn down and difficult to see. Eggs (not shown) are white. The larvae are yellow-white with a broad brown head and no legs. Larval development includes four larval moults before pupation

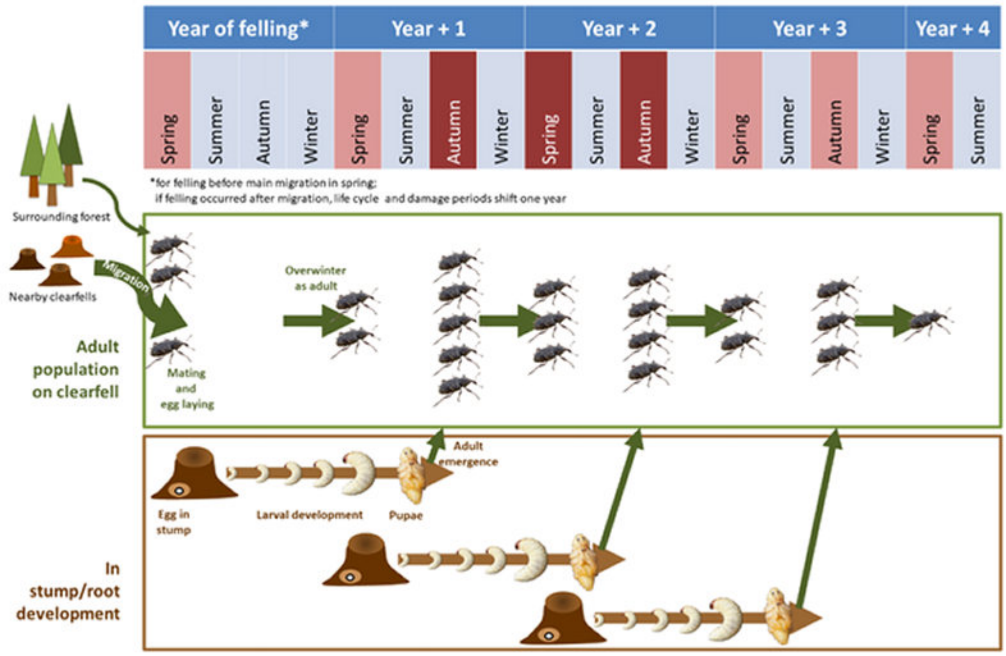

Figure 2. Schematic life cycle and population dynamics of pine weevil on a clear-fell site

1.3 Irish forestry in the context of pine weevil

Nearly 11% of the land of Ireland is afforested (over 770,000 ha in 2017 (Forest Service, 2018)) and national policy is to encourage afforestation to reach a target of 17% by 2030.In Ireland, the vast majority of forest stands are managed under the clearfell and replant system with a standard forest rotation of 40-50 years; it is a condition of felling licences that sites must be replanted. As described above, pine weevils are attracted to these clearfell areas creating habitat conducive to high density populations. Most of the State forests, which were established since the 1920s, are in the reforestation phase. Increasingly, plantations in the private and farm forestry sector planted in the 1990s, where the majority of the growth is taking place, are coming up to felling and restocking in the next ten years. Approximately 10,000 ha of forests are felled and restocked annually, of which about 80% is Coillte and 20% in the private sector. This is expected to increase to 16,000 ha per annum (50% state and 50% private). An increase in felling and replanting will increase the large pine weevil problem: more felled stumps mean more breeding material and more replanted seedlings means potentially more damaged seedlings. Conifer species (mainly Sitka spruce) are the dominant species present, representing 71.2% of the stocked forest area (Forest Service, 2018). Although only conifers support pine weevil development, the pest attacks all woody species. Thus, pine weevil poses a significant threat to Irish forestry, and the extent of the weevil problem will expand at the same time as existing chemical controls are withdrawn. Unlike state forestry, the private forestry sector has limited experience of dealing with large pine weevil, and so its increasing importance of for the private sector creates a need for strategy and information dissemination about this pest.

Ireland is committed to **Sustainable Forest Managemen**t (SFM).The **Irish National Forest Standard** outlines the basic criteria and indicators relating to the implementation of SFM. More specifically, **Forest Protection Guidelines**, which apply to all grant-aided projects and to all activities associated with a felling license in Ireland, set out the practical measures based on the principles of SFM and include a list of measures for prevention and control of the large pine weevil. For assessment at the local level, various independent and privately run schemes of forest certification have been developed. The main independent **SFM certification schemes** operating in Ireland and other European countries are The Forest Stewardship Council (FSC) (www.fsc.org) and The Programme for the Endorsement of Forest certification schemes (PEFC)(www.pefc.org).
Coillte forests are both FSC and PEFC certified. Private owners are increasingly interested in certification, with group certification the main option as certification costs are shared amongst many forest owners. There are many Forest Owners Groups active in Ireland, set up and/or supported by Teagasc. The move towards certification is driven by market demand as it is increasingly difficult for Irish sawmills to export uncertified timber (Teagasc, 2021).

Currently the main approach to prevent pine weevil damage in Ireland is to use chemical insecticides (Section 3). However, there are increasing concerns for human health and natural ecosystems from the use of chemical insecticides (Anonymous, 2015; Forest Stewardship Council Sweden, 2014). Alternatives for plant protection products are needed, as according to the Sustainable Use of Pesticides Directive (SUD;2009/128/EC) and the Irish National Action Plan on the SUD (DAFM, 2019) reliance on chemical pesticides should be reduced while integrated pest managements (IPM) should be promoted.

1.4 Integrated Pest Management

Integrated Pest Management (IPM) is an effective and environmentally sensitive approach to pest management that takes the ecology of the pest species into consideration. Information on pest biology, in combination with available pest control methods, is used to manage pest damage by the most economical and environmentally sensitive means, and with the least possible hazard to people, property and the environment. In IPM all possible options including cultural practices, biological control, application of pesticides and physical protection are taken into consideration. Depending on the specific properties of each site, and with the help of decision support tools, appropriate protection methods and their timing can be selected. Based on knowledge about the life cycle of the pest, application of e.g. pesticides can be reduced to times when the insects are most vulnerable to it.

Ideally, pesticide-free management for pine weevils would be reached in the future and progress towards this goal has been made in Sweden (Forest Stewardship Council Sweden, 2014, 2018; Jägestedt, 2019). However, due to a higher estimated level of pine weevil population in Ireland and the UK (Willoughby et al., 2017), it is unlikely that the same progress can be made in these islands, and chemical insecticides will probably still be economically necessary as part of IPM for pine weevil.

IPM for pine weevil: current practice in Irish forestry

Coillte has implemented steps towards the use of IPM methods in state forests (Anonymous, 2016). Alternative methods to pesticides are considered based on a "Weevil management decision chart" (Figure 4) before any action is taken (Anonymous, 2016). To inform the decision, "Stump hacking" is used to predict the likely weevil pressure on a site. Non-pesticide management options that are used include early planting, use of more vigorous planting stock, mounding and feeding barriers. Where insecticide use is indicated, dipped plants are used followed by top-up sprays if required based on the results of stump hacking and crop monitoring. New approaches are constantly tested and evaluated for incorporation into IPM (Anonymous, 2016). The Irish Forestry Unit Trust adopts a similar approach in its forests and includes planting higher tree numbers initially, to absorb moderate weevil mortalities (Anonymous, 2016). The measures adopted by Coillte are also recommended by Teagasc for private forestry (Teagasc, 2020). Each of these approaches is explained in more detail later in this document.

IPM for pine weevil in the UK

Extensive research has been undertaken on the large pine weevil in the UK by Forest Research, resulting in a number of useful "Information Notes" on pine weevil (Heritage & Moore, 2001; Moore, 2004; Wainhouse et al., 2007) and, more recently, a comprehensive document entitled "Interim guidance on the integrated management of *Hylobius abietis* in UK forestry" by (Willoughby et al., 2017). This report should apply largely to Ireland, though pertinent ways in which silviculture differs between UK and Ireland should be noted: (1) There is less regional variation in the life cycle duration in Ireland with less likelihood of univoltine cycles compared to the UK. (2) Nursery treatments with insecticides in the UK are by spraying the seedlings, whereas in Ireland the seedlings are dipped. (3) A fallow period of at least five years is discussed as an option in the UK, but in Ireland, the felling licence limits the fallow time. (4) The *Hylobius* Management Support system used in the UK to predict pine weevil pressure on a clearfell site was not found suitable for use in Ireland.

1.5 Aim of this report

This report compiles information on protection methods against the pine weevil that were, are or could be considered in Ireland. Many different approaches to prevent pine weevil damage have been developed in a variety of European countries. Due to differing climate condition and/or silvicultural methods, protection methods developed elsewhere must be evaluated under the specific circumstances of each country's forestry.

This report includes protection methods that are described in the scientific and grey literature with the addition of stakeholder experience. As well as successful approaches, we include methods that were not successful in other countries, as some of these approaches might depend on environmental conditions. The inclusion of unsuccessful methods provides a record of what has been tried, so unnecessary repetition is avoided, as well as inspiration for new approaches.

The protection methods in this report are structured into the four categories "**cultural**", "**chemical**", "**biological**" and "**physical**" methods. These are followed by a section on decision support tools, which can be used to inform the choice of whether and which protection to employ.

2.SITE FACTORS AND SILVICULTURAL METHODS INFLUENCING THE LARGE PINE WEEVIL

Cultural methods of plant protection are practices that either avoid high levels of pest infestation or develop conditions that are unfavourable for the pest. In the case of pine weevil, this includes silvicultural measures adopted mainly in regard to pine weevil (such as “hot planting” of plants with large root collar diameter). In this section we also include factors that influence the risk of pine weevil and can be taken into account when assessing the risk of damage on site, and hence the appropriate mitigation strategy (see Figure 4).

Table 1: Summary of site factors/silvicultural methods that increase and decrease the risk of pine weevil damage

Factor	Increaed Risk	Decreased Risk
Soil Type	Peat	Mineral; scarification, mounding
Felled Crop	Conifer, especially pine	Broadleaf
Location	Recent clearfell areas nearby	No recent clearfells nearby
Planting stock	Conifer	Bare-rooted; large stem diameter
Vegetation	Grassy	Woody (e.g. bramble)
Time of planting		Direcly (before weevils can develop on site)
Time of felling/planting	Refer to Fig. 3	Refer to Fig. 3
Forest management	Clearfell	Continuous cover forestry/shelter trees

SITE FACTORS

2.1 Soil

Soil properties influence the extent of pine weevil damage (Luoranen et al., 2017; Wallertz et al., 2018), largely due to differences in behaviour of adult pine weevils which dislike crossing bare mineral soil. Generally, plants in bare mineral soil suffer less damage than plants in organic-rich humus soils (peats) (Björklund et al., 2003). The soil on a clearfell cannot be changed, but there are some ways of manipulating it that can influence pine weevil damage, such as scarification and mounding.

Soil scarification is a method often used in Scandinavian countries (Petersson & Örlander, 2003; Pitkänen et al., 2005; Von Sydow, 1997). The main result is that the original topsoil is replaced by different soil. Scarification reduces the number of seedlings killed (Huser, 1979; Petersson & Örlander, 2003). There are different methods of scarification, and the choice of which one to use is dependent on site characteristics (Wallertz et al., 2018). In the context of pine weevil protection, the topsoil is usually a humus/peat soil layer that is replaced by mineral soil. Clearfells that have a thin humus/peat soil layer with mineral soil underneath can be more easily scarified than clearfells with thick humus/peat soil layer. Scarification must be conducted properly as humus that is mixed into the mineral soil reduces the effect (Petersson & Örlander, 2003; Petersson et al., 2005). The planting location within the scarified areas is also important (Pitkänen et al., 2005): planting centrally in the scarified soil increases the positive effect of scarification compared to planting at its border (Luoranen et al., 2017; Pitkänen et al., 2005). The effect of scarification in protecting trees against weevils is slowly reduced by grass colonising the scarified areas (Örlander & Nordlander, 2003).

Scarification can, but does not have to, include **mounding** (Fig. 3A). Mounding reduces the amount of pine weevil feeding (Nilsson & Örlander, 1995; Nordlander et al., 2005; Örlander & Nilsson, 1999). This might be due to pine weevils having difficulty climbing sandy slopes (Nordlander et al., 2005). Mounding does not necessarily turn the mineral soil on top, but the slopes of the mound should still influence pine weevil movement. Furthermore, competition from other vegetation (see below) for the seedlings is reduced. Mounding is performed for other purposes, such as water regulation. Currently it is practised on applicable sites in Ireland for better plant growth. Not all soil types are suitable for mounding and a lot of mounding is done on afforestation sites, where pine weevil are generally not a problem (Forest Service, 2018).

Fertilisation and **soil amendment** can influence plant growth. The decision to fertilise is mostly governed by economic reasons.

A B

Figure 3. A. Planting in mounds and/or in mineral soil can reduce pine weevil damage. B. Fresh brash can be used as alternative food source by pine weevil

Fertilisation can change the chemical composition of plants and thereby influence pine weevil feeding. Fertilisation, especially with phosphorous, but also other fertilisers (N, K, Mg) enhanced plant growth but also resulted in increased pine weevil feeding damage (Blanch et al., 2012; Zas et al., 2008; Zas et al., 2006). Plants that are rich in silicon are usually harder for insects to chew than silicon-poor plants, but the addition of silicon to the soil did not influence pine weevil damage in trials conducted in Ireland (Hogan et al., 2018).

2.2 Location

It is difficult to predict the size of pine weevil population at any given place (Von Sydow, 1997; Zumr & Stary, 1994). Local pine weevil populations on a clearfell are affected by landscape factors, such as the presence of **older clearfells nearby** as a source of weevils. Based on laboratory studies in Sweden, pine weevils can fly on average 10 km with some individuals reaching distances of up to 80 km (Solbreck, 1980). The extent and scale of pine weevil flight in Ireland is unknown. Data from Sweden and the UK respectively indicate that weevil flight is temperature dependent, only occurring at temperatures greater than 18oC (Solbreck & Gyldberg, 1979). Their ability to fly has been observed to decline due to regression of flight muscles after the main migratory period in May (Tan et al., 2011), but further north in Scotland flight has been observed to occur during June (R. Moore, Forest Research, pers. comm.) Therefore, flight might be expected in a warm May/June period.

2.3 Clearfell site properties

In addition to older clearfell sites nearby, **neighbouring forests** are also a source of pine weevils, where they exist in low numbers. Suitability of standing forests as a source of adult weevils varies. For example, a study in the Czech Republic found that old spruce forests had the lowest pine weevil population, compared to pine forests and mixed forests (Zumr & Stary, 1994).

The species of the previous crop affects the number of weevils multiplying on site. Pine weevils only develop in conifer stumps, but not all conifer species are equally suitable for them. Pine weevil develop faster and in higher numbers in pine than in spruce (Bejer-Petersen, 1975), while some species such as Japanese larch are much less suitable for pine weevil development, with high mortality of larvae (Thorpe & Day, 2002).

The impact of **vegetation** on weevil damage is unclear. Positive, negative or neutral effects have been reported (Nilsson & Örlander, 1995; Örlander & Nilsson, 1999; Örlander et al., 2001; Petersson & Örlander, 2003; Wallertz et al., 2005) or effects were seen only on certain sites (Stokes & Willoughby, 2011). The effect of vegetation on weevil damage may depend on soil type. For example, on mineral soil, vegetation experimentally placed around seedlings increased feeding damage, as pine weevil used the vegetation as shelter (Petersson et al., 2006), while on humus/peat soil, vegetation as shelter might not be as attractive to pine weevils as they can more easily hide in the soil. Woody plants such as bramble (Rubus fruticosus) can act as alternative food sources, diverting attack from the seedlings, and Willoughby et al. (2017) discuss the benefits (and risks) of leaving non-invasive woody plants on site, while maintaining areas of clear mineral soil immediately surrounding tree seedlings, as a possible element in a pine weevil IPM system.

Shelterwood or **overstory trees** reduce the amount of weevil debarking compared to clearfell sites (Löf, 2000; Löf et al., 2005; Petersson & Örlander, 2003; Pitkänen et al., 2005; Wallertz et al., 2006; Wallertz et al., 2005), possibly by providing an alternative food source (Löf et al., 2005). The denser the shelterwood the better the protection of seedlings planted underneath (Löf et al., 2005). Shelterwoods may also be used to provide seed source, allowing natural regeneration, with the shelter trees being kept until the regenerated seedlings have reached a certain minimum stem diameter Wallertz et al. (2005). Shelterwoods are currently not used in Ireland, though standing trees may be left for biodiversity objectives. A protection effect similar to that of shelterwood can possibly also be provided from **forest edges** (Nordlander et al., 2003). Up to distances of approximately 15 meters from a forest edge, feeding by pine weevil was at least halved compared to the centre of the clearfell site (Nordlander et al., 2003), and this was attributed to the availability of alternative food for the weevils rather than to microclimate effects (Nordlander et al., 2003). However, standing forests are also a source of weevils as noted above.

Continuous cover forestry (CCF) could be considered as an extreme case of shelterwood. Therefore, it is not surprising that the number of pine weevils and their damage on seedlings is reduced in CCF (Bjorkman et al., 2015; Mason et al., 2004). CCF has recently been introduced to Ireland and although relatively few woodlands are currently being managed on CCF principles, it is predicted to become more important in the future (Wilson & O'Tuama, 2019).

Recently, both Coillte and private forest owners have started to transform forests to CCF. Grant aid from DAFM is available for the conversion (Department of Agriculture Food and the Marine, 2019). Coillte is using CCF for aesthetic purposes in some areas. Not all sites are suitable for CCF (Teagasc, 2016). The commercial forestry and associated businesses, e.g. saw mills, to date is adapted to clearfell and replant forestry. There is a growing interest and pressure for the adoption of alternative forest management systems to clearfell and replant, and so such systems may be used on a wider scale in the future. These alternative systems are being promoted within the European Forest Strategy 2030. Not having to use chemicals is promoted as one of the benefits of adopting CCF and for not having to treat natural regeneration in particular.

2.4 Influence of harvesting practices

Felling date has an important impact on pine weevil damage. It is important to consider the time of felling in relation to pine weevil colonisation and egg laying. Clearfells from early in the year can be colonised by pine weevil during the same year, whereas autumn fellings are colonised during the next year's migration (Moore, 2004). Clearfells made during the migration period (May to July) can be colonised either during the same or the following year; hence, on these clearfells it is especially difficult to predict when pine weevil outbreak will occur (Moore, 2004). In a UK study, pine weevil larvae developing in stumps from early fellings were heavier than in stumps from late fellings, though late-felled stumps had more larvae and higher numbers of emerging adults than early-felled stumps. A Forestry Commission Note includes a table that relates time of felling of Sitka spruce to the risk posed to trees planted at various times post felling (Moore, 2004; Moore et al., 2004), as shown in Figure 4.

Harvest residues, such as branches (**slas**h or **brash**, Fig.3B) may have small effects on pine weevil damage (Holt Hanssen et al., 2018; Örlander & Nilsson, 1999). These residues can probably be used by pine weevil as food source for about 3 weeks after harvest (older residues are usually too dry) (Örlander et al., 2001), and so could help reduce feeding damage on trees planted immediately after felling. Slash can however also serve to attract pine weevils and thereby increase the population (Holt Hanssen et al., 2018). In Ireland, slash is usually bundled into windrows and left on site, especially on mineral soils. On certain clearfell sites, removal would not be practically possible. In the future, brash might have potential as biomass e.g. for biofuels. In the UK private forest owners already take out brash for use as biomass products.

Stump removal for bioenergy is practised in some countries, but not currently in Ireland due to both the large environmental impact and the fact that there is no market for the stumps at present. Stump removal reduces breeding material and shelter for pine weevil, but the remaining roots could provide food to sustain a large enough population (Walmsley & Godbold, 2010).

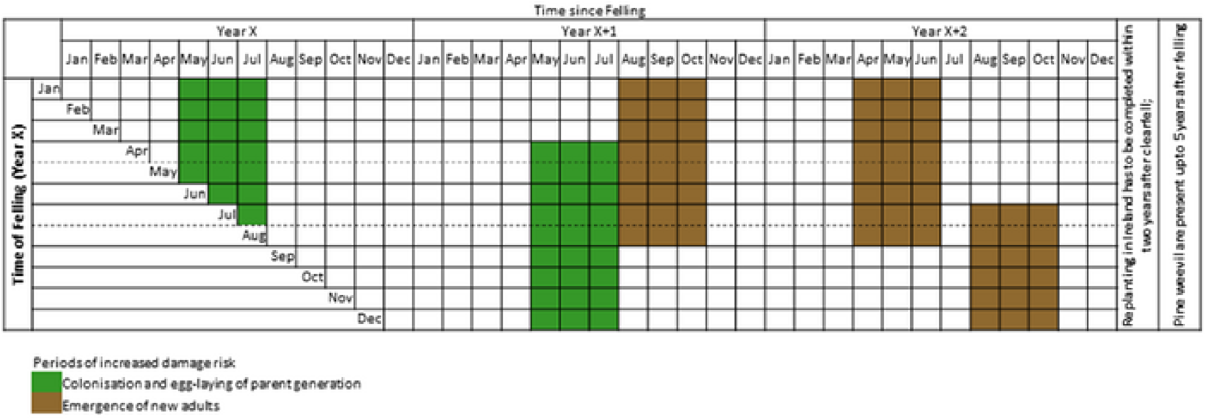

Figure 4. Timing of colonisation/egg laying, adult emergence and damage periods occurring on clearfelled spruce sites (Forestry Commission).

In a Finnish study, seedlings planted on sites where stumps had been removed but left in situ had less weevil damage than stem-only harvested plots (Rahman et al., 2015). New more environmentally sound methods of stump removal are sought in the UK and elsewhere.

The **fallow period** after harvest has a large influence on the amount of pine weevil damage (Glowacka et al., 1991; Örlander & Nilsson, 1999; Von Sydow, 1997). The options with the least pine weevil damage seem to be planting directly after harvest ("green planting" or "hot planting") or after no less than 3-4 years of fallow period (Glowacka et al., 1991; Örlander & Nilsson, 1999; Von Hofsten & Weslien, 2005; Von Sydow, 1997). The length of a full fallow period in the UK to avoid significant damage to untreated trees is defined by (Moore, 2004). However, current Irish regulation (Forestry_Act, 2014) requires replanting within two years of felling as a condition of a felling licence. Thus, waiting until the pine weevil population on the clearfell site has declined is not an option. Moreover, weed cover can be a large problem after fallow, especially on more fertile sites. Coillte has practised green planting in recent years, with positive outcomes, and will probably mainly green plant from 2025.

Since pine weevil damage is seasonal, with peaks in spring and late summer, **planting at different times** of the year should result in different amounts of damage (Moore, 2004). In Ireland, planting occurs from the end of November until June. Generally, private owners have more flexibility in when to plant compared with state forests. State forests have many different contractors and a large area to cover; therefore, there are often contracts in place that do not give much flexibility.

In Scandinavia, conflicting results were found regarding late season planting (Luoranen et al., 2006; Nilsson & Örlander, 1995; Nordlander, Hellqvist, et al., 2017; Örlander & Nilsson, 1999; Wallertz et al., 2016), but indications are that planting in June or autumn (August and September) instead of May might reduce damage (Nordlander, Hellqvist, et al., 2017; Wallertz et al., 2016). In the UK it is recommended to plant from October of the third year after felling for clearfell sites felled in the first quarter of the year and from October of the fourth year after felling for sites felled from April onwards (Moore, 2004). However, the practice in Ireland is moving towards direct planting ("green planting" with no fallow period, as noted above.

2.5 Seedling properties

The extent of pine weevil damage depends on a variety of seedling properties, including species, size and general condition. Many of the properties are connected to plant defence, such as number and distribution of resin ducts, but also to nutrition such as the nitrogen content of the bark (Wainhouse et al., 2010). Genetic variation of the seedlings can be important in this context (Zas et al., 2017; Zas et al., 2005).

Pine weevils feed on all woody trees and shrubs. Deciduous trees and shrubs are also fed upon, although to a smaller extent than conifers (Leather et al., 1994; Löf et al., 2004; Löf et al., 2005; Toivonen & Viiri, 2006; Wallertz et al., 2014). Amongst conifers, weevils prefer to feed on some **species** more than others. Seedlings of Sitka spruce and Douglas fir were the most attacked, most killed and had the greatest debarked area out of seven tree species tested in Sweden (Wallertz et al., 2014). Norway spruce and lodgepole pine were next, followed by Scots pine and then hybrid larch (Wallertz et al., 2014). Differences in survival of tree species may be accounted for both by the feeding preference of the weevils (influencing the amount of damage inflicted) but also by differences in the ability of the species to tolerate damage (Carrillo-Gavilán et al., 2012; Zas et al., 2011). **Bark thickness** influences the ratio of deep feeding to shallow feeding by pine weevils; thick bark makes seedlings more resilient against pine weevil damage, as more of the feeding is superficial, increasing the likelihood of effective wound repair (Wainhouse et al., 2005).

Size of tree at planting: The risk of severe damage of seedlings is reduced with a greater initial diameter. For example, Norway spruce became less attractive for pine weevils with root collar diameter (RCD) of more than 10 mm (Wallertz et al., 2005). A minimum RCD of 6 mm and only Size 1 plants are recommended by Coillte for reforestation sites; lodgepole pine plants were grown in plugs in nurseries and provided much greater RCD.

Bare-root versus containerised seedlings: In Ireland and the UK, most of the trees planted are bare-rooted, while in Scandinavia, mainly containerised trees are used. **Deep planting** of containerised seedlings, i.e. 8 cm under the soil surface instead of 3 cm, reduced the debarked area on seedlings in trials in Finland (Viiri & Luoranen, 2017). Although pine weevil prefer to feed underground when no shelter can be found (Nordlander et al., 2005), deep planting does not increase the amount of feeding under the soil (Luoranen & Viiri, 2016; Viiri & Luoranen, 2017).

Naturally regenerated seedlings are subject to less pine weevil damage than planted seedlings (Selander et al., 1990). Mortality caused by pine weevil damage in **bare-rooted** seedlings is lower than that of **containerised** seedlings, probably due to the larger **stem base diameter** at time of planting (Örlander & Nilsson, 1999). The size of the pots in which containerised seedlings had grown influenced their susceptibility to pine weevil damage in the first three years after planting (Johansson et al., 2015).

Pine weevils prefer to feed on seedlings over **cuttings** and attack seedlings more, causing more damage and higher kill rates (Hannerz et al., 2002; Kennedy et al., 2006). Although cuttings are smaller and thinner after three years (Hannerz et al., 2002), they might have a more developed defence system and are therefore not preferred by pine weevils (Kennedy et al., 2006). In Ireland, cuttings represent a very small proportion of planting stock. Perhaps root stock for cuttings would have to have a greater RCD and subsequently have greater survival.

For the future, there are prospects for choosing or breeding stock that is less susceptible to pine weevil damage. New breeding methods (e.g. embryonic somatogenesis- a clonal propagation method using somatic cells) might make it easier to select material for **resistance** against the pine weevil (Puentes et al., 2018). Genetic engineering might be a possibility to protect seedlings in the future, while genotyping and phenotyping are approaches to improving stock that have been successfully used in breeding for resistance against the North American pine weevil (Lenz et al., 2020). Resistant tree breeding is generally a medium to long-term approach requiring sustained investment and co-ordination; adequately resourced and well-planned resistant tree programmes can contribute to strategies to mitigate impacts from pests (Woodcock et al., 2019).

2.6 Trapping adult weevils for population reduction

Traps can be used to monitor weevil numbers (see 7.1), but traps have also been used for nearly two hundred years to try to reduce pine weevil populations (Lalik, Galko, Kunca, et al., 2021). There are two basic kinds of trap, each with many possible modifications: (1) Billet traps: pieces of host trees – mostly conifer trunks or thick branches – are placed on the ground and weevils feeding on them are collected at regular intervals (Kuzminski & Bilon, 2009). (2) Pitfall traps that pine weevil fall into and are unable to crawl out of again (Nordlander, 1987). These are often baited with either host material or attractive synthetic smells (Lalík et al., 2019; Moreira et al., 2008; Voolma et al., 2001; Zumr et al., 1995), and usually contain a liquid in which the pine weevils drown (Voolma & Sibul, 2006). These two types of traps can be combined by placing a hole or pit underneath the billet traps to prevent the weevils from escaping. However, setting, controlling and collecting traps on clearfells is labour intensive, and a study in Romania found that mass-trapping of the large pine weevil using baited pitfall traps was unable to protect seedlings planted on fresh clearfell areas, even using a high number of traps per unit area (100 traps/ha) (Olenici et al., 2016).

2.7 Other factors

Temperature and light influence pine weevil activity. Pine weevils feed more at night than during the day (Fedderwitz et al., 2014). In a field experiment, artificially shaded seedlings were attacked less often than non-shaded seedlings, but it is not clear that this was an effect of shading, since the screen used to provide shade also restricted access by pine weevil (Heiskanen, 2004). A Swedish study investigated the effect of shading on clearfells; feeding was more intense in the centre of clearfells than at the edges, but this was ascribed mainly to the effect of alternative food sources at the edge, rather than an effect of microclimate (solar radiation, temperature) (Nordlander et al., 2003).

In Sweden, **burning** of a regeneration site is often done within 4 years of harvest, and replanting after another 1-2 years (Von Hofsten & Weslien, 2005). Clearfell burning increases the population of pine weevil (Pitkänen et al., 2008) and damage on planted seedlings (Pitkänen et al., 2005). Pine weevil damage on burned sites only decreased after at least 2 years post burning (Von Hofsten & Weslien, 2005). No planned burning of clearfells is performed in Ireland, but accidental fires may affect weevil damage.

3.CHEMICAL METHODS OF PROTECTION AGAINST PINE WEEVIL

Chemical insecticides (cypermethrin and acetamiprid) have been the standard method used to protect against pine weevil in Ireland. In the UK, the approved chemical insecticides against pine weevil are alpha-cypermethrin, cypermethrin and acetamiprid (Willoughby et al., 2017). Seedlings can be treated with insecticides at three stages: pre-planting in the nursery, post-planting or post-planting top-up sprays (Forest Stewardship Council Sweden, 2014). Pre-planting has two options: dipping plants in insecticide solutions or using spray booths to apply the insecticide (Willoughby et al., 2004; Willoughby et al., 2017). In Ireland, if a risk of pine weevil damage has been established on the clearfell, seedlings are usually dipped in the nursery before delivery to the sites. Top-up post-planting spraying might be necessary for pre-treated seedlings if insect pressure is high (Willoughby et al., 2017). Top-up sprays are often necessary in the spring of the year after planting, but might already be necessary in the autumn of the planting year (Willoughby et al., 2017). In the autumn of the second year, Sitka spruce seedlings are usually large enough to resist pine weevil damage, whereas other, smaller, species might need more years to develop adequate protection (Willoughby et al., 2017). Post-planting application is usually done with targeted sprays (point sprays limited to on/around the seedlings). Application of insecticides in the nursery has a lower environmental impact and is therefore preferred. Therefore, it is advised against planting untreated seedlings on high-risk clearfells as this would require immediate spraying in the field. Since seedlings are either treated in the nursery or with targeted sprayers, risks of exposing bees to insecticides by treating non flowering seedlings is minimal (Anonymous, 2015). Contamination of water is prevented by minimising field application of insecticides, which are also only used beyond a safety margin around water areas (Anonymous, 2015).

3.1 Cypermethrin

Until recently, products containing the active ingredient cypermethrin were the only effective insecticide used in Ireland against pine weevil (Anonymous, 2017). Cypermethrin reduces pine weevil feeding and increases seedling survival (Nordlander & Hellqvist, 2012; Nordlander et al., 2011; Shtykova et al., 2008). Cypermethrin is considered a high hazard chemical by FSC due to its risk for aquatic organisms including fish (Ullah et al., 2018), and its use in FSC certified forests was allowed only until March 2021 under the terms of a derogation granted by FSC to Coillte Teoranta and Irish Forestry Unit Trust (Anonymous, 2016). PEFC allows the use of cypermethrin with the requirement to adhere to national legislation. The product “Forester” containing cypermethrin as the active substance has been used for pre- and post-planting treatment in forestry in Ireland.

Cypermethrin was permitted for use in forestry by the Pesticide Registration and Control Division (PRCD) of the Irish Department of Agriculture, Food and the Marine (DAFM) (PCD, 2021), but products for use in forestry were revoked from February 1st, 2022 (with a use-up period allowed), following the review of cypermethrin at EU level. A report on health of forest workers during seedling planting in Sweden showed no acute negative health effects of planting Forester-treated seedlings after one week (Elfman et al., 2009) and a European Food Safety Authority report concluded that while there was no evidence that use of cypermethrin would compromise the health of operators or the general public, it posed a risk to aquatic organisms (EFSA, 2018).

3.2 Acetamiprid

Since 2019, cypermethrin is being phased out by Coillte as pine weevil protection and replaced by acetamiprid. The products “Gazelle SG” and “Ceta SG”, containing acetamiprid, are approved by PCRD for off-label use in forestry in Ireland (PCD, 2021). Acetamiprid can be used both for pre-planting treatment as well as for top-up spraying in the field (Willoughby et al., 2017). Acetamiprid was successful in knocking-down and killing pine weevil in laboratory experiments (Malinowski, 2010; Olenici et al., 2014). Since 2019, Coillte has used acetamiprid as protection against pine weevil with positive experience. In field trials in the UK, acetamiprid gave comparable levels of protection to cypermethrin without causing phytotoxicity (Hardy et al., 2020; Moore et al., 2021; Willoughby et al., 2020).

Acetamiprid is a neonicotinoid, a group of chemicals that have attracted considerable attention in recent years, being implicated in the decline of pollinators particularly bees (Decourtye & Devillers, 2010; Laurino et al., 2011; Stanley et al., 2015). Therefore, several neonicotinoids are not allowed to be used outdoors in the EU since 2018 (European Commission, N/A). Acetamiprid was determined to have a comparably low risk. Its toxicity to bees is much lower compared to many other insecticides, and it is classed as practically not toxic for birds and fish (Badawy et al., 2015; Decourtye & Devillers, 2010; Stanley et al., 2015). Although it may have sub-lethal effects on bee behaviour (El Hassani et al., 2008), it is even recommended for use on flowering plants, further underlining the low bee toxicity (Stanley et al., 2015). Acetamiprid is calculated to be at least 500 times less toxic to aquatic life than cypermethrin or alpha-cypermethrin and not to pose any additional risk to operators, bystanders and the wider environment (Willoughby et al., 2020).

3.3 Chlorantraniliprole

Chlorantraniliprole is a diamide insecticide registered in Ireland under the name Coragen for use against insects in a wide range of crops such as apples, carrots, maize and turnips (PCD, 2021). Chlorantraniliprole has a different mode of action to other insecticides: it affects the insect's ryanodine receptors, thereby affecting muscle regulation, causing paralysis and death (Bassi et al., 2009; Cordova et al., 2006). It is active against chewing insects by ingestion and contact and has been shown to have good efficacy against many insect pests including adult Colorado potato beetle (Bassi et al., 2009; Richardson et al., 2020) . Chlorantraniliprole was tested against pine weevil by Coillte in a local field trial with positive outcome, and broader trials are planned for 2022. The product Coragen is approved for off-label use in forestry (PCD, 2021). It also "showed promise" in UK field trials, and it was deemed worthy of further study (Willoughby et al., 2020). Follow-up experiments by Moore et al. (2021) confirmed that pre-treating plants with chlorantraniliprole gave protection against pine weevil for the first growing season, but they concluded that top-up sprays would be needed for the second growing season (as was also the case for plants pre-treated with acetamiprid). The price of chlorantraniliprole has dropped recently making this chemical a more attractive option in the future. A further advantage is that chlorantraniliprole seems to be relatively safe for pollinating bees (Dinter et al., 2009; Williams et al., 2020).

3.4 Other chemicals

Other pyrethroids that have been investigated include deltamethrin and lambda cyhalothrin.

Deltamethrin protected seedlings against pine weevil in trials in European countries (Glowacka et al., 1991). However, the effect was short-lived, and in areas with high pine weevil pressure, a second application in the field would be necessary (Viiri et al., 2007). Deltamethrin application during the growing stage of seedlings did not adversely affect seedling health (Luoranen & Viiri, 2005). Deltamethrin has a better environmental profile than cypermethrin by orders of magnitude, but still has negative impacts (Lu et al., 2019). It is registered as an insecticide in Ireland (PCD, 2021). It is not allowed to be used in SFC certified forests in Ireland (Forest Stewardship Council International, 2017), and there has been no interest in using deltamethrin in Irish forestry.

Lambda-cyhalothrin. In laboratory tests, pine weevils fed less on food treated with lambda-cyhalothrin (Rose et al., 2005) and showed symptoms of nerve damage after 7 days (Luoranen & Viiri, 2005). Lambda-cyhalothrin showed no phytotoxic effects with concentrations of 2% or 4% (Luoranen & Viiri, 2005). It was included in one of the recent UK field experiments, with inconclusive results; at sites with low pine weevil pressure, it showed a level of protection that was not significantly different from alpha-cypermethrin, but provided poor protection at high pressure sites (Willoughby et al., 2020). Based on these results and its greater toxicity to mammals and birds relative to acetamiprid or chlorantraniliprole, further investigation into this chemical was not considered to be high priority (Willoughby et al., 2020). Products containing lambda-cyhalothrin are registered as insecticides in Ireland, and some products have off-label use in forest nurseries, but not forestry (Anonymous, 2019a, 2019b). Lambda-cyhalothrin is the primary agent used for aphid control in Irish agriculture.

Spinosad was evaluated against the pine weevil in the UK; protection in the trials was found to be insufficient, but the authors felt that it might have potential if methods of deployment could be improved (Willoughby et al 2020). Spinosad is an insecticide based on bacterial fermentation products and has both contact and oral toxicity against insects (Toews & Subramanyam, 2003).

Sulfoxaflor may have potential for pine weevil control in the future. Sulfoxaflor is a sulfoxamine, which works on the same receptors as neonicotinoids. It is widely used on a variety of crops on all continents (Tamburini et al., 2021), and is currently approved for use in Irish agriculture (Anonymous, 2019b). However, a recent review by the European Union (EU) indicates it will be revoked for outdoor use due to concerns about toxicity to bees (Pesticide Action Network, 2022). Compared to other chemicals, it is relatively environmentally friendly and has shown no significant impact on bees (Tamburini et al., 2021). There are no reports of it being tested against pine weevil.

Cyantraniliprole belongs to the same chemical class (anthranilic diamides) as chlorantraniliprol. It is currently approved in the EU for the control of aphids in a wide range of horticulture crops (PCD, 2021). The registration status of cyantraniliprole may change in 2022. The chemical is very expensive, but has shown promise as a systemic insecticide against various phytophagous weevils in North America and elsewhere (Malamura et al., 2021).

Methyl jasmonate is one of several **chemical elicitors** that affect the defence system of plants. By inducing the defence of plants before they are actually threatened by a herbivore, it is possible to upregulate the defences without physically injuring the plants. Methyl jasmonate and other jasmonic acids have been evaluated in many different systems including pine weevil damage on conifer seedlings. The protective effect of methyl jasmonate against pine weevil was tested in the field both in Sweden and Spain, and results showed a reduced damage area, reduced risk for girdling and (in some cases) reduced risk for seedling mortality (Zas et al., 2014). However, treated plants also had temporarily reduced growth (Zas et al., 2014). Since the application of methyl jasmonate can only induce the plant's own defences, it might not be effective under high pine weevil pressure (Fedderwitz, unpublished data). Thus, it is doubtful that methyl jasmonate would present a suitable alternative for Ireland.

3.5 Antifeedants and Plant extracts

Large numbers of antifeedant compounds and plant extracts have been screened for antifeedant activity against pine weevil (Bohman et al., 2008; Sunnerheim et al., 2007; Unelius et al., 2018), but none of them is used commercially. Antifeedant chemicals act in various ways: they can repel an insect from feeding without making contact with the material (repellent), suppress the feeding after one bite (suppressant) or deter from further feeding after several bites (deterrent) (Klepzig & Schlyter, 1999). Chemical properties such as low polarity, small size and high lipophilicity are generally important for good antifeedant activity against the pine weevil (Sunnerheim et al., 2007). Appendix Table 2 summarises extracts that have shown potential to reduce feeding damage (Eriksson et al., 2008; Månsson & Schlyter, 2004). One of the more commonly tried group of plant extracts are those of the Indian neem tree (Azadirachta indica). Several different neem extracts have been tested (Olenici & Olenici, 2006; Thacker et al., 2003). Some products contain only the active ingredient, azadirachtin, while other products also contain additional plant oils (Luik et al., 2000). Neither azadirachtin nor any of the neem extracts that were tested in the UK give adequate protection against pine weevil in the field, and azadirachtin showed severe phytotoxic effects, especially at high concentrations (Willoughby et al., 2017; Willoughby et al., 2020).

Antifeedants can be sourced from microbes as well as plants. Some fungi that colonise wood produced volatile organic compounds that were either repellent to weevils or masked the odours of host plants (Azeem et al., 2013; Azeem, Rajarao, et al., 2015; Azeem, Terenius, et al., 2015; Skrzecz & Moore, 1997). Pine twigs colonised by a species of Penicillium were less attractive than uncolonised food, and it was suggested that forest waste material could be fermented by appropriate microbes to produce a weevil repellent (Azeem et al., 2013; Skrzecz & Moore, 1997).

3.6 Insecticide registration

Plant protection products are regulated in Ireland by the Pesticides Regulation and Control Division (PRCD) of DAFM. There are very few insecticides registered for use in forest nurseries (two products based on fungi) and in forestry just one product containing cypermethrin, to February 2022 (PCD, 2021). However there are several products that can be used off-label (PCD, 2021). For forest nurseries this includes insecticides with the active ingredients acetamiprid, Bacillus thuringiensis, chlorantraniliprole, flonicamid, indoxacarb, lambda-cyhalothrin, spirotetramat and spinosad (PCD, 2021). For forestry use there are off-label authorisations for insecticides containing acetamiprid and chlorantraniliprole (PCD, 2021).

4.PHYSICAL METHODS

Physical protection methods have been developed since the 1970s, mostly in Sweden (Nordlander, Wallertz, et al., 2017) with reports from more recent trials available online in Swedish with English summaries (Hellqvist, 2017). Physical protection has replaced insecticide treatment of seedlings to a large extent in Sweden during the past decade (Forest Stewardship Council Sweden, 2018; Swedish_Forest_Agency, 2021).

There are two major approaches for physically protecting a seedling: stem coats and barriers. Stem coats are usually a liquid that is sprayed on the seedling and forms a protective layer around the stem after drying. Barriers are structures, often made of plastic or coated paper, that are placed around the seedling and prevent weevils from reaching the seedling. Some of the methods mentioned in the text are listed in Table 2.

4.1 Coatings

Stem coats prevent the weevil from feeding on the stem by producing a protective layer on top of the bark (Nordlander et al., 2009). About 50%-80% of the lower stem is covered with the coat for effective protection (Anonymous, 2017; Nordlander et al., 2009; SCA, 2017). Besides preventing feeding, the coating also reduces the volatile emission of plants making them less attractive/harder to locate for pine weevil (Nordlander et al., 2008; Petersson et al., 2004). Many different substances were tested during the development of stem coats, especially during the 1990s and 2000s (e.g. Eriksson et al., 2017; Nordlander et al., 2008; SCA, 2017), and development still continues. Stem coatings can be based on a wax, latex or artificial rubber (Nordlander et al., 2008). In general, the coat is sprayed onto the stem and when it hardens it forms a protective layer. Coats containing paraffin wax are heated to 70°C before being sprayed (Nordlander et al., 2008). Acrylate- or resin-based coats have also been tested, especially with the addition of deterrent substances (Nordlander et al., 2008) or antifeedants that can be released over time (Shtykova et al., 2008). Many coats additionally contain particles that further prevent pine weevil from reaching the stem of the seedlings. These coats are often based on bonding agents such as glue or an acrylate (Hellqvist, 2017; Nordlander et al., 2009; SCA, 2017) and particles most commonly based on fine sand (silicate), but clay has also been tested (Johansson, 2008; Nordlander et al., 2009; SCA, 2017).

Table 2: Coatings and barrier guards mentioned in the text

Product	Description	Tested in Ireland or UK
Stem coats		
Conniflex	Sand and glue	UK (Moore, pers. Comm)
Ekowax	Parrafin wax	----
Flexcoat	Polysaccharide	UK (Willoughby et al., 2020)
Hylonox	Mineral and glue	---
KvaaeWax	Wax	UK (Moore et al., 2021; Willoughby et al., 2020)
Trunkcoat	Latex with epoxy particles	Ireland (Anonymous 2017)
Woodcoat	Sand and latex	---
Barrier Guards		
Biosleeves	Biodegradable plastic tube	UK (Willoughby et al., 2020; Hardy et al. 2020)
Multipro	waxed cardboard tube	UK (Hardy et al., 2020; Moore et al., 2021; Willoughby et al., 2020)
WeeNets	plastic nets	Ireland (Anonymous, 2017) UK (Willoughby et al., 2020)

Particle containing coats have either the bonding agent sprayed first onto the stem and afterwards covered with particles or alternatively a mixture of the bonding agent and particles is directly applied (Hellqvist, 2017; Nordlander et al., 2009; SCA, 2017). Seedlings are coated in the plant nursery and no follow-up coating is done. Planting in the field does not require additional preparation but nonetheless it is often done in conjunction with site preparation measures which increase the protective effect (Eriksson et al., 2017).

Early stem coatings did not provide as much protection as insecticides in respect to debarked area and proportion of pine weevil killed seedlings (Nordlander et al., 2008; Petersson et al., 2004). However later stem coatings, especially in conjunction with soil scarification, have been successful as protection against pine weevil in Sweden (Eriksson et al., 2017; Nordlander et al., 2009). Indeed, **Conniflex** – which is one of the most used particle-containing coatings – was equally as good at protecting seedlings from pine weevil damage as chemical insecticides (Wallertz & Johansson, 2008). A Swedish monitoring program looking at Conniflex treated seedlings for three years post-planting recorded an average plant survival of 93% (Hellqvist, 2014; Luoranen et al., 2022).

In field trials in Sweden, there was a lot of variation both between years and between clearfells in the percentage of coated seedlings attacked by pine weevil (Hellqvist, 2014). Most of the damage on coated seedlings is above the coat, on the unprotected area of the seedlings (Hellqvist, 2014). Weevils can climb over the coat and feed on the unprotected top shoot, but this is not commonly observed on seedlings with intact coating. Cracks in the coating and failures in application, especially directly above the root base, also reduce the protection effect of stem coats dramatically (Hellqvist, 2014; Nordlander et al., 2009). The potentially higher population density in Ireland might be a problem in this regard for the use of physical protection. With higher pine weevil densities, it is more likely that they will overcome the coat.

"Plant death by unknown reasons" is more often observed on coated seedlings than on untreated or insecticide treated seedlings, especially in conjunction with drought (Hellqvist, 2014). With all stem coatings there is a risk of phytotoxicity and strangulation of the seedling (Petersson et al., 2004). Phytotoxicity might be due to chemicals in the coat disrupting the plant's chemistry (Petersson et al., 2004). Strangulation can occur if the coat is not flexible enough to give seedlings room to increase the stem diameter while growing (Johansson, 2008; Petersson & Örlander, 2003; Petersson et al., 2004). If the coat is not flexible enough to allow for the stem diameter growth, the coat will either crack and thereby be vulnerable to pine weevil attack, or the coat will strangle the seedling (Johansson, 2008; Petersson et al., 2004).

Another issue during the development of stem coats was that they often degraded after one season (Nordlander et al., 2008). Since pine weevil damage is an important cause of death during the first two to three seasons, this is not enough (Eriksson et al., 2017). Hence, coatings currently used (e.g. Conniflex) were tested for three seasons to make sure that degradation does not occur before the main threat of pine weevils has passed (Nordlander et al., 2009). On the other hand, an advantage of stem coatings is that the coating naturally degrades and do not leave plastic litter on the clearfells, unlike some barrier guards (Eriksson et al., 2017).

Adding antifeedants to physical coats increased their protective effect, with the effect depending on the particular antifeedant used (Månsson et al., 2006; Shtykova et al., 2008). The antifeedant (d,l)-cis-dihydropinidine in a latex coating resulted in the same antifeedant index as cypermethrin (Shtykova et al., 2008).

4.2 Barrier guards

Feeding barriers are straight or conical tubes or bags that are placed around the seedling's lower stem (Johansson, 2008; Nordlander et al., 2008). Many barrier guards are made from polypropylene or paper, which is coated with a slippery surface such as polyvinylchloride (PVC) (Nordlander et al., 2008; Petersson et al., 2004). The exact design and strength of the plastic used can differ between barriers (Nordlander et al., 2008). Feeding barriers work in a similar manner to coats by preventing pine weevils from reaching the stem. They are placed around the lower part of the tree without touching the stem bark for the largest part (Petersson et al., 2004), though some cones or bags have slim upper openings that might touch the stem (Johansson, 2008). Feeding barriers are further differentiated into those with or without a collar (Petersson et al., 2004). The collar is located on the upper end of the barrier and makes it difficult for the pine weevil to climb over (Petersson et al., 2004). Netting against feeding damage can also cover the entire seedling to create a feeding barrier.

Barrier guards can be applied at different time points, depending on the design (Johansson, 2008). Barrier guards without collar can be applied during planting (Johansson, 2008). The seedling is placed into the protection from above and sometimes a strip or string on the base of the barrier goes around the roots and keeps the protection in place (Nordlander et al., 2008). However application during planting would need larger or specialised planting tubes to allow space for the barrier (Johansson, 2008; Jonsnäs, 2012). Barrier guards with collar have an open side which is closed when placing it around the seedling (Nordlander et al., 2008). These could potentially be applied in the plant nurseries before packing, but then they require more space during transport (Nordlander et al., 2008). Alternatively, they can be attached after planting (Johansson, 2008). Some barriers with collars are even installed around the seed of containerised plants (Nordlander et al., 2008; Petersson et al., 2004). The seedlings then grow inside the protection.

The barriers have to be correctly installed, otherwise the protective effect will be reduced (Nordlander et al., 2008). If barriers are not correctly installed and there is a gap between soil and seedling, pine weevils can crawl inside the barriers and feed on the seedlings. Barriers with collars should not have contact between collar and soil, because that removes the effect of the collars (Nordlander et al., 2008). Barrier guards with collars have been shown to have similar protection effect as permethrin in Sweden, both in respect of seedling mortality and severe insect damage (Petersson et al., 2004). Barrier guards without collars were not as successful, but still had a protective effect compared to unprotected seedlings (Petersson & Örlander, 2003; Petersson et al., 2004).

The barriers have to disintegrate after some years to allow the plant to grow, otherwise it could potentially strangle the growing seedlings or their roots (Nordlander et al., 2008). Some barriers therefore have a predetermined breaking point (Nordlander et al., 2008).

Figure 5: Pictures of physical protection e.g. stem coatings and barrier guards. L to R; Coniflex, Cambiguard, Ekovax and Multipro. Photos: Claes Hellqvist, SLU

PHYSICAL METHODS

4.3 Physical methods: prospects for Ireland

In Sweden bare-rooted seedlings are protected with Ekowax (Norsk Wax), MultiPro (Svenska Skogsplantor), Hylonox (Organox) or Woodcoat (Interagro). Feeding pressure of pine weevil in Ireland and the UK is very high and there are concerns that physical protection would not be as successful here as in Sweden (Willoughby et al., 2017). Also, logistical issues due to differences in the planting stock used (mainly containerised in Sweden and bare-rooted in Ireland and the UK) may further limited use of physical protection methods such as Conniflex in the UK and Ireland (Willoughby et al., 2017).

Coillte has tried two different physical protection methods, **WeeNets** in 2006-2007 and **Trunkcoat** in 2015 (Anonymous, 2017). Trunkcoat, a latex stem coat, was tested by Coillte on four sites. Pine weevil feeding was reduced on treated seedlings, but the treatment itself was phytotoxic. WeeNets (a lightweight netting) were placed on containerised trees at the nursery and planted on five sites. The protection was insufficient, because pine weevil climbed over the top of the net to feed above it (Anonymous, 2017). Alba (Alba, 2019), the company producing WeeNets, has developedWeeBars, that are supposed to prevent weevils from climbing over the top of WeeNets, and are made from biodegradable plastics. These could solve one of the problems arising from previous trials.

Several of the physical protection methods found to be successful in other countries were included in field trials in the UK, but they were found to be generally ineffective (Willoughby et al., 2004; Willoughby et al., 2017; Willoughby et al., 2020). These included flexible stem coatings applied before planting which were wax (Kjvaae Wax), polysaccharide stem coating (Flexcoat) and a sand and glue-based stem coating (Conniflex) as well as physical barriers: plastic guards fitted on site after planting (MultiPro and Biosleeve) and lightweight plastic nets (WeeNets) fitted around the root plug and lower stem of the tree at the nursery. While levels of protection varied between sites, wax treatments and physical barriers Multipro and Biosleeve and to a lesser extent Weenets were judged to have potential (Willoughby et al. 2020) and this was confirmed in follow-up field trials (Moore et al., 2021). While Kvaae Wax gave reasonable protection, its operational use in the UK is limited due to factors including reports of phytotoxicity, variable performance especially on high weevil pressure sites, and a tendency for treated trees to stick together in planting bags. Protection by barriers such as Multipro was acceptable on sites with low to intermediate weevil pressure, but it was recommended that they only be used on sheltered sites and that their use should be combined with a reliable method of predicting weevil damage as well as planting stock with large root collar diameter and without large side branches, and suitable site preparation to produce a weed and brash free area around the tree (Willoughby et al., 2020; Moore et al., 2021).

An independent series of trials confirmed the potential of physical barriers: Multipro and Biosleeves provided excellent protection; however, their effectiveness was compromised by operational difficulties such as poor installation or site-specific problems such as larger branches or stony soil (Hardy et al. 2020). In addition to their use being restricted to suitable sites, high costs are also a drawback of physical barriers (Willoughby et al., 2020; Hardy et al., 2020). A further challenge in the use of stem coats such as Conniflex is that they need specialised machinery for application (Nordlander et al., 2009). The technology to apply the coats was developed for containerized plants, but In Ireland most seedlings are produced bare-rooted and therefore the introduction of stem coats would be require adaptation (Anonymous, 2017). Finally, barriers might potentially be a source of plastic pollution in forests if they are not completely biodegradable (Willoughby et al., 2017).

Despite their limitations, physical protection is an option in Ireland and the UK on clearfells where the predicted pine weevil risk is low, as part of an IPM system for pine weevil (Moore et al., 2021; Willoughby et al., 2017). In their assessment, Moore et al. (2021) make use of formal trials as well as anecdotal reports from user trials. They recommended that the Conniflex sand and glue system that is extensively used in Sweden for treating cell-grown planting stock be subjected to further tests in UK and Irish conditions.

Coillte continues to include various physical protection methods in its field trials. The practicability and protective effect of coats made of biodegradable plastic is being tested in small scale experiments in Ireland by Adam Gordon Forestry (pers. comm., Adam Gordon 2022).

5. BIOLOGICAL METHODS

Biological control relies on natural enemies to kill the target pest. These enemies can be predators, parasites or pathogens. Biological control has been extensively studied in agricultural systems (e.g. (Bartual et al., 2019; van Lenteren et al., 2018)) and natural enemies are commercially available for control of several pests of horticulture and agriculture. There are two broad approaches that might be considered for pine weevil management: encouraging naturally occurring enemies by augmenting their populations or by modifying the habitat, or the more widespread approach of applying a mass-produced biopesticide in much the same way as chemical pesticides are applied. Biological agents that have been investigated for use against pine weevil include parasitic wasps, entomopathogenic (insect-killing) nematodes and entomopathogenic fungi, as detailed below. Many biological methods are aimed at reducing the overall population of weevils, including by killing the stages developing in the stumps, rather than directly protecting seedlings.

5.1 Entomopathogenic nematodes

Entomopathogenic nematodes (species of *Steinernema* and *Heterorhabditis*) are parasites that actively seek out and kill insects. These nematodes have several advantages over chemical pesticides, including safety to humans and the environment, and the ability to seek out the target in soil or other cryptic habitats (Lacey et al., 2015). Compared to other biopesticides, they kill rather quickly, typically within 2 days at optimum temperatures. These nematodes occur widely in soils, including in Irish forest soils (Harvey et al., 2016), and several species are commercially produced in bioreactors, formulated and shipped for use against pests such as the black vine weevil *Otiorhynchus sulcatus*. Use of nematodes against pine weevil was pioneered by Forest Research UK (Brixey et al., 2006) and nematodes have been used operationally in the UK. Nematodes applied around tree stumps can seek out and parasitise pine weevils developing inside them, thereby reducing the number of adults emerging onto the site. Research in Ireland has shown that nematodes can reduce the number of adults emerging by up to 85% in small scale trials in which nematode suspension was applied by hand (Dillon et al., 2007; Dillon et al., 2006) (Fig 6). The nematodes are applied in early summer when the first generation of weevil larvae and pupae are present. **Soil type and structure** influence nematode movement and persistence (Harvey & Griffin, 2016; Kapranas et al., 2017; Kruitbos et al., 2010), but nematodes suppressed pine weevil satisfactorily in both mineral and peat soil (Kapranas et al., 2017).

Coillte conducted large scale trials using *Steinernema carpocapsae* in 2007 and 2008, which were monitored as part of a COFORD funded project (ABATE, 2008). The nematodes were applied using a method designed by Forestry Commission UK: nematodes in water suspension were applied at a rate of 3.6 x 106 individuals per tree stump, using a spray rig mounted on a forwarder and fitted with flexible hoses that could be directed at each stump (Fig. 6D). This targeted spraying of stumps minimises the threat to non-target insects on the site (Harvey et al., 2012). In 2007, nematodes were applied by Coillte, in collaboration with the Forestry Commission, to 150 ha over 10 sites, while in 2008 Coillte treated 71 ha over 5 sites. Nematodes could reduce weevil numbers below damaging levels as long as populations in the stumps were not too high (ABATE, 2008). However, since additional adult weevils can migrate in from neighbouring clearfells, it was concluded that managing weevil populations with nematodes would require a truly integrated approach at the forest level rather than just for individual sites. In the UK, the only area where nematodes are regularly used is in Wales, where clearfells are routinely treated with nematodes in an area-wide approach. Further limitations to the use of nematodes are their high cost, the need for large amounts of water, and unsuitability of terrain on certain sites.

Figure 6: Entomopathogenic nematodes are applied as infective juveniles (A) which actively seek out hosts in soil and can enter the stump to infect pine weevils. Nematodes can be applied by hand in small scale trials (B) or delivered by hose from a modified forwarder for operational use (D). The success of nematodes can be assessed by monitoring numbers of weevils emerging into traps erected over treated and untreated stumps (C).

5.2 Entomopathogenic fungi

Entomopathogenic fungi (EPF) occur naturally in soil where they can infect and kill insects. Some, most notably ***Beauveria bassiana*** and ***Metarhizium anisopliae***, have been developed as bio-insecticides. For example, Met52 is a product based on spores of *Metarhizium anisopliae* that can be used against many pest species, and it is registered for use against black vine weevil (*Otiorhynchus sulcatus*) in horticulture in Ireland. EPF that have been tested against pine weevil include several species of *Metarhizium* and *Beauveria* as well as Isaria fumosorosea (Ansari & Butt, 2012; Barta et al., 2019; Mc Namara et al., 2018; Popowska-Nowak et al., 2016; Wegensteiner & Führer, 1988; Williams et al., 2013). In laboratory trials, larvae and pupae stages were more susceptible to EPF than adult weevils, with *M. brunneum* being the most efficient species in causing mortality of all stages (Ansari & Butt, 2012). 100% mortality was attained after 4-6 days for late-instar larvae and pupae and after 12 days for adults (Ansari & Butt, 2012). *B. bassiana* has been found to infect and kill pine weevil naturally in Sweden, Austria and Poland (Wegensteiner et al., 2015), while *B. caledonica* has also been found naturally infecting pine weevil larvae in Ireland (Glare et al., 2008); McNamara, Williams, Griffin, unpublished data).

Research in Ireland has shown that diverse EPF occur naturally in the weevil habitat (stumps on conifer clearfell sites) and both native and commercial strains were tested against both developing and adult pine weevil stages (Fig. 7 A, B). In a survey of Irish clearfell sites, several native species of EPF including *B. bassiana*, *B. caledonica* and *M. anisopliae* were recovered from the stump environment (bark, soil and pine weevil larvae) (MCOP, 2016). Indigenous strains caused equivalent mortality for pine weevil larvae as commercial EPF strains (MCOP, 2016). In field trials, EPF were applied to stumps at different times: either shortly after trees were felled, before weevil colonisation of stumps, and after weevil colonisation, when susceptible stages were present (the time for nematode application) (Williams et al., 2013). The early application was trialled as application at the time of felling would reduce costs of the operation. However, application of EPF to stumps did not significantly reduce emergence of adult pine weevil (Mc Namara et al., 2018; Williams et al., 2013). This poor field performance is probably related to the cryptic habitat of the target stages, within the tree stump and at depths of up to 50 cm underground. Unlike nematodes, which actively search for hosts, spores of EPF are passively transported. Laboratory studies showed a synergistic effect of EPF and chemical insecticides including cypermethrin and acetamiprid against adult weevils, and one EPF-chemical insecticide combination was field tested in Ireland (MCOP, 2016). One or both agents were applied to seedlings and weevil damage was compared to that on untreated controls. The approach showed promise but would require further optimisation of fungal strain and application methods (MCOP, 2016).

Figure 7: Biocontrol of pine weevil. Weevils (A: larva in a tree stump and B: adult) infected by the entomopathogenic fungus *Beauveria* with fungal hyphae growing from the insects. C. A female *Bracon hylobii* parasitoid lays eggs through tree bark onto a pine weevil larva underneath (Photo: Cliff Henry).

Alternatively, EPF could be targeted against adult weevils, which are also susceptible (Ansari & Butt, 2012; Pavlik et al., 2016). Two species, B. bassiana and B. pseudobassiana, were found to occur at low prevalence on adult pine weevils in Slovakia, and when tested in outdoor trials, could kill pine weevils feeding on treated spruce saplings (Barta et al., 2019). However, it takes a relatively long time for adult weevils to die (Ansari & Butt, 2012; Barta et al., 2019). For example, in lab trials the most virulent strain tested by Barta et al. (2019) resulted in 30% morality on day 12 and 83% mortality on day 21 (Barta et al., 2019). A carrier that has been colonised by B. bassiana and that attracts H. abietis adults has been patented, and this “lure and kill” strategy gave promising results in field trials in Slovakia (Lalik, Galko, Nikolov, et al., 2021). The study concluded that these carriers could be suitable for reducing pine weevil abundance in forest, and probably has minimal effects on other invertebrates (Lalik, Galko, Nikolov, et al., 2021).

In recent years there has been considerable interest in colonising plants with EPF as endophytes, growing within the plant (e.g. Jaber and Ownley (2018); Mann and Davis (2021)) and this approach was tested as part of the MCOP project. EPF applied to seeds or seedlings colonised both Sitka spruce and lodgepole pine and persisted endophytically within the seedling for at least 9 months without any adverse effects on plant growth (MCOP, 2016). This method has potential for longer term plant protection, but would require further research to confirm that the endophyte persisted as the trees grew and gave protection against feeding by weevils in the field.

5.3 Bacillus thuringiensis

The bacterium *Bacillus thuringiensis* (Bt) produces toxins that rapidly kill insects when ingested. Globally, it is the most widely used bioinsecticide, with a wide range of strains that differ in their specificity for different insects. Recent research in Sweden tested three Bt strains against adult pine weevil in the laboratory, with lethal effects; unexpectedly, a Diptera (fly)-targeted strain had a greater effect than Coleoptera (beetle) specific strains, with reduced feeding after 3 days and highest mortality 7-14 days after Bt-exposure (Tudoran et al., 2021). The study concluded that Bt has potential in the management of *Hylobius* and that more strains should be evaluated (Tudoran et al., 2021).

5.4 Wood decaying fungi

There has been some interest in the use of wood-colonising fungi to make stumps less attractive to adult weevils, or less suitable for weevil development. *Phlebiopsis gigantea*, a common saprophytic fungus that is applied to stumps as a biological control of fomes root rot (*Heterobasidion annosum*) in some parts of Europe, alters both the physical and chemical composition of the wood. Pine colonised by *P. gigantea* was reported to have reduced egg-laying by pine weevil and reduced larval survival (Skrzecz, 1996). Although pine weevil larvae seemed to avoid root areas that were infected with P. gigantea, its presence in stumps did not have an effect on pine weevil reproduction (Smits & Gaitnieks, 2013). Since *P. gigantea* does not occur naturally in Ireland, it has not been tested or deployed in Irish forests. A strain of *Trichoderma koningii* applied to spruce stumps in Ireland had no effect on the number of pine weevils developing in those stumps, possibly due to the low structural decay of wood caused by this fungus (Dillon et al., 2008). In a Swedish study, treatment of pine or spruce stumps to either promote or retard microbial activity had no effect on pine weevil reproduction, but fewer weevils emerged from stumps treated to retard microbial activity than from other stumps (von Sydow & Birgersson, 1997). There has also been interest in using fungi to make young trees less attractive; both *P. gigantea* and *Trichoderma harzianum* made pine branches less attractive as a food source for adult weevils (Azeem et al., 2013; Skrzecz & Moore, 1997). Wood-colonising microbes have also been investigated as a source of anti-feedants (see section 3.5).

5.5 Natural products

Research is ongoing on a novel approach, using products derived from marine algae and crustacean waste for the control of pine weevil, in a partnership between Nutramara Ltd, Coillte and Waterford IT (pers. Comm. Dr Henry Lyons, Scientific Director of Nutramara Ltd).

5.6 Natural biocontrol: Native parasitoids, parasites and predators

Bracon hylobii is the best-studied parasitoid of the large pine weevil (Everard et al., 2009; Faccoli & Henry, 2003; Harvey & Griffin, 2012; Henry; Henry & Day, 2001; Moore, 2001), with potential impact on weevil populations. It lays its eggs in pine weevil larvae, resulting in their death (Brixey, 1997)(Fig. ff C). It is a specialist wasp with pine weevil being one of only two known hosts for this species (Kenis et al., 2004). The natural occurrence of *B. hylobii* is highly variable (Henry, 1995). On certain sites high levels of parasitism of up to approximately 80% of larvae are possible and on these sites an impact on the pine weevil population is likely (Henry, 1995). However, high parasitism rates are usually only reached in the third season after clearfell (Henry, 1995). The possibility of augmenting natural populations was tested in Ireland. Some 40,000 laboratory-reared individuals of *B. hylobii* were released onto clearfell Sitka spruce sites around Ireland with variable results. On some sites, plots where parasitoids were released had nearly three times the parasitism rate of control plots (Henry & Day, 2011). It was concluded that major improvements in the culture method of the parasitoid (which must be reared on its host) would be needed if mass release were to be a cost-effective approach. Sylvicultural methods to make sites more congenial for the parasitoid have been suggested, such as provision of food sources for adult parasitoids (e.g by encouraging flowering plants on sites). Brash reduced the parasitism rate of adult weevils by *B. hylobii* (Henry, 1995).

Apart from *B. hylobii*, only one other parasitoid, *Dolichomitus tuberculatus*, attacks pine weevil larvae, but hardly anything is known about it (Kenis et al., 2004). The parasitoid wasp *Perilitus areolaris* attacks and kills pine weevil adults (Gerdin & Hedqvist, 1984). Studies from central Europe from the mid-60s showed parasitisation rates of either 1-4% or 15-16% (Kenis et al., 2004). *P. areolaris* seems to be quite common in Sweden, attacking 20% of sampled weevils, and probably has local influence on the pine weevil population size (Bylund et al., 2003). Neither *D. tuberculatus* nor *P. areolaris* has been reported in Ireland (NBDC, searched July 2021), though field-collected adult weevils were very occasionally found to be parasitised (personal observations of authors) presumably by P. areolaris.

Sporozoan parasites, such as *Gregarina hylobii* and *Ophryocystis hylobii*, and microsporidium Nosema hylobii have been found in adult pine weevil of different European populations (Purrini & Ormieres, 1982; Wegensteiner et al., 2015). There is not much known about their effects on pine weevil survival and behaviour (Kenis et al., 2004). Individuals Infected by sporozoans did not exhibit many symptoms, although feeding might be slightly reduced before death (Purrini & Ormieres, 1982).

Predators: Studies in Sweden showed that seedlings attended by ants had less feeding damage compared to seedlings without ant attendance (Manak et al., 2015, 2017; Manak et al., 2013). This reduction is probably based on non-consumptive predator-herbivore interactions i.e. the presence of (or harassment by) ants distracting pine weevils from feeding (Manak et al., 2016). In these studies, ants were attracted to the seedlings using sugar baits. How these effects of ant-attendants can be practically used for seedling protection is however a difficult question. Apart from ants, other insects, birds and mammals could feed on pine weevil (Kenis et al., 2004). However, if and how much they predate on pine weevils is poorly known. Since pine weevil development takes place within stumps/roots and adults spend much of their time hidden in the soil, predation levels can be assumed to be low. Adults are exposed when feeding on seedlings, and white wagtail, thrush and jackdaws have been observed to feed on them (Nordlander et al., 2008). Adults are also vulnerable to predation when migrating. Several potential invertebrate predators have been found in pine weevil habitat, but the only reports of attack are by the robber fly Laphria sp. on adults and by various beetles on larvae (Kenis et al., 2004). The carabid ground beetle Pterostichus madidus, a generalist predator, was shown to feed on pine weevil larvae as they migrate from one food source to another (Salisbury & Leather, 1998). The impact of predation by vertebrates and invertebrates on pine weevil populations has not been quantified.

6. INTEGRATION OF DIFFERENT METHODS

PIn IPM, more than one method may be used to protect against pest damage. Some methods may have additive effects, while others may act synergistically (the effect of combined methods are greater than expected based on the performance of each method on its own).

For example, physical protection and soil scarification can have a synergistic effect on seedling survival (Petersson & Örlander, 2003; Wallertz & Petersson, 2011), possibly due to vegetation having a negative effect on the protection of physical methods (Petersson & Örlander, 2003). In experiments in southern Sweden where unprotected seedlings suffered 88% mortality after 3 years, the combined used of three methods – scarified soil, physical protection and shelterwood – had additive effects, giving protection equivalent to that of insecticide, where mortality was insignificant (Petersson & Örlander, 2003). Willoughby et al. (2020) recommend that physical protection only be employed in conjunction with cultural practices including suitable site preparation to create a weed and brash free space around the planted trees.

Chemicals can be applied together with an adjuvant (a substance that enhances the effectiveness of the chemical), to ensures that the insecticide adheres to the plant, thus reducing the application rate and prolonging the efficacy of a single treatment. Coillte trialled combinations of cypermethrin with “Flexcoat” and subsequently Ayeflex (Anonymous, 2017). The use of the adjuvant is designed to reduce both the use of insecticides in nurseries and the necessity for top-up sprays in the field (Anonymous, 2017).

Laboratory studies showed a synergistic effect of EPF and chemical insecticides including cypermethrin and acetamiprid against adult pine weevils, with increased speed of kill in the combinations than expected based on results for the agents trialled on their own (MCOP, 2016; van Vlandereren et al., in prep.), and a field trial in Ireland showed promise for using reduced rate of chemical insecticide in combination with EPF (MCOP, 2016).

7. DECISION SUPPORT SYSTEMS

In general, IPM is a decision-based process, requiring knowledge of the current or predicted pest status to inform decisions as to the choice and/or timing of pest management procedures. The decision-making process can range from general scouting for pests in the field and application of control when a threshold is reached, to more complex web-based decision support systems that take account of several factors to estimate risk and then recommend management options based on that risk. Here we describe systems employed in Ireland, the UK and Sweden, including two web-based systems (HMSS in the UK and the Swedish Snyttbaggemodellen).

7.1 Assessing population density and monitoring damage levels

To decide which management options (if any) to apply requires knowledge of the current or predicted population level of the pest. There are two approaches to monitoring pine weevil populations: monitoring the population within a stump ("stump hacking"), which will give an indication of the number of weevils developing on the site, or monitoring numbers of adult weevils present on site, which accounts for in-migration as well as weevils that developed on site. Coillte uses a decision support tool based on stump hacking (see below). Some private contractors in Ireland also adopt this approach.

Stump hacking estimates the size of the expected weevil population on a clearfell before planting. Stump hacking is performed by removing the bark of one quarter of the stump, including one major root and two root junctions, using a wood chisel or spade, and counting the number of larvae and pupae (Teagasc, 2020)(Fig. 8). Based on the results, the necessity of applying insecticides or using insecticide-treated seedlings can be evaluated.

Traps of various kinds can be used to monitor adults present on site. **Billet traps**, consisting of a branch or stem piece, placed on sites attract feeding pine weevils. This approach is used in conjunction with the HMSS described below. In Poland, billets or IBL-4 traps (Chemipan R&D Laboratories, Warsaw, Poland) have been used (Skrzecz et al., 2021). In Romania, **toxic bark traps** are used. Alternative to bark pieces, artificial traps with synthetic attractants (alpha pinene and ethanol) can be used. These are often **pitfall traps** that drown the pine weevil in a liquid and thus prevent them from leaving the trap (Nordlander, 1989; Zumr & Stary, 1995). The number and spacing of traps, and the timing of their deployment, can influence their validity in reflecting damage levels and pine weevil populations.

Stump hacking 1

Stump hacking 2

Stump hacking 3

Stump hacking 4 [all four images Coillte]

Figure 8: Stump hacking to estimate the population of pine weevil developing on a site. Bark is removed from a quarter of each of five stumps and the number of larvae and pupae is counted

An automatic device for real-time monitoring of adult pine weevil has been developed by the UK company Spotta (https://www.spotta.co/forest-pod), in collaboration with Forestry and Land Scotland. The system uses proprietary patented ultra-low power image recognition and lure dispensing technology. On-site “pods” are designed to attract and detect weevils and send the information to the remote user. Pods are expected to operate for an entire season without user input, and are placed at a frequency of one per hectare. In a similar approach, the HylopodTM, developed by a consortium including Forest Research UK, provides manual or remotely sensed weevil data which can be integrated with the HMSS monitoring system (section 7.3), and research is underway to use these pods in conjunction with entomopathogenic nematodes or fungi as part of a “lure and kill” strategy (Roger Moore: https://www.teagasc.ie/crops/forestry/news/2022/pine-weevil-conference.php).

Alternatively, **control areas** planted with untreated seedlings within the clearfell are used to monitor pine weevil pressure. In Romania, control areas of 5 x 10 m are used. The number of control areas per hectare depends on the size of the site: 4 on sites up to 3 hectares, 2 on sites of 3-10 hectares and 1 per hectare on larger sites. Regular monitoring of the seedlings on the control sites gives an indication of pine weevil pressure and the necessity of top-up sprays.

7.2 Ireland: Coillte's Weevil Management Decision Chart

Coillte refers to a Weevil Management Decision Chart on each site before deciding on any plant protection methods against the pine weevil (Anonymous, 2017), as outlined in Figure 9. Based on the results of stump hacking (see above) in conjunction with site properties and knowledge about the previous crop, the site manager evaluates the risk of expected weevil damage. If the risk is judged as low, either no action is taken or dipped plants and/or plants with large root collar are planted. If the risk is moderate to high, more steps of evaluation follow. If possible, green planting with dipped and/or large root collared plants is performed. Otherwise, if a longer fallow period is necessary, dipped plants with a large root collar will be planted. Independent of the decision before planting, sites are regularly investigated with stump hacking and crop monitoring, so that top-up sprays can be performed when necessary.

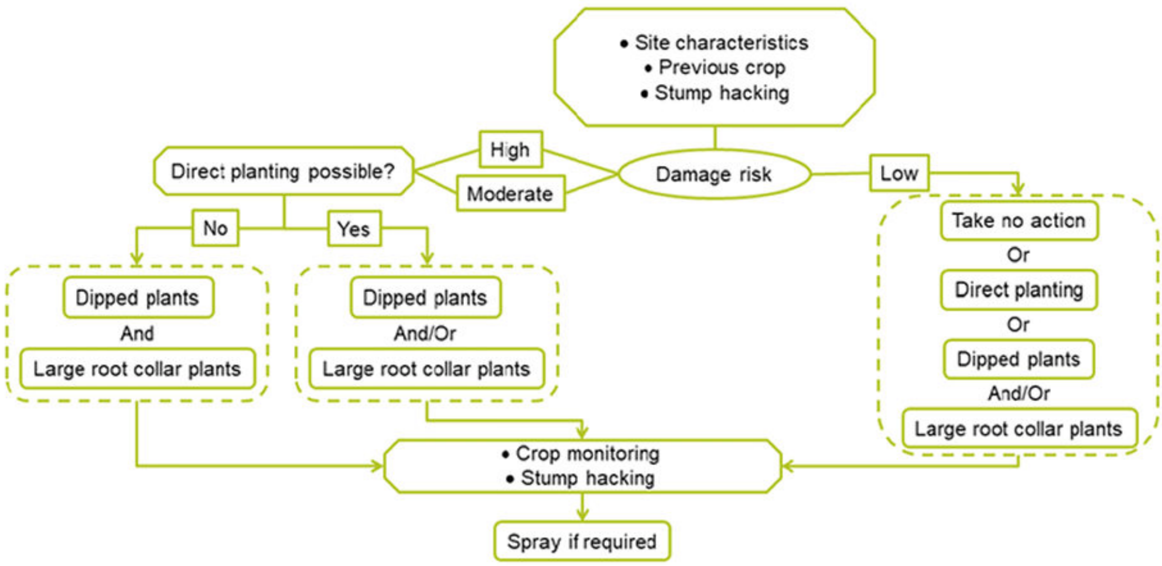

Figure 9: Decision support flow chart (modified based on Coillte)

7.3 UK Forestry Commission's HMSS

Willoughby et al. (2017) describe the decision support system used in the UK, and discuss the possible responses, which include: (1) "Take no action" (a high risk strategy without intensive monitoring, and therefore not recommended); (2) "Avoid the problem" (alternative silvicultural systems or species, fallow ground strategy, manipulating ground vegetation, and using good quality planting stock), or (3) "Take remedial action" (biological control with entomopathogenic nematodes, mulching and de-stumping, physical protection and insecticides).

Dr Roger Moore of Forest Research UK has developed the *Hylobius* Management Support System (HMSS), a web based tool helping foresters to minimise pine weevil damage on their replanting sites (Forest_Research, 2021). The system also considers amount of pesticide usage, costs and forest production certification as well as management goals. Cost reduction is mainly linked to reduced and correctly timed application of insecticides. The recommendations for timing of management actions and insecticide treatments are based on the site information that is put into the system and the size of the pine weevil populations. The HMSS is based on the research experience in the UK. The HMSS in its current form was found to be unsuitable for use in Ireland due to differences in silvicultural practices, including the length of fallow period. In the UK, fallow periods of up to 5 years, compared to 2 years in Ireland, are allowed and this is included in the HMSS.

7.4 Swedish "Snytbaggemodellen"

The software "snytbaggemodellen" (pine weevil model) (http://www2.ess.slu.se/snytbagge/default.htm) was developed by Swedish researchers to help assess the costs of protection methods against pine weevil damage in comparison to the costs caused by pine weevil without protection. The model is based on results of field experiments in southern Sweden from 1990 to 2004. It is only valid for southern Sweden and for planting of Norway spruce. The model gives an estimation of the survival and costs of the living plant based on the factors chosen. The following factors are taken into consideration within the model:

- Fallow period (1-4 years): An increasing fallow period increases the survival of seedlings.
- Number of plants to be planted per hectare (for assessing costs of planting and replanting): Does not influence seedling survival.

- Soil scarification (none, mounding and other methods of soil scarification): There are differences between the different scarification methods, but they all improve seedling survival compared to unprepared soil.

- Shelterwood (yes/no): Presence of shelterwood without other protection approximately doubles seedling survival.

- Seedling protection (none, insecticides, or physical protection): Plant protection highly increases seedling survival.

- Reapplication of protection (yes/no): Reapplication has only a small effect compared to single application.

- Plant type (bare-root vs. containerised; seedling age): In Sweden, alot of containerised seedlings are planted, and bare-root seedlings are usually older than containerised seedlings. Thus, there is a correlation between age, plant type and root collar diameter. Increased root collar diameter increases seedling survival.

Combining two of the factors that positively influence seedling survival has a synergistic effect in the model. Adding a third method usually does not further increase seedling survival, or does so only slightly.

8. PERSPECTIVES FOR IRELAND

The large pine weevil is a very significant forest pest in Ireland; inability to manage it adequately would make reforestation difficult or impossible, and since reforestation is becoming increasingly important in Irish forestry, this would pose a serious threat to both the forest industry and the role of forests in climate change mitigation. Therefore, its effective management is imperative. This pest is also of European importance, and we can learn a lot from the experience of others, particularly Sweden and the UK.

A vast amount of pine weevil research has been done in Sweden, including the development of physical barriers, but since the conditions there (including weevil population size) are quite different, methods developed in Sweden need to be carefully evaluated for use in Irish conditions. Conditions in Britain are a closer match for those in Ireland, and Ireland can benefit from the extensive research of our neighbours, including that of Forest Research UK. There are two main groups with Hylobius research remits in the UK and Ireland aimed at fostering collaboration and the exchange of knowledge about pine weevil: a more formal focussed “Hylobius Working Group” comprising Coillte and forest enterprises and state agencies of the constituent countries of the UK, and the Hylobius Industry Research Programme (HIRP) group which is a collaborative cross-industry body working to support research into the management of pine weevils in forestry plantations in UK and Ireland with members from state and private forestry sectors, Forest Research and academia. Forestry practices differ between Britain and Ireland in several respects, and there is a need to test novel solutions developed elsewhere under Irish conditions. Coillte conducts trials of the more promising chemical and physical protection methods.

The main approach to protecting plants on reforestation sites is by treating them with chemical insecticides. The specific chemicals used for this have changed over the years in response to changing availability and safety concerns, most recently from cypermethrin to acetamiprid. Although the pace at which new insecticides become available has slowed, new chemistries continue to be developed or to be tested against pine weevil, such as chlorantraniliprole. It is difficult to envision weevil control without chemical protection, as there is no simple alternative that is applicable across all sites. However, in line with sustainable forestry goals, it is generally desirable to use the least harmful chemicals available, and to reduce their use as far as possible. Some sites may not need treatment due to being low risk, while others may be protected using alternative approaches. Physical barriers can be useful, but they are expensive and suitable for use only on some sites. The only potential biological method so far seems to be the use of nematodes to suppress weevil populations.

As is the case for physical barriers, nematodes are expensive and not appropriate for all sites; moreover, their application has additional logistical requirements such as the need to transport a specialised spray rig and a large volume of water to sites. Entomopathogenic fungi have received less attention, with a limited range of species and strains tested to date. There is scope for innovative formulations and approaches incorporating fungi, including "lure and kill" strategies.

Central to an IPM approach to pine weevil is the ability to accurately predict risk on a site-by-site basis, so that appropriate measures are adopted for each site. The method currently used by Coillte relies on stump-hacking to assess the weevil population developing on site, together with expert knowledge of site location and other factors to estimate risk from neighbouring sites. Populations of weevils estimated by stump-hacking give a reasonable estimation of the numbers of weevils actually emerging on site in the season after hacking. This is shown by plotting numbers of developing weevils estimated by hacking in early summer against numbers of weevils collected in emergence traps erected over stumps on the same sites in later summer/autumn of the same year (Fig. 10). In general, there is a good correspondence between numbers in stumps and numbers emerging on sites, but there are some discrepancies, both over- and underestimates of emergence. An overestimate of emergence from stump-hacking may be explained in part by some of the in-stump population remaining in the stumps over winter. More concerning is an underestimate of emergence based on stump hacking, which can lead to no or limited action being taken and higher damage than expected. Understanding discrepancies between hacking and emergence could improve the value of stump hacking as a prediction tool.

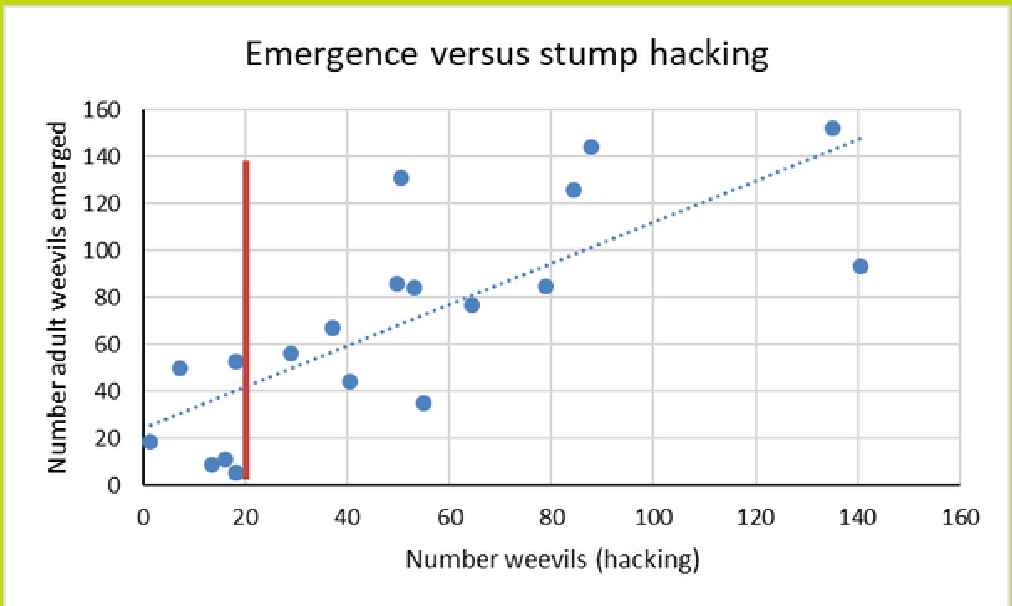

Figure 10: Numbers per stump of adult weevils emerging in late summer/autumn versus numbers of developing weevils in stumps hacked earlier in the season on nineteen sites. Data are from untreated control stumps in nematode field trials reported in Williams et al. (2013) and Kapranas et al. (2017). The vertical line corresponds to the threshold (5 weevils per quarter stump) above which spraying is recommended.

PERSPECTIVES FOR IRELAND

Knowledge of pine weevil population dynamics in Ireland is based on the expert knowledge of foresters along with information from other countries. There have been no formal structured studies of weevil population dynamics, though some data are available from field trials (such as the data in Figure 5). A model (based on Wainhouse et al (2014)) developed as part of the PW-IPM project (DAFM 17/C/228) integrates this information with temperature data to forecast the time at which adults will emerge onto a site (pineR, 2022). Stump-hacking (which is used to estimate numbers of weevils) can help refine the predicted time of weevil emergence, based on the stages of weevils present in the stump.

Since predicting weevil risk is such a key component of IPM, efforts to improve the accuracy of stump hacking as a predictive tool and/or to test other approaches for incorporation into a decision support tool would be worthwhile. While the HMSS *Hylobius* decision support system developed in the UK did not work effectively in Ireland, there could be potential to either work with Forest Research to adapt it to Irish conditions, or to develop a system appropriate for Irish forestry de novo. This would be in keeping with Coillte's "connected forests" approach (https://www.coillte.ie/our-business/our-projects/connectedforest/) and would also be of benefit to private forestry consultants. Any such system should be compatible with the current practice of stump hacking.

Prediction of weevil numbers and hence damage on a site must be understood in the context of climate change, particularly the increased temperatures that are expected. Flight of pine weevils is common in Scandinavia, resulting in colonisation of distant sites, while in UK and Ireland there are currently few reports of flight. However, increased summer temperatures expected with global warming could pose an increased risk of flight, with greater numbers of weevils potentially arriving on new sites. In this situation, the relative importance of on-site emergence would decrease, and this may need to be factored into any decision support system. Temperature in the stump affects the rate at which weevils develop from egg to adult (Inward et al., 2012) so increasing temperature may result in earlier emergence of weevils (Figure 11), as predicted for the UK (Wainhouse et al., 2014).

Changes in voltinism (the duration from egg to egg-laying adult) are also predicted for future climates in the UK, with an increase in the proportion of weevils with a one-year cycle, especially in southeast England, and a decrease in the proportion showing a 3-year cycle (currently the predominant pattern in upland regions of Scotland and Wales) (Wainhouse et al., 2014). Preliminary modelling using the Wainhouse et al model also forecast a decreased proportion of weevils displaying a 3-year lifecycle (Williams et al., unpublished; Figure 12).

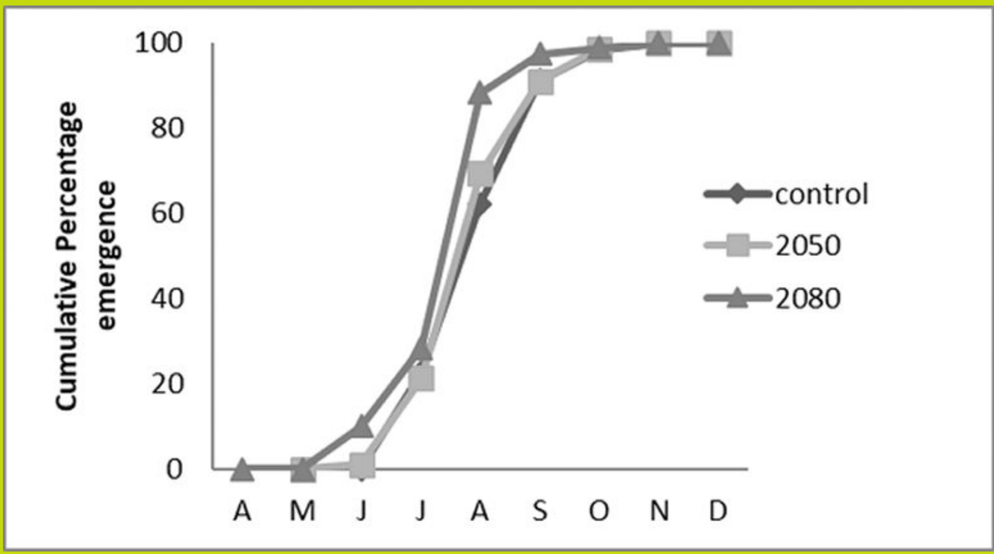

Figure 11: Emergence of weevils from stumps in current ("control") climates (based on data from 11 forest sites in Ireland) and model-predicted times for future climates in 2050 and 2080. (Williams et al unpublished).

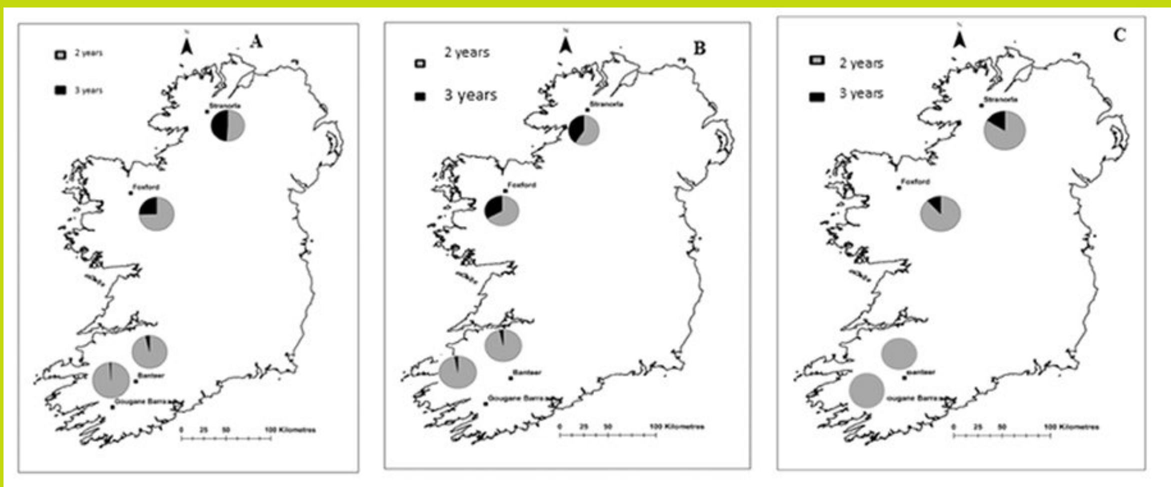

Figure 12: Predicted geographical variation in voltinism of *Hylobius abietis* across four forest sites A: current climate, B: 2050s and C: 2080s. Key indicates life cycle duration (voltinism of 2 or 3 years). (Williams et al unpublished)

Knowledge transfer

With more and more private forestry in Ireland reaching the fell and replant phase, the need for decision support increases. Many private contractors are so far specialised on afforestation management and are only slowly moving into reforestation. Thus, private owners will increasingly need support in dealing with this issue. Coillte, with its extensive experience in the management of pine weevil, on-going field trials of new approaches, and membership of the UK-Ireland Hylobius industry research groups, is an important source of information for the private sector.

Teagasc has a key role in disseminating information on pine weevil to the private sector, through its web site, open days, and knowledge transfer groups. A booklet in Teagasc's Farm Forestry Series entitled "Managing Pine Weevil: Methods and Option" was produced in 2020 as an outcome of the DAFM-funded PW-IPM project, with input from Coillte. However, as new methods of dealing with this pest are developed, this booklet will become dated, and will need to be updated, at least electronically.

There is scope to improve the dissemination and exchange of information on pine weevil management in Ireland. There could be value in a special interest group of key stakeholders such as ITGA and/or other growers' associations, Coillte, Teagasc and DAFM (including Forest Service and PCS), meeting annually to discuss the Hylobius situation to exchange information on strategies and approaches to pine weevil management, and ensure effective dissemination to interested parties.

9. CONCLUSION/RECOMMENDATIONS

The *Hylobius* Industry Research Programme (HIRP) of Britain and Ireland has identified five priorities to address the threat of pine weevil (Box 1).

Box 1. Priorities to address the threat of *Hylobius*, identified by the Hylobius industry research group

1. To develop **alternatives to chemicals** that work in areas of high *Hylobius* population, including physical barrier products.

2. Develop a viable **biocontrol** option, using insect pathogenic organisms such as fungi and nematodes that prey on and kill *Hylobius*.

3. Identify a range of alternative, weather-resistant, **non-neonicotinoid pesticides** that have low environmental impact and that might be used as a last resort if other methods of non-chemical protection fail.

4. Develop an **improved predictive *Hylobius* population model**, appropriate for use in all situations.

5. Create a **regularly updated guide** on *Hylobius* integrated pest management for use by all stakeholders across the sector.

(source: Farm Advisory Service Scotland https://www.fas.scot/article/large-pine-weevil-the-small-pest-causing-a-big-problem-for-restocking/May 2020)

In Ireland, Priorities 1-3 (Alternative and improved means of protecting newly planted trees) are addressed on the one hand by regular field testing by Coillte of novel chemicals and other approaches developed elsewhere, and on the other hand by targeted research projects on alternatives such as nematodes, sea-weed extracts and stem coats, involving industry/academia partnerships.

Recommendations from this project

(1) Ensure effective supports (financial/other) for field trials of promising products or approaches in Ireland

(2) Support for novel alternatives from fundamental research to commercial development, especially where novel solution may have export market (DAFM/other state funding including Enterprise Ireland)

(3) Validate and refine Coillte's existing decision support system, and evaluate for use in the private sector

(4) Consolidate knowledge of pine weevil population dynamics in Ireland, including regional trends and patterns, taking into account future climates; probability and distance of weevil flight is a key concern

(5) Revisit the UK HMSS system or develop a predictive model for pine weevil in Ireland. Stump hacking should be incorporated as a base-line

(6) Ensure knowledge transfer to the private sector, including one-day training sessions for private forestry consultants and updating the Teagasc booklet (produced in 2020) as required

(7) Establish a national *Hylobius* interest group with representatives of key stakeholders such as ITGA, Coillte, Teagasc and DAFM (including Forest Service and PCS)

(8) Consolidate information on *Hylobius* populations, risk factors and mitigation strategies (such as biomass removal) from end-users. The value of anecdotal reports could be enhanced by incorporation into a centralised system. Feeding user experience back into a national management/forecasting system would validate and improve the system.

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