Control and Management of the Pine Weevil *Hylobius abietis L.*

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Abstract

The pine weevil, *Hylobius abietis* L., is a pest of economic importance causing massive damage to conifer seedlings planted on reforestation sites. The lack of effective methods to prevent establishment of *H. abietis* in newly-harvested sites makes it a threat to European forests. The biology and ecology of the pine weevil have been intensely studied through the years. However, in light of current and future climate change much of the knowledge gathered thus far may need to be re-evaluated under these new conditions. Changes in temperature and other climatic variables may strongly change, for example, the development of the weevil and its distribution. Such changes may result in higher population numbers and increase the feeding pressure on newly planted seedlings, thus making it a novel pest in certain areas or increasing its pest status in others. There is a need to synthesize our current understanding on the biology, behavior and methods of damage control by the pine weevil *H. abietis*, in order to identify knowledge gaps and propose new management practices. In this review, we present such an overview and provide several examples on how this knowledge could be expanded or used to meet future challenges.

Keywords: Control, *Hylobius abietis,* monitoring, prevention

Introduction

Hylobius abietis is considered to be the main pest of forest plantations across Europe, at least in 15 countries and on approximately 3.4 mil. hectares of forest (McNamera *et al.*, 2018), and also in Asia (Leather *et al.*, 1999). The large pine weevil became a pest starting in the 19th century (Leather *et al.*, 1999) and it remains a threat, especially given current regulations against the application of pesticides in forest sites, synthetic pyrethroids such as deltamethrin and cypermethrin (Leather *et al.*, 1999), although deltamethrin has been shown to have low persistence (Viiri *et al.*, 2007). However, in Romania it became a pest much later since clear cutting of conifer forests started later than the rest of Europe. Regeneration has been done either naturally or through seed planting during the first few decades of the 20th century (Olenici, and Olenici, 1994). Thus, the first reports of attacks by *Hylobius* started during the 4th decade of the current century (Leather *et al.*, 1999), with the first written studies on the species dating from around the same time (Olenici, and Olenici, 1994). Currently, there are no official estimates on the amount of bark-feeding damage produced by *H. abietis* in Romania, where the main problems occur in nurseries.

In light of the challenges we face due to global warming, it is imperative that we examine various current and future alternatives to control this species, as well as re-evaluate the knowledge gathered so far. The potential influence of climate change on the pine weevil is relatively unknown, therefore there is a need to increase and update the current information. Some studies have shown that changes in the pine weevil's life cycle can occur (Inward *et. al.*, 2012), thus, we can expect the species distribution and population to differ from the current one. Considering that host plant distribution and adaptation are also likely to change with global warming (Dyderski *et al.*, 2017) their susceptibility to attack by insect pests could increase or decrease under future scenarios. . In this article, we focus on identifying the knowledge gaps and the information gathered so far in order to pose unanswered questions and new possibilities of protecting the seedlings against the pine weevil. We present an overview of the life cycle of the pine weevil, as well as damage and control measures.

Life cycle

Hylobius abietis develops in roots or stumps of dead conifer trees, laying its eggs in the bark of conifer stumps. Although predominantly semivoltine, the influence of temperature on weevil mass is likely to have a positive effect on fecundity and overwintering survival (Inward *et. al.*, 2012). Depending on the microclimate and the quality of the stumps, the life cycle can be between 12-36 months, but it can reach 5 years in areas with cold climate (Dillon and Griffin, 2008). Considering they are poikilothermic organisms, all insects have their development conditioned by the temperature of the environment. In *Hylobius abietis'* case, this influence is manifesting itself much stronger than in other species due to the its long oviposition period; and also, that the larva can develop at various soil depth levels. In Europe, the amount of time needed from the moment of emergence from the egg up to its first reproduction is around 2 years (CABI, 2015). Furthermore, the development highly depends on the quality of the host, temperature and oviposition factors. Populations vary in size, depending on the age and condition of the host plant (Davis *et al*., 2008).

Adults generally emerge from hibernation during the spring, when the temperatures reach 8-9 °C (Nordenhem, 1989). The activity of the adult is very dependent of temperature, light and humidity, preferring a temperature of approximately 20 to 25 degrees for feeding and oviposition (Christiansen and Bakke, 1968). Flight takes place at temperatures of over 18-19 °C, with a wind speed of 3-4 m/s-1 (Day *et al.*, 2004). Adults disperse looking for new hosts where they will feed up to maturity in the crowns of adult trees (Day *et al.*, 2004). According to Fedderwitz *et al.* (2014) pine weevils allocate 6% of their time to feeding, making 4-5 meals a day, eating about 13 mm^2 (debarked stem area) per meal. Feeding depends on the species of conifer, the depth of bark and temperature (Day *et al.*, 2004). Adults feed on the stem and roots of seedlings, and can often be found in the crowns of adult trees (Fedderwitz *et al.*, 2018).

Copulation takes period between May and August, which is a relatively long period (Lekander *et al*., 1985). Tilles *et al.* (1986) showed that *H. abietis* individuals do not use pheromones to recognize one another over high distances, but merely over a few centimeters. However, sex-specific recognition occurs at very short distances (Tilles *et al.* 1987). After mating takes place, the females lay their eggs in the fresh stumps of conifers. Feeding as well as oviposition are affected by climate conditions (Bylund *et al.*, 2004). Oviposition takes place from May up until September, with a peak in the middle of May up to the beginning of June (Leather *et al.*, 1999). Larvae emerge and start feeding subcortically on the bark. Host quality for feeding larvae has a large impact over the early stages of reproduction of the pine weevil (Thorpe *et al.,* 2008). In general, for the larva in their 3rd and 4th instar as well as for the adults, overwintering takes place in the pupal chambers (Nordenhem, 1989). As the temperature drops (generally under 8 °C), adults migrate towards the soil for hibernation (Leather *et al.*, 1999), usually being found in the soil litter of mature forests. The insect behavior is dependent on environmental factors and the insect itself physiologically speaking (Leather *et al.*, 1999). Nordenhem and Eidmann (1991) suggest that *H. abietis* has a different reaction to various attractants depending on its development stage. The spatial orientation of the adult is dependent on light and humidity, and the response to these factors varies according to the insects' developmental stage (Leather *et al.*, 1999). The weevils respond also to acoustic signals and volatiles of host plants (Leather *et al.*, 1999).

The potential effects of climate change on the pine weevil´s life cycle have been little studied, although longer summers and increased temperatures are likely to have an effect on the weevils (Tan *et al.*, 2010). Thus, potentially leading to future increases in pine weevil population size and the damage to planted seedlings. To identify morphological changes in the pine weevils, related to climate change, we could examine the sexual organs of the adults. Identifying changes related to the timing of sexual maturity could give an indication of how mating and oviposition might shift due to climate change. Thus, providing a window of opportunity to interfere with its cycle and use this as a control method. Such studies have been done on *Listronotus maculicollis* (Coleoptera: Curculionidae) (Wu *et al.*, 2017), and it has been shown that low temperature prevented reproductive development. If we examine the effect of different climatic variables on the reproductive development of the pine weevils, we could potentially use this information to enhance pest control in future scenarios.

Damage

Hylobius abietis causes damage especially to hosts freshly planted in clear cuts or next to 2-3 year old forests or trees with damaged branches (Leather *et al.*, 1999; CABI 2015). The damaged tissue emits chemicals that attract the adults recently emerged from infested sites to new hosts. Transplanted seedlings are vulnerable because the population densities of weevils on a site are often large relative to the availability of conifer stem material (Leather *et al.*, 1999). Therefore, high levels of damage to seedlings and subsequent mortality are common in the plantations.

It has been shown that the damage can be influenced by the type of soil used when planting the seedlings, the damage being reduced when seedlings were planted in mineral soil (Kindvall *et al*., 2000). The pine weevil avoids feeding on seedlings planted in mineral soil, however if vegetation is present, the pine weevils are encouraged to stay and feed on the seedlings (Petersson *et al*., 2006). In a similar manner, it is recommended to retain green trees in sites where burning is applied as a silvicultural treatment, in order to reduce the damage caused by the pine weevils (Pitkänen *et al.,* 2005). Further studies have shown that retention of trees could provide an alternative food source, therefore reducing the damage towards seedlings (Pikänen *et al.*, 2008).

In Romania, although we use both shelterwood system and clear cutting, our silvicultural systems do allow for natural regeneration to take place. In the sites where *H. abietis* occurs, it is recommended to take control measures to prevent major seedling mortality (Leather *et al.*, 1999; Albrecht *et al.*, 2008). Without control measures, young plantations, about 2 years old, suffer between 30 and 100% seedling mortality in Europe (Albrecht *et al.*, 2008; CABI 2015). The damage is not consistent between plantations, it can differ from one plantation to another. This is because each site has a different microclimate and different substrate. To improve pest control, variables at different sites could be examined, and levels of pine weevil damage assessed in relation to manipulation of these variables. Results from different sites could be compared, and a general pest control approach could be recommended.

The influence of silvicultural techniques over the populations of *H. abietis* is complex and poorly understood (Leather *et al.*, 1999). Freshly cut parcels, as well as those resulting from forest fires, are invaded by a large number of beetles from the first vegetation period after the appearance of these surfaces. There are numerous observations confirming that the most powerful infestations occur in these areas (Olenici and Olenici, 1994). Most of the population attacking a fresh plantation comes by migration from one site to another, very few result from the overwintering grounds of the remaining stumps. The pine weevils that fly quickly occupy the entire surface uniformly; while the weevils moving on the ground focus initially in the edges of the site slowly advancing towards the center, with a speed of up to 30m/day without a preferred direction (Olenici, and Olenici, 1994).

Control

Measures to reduce and control levels of damage by *H. abietis* are necessary in areas where silvicultural practices include clear-cutting and re-planting to regenerate the forest (Wallertz *et al.*, 2014). In Romania, due to common occurrence of mixed forests, the percentage of economical loss has not been as great as in other European countries that focus on monoculture stands. In the past, seedling protection against the pine weevil involved pre-planting and/or post-planting application of insecticides, e.g. pyrethroids. Pre-planting pesticide application was done to the bare roots of seedlings, while post-planting refers to spraying the seedlings with lower concentration of pesticide (Leather *et al.*, 1999). It has been shown that pine weevils tend to avoid untreated seedlings over pesticide treated seedlings (insecticides: imidacloprid and neonicotinoid); moreover, the death of the pine weevils can occur up to 3 weeks from treatment (Rose *et al.*, 2005). Thus, a variety of different strategies have been used to prevent and reduce damage by the pine weevil.

Control methods include, among others, monitoring of *H. abietis* populations and mass-trapping of the insects. Estimating the number of adult weevils in forest plantations is done using traps, manufactured from branches, freshly cut pieces of fresh bark or traps with various attractants. The traps have to be installed in the conifer plantations in the beginning of April up until September, and they have to be checked every week in order to monitor the number of adults caught. Olenici and Olenici (1994) have found, in the course of two years, a series of areas with moderate attack, strong attack and even very strong attack despite of the different measures of protection applied on the sites, including toxic bark. The failures are due to various causes: not enough traps, late placement of traps or late replacement, and possibly the pesticide used (e.g., pesticides such Detox or Heclotox may be too old to be effective; Decis has very short duration time, especially in low concentration (Olenici and Olenici, 1994). Although the insecticides Decis and Karate Zeon seem to be effective against the pine weevil, they can have long-term effects on the seedling growth and development (Luoranen and Viiri, 2005). Other trapping methods included using baited pitfall traps of various designs containing bait fluid, a mix of turpentine and ethanol (Voolma, 1994). Later on, Olenici and Olenici (2006) have tested NeemAzal-T/S successfully, although a concentration of 20% or more proves effective.

Albeit the mechanism underlying host recognition by the pine weevil is not fully understood, the principle of luring the weevils with the volatiles from fresh bark or branches (especially pine and spruce) has been used since the end of the last century (Leather *et al.*, 1999). In Romania, the bark traps have been recommended in most papers published before 1960 (Olenici, and Olenici, 1994). After 1960, most cases recommend using toxic bark traps, treated with basic pesticides such as DDT or HCH (Olenici and Olenici, 1994). In the years before 1960, the product used to treat the traps was based on arsen (Hylarsol) (Olenici and Olenici, 1994). Before the widespread availability of pesticides, mass captures were done using sawdust piles (Leather *et al.*, 1999); this method being used only if there was no felling nearby (Leather *et al.*, 1999).

Other methods used to prevent and decrease damage by pine weevils include protective collars (Lindström *et al.*, 1986) and shelters (von Sydow and Örlander, 1994). A mechanical method, Conniflex, based on protecting the seedlings physically against the gnawing of *H. abietis*, has been described and evaluated in the field in forest plantations in Sweden. Conniflex is based on covering the stem with a layer of particles that do not allow the weevil to feed on the bark (Nordlander *et al.*, 2008). This method appears to be more costly and requires substantial labor and time, considering the vast number of seedlings used in a forest plantation.

Additionally, various experiments have been carried out in Sweden to protect seedlings against *H. abietis* with the use of antifeedants (Nordlander, 1989). There have been attempts in finding antifeedants in non-host plants for the protection of Scots pine and Norway spruce seedlings. Tests pointed out that nonanoic acid has strong antifeedant properties against the pine weevil (Månsson, 2005). Furthermore, it has been shown that the feces of pine weevils contains some compounds with antifeedant effects (Borg-Karlson *et al.*, 2006). Anzeem *et al*. (2013) has later shown that the antifeedant compounds originates from microbes present in the frass and feces of ovipositing females, and could be used as an ecological alternative to insecticides.

In the following years, the idea of using entomopathogenic nematodes has been considered (Collins, 1993), as well as parasitic wasps (Henry, 1995) and other natural predators as control methods. Entomopathogenic nematodes (EPNs) of the families *Steinernematidae* and *Heterorhabditidae* (*Nematoda: Rhabditida*) have been shown to be lethal to insects, targeting the developmental stages of the pine weevil with the aim of suppressing the population (Dillon *et* al., 2006). *Steinernema carpocapsae* has been applied successfully to pine weevils at different stages of development, located in Sitka spruce stumps (Brixey *et al.*, 2006), with this species being more effective at killing adults of *H. abietis* than *H. downesi* (Girling *et al.* 2010).

Two blue stain fungi of the genus *Ophiostoma* and a yeast, *Debaryomycetes hansenii*, have been isolated from pine weevil frass, and been shown to produce Methyl salicylate (MeSA). MeSA is a compound that has proven to be a repellent or attractant between organisms; in the pine weevil's case having an inhibitory feeding effect (Anzeem *et* al., 2015). Beauveria *caledonica*, aentomopathogenic fungi isolated from *H. abietis* habitat, seems promising in suppressing the weevil population together with *Metharizium brunneum* and *Beauveria bassiana. M. brunneum* can persist in the felling site for at least two years, but more studies are necessary to determine their efficiency (McNamara *et. al.*, 2018).

Silvicultural practices have also been adapted to control or reduce damage by the pine weevil. According to Scott and King (1974) the population of *H. abietis* could be reduced by removing the stumps from clear cuts, which in turn could be used as source of bioenergy. Theoretically, stump removal can reduce pine weevil damage (Rahman *et al.*, 2016), however it is very costly. In Romania, debarking of stumps is practiced instead, being a measure that requires less time and effort and is therefore more affordable. In a similar way, it was recommended to use wood pole traps to attract weevils. Controlling the poles periodically, the weevils are collected and destroyed and the poles infested with eggs and larvae are burned, thus destroying the developing generation (Olenici and Olenici, 1994).

Wallertz *et al.* (2016) support the idea of an early planting (in autumn). Planting earlier allows the plants to grow and become more tolerant to pine weevil damage. Also, the plants manage to accumulate more biomass than the ones planted in winter/spring the following year. In a similar way, Nordlander *et al.* (2017) has shown that planting after the pine weevil emigration from clear-cuts is a better option compared to the current planting time. In addition to planting period, Hansen *et al.* (2017) hypothesized that harvesting of forest residues and the residue removal rate could have effects on the growth of Norway spruce seedling, and subsequently pine weevil damage. The results showed that where residues were removed, the seedlings had a better growth and the pine weevil damage was reduced (Handsen *et al.*, 2017).

Mounding is an alternative used in Finland for Norway spruce seedlings. This practice promotes the growth of the seedlings after planting, resulting in more vigorous plants capable of recovering from pine weevil damage (Örlander and Nilsson, 1999). Luoranen *et al.* (2017) investigated whether mounding is efficient in preventing or reducing pine weevil damage in Norway spruce, for seedlings planted without insecticide treatments. Results have shown that the method has potential in mounds covered with pure mineral soil, if the seedlings stem has over 4mm diameter. Another ecological mean of protection for seedlings could be the use of over-stories. It has been shown that over-stories of Norway spruce will decrease herbivory from the pine weevil in under-planted seedlings (Lof *et al.*, 2004).

Lately, a large number of studies have focused on inducing the resistance of plants using the plant hormone methyl jasmonate (MeJa) (produced by plants various developmental processes and when stressed). Scots pine (*Pinus sylvestris* L., *Pinaceae*) produces a terpenoid resin which consists of monoterpenes and resin acids that offer protection against herbivores and pathogen attacks (Heijari *et al.*, 2005). The changes in plant growth and chemical parameters after the MJ treatments indicate shifts in carbon allocation towards defense, but MJ also affects plant physiology and xylem development. Terpenoid resin production is tissue-specific, but generally increased after MJ treatments, which means that this compound may offer potential protection of conifers against herbivores (Heijari *et al.*, 2005).

Other novel methods of plant protection could be explored. For instance, breeding trees for increased resistance against the pine weevil. Genetic variation for the levels of pine weevil damage received by plants has been found for Norway spruce and families with greater resistance have been identified (Zas *et al.,* 2017). Thus, there is future potential for developing resistance breeding program in Norway spruce. Additionally, a clonal propagation method (somatic embryogenesis, SE) has been recently shown to confer greater resistance against pine weevils in Norway spruce (Puentes *et al.,* 2018). Plants produced via SE or families with greater resistance could be used for re-planting in sites with high pine weevil pressure. Moreover, direct methods of controlling pine weevils are also being explored. For example, studies on other *Curculionidae* species have shown that sterilization of male adults is possible without damaging their mating ability, thus it should be taken in consideration for *H. abietis* as future control method (Sales *et al.*, 2018).

Conclusions

Our understanding of the biology of the pine weevil, *Hylobius abietis* L., is vast, covering information from the morphology, life cycle, behavior, damage and means of control. Despite the depth of our knowledge on this insect, the pine weevil continues to be a pest causing immense damage and loss of plant material in European forests. Given the challenges we face with global changes in many climatic variable, much of the current knowledge should be evaluated under these future scenarios. Changes in the pine weevil's development might be drastic and entail adapting forest management practices and control measures. In particular, questions with regards to the emergence and sexual maturity of the insect should be addressed, as they could offer a clear and specific window to suppress the population. This should be accompanied by improvement of the plant material. Novel ideas of increasing the plant resistance as well as introducing plant material with repellent properties should be further considered.

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