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Insects Associated with Reforestation and Their Management in Poland

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Abstract

Weevils (Coleoptera: Curculionidae) are the most important pest insects of forest plantations established on clear-cut areas, and *Hylobius abietis* is a pest insect of great economic importance in Europe. *Pinus sylvestris* plantations and thickets established on sandy soils or postfire areas can be severely impacted by *Cneorhinus plagiatus* and *Brachyderes incanus*. Young pine forests weakened by biotic and abiotic factors are particularly susceptible to *Pissodes castaneus*. Buds and shoots of *P. sylvestris* trees are mainly damaged by Lepidoptera larvae. For many years, chemical treatments have been the main way of protecting forests against insects. At present, to reduce the pollution of forest environments with insecticides, the strategy of integrated pest management (IPM) was put into practice. It involves prophylactic measures to increase plant resistance to insect attacks and to select appropriate control methods based on a multistep decision support system (DSS). Nonchemical control measures aim at collecting pest insects in traps fitted with attractants and biological methods, mainly based on entomopathogenic nematodes (EPNs) and wood-decomposing fungi. Chemical insecticides are used only in cases of high threats to reforestation stands. This paper presents the state of knowledge concerning pest insect management in forest plantations in Europe, with particular emphasis on insects occurring in Poland.

Keywords: forest plantations, *Hylobius abietis*, *Pissodes castaneus*, *Brachyderes incanus*, protection, IPM

1. Introduction

In Poland, forests cover a total area of around 9.2 million hectares, taking up 29.4% of the land area [1]. Poland is therefore one of the countries with the largest forest areas in central Europe. The main forest type is coniferous forest, accounting for 70%, with Scots

pine (*Pinus sylvestris* L.) as the dominant species, especially in the center and the northern parts, where it takes up to 58.5% of the forest area. Norway spruce (*Picea abies* (L.) H. Karst) and European beech (*Fagus sylvatica* L.) prevail in the South, mainly in the mountains. Each year, the share of deciduous trees has been increasing, and oaks (*Quercus* spp.), due to their high ability to adapt to various habitats, now belong to the most common trees in Polish forests (8%) [1].

Monolithic species composition, even-aged forest structure, is a result of reforestation of thousands of hectares destroyed during World War II, and unfavorable atmospheric conditions resulting from influences of maritime and continental climates are the causes of the susceptibility of some stands to a variety of harmful biotic and abiotic factors. Among European forests, the Polish forests belong to the ones which are most threatened by biotic factors, mainly insects and pathogenic fungi occurring cyclically in the forms of mass outbreaks or epiphytotics and affecting thousands of hectares. In the years 2011–2013, the areas threatened by pest insects exceeded more than 4.2 million hectares each year, representing more than 23% of the total forest area [1].

Current problems of forest protection concern weakness of forest stands caused by climatic changes, which intensify previously infrequent phenomena such as extreme heat and droughts and violent storms, often accompanied by powerful hail, hurricane winds and whirlwinds, as well as floods. Repeated influence of these forces weakens forest stands, which are subsequently attacked by pests or colonized by fungal pathogens. Long-lasting droughts, which became more common during the last two decades, were one of the major factors which started the process of large dieback of Norway spruce forests in the mountains intensified by the outbreak of European spruce bark beetle *Ips typographus* (L.) and pathogens from the genus *Armillaria* [2]. In pine stands, disruption of water balance can become a major factor leading to dying of Scots pine forests due to the diseases caused by *Gremmeniella abietina* (Lagerb.) M. Morelet, *Cenangium ferruginosum* Fr., and *Sphaeropsis sapinea* Fr. Fungi. Water-related stress leads to weakening of broadleaved, especially oak *Quercus* spp. stands, which are being attacked by *Agrilus* spp. beetles and pathogens from the genus *Phytophthora* [3]. It is possible that long-lasting droughts initiated the development of infectious ash disease caused by *Chalara fraxinea* fungi, which resulted in dieback of *Fraxinus* spp. forests throughout Europe [4]. Hurricane winds in lowlands and in the mountains cause the damage to coniferous forests by pulling and breaking the trees which provide a place for development of secondary pests, mainly from subfamily Scolytinae [5]. Hail storms as well as heavy snow falls combined with glaze ice on pine branches lead to damage in a form of broken and twisted trees, which are often attacked by weevils *Pissodes* spp. [6]. In addition, root systems damaged by drought, sudden freezes, or torn as a result of hurricane winds become a “gateway” for infection fungal pathogens initiating a multistage disease of stands, involving harmful insects. Moreover, climate warming increases probability of arrival to Central Europe of new insect and fungal species, which are more common in areas with higher air temperature. The presence of such species in Poland could be of an invasive form, and therefore setting up of continuous monitoring of such organisms’ presence is essential.

Forests can be susceptible to insect attacks at all stages, and forest plantations newly established on clear-cuts left after harvesting of old stands facilitate the concentration of insects associated with specific stand ages (**Photo 1**). In Poland, weevils (Coleoptera: Curculionidae) represent the most important group of pest insects of 1–5-year-old forest plantations established on clear-cuts [7–9]. The aim of this paper is to present the most important insect species damaging forest plantations and their management, including methods to estimate and reduce their numbers.



Photo 1. Typical *Pinus sylvestris* plantation in Poland.

2. Pest insects in forest plantations

2.1. *Hylobius abietis*

The large pine weevil *Hylobius abietis* L. is one of the pests with the greatest economic importance in Europe [10, 11]. The spruce weevil *Hylobius pinastri* Gyll. is another species damaging young forest plantations, but it occurs only occasionally and has a lower impact than *H. abietis*. In Poland, both species have been recorded every year throughout the whole country. Over

the last twenty years, the area of their occurrence has decreased from more than 40,000 ha in 1995 to just about 10,000 ha in 2015.

During the growing season, two distinct periods of increased occurrence of *H. abietis* in reforestation areas can be clearly defined [12–14]. The first period of pest mass occurrence, representing a significant threat, usually appears in May due to the migration of beetles from adjacent stands attracted to the monoterpenes emanating from the resin of fresh stumps left after harvesting of old coniferous trees in the reforested areas. These volatiles include α -pinen and 3-carene, which show synergistic effects with ethanol [15, 16]. These compounds are also used in practice as kairomones in bait traps to attract and collect weevils. The studies of Azeem et al. [17] showed that *H. abietis* beetles are the vectors of fungi *Ophiostoma canum* (Münch), *Ophiostoma pluriannulatum* (Hedq.) Syd. and P. Syd., and yeast *Debaryomyces hansenii* (Zopf) Lodder and Kreger-van Rij., which produced methyl salicylate that strongly reduced the large pine weevil's attraction to the *P. sylvestris* volatiles. The second period of mass occurrence takes place in August or September as the result of hatching of the second generation developed from eggs laid in the spring of the same year.

The first appearance of beetles on clear-cuts depends on the weather conditions, especially on air temperature. Similar to observations made in Norway [18, 19], in Poland, weevils leave their wintering places when air temperatures exceed 10°C, which is usually at the turn of April and May. The beetles move on foot or fly from adjacent stands, attracted by volatiles emanating from the resin of fresh woody debris left after harvesting [11, 12]. They can fly in May and June [11]. Not much is known about the distance they can cover, but in Poland, marked insects were found at a distance of 2 km from the place of release [20]. In a study in Sweden, the range of weevil flight oscillated between 80 and 100 km [21]. It is assumed that in one day, beetles can fly a distance of 10 km, while they can walk a distance of 50 m. However, questions remain concerning the period of the development cycle in which beetles lose their ability to fly. Nordenhem [22] observed young and mature beetles, which have already copulated, flying. This view is supported by Korczynski [20], who stated that the beetles lose their ability to fly in a certain period of the growing season, possibly due to temporary weakness of the muscle wings.

In Poland, the large pine weevil population reaches its maximum of abundance in the second half of May [23]. In addition to young beetles, the population also consists of older individuals that have wintered two to three times. Generally, beetles that have wintered in warmer positions appear first, followed by those which have wintered in colder areas [24, 25]. The beetles avoid reforestation areas with high humidity [26]. Analysis of changes in the spatial distribution of the seedling damage caused by the large pine weevil showed that initially, beetles accumulate on the edge, making their way into the central zone of the forest [27].

According to Korczynski [27], feeding activity peaks in the evening hours, while Christiansen and Bakke [19] observed highest feeding activities at night, when air temperatures oscillated between 19 and 28°C. These results were partially supported by Fedderwitz et al. [28], who observed that most of the beetles under laboratory conditions were feeding in the second half of the dark phase and in the first hours of the subsequent light phase. They also showed that weevils spend only 6% of their time feeding. Temperatures above 30°C cause the disappearance of the activity of the insect [29].

The seedlings of all conifer and some deciduous (e.g., *Betula* spp. or *Quercus* spp.) tree species can be damaged by *H. abietis*. The weevils chew patches in the bark of stems and lateral shoots, causing their deformation and even death [30–32]. The large pine weevil also feeds on bark and needles of young shoots in older stands, including trees left on the clear-cuts for natural regenerations. Experiments on food selectivity showed that species of the genera *Pinus*, *Picea* and *Larix* spp., especially *P. sylvestris*, *Pinus strobus* L., *P. abies*, and *Larix decidua* Mill., are the most attractive food sources for *H. abietis* beetles [31, 32].

After supplementary feeding, the beetles copulate, and at the turn of May and June, the females start to lay eggs on the roots of stumps or on coarse woody debris such as soil branches and piles of bark remaining after tree debarking. According to Bylund et al. [33], *H. abietis* female lays approximately 70 eggs during the first season. In Poland, Korczyński [34] observed that during the growing season, one female laid up to 100 eggs, mainly in the second half of June.

Fresh stumps of coniferous trees and their roots are the most important breeding bases for *H. abietis* development. Experiments conducted in Sweden showed that monoterpenes α - and β -pinen, 3-carene, and terpineol, secreted by the roots of stumps, attract the beetles to the breeding bases [35]. The stumps remain suitable as breeding sites as long as the cambium remains in good condition. According to a study conducted by von Sydow and Birgersson [36] on Scots pine and Norway spruce, during the first months after cutting, a number of chemical and physical processes get activated in the stump, followed by a decrease of stump humidity, a reduction of the number of living wood cells, and a decline of ethanol concentrations, attracting species of the family Curculionidae. The studies estimated the attractiveness of various coniferous species as breeding material for the large pine weevil and showed that stumps of *P. sylvestris*, *P. abies*, and *L. decidua* are more often colonized by the pest than stumps of other species [37]. Based on laboratory tests, Nordenham and Nordlander [38] found that females can lay their eggs directly on the ground. In a similar study, Pye and Claesson [39] showed that about 90% of females lay eggs at a depth of 5–10 cm near the roots distributed around the stem base. Once the larvae have hatched, they chew tunnels down the roots, reaching a length of up to 1 m. Skrzecz [40] analyzing colonized *P. sylvestris* stumps found most of the larvae on roots with a diameter of 2–4 cm and reaching a depth of 0.5 m. In the case of *H. abietis* larvae wintering in stumps, they were found in roots with a diameter of up to 2 cm. Most likely, such behavior protects the insects against low winter temperatures when soils are frozen. According to Eidman [41], the development of eggs lasts from 12 to 16 days at temperatures oscillating between 20 and 28°C. After oviposition, the females do not die, but feed and spend the winter in the forest litter; in the following year, they oviposit again after supplementary feeding in spring.

The length of larval development depends mainly on the temperature. In Poland, the large pine weevil develops one generation yearly. Dominik [42] stated that in shaded places under the canopy, the development can be extended, leading to a 2-year generation. At the same time, this author demonstrated that the sunlight, influencing soil temperature, is the main factor impacting *H. abietis* development. These results were confirmed by Kuziemska-Grzeczka [43], who observed faster development of this pest insect in sunny areas than in shaded ones. Eidman [41] reported that under laboratory conditions, the larvae develop within 97 days at a temperature of 11°C, while at 25°C, development is completed within 42 days. Temperatures

below 20°C can cause a diapause of the last instar larvae lasting from 60 to 220 days. The larvae pupate in the pupal chambers where they remain for one to five weeks. The young beetles stay in the pupal chambers up to three weeks and hatch in August or September of the same year. Some of the beetles overwinter in the chambers and leave them in the spring of the following year. Despite many studies on the biology of *H. abietis*, we do not know much about the influence of temperature on the development of these insects, especially in the context of global warming. Daegan et al. [44] studied the effect of temperature on the development and life cycle regulation of the large pine weevil in the aspect of projected climate warming, i.e., an increase of mean temperatures in the UK by the 2080s. They confirmed a linear relationship between temperatures and *H. abietis* development rates, concluding that the predicted increase in average temperatures may result in the development of two generations during one year, even in northern European countries. In connection with climate change, which also affects the distribution of insects, Barredo et al. [45] proposed to establish an open European database of geo-referenced insect pest distributions, including that of *H. abietis*.

2.2. *Pissodes castaneus*

The banded pine weevil *Pissodes castaneus* (De Geer) is one of most dangerous pest insects in forest plantations and thickets weakened by biotic factors, mainly pathogenic fungi and deer, as well as abiotic factors, including drought, hail, and fire [46]. It is a species commonly found in Europe, especially in northern Italy, Austria, Germany, the Asian part of Russia, and Turkey, as well as in North Africa [47, 48]. In 2001, it was introduced to South America, where it was initially described in Brazil, Argentina, Uruguay, and Chile [49]. In South America, it damages *Pinus taeda* L. and Douglas fir *Pseudotsuga menziesii* (Mirb.) Franco, while in Europe, many species of pines, primarily *P. sylvestris*, *Pinus pinaster* Aiton, and *Pinus pinea* L., are affected. In Poland, *P. castaneus* is commonly found in *P. sylvestris* plantations and thickets (**Photo 2**). From 2000 to 2015, the area of its occurrence increased in Europe, including Poland, to over 8000 ha per year.

In central and southern Europe, *P. castaneus* develops two generations per year, whereas only one generation is observed in northern European countries. The beetles leave their wintering places in the first half of April and then feed on the buds and young shoots of *P. sylvestris*, which is usually insignificant, but in the case of mass occurrence, it can lead to severely inhibited shoot growth. In May, the females lay their eggs on the lower parts of Scots pine stems, generally between the root collar and the second whorl of branches. Alauzet [50] found that under laboratory conditions, the females can produce over 500 eggs in their lifetime. After 8–10 days at 22–23°C, the larvae hatch and start to excavate galleries under the bark of stems, causing die-back of infested trees [47]. The constructed galleries end with pupal chambers in which pupae can be found between May and July. The beetles of the second generation hatch in late June and early July and start feeding immediately; in July and August, the females oviposit. The first larvae can be observed from the second half of August. During warm summers and autumns, the larvae develop to pupae or beetles and then overwinter. In the case of a cold spring or autumn (air temperature <10°C), the development of the first and, consequently, the second generation is longer, and the insects overwinter as larvae, pupae, or rarely as beetles [51].



Photo 2. *Pinus sylvestris* seedling with the characteristic symptoms of the colonization by *Pissodes castaneus*: leaks of resin on a stem, hanging top shoots.

2.3. *Cneorhinus plagiatus*

Very young (1–2-year-old) Scots pine plantations and thickets established on previous fire areas, especially on poor, sandy soils, can be heavily affected by weevils of the species *Cneorhinus plagiatus* Shall. These beetles occur in reforestation areas in April and May and feed on the buds, needles, and bark of *P. sylvestris* seedlings during the night. Mass appearance of both species may lead to severe seedling damage or even death within a relatively short time. During the day, beetles stay in the soil close to the root collars of the seedlings. The insects copulate in May and the females oviposit 30–50 eggs into the soil. The larvae feed on the roots of herbaceous plants. Pupation and overwintering take place in the soil. In Poland, *C. plagiatus* is currently not of economic importance as it is only recorded in less than 10 ha per year.

2.4. *Brachyderes incanus*

The weevil *Brachyderes incanus* L. mainly attacks newly established *P. sylvestris* plantations on postfire areas [52]. Although this insect is also present in plantations on depleted post-agricultural land, it is characteristic for large areas damaged by fire. In Poland, the area of mass occurrence of this insect has reached over 20,000 ha of postfire land since the 1990s but does not exceed 20 ha per year. The beetles usually feed on *P. sylvestris* needles, but during mass appearance, they can also cause damage to *Picea* or *Larix* needles and even to the bark of young *Betula* or *Quercus* trees.

The insects feed on needles of the two highest whorls of branches. Although they can damage up to 95% of these needles, the infested trees have not died because one-time feeding is not detrimental to growing trees. However, repeated feeding can lead to growth inhibition and significant weakening, resulting in death in some cases.

The insect produces one generation per year. The beetles overwinter in the forest litter and start to feed in April–May; at the beginning of June, the females oviposit eggs into the soil. Depending on air temperature, after 2–6 weeks, the larvae feed on roots of shrubs, trees, and grass growing in reforested areas. Larvae pupate in August and the new generation of beetles appears toward the end of August, in September, or at the beginning of October.

2.5. Other species of low economic importance

Table 1 lists other species of pest insects occasionally occurring in Poland on small areas of forest plantations and thickets. Buds and shoots of Scots pine trees younger than 15 years are mainly damaged by Lepidoptera larvae. At present, the European pine shoot moth *Rhyacionia buoliana* Schiff (Lepidoptera: Tortricidae) is the most common and important pest in Polish pine thickets. It finds suitable conditions for its development in sunny and weakened stands, which become reservoirs of this pest. Severe infestations of pine trees by the European pine shoot moth inhibit height growth, cause deformations of trees, and thereby lower the value of timber products.

Pine needles and buds are also infested by *Exoteleia dodecella* L., which appears in Poland in stands of all stages, but most rapidly and in largest numbers in plantations and thick-

ets aged 6–30 years. For a number of years, considerable damage in pine thickets caused by *Thecodiplosis brachyntera* Schwaegr. and accompanied by *Contarinia baeri* Prell. (Diptera: Cecidomyiidae) has been reported. The larvae of these Diptera suck on needles and cause premature shedding and dropping. Similar damage to pine needles is also caused by the weevil *Brachonyx pineti* Payk. From the group of sucking insects, the pine bark bug *Aradus cinnamomeus* Panz. (Hemiptera: Aradidae) can be a serious pest in young pine stands. It occurs on dry and depleted soils and in areas affected by industrial pollution.

Insect species	Damaged species	Damaged parts of tree	Insect instar causing damage
<i>Rhyacionia buoliana</i> Denis and Schiff. <i>Rh. duplana</i> Hübner <i>Blastethia turionella</i> L. (Lepidoptera: Tortricidae)	<i>Pinus sylvestris</i>	Buds, shoots	Caterpillar
<i>Aradus cinnamomeus</i> Payk. (Hemiptera: Aradidae)	<i>Pinus sylvestris</i>	Stem	Larva, imago
<i>Neodiprion sertifer</i> Geoff. (Hymenoptera: Diprionidae)	<i>Pinus sylvestris</i>	Needles, shoots	Larva
<i>Acantholyda hieroglyphica</i> Christ (Hymenoptera: Pamphiliidae)	<i>Pinus sylvestris</i>	Needles	Larva
<i>Barbitistes constrictus</i> Brunner von Wattenwyl (Orthoptera: Tettigoniidae)	<i>Pinus sylvestris</i>	Buds, needles	Imago
<i>Exoteleia dodecella</i> L. (Lepidoptera: Gelechiidae)	<i>Larix decidua</i> <i>Pinus sylvestris</i>	Needles	Caterpillar
<i>Dreyfusia nordmannianae</i> Eckst. (Hemiptera, Adelgidae)	<i>Abies alba</i>	Needles, shoots	Larva
<i>Cryptocephalus pini</i> L. (Coleoptera: Chrysomelidae)	<i>Pinus sylvestris</i> <i>Picea abies</i> <i>Abies alba</i>	Needles	Imago
<i>Brachonyx pineti</i> Payk. (Coleoptera: Curculionidae)	<i>Pinus sylvestris</i>	Needles	Larva
<i>Thecodiplosis brachyntera</i> Schwägrichen (Diptera: Cecidomyiidae)	<i>Pinus</i> spp.	Needles	Larva
<i>Contarinia baeri</i> Prell (Diptera: Cecidomyiidae)	<i>Pinus sylvestris</i>	Needles	Larva
<i>Hylastes</i> spp. Erich. (Coleoptera: Curculionidae)	<i>Pinus</i> , <i>Picea</i> , <i>Abies</i> spp.	Stem	Imago
<i>Magdalis</i> spp. Germar (Coleoptera: Curculionidae)	<i>Pinus</i> , <i>Picea</i> , <i>Abies</i> spp.	Shoots	Larva, imago

Table 1. Insect pests of less economic importance in Polish young conifer stands.

3. Integrated management of weevils in reforested areas

3.1. Background

In Poland, contemporary forest protection against insect pests is based on the strategy of integrated pest management (IPM) (**Figure 1**). The plant is the main objective of all treatments, and its genetic specificity, response to the colonizing organisms, and the relationship with the environment are taken into account. Prevention based on prophylactic measures is a very important element of this strategy and followed by protection methods in which priority is given to biological and biotechnical methods covering the use of biological insecticides and also substances that affect insect behavior. Chemical treatments, as the last option, are used when other methods are not effective and in cases of high threats to crop sustainability.

In practice, prophylactic measures are aimed at strengthening stand resistance to attacks by pest insects and take into account the recommendations of forest silviculture, utilization, and

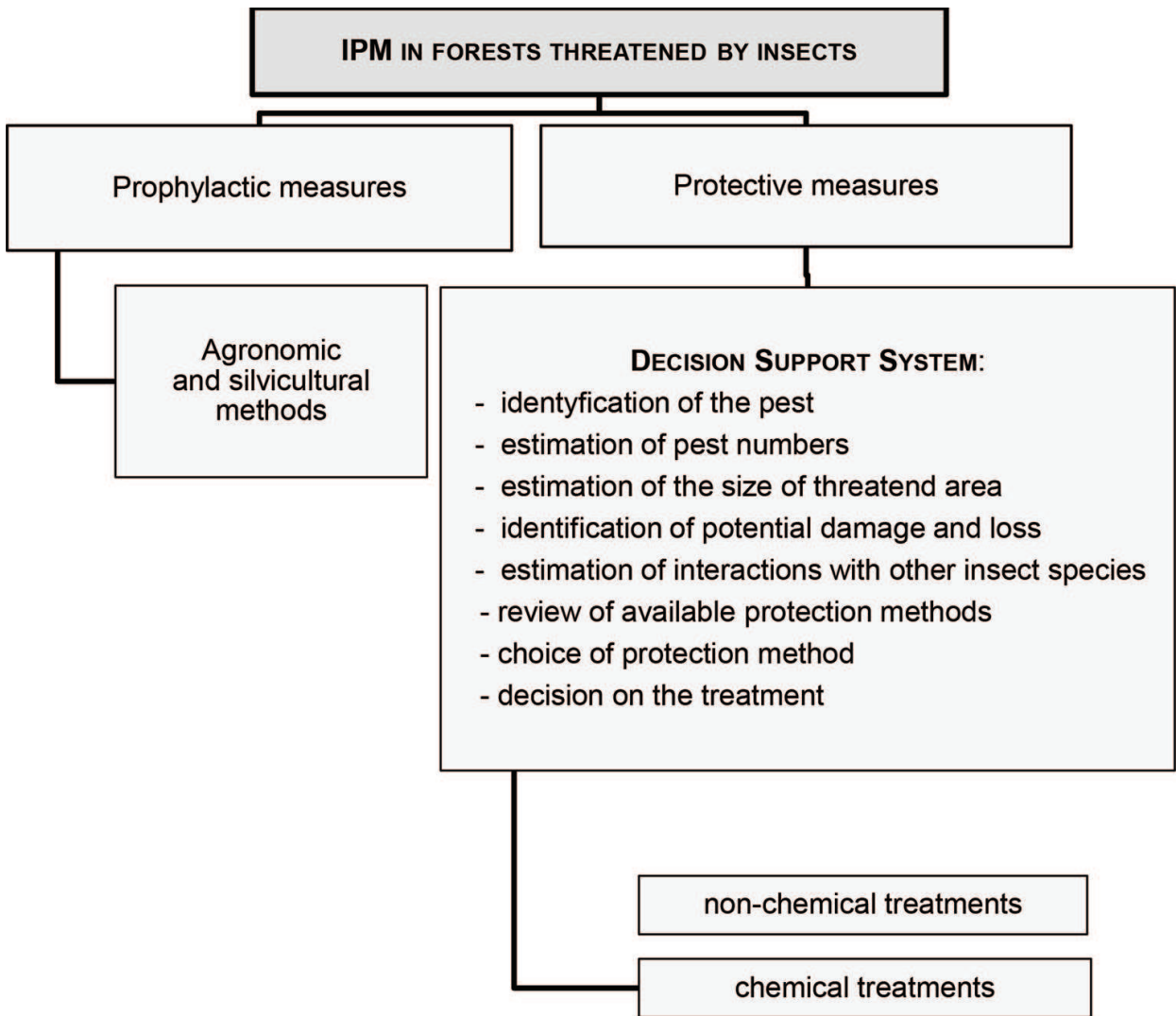


Figure 1. Integrated pest management to protect forests against pest insects.

protection. The most suitable protection method is selected on the basis of a multi-step decision support system (DSS), which includes identification of the pest and determination of the amount of tree damage, estimating potential losses. It is also important to define potential interactions, e.g., coexistence with other species of pest insects. The final stage of DSS includes a review of available protection methods and selects the most appropriate method for the given situation.

Protective measures are mostly taken to reduce the abundance of *H. abietis*, in some cases also of *P. castaneus*. Treatments that protect crops against other species of insects are performed locally in small areas. The integration of different methods to reduce the damage caused by insects in forest plantations, particularly by *H. abietis*, is an example of the IPM strategy. It was developed based not only on research but also resulted from long-term observations of pest biology and ecology and scientific analysis of the causal sources of pest outbreaks. Integrated pest management strategies to protect reforestation stands against *H. abietis* were also introduced into the UK to replace the use of insecticides, with particular emphasis on the development of methods of risk assessment as well as biological control methods with the use of entomopathogenic nematodes (EPNs) [53, 54]. In Sweden, the IPM strategy, in addition to risk assessment, includes the use of different barriers on seedlings and silvicultural measures, such as soil scarification and leaving the shelter trees on site to reduce the damage [55–58].

3.2. Prophylactic measures

Clear-cutting is the method most frequently employed in Polish forests. Postcutting regeneration leads to the formation of evenly aged stands of poor species composition, mainly Scots pine and Norway spruce. This facilitates the concentration of pest insects associated with defined developmental phases of stands. The most important preventive measures include agronomic and silvicultural methods that improve seedling growth, making them more resistance to insect damage.

The establishment of forest plantations composed of a variety of trees species or the promotion of natural regeneration on sites with favorable regeneration conditions can increase resistance of the biocoenosis to pest insects. Results of Scandinavian studies showed that naturally regenerated plants were less susceptible to weevil attacks than planted ones. Water stress and some other physiological effects related to transplantation may be some of the reasons why planted trees are more susceptible to insect attacks.

According to Moore et al. [53], the within-season felling date is one of the most important factors affecting the development of *H. abietis* in stumps, its abundance, and damage to seedlings. In the second year after felling, they observed more weevils in the stumps created between May and early August than in those from late August to November. Similar results were obtained by Korczynski [59] who stated that in plantations established in areas where the stand was felled in winter, the number of *H. abietis* beetles was in all cases higher than in adjacent stands, whereas in plantations established on summer clear-cuts, the number of these insects was always smaller. Similarly, Skłodowski [60] stated that plantations established on clear-cuts from summer showed low susceptibility to the large

pine weevil. In contrast, Koehler and Kolk [61] considered that plantations established on clear-cuts established in May–June are increasingly threatened by insects than those established on clear-cuts from autumn or winter. In their opinion, *H. abietis* prefers to colonize stumps created during the summer period.

Delaying replanting for two to four years after clear-cutting can be another method to reduce *H. abietis* abundance in plantations. Damage is reduced because most of the weevils would have left the area before the beginning of reforestation activities [62]. Although this method is recommended for Poland, it can only be applied on 1–2-year-old areas, as intensive weed growth, resulting in high costs for weeding, renders this practice unsuitable [60]. In Poland, the planting takes place during early spring (March–April), frequently on fresh or 1-year-old clear-cuts, i.e., before the heaviest attack of *H. abietis* in May. Similar rules apply in Sweden, where Wallertz et al. [63] estimated the effect of planting time on *H. abietis* damage to *P. abies* seedlings. They found reduced damage to trees planted in August–September on clear-cuts established in January of the same year compared to late planting in November or May the following year.

From the start, the planted seedlings require optimal growing conditions. Proper site preparation by soil scarification and weeding, then careful handling, and planting are very important for the further development of trees and make them more resistant to weevil attacks [62, 64]. Örländer and Nordlander [65] found that fresh scarification significantly reduced *H. abietis* damage and increased seedling survival. These results were supported by Björklund et al. [66], who observed less damage to seedlings planted into pure mineral soil. They concluded that the presence of pure mineral soil around seedlings reduces the likelihood of damage caused by the large pine weevil. Similarly, Skłodowski [60] reported lower numbers of beetles collected by traps placed on the mineral soils. To effectively reduce impacts of *H. abietis*, soil scarification should be carried out in the first year after clear-cutting [62]; after two or four years, it has no effect on insect attacks. Adjustment of tree species composition and increasing the share of deciduous species, which are much less susceptible to these pest insects, can help to keep crops in good health condition and prevent mass occurrences of pest insects.

The size of the reforested area also has a significant effect on the number of weevils and the extent of the damage [64, 67]. Previous studies have found that larger areas are more threatened by pest insects than smaller ones. Korczynski [68] observed the correlation between the increase of damage to seedlings and the increase of distance from the plantation edge. In Poland, clear-cuttings usually do not exceed an area of 4 ha, and 1–2-year-old *P. sylvestris* seedlings are used for reforestations. Larger seedlings are more susceptible to damage than smaller ones, and this observation was supported by Korczynski [69], who found that higher seedlings ($16 \leq 35$ cm) were more frequently damaged by the large pine weevil than lower ones ($5 \leq 15$ cm).

Swedish studies showed reduced seedling damage on plantations with shelter trees. This may result from an extra supply of food, such as bark of branches and ground vegetation under the shelter trees [70–72].

3.3. Estimation of population numbers and risk assessment

A number of studies have predicted and assessed *H. abietis* damage in forest plantations; however, so far, no successful methods to prevent such damage have been developed. The main reason for this might be the large number of factors influencing the dispersal of these insects. Leatcher et al. [11] listed four categories of risk factors related to large pine weevil biology—(1) suitability of breeding site, (2) weevil development rate, (3) planting site factors, and (4) weevil-seedling interactions—whereas Wilson et al. [73] indicated eight categories related to forest location, felling and planting, adjacent forest, soil, stumps, weevils, vegetation, and treatments.

An important part of these studies is the relationship between pest abundance and the extent of the damage. Some authors suggest that even in periods of high weevil abundance, seedling damage can be relatively small, while serious impacts can be recorded when pest abundance is low [7]. Results of Swedish and Polish studies showed that the numbers of beetles and impacted seedlings were only positively correlated in 1–2-year-old plantations. In Poland, the 1980s, a method of estimating the damage caused by *Hylobius* beetles was developed [7]. This method was based on the comparison of the damaged bark surface of 30 sections (20 cm long and 1 cm diameter) detached from fresh pine branches and placed in the investigated plantations. However, this method was never adopted in practice. In the UK, a method of risk assessment was developed and introduced to the strategy of Integrated Forest Management for *H. abietis*. It was based on the correlation between the time of clear-cutting and the period of oviposition and, subsequently, the extent of damage caused by the beetles [53, 54].

At present, assessment of weevil threats to plantations is based on the number of beetles captured in different kinds of traps baited with kairomones to attract weevils. Experiments with mass trapping systems were conducted in Sweden in the 1980s, where pitfall traps baited with resin derivative α -pinen and ethyl alcohol that act synergistically were evaluated [74]. Swedish traps with different modifications have been applied in several European countries in *H. abietis* control programs [13, 75–77]. In the UK, the emergency trap was developed to capture and monitor the population of *H. abietis* and its parasitoid *Bracon hylobii* Ratz. developing in the stumps [78]. The trap baited with turpentine and ethanol is formed by a tripod covered by a net and placed over a cut stump.

In Poland, to assess the risks for forest plantations, it is recommended to observe changes in pest abundance from April to September, based on the numbers of beetles captured in traps made from freshly cut *P. sylvestris* billets, slices of fresh bark (**Table 2** and **Photo 3**). It has been accepted that a single trapping of more than 10 *H. abietis* beetles provides a basis for taking protective methods. In the 1990s, IBL-4 pipe traps were developed and introduced into Polish forestry to monitor and control *H. abietis* populations (**Photo 4**). This trap consists of a pipe 60 cm in length and 10 cm in diameter, with two rows of inlet holes. This construction prevents the escape of beetles from the trap. The trap is baited with a mixture of α -pinen and ethanol and works as a food attractant. Contrary to pine billets, the use of IBL-4 traps

Insect species	Type of traps and their use
<i>Hylobius abietis</i> , <i>H. pinastri</i> <i>Cneorhinus plagiatus</i> , <i>Hylastes</i> spp.	<ul style="list-style-type: none">– Pine billets; size, length of 1 m, diameter of 10–15 cm; slightly stripped on one side and this side placed on the ground– Fresh bark of pine or spruce; size, 30 × 30 cm; placed with phloem to the ground– Bundles of fresh coniferous brushwood; size, length of ±30 cm, diameter to 10 cm– Pine wood rings in a bark placed in the holes; the size of holes, 30 × 30 cm IBL-4 traps baited with an attractant Placing the traps from April to September Recommended trap density: <ul style="list-style-type: none">– 5–10 traps/ha in risk assessment– To 50–100 traps/ha in protective measures Checking the traps: 1–3 times/week depending on the pest numbers Dry traps exchanged for new ones
<i>Pissodes castaneus</i>	<ul style="list-style-type: none">– Sections of pine stems prepared from living trees: length of ±1.5 m; the diameter of 6–10 cm Placing the traps in early April: digging into a soil to a depth of 30 cm Recommended trap density, 10–20 traps/ha Checking the traps, 1–2 times/week Colonized traps are removed and destroyed
<i>Rhyacionia buoliana</i>	<ul style="list-style-type: none">– Sticky trap (triangular or rhombic) with a dispenser containing a sex pheromone to collect the males of small butterflies Recommended trap density, >30 traps/ha Traps are hanging out before butterflies swarming—in the second half of June

Table 2. The use of traps for estimation of insect numbers and their control in forest plantations and thickets.

is much more effective and less time-consuming (**Photo 5**). Sklodowski and Gadzinski [79] compared the effectiveness of pine billets and IBL-4 pipe traps and found that pipe traps collected almost three times more beetles. The high effectiveness of IBL-4 traps was also confirmed by Kuzminski and Bilon [80], who estimated numbers of large pine weevils collected by different types of traps, including Scots pine billets and slices with or without addition of sawdust soaked with turpentine. The use of natural traps in forms of fresh pine bark or branches impregnated with a combination of α -pinene, turpentine, and ethanol was most effective; this method has also been carried out in Spain [81]. The results showed that most beetles could be caught using pine bark soaked with a mixture of these substances. There was no significant difference between the use of α -pinen and turpentine, and using pine bark with turpentine and ethanol was recommended as an effective and cost-efficient method to monitor *H. abietis* populations.

Natural Scots pine traps are also used to evaluate threats by other weevils, such as *C. plagiatus*, *Hylastes* spp., *Otiorhynchus* spp., and *Magdalis* spp. In order to successfully evaluate threats, plantations established on sandy soils and postfire areas should be subject to special control during the spring. Estimations of insect occurrence are performed on the basis of beetle numbers collected by traps and on the basis of needle damage.



Photo 3. *Pinus sylvestris* billet used for protection of reforestations; under the trap there is a hole to collect *Hylobius abietis* beetles.

Evaluation of the number of *P. castaneus* and the level of damage to *P. sylvestris* plantations and thickets is performed on the basis of the number of trees colonized by the pest on areas of its occurrence in the previous years and in young forests weakened by biotic (fungi, insects, deer) and abiotic (drought, hail, fire) factors. The observations are performed every two to three weeks from mid-May to the end of September.

Susceptibility of *P. sylvestris* plantations to *B. incanus* is evaluated on the basis of beetle number per tree and percentage share of damaged needles of the highest whorl of branches [52, 82]. Observations should be made at the turn of April and May and in September. The number of beetles is determined every few days on 10 randomly selected trees by shaking them and counting the beetles dropping on sheets placed under the tree canopy. The degree of threat is then defined as the average number of beetles per tree calculated based on the results of 10 trees according to the following classification of threat:

- weak: five beetles/tree, damage to needles <30%
- medium: 6–30 beetles/tree, damage to needles 31–60%
- strong: >30 beetles/tree, damage to needles >60%

In the case of *Neodiprion sertifer*, evaluation of pest numbers in forest plantations and thickets is performed in early autumn on the basis of the number of eggs found in the trees. The level



Photo 4. IBL-4 trap used for collection of *Hylobius abietis* beetles.

of the threat depends on the age of the trees and is critical for 3–10-year-old forests, when the number of eggs reaches, respectively, 50–1,500 per tree. Evaluation of threats by *Tortricidea* spp. is based on the estimation of the number of pine buds or higher shoots damaged by larvae. It is generally carried out from May 15 to June 15 and consists of the observations of 30 trees growing on the edge and 30 trees growing in the center of the forest. Critical damage is defined as damage of at least 30% of buds or shoots. A complementary method of *Rh. buoliana* observation involves the counting of butterflies attracted by pheromone traps installed before the start of swarming in the second half of June (**Table 2**).

Assessment of the occurrence of *A. cinnamomeus* should be carried out in Scots pine plantations and thickets where cracking and pushing aside of bark scales as well as yellowing of needles are observed. In the threatened young stands, three pairs of control trees (one at the edge, two in the center of the stand) are evaluated. Subsequently, sticky bands (5 cm width) are placed on the control trees at a height of 20 cm in early spring, the period in which the insects leave their wintering places, or in autumn—the period in which the insects retreat to their wintering places in the forest litter. The sticky bands are checked every week; the stand is seriously threatened when 10 insects are found within the plantation and 50 insects on one tree.



Photo 5. *Hylobius abietis* beetles collected by IBL-4 trap, visible dispenser in the form of tube filled with synthetic attractant.

3.4. Physical methods and baited traps

Different mechanical methods are integrated to effectively reduce damage caused by weevils. In Sweden, plastic collars and coated barriers of paper or plastic fibers were designed to surround and protect seedlings from damage caused by *H. abietis* weevils [55, 83, 84]. In 2009, Nordlander et al. [85] described a new method of physical protection which consists of covering the lower part of the seedling stem with flexible sand coating (Conniflex). The use of this kind of barrier resulted in increased survival rates of 97% of *P. sylvestris* and 86% of *P. abies* seedlings.

In Poland, at the turn of March and April, it is recommended to dig grooves with vertical walls (width and depth of 25–30 cm) along the border to older stands, where beetle invasion is expected (**Photo 6**). The grooves surrounding the plantations are commonly used to collect *H. abietis* weevils walking from adjacent stands into the plantations. Additionally, sections of fresh pine branches are placed in the grooves to collect and stop more beetles. To directly reduce the number of weevils (*H. abietis*, *C. plagiatus*, *Hylastes* spp.), freshly cut and split billets, pieces of fresh pine bark, or IBL-4 traps are used. For control measures, approximately 20–40 traps are set per 1 ha of plantation. Unfortunately, IBL-4 traps can also collect nontarget insects [79, 86], and only 92% of all caught insects were large pine weevils. The majority of



Photo 6. Plantation surrounded by groove with slice of pine wood to collect pest beetles.

captured nontarget insects belonged to the family Carabidae, which entered the traps accidentally or on the search for shelter. Beetles from the families Dermestidae, Geotrupidae, and Silphidae that feed on dead insects were probably attracted by the smell of decomposing insects inside the traps. Removal of stumps from the clear-cuts can reduce populations of

the large pine weevil within reforestation areas [77], but in Poland, this method is time- and labor-consuming and not used in practice.

Damage caused by *P. castaneus* may be avoided by controlling the breeding of these insects in pine thickets. Potential breeding material such as windfalls, stems broken by wind, or trees damaged by fire is removed from the thickets. In areas with *P. castaneus*, trees showing signs of infestation are removed during the winter or before the end of April to destroy overwintering larvae. In areas with high density of pest populations, special “trap stems” may be prepared and placed before the middle of April (Table 2). They are examined at certain intervals, and when heavily infested by *P. castaneus*, they are peeled to destroy the larvae. Mechanical methods of *Rhyacionia bouliana* and *E. dodecella* control are not used in practice. The method of hand picking of infested buds, which has been suggested in some cases, is impractical for most situations. Also, mechanical control of *A. cinnamomeus* or weevils damaging pine needles is not feasible.

3.5. Biological methods

3.5.1. Pathogens

Wegensteiner et al. [87] reported for the first time the occurrence of the eugregarine *Gregarina hylobii* Fuchs, the neogregarine *Ophryocystis hylobii* Purrini and Ormières, and the microsporidium *Nosema hylobii* Purrini in populations of *H. abietis* and *H. pinastri* from a few locations in Austria and Poland.

Some species of entomopathogenic fungi may be important in regulating numbers of the large pine weevil. *Beauveria bassiana* (Bals.-Criv) Vuill. and *Metarhizium anisopliae* (Metsch.) Sorok. belong to the most common species developing on *H. abietis*. Popowska-Nowak et al. [88] studied the species structures and densities of entomopathogenic fungi in soils of forest plantations in Poland. They isolated five species of entomopathogenic fungi: *B. bassiana*, *Isaria farinosa* (Holmsk.) Fr., *Isaria fumosorosea* Wize, *M. anisopliae*, and *Verticillium lecanii* (Zimm.), of which *I. fumosorosea* and *M. anisopliae* were found most frequently.

So far, there is little information on the potential use of entomopathogenic fungi in controlling *H. abietis*. Wegensteiner and Fuhrer [89] found mortality rates of up to 100% for large pine weevil beetles infected with conidia of *B. bassiana* under laboratory conditions. However, no fungal infections were noted in beetles feeding on bark treated with the fungus under field conditions. Similar results were obtained by Ansari and Butt [90], who observed 100% mortality of all growth stages of the large pine weevil infected by *B. bassiana* and two fungi of the genus *Metarhizium*: *Metarhizium robertsii* (Metschn.) Sorokin and *Metarhizium brunneum* Petch. under laboratory conditions. Williams et al. [91] carried out field experiments to control populations of the large pine weevil with *B. bassiana* and *M. anisopliae* applied together with entomopathogenic nematodes of the species *Steinernema carpocapsae* (Weiser) and *Heterorhabditis downesi* (Stock, Griffin, and Burnell). They observed a higher effectiveness of nematodes, which were responsible for 50% mortality of *H. abietis*, while fungi infected 20% of larvae and pupae of the pest. No synergy effect between the applied species of nematodes and fungi was found. The use of metabolites of fungi growing in the insect environment

could be another direction in plant protection against pests. Azzem et al. [92] isolated the fungus *Penicillium expansum* Link ex. Thom from feces and frass of *H. abietis* and described its metabolites (styrene and 3-methylanisole), which reduced the weevil's attraction to pine twigs in multi choice tests. These authors suggest that metabolites produced by microbes may be useful to reduce the damage caused by *H. abietis* and can be considered as alternatives to chemical insecticides.

A number of studies have evaluated the use of entomopathogenic viruses from the family Baculoviridae to control forest pest insects. In the case of insects occurring in young forests, especially in 5–15-year-old stands, the experiments were set up to evaluate the efficacy of the granulosis virus in the biological control of *Lepidoptera* larvae. Preliminary laboratory and field tests were established to use the granulosis virus of the codling moth *Laspeyresia pomonella* L. against *R. buoliana* [93]. The promising results of the first experiments indicated that granulosis virus might be suitable for microbial control of these pests. *N. sertifer* and its virosis belong to the most frequently reported example of biological control [94]. Research on the practical use of nuclear polyhedrosis virus of *N. sertifer* (NsNPV) causing epizootic has been conducted from the 1940s. Since then, NsNPV has been tested and practically applied in many countries, including Canada, the USA, Germany, the UK, Sweden, Finland, Norway, Russia, Austria, Poland, Balkan countries, and Italy. In Poland, due to the lack of registration and the low risk by this species, viral preparations are not currently used in practice.

3.5.2. Parasitoids

In natural environments, parasitoids from Hymenoptera (Braconidae) belong to the group of natural enemies regulating populations of the large pine weevil. This group includes *B. hylobii* (Ratzeburg, 1848), *Perilitus areolaris* (Gerdin & Hedqvist, 1985), and *Perilitus rutilus* (Nees, 1812). *B. hylobii* was described in many European countries (Hedqvist 1958). In the UK, it occurs wherever larvae of *H. abietis* are found and can cause mortality of up to 50% of *H. abietis* larvae developing in Sitka spruce (*Picea sitchensis* CARR.) stumps during the first three years after felling [95–97]. Henry and Day [96] studied the interactions between *B. hylobii* and *H. abietis* larvae and evaluated the possibility of the use of braconids to suppress large pine weevil populations.

Research on the use of natural enemies to limit numbers of *P. castaneus* has been concentrating mainly on the biology of parasitoids. So far, Alauzet [46, 98] and Kenis et al. [99, 100] provided most of the information on the parasitoids of *P. castaneus*. These authors listed species from Braconidae, such as *Eubazus semirugosus* (Nees), *Eubazus robustus* (Ratzeburg), *Eubazus crassigaster* (Provancher), and *Coeloides abdominalis* (Zetterstedt).

3.5.3. Competitive fungi

In Poland, a biological method to suppress *H. abietis* populations breeding in Scots pine stumps was developed in the 1990s. The experiments aimed at the use of *Phlebiopsis gigantea* (Fr.: Fr) Jülich—a fungus decomposing the stumps and disturbing the development of *H. abietis* in colonized stumps [23, 101]. The results indicated that *Ph. gigantea* grows rapidly on the cambium of stumps, making them unsuitable for pest development. It was also found that infection of

stumps with mycelium of *Ph. gigantea* reduced the number of eggs on stumps and their roots. Subsequent field studies were conducted to evaluate the abundance of *H. abietis* beetles and the extent of seedling damage in 1–3-year-old plantations established on clear-cuts with pine stumps treated with *Ph. gigantea*. Evaluation of pest catches in traps in the second growing season following the treatment showed that pest abundance in plots treated with the fungus was 40% lower than in untreated plots, probably due to lower attractiveness of stumps colonized by *Ph. gigantea*. The reduction of weevil numbers could have also been caused by increased mortality of pest larvae in infected stumps. In addition, in the clear-cuts with infected stumps, less *P. sylvestris* seedlings were damaged by the large pine weevil. Based on these results, *Ph. gigantea* application was introduced into practice as a part of IPM.

3.5.4. Botanical antifeedants

Along with more information about the effectiveness of the insecticide azadirachtin, (a natural compound isolated from *Azadirachta indica* A. Juss). in plant protection, a number of experiments were undertaken to apply this compound against new groups of pest insects. There was described the antifeedant influence of azadirachtin on *H. abietis* under laboratory conditions, while field treatments of Norway spruce seedlings resulted in reduced damage to seedlings protected with azadirachtin [102, 103]. Other studies showed an insecticidal activity of azadirachtin only when this substance was used in high concentrations, which makes this method unviable from the economic point of view [104]. Despite promising results, azadirachtin was not registered for the protection of young forests and cannot be used against forest weevils.

In Poland, problems of the influence of extracts from plants of different species on *H. abietis* feeding were examined by Korczynski et al. [105, 106], who found antifeedant activity of common box (*Buxus sempervirens* L.), large-leaved lupine (*Lupinus polyphyllus* Ldl.), fern (*Dryopteris filix-mas* L.), and spurge (*Euphorbia peplus* L.). Kuzminski [107] described the repellent activity of extracts from anemone (*Anemone nemorosa* L.) against beetles. Unfortunately, the results of these studies have not found practical application.

Intensive research on the use of plant-derived antifeedants has been conducted for many years in Sweden, where extracts from the bark of 38 tree and shrub species were tested for antifeedant activity against *H. abietis* [108]. The study found that the bark of willow (*Salix caprea* L.), aspen (*Populus tremula* L.), yew (*Taxus baccata* L.), ash (*Fraxinus excelsior* L.), and especially lime (*Tilia cordata* Mill.) contains compounds which inhibit feeding activity of the large pine weevil. In further studies, carboxylic acid, limonene, carvone, and verbenone compounds, which demonstrated antifeedant activity against *H. abietis* in laboratory experiments, were isolated from extracts of *T. cordata* bark [109].

3.5.5. Nematodes

In northern Europe, studies to evaluate the possibility of using nematodes from two families, Steinernematidae (*S. carpocapsae*, *Steinernema feltiae* Filipjev, *Steinernema kraussei* Steiner) and Heterorhabditidae (*Heterorhabditis bacteriophora* Poinar, *Heterorhabditis megidis* Poinar,

Jackson & Klein and *H. downesi* Stock, Griffin & Burnell), have been conducted to reduce the populations of *H. abietis* larvae. Entomopathogenic nematodes (EPNs) have many attributes of an excellent biological control agent: they naturally occur in the soil environment; they are safe for mammals and other organisms, including humans; and they are characterized by long-term survival in the absence of host insects [110]. In addition, the potential of nematodes is not weakened by the simultaneous use of plant protection products. For these reasons, the use of preparations based on EPNs does not exclude the use of chemical pesticides [111]. In addition, EPNs for plant protection can also be produced on a large scale [112].

Treatments to reduce *H. abietis* populations consist of spraying of stumps and adjacent soil with suspensions of EPNs containing 3.5 millions of nematodes/stump. In northern European countries, the application of EPNs against the large pine weevil takes place in June, when pine weevil larvae that hatched from eggs laid between the end of May and the beginning of June are present in the stumps. The first attempts to reduce *H. abietis* using *Neoplectana carpocapsae* Weiser (= *Steinernema carpocapsae*) were performed in Sweden, where mortality rates of 50–60% were obtained [113, 114]. The use of different nematode species of the genera *Steinernema* and *Heterorhabditis* in Ireland resulted in 60–80% reduction of larvae [115–117]. Field studies carried out in Scotland resulted in a reduction of the number of pine weevil larvae of 60% [118, 119].

Similar EPN applications were conducted in Poland; however, treatments were applied at different times. Nematodes were not applied in the summer season, but in early autumn, when mainly overwintering *H. abietis* larvae were present in the stumps. The choice of this treatment timing was based on results obtained after the application of EPNs in mid-June to reduce the newly emerged larvae of the first generation [120]. Only 5% mortality of *H. abietis* in treated stumps was observed, which did not differ from natural pest mortality in nontreated stumps. Most probably, these results were influenced by unfavorable weather conditions for nematode development during the study (high air and soil temperatures, lack of precipitation), which might have caused increased nematode mortality. On the other hand, applications conducted in early autumn—when weather conditions were considerably more beneficial for nematode development—indicated nematode parasitism in 80% of large pine weevil larvae overwintering in treated stumps. Subsequent studies aimed at evaluating the effectiveness of commercially produced biopreparations and consisted of the spraying of *P. sylvestris* stumps with *S. carpocapsae*, *S. feltiae*, *H. bacteriophora*, *H. downesi*, and *H. megidis*. All tested nematodes showed the ability to parasitize *H. abietis* larvae overwintering in *P. sylvestris* stumps. Highest mortality rates were observed in the groups of larvae parasitized by *S. carpocapsae* and *H. downesi* and lowest rates in larvae parasitized by *H. megidis* [121].

In summary, despite many attempts to use natural enemies to reduce *H. abietis* populations, the range of biological methods is very limited and potentially applies to entomopathogenic nematodes and saprotrophic fungi used to suppress *H. abietis* populations developing in stumps. Currently forest protection does not possess effective methods of biological control which can be used to suppress populations of other insect species affecting the youngest forests.

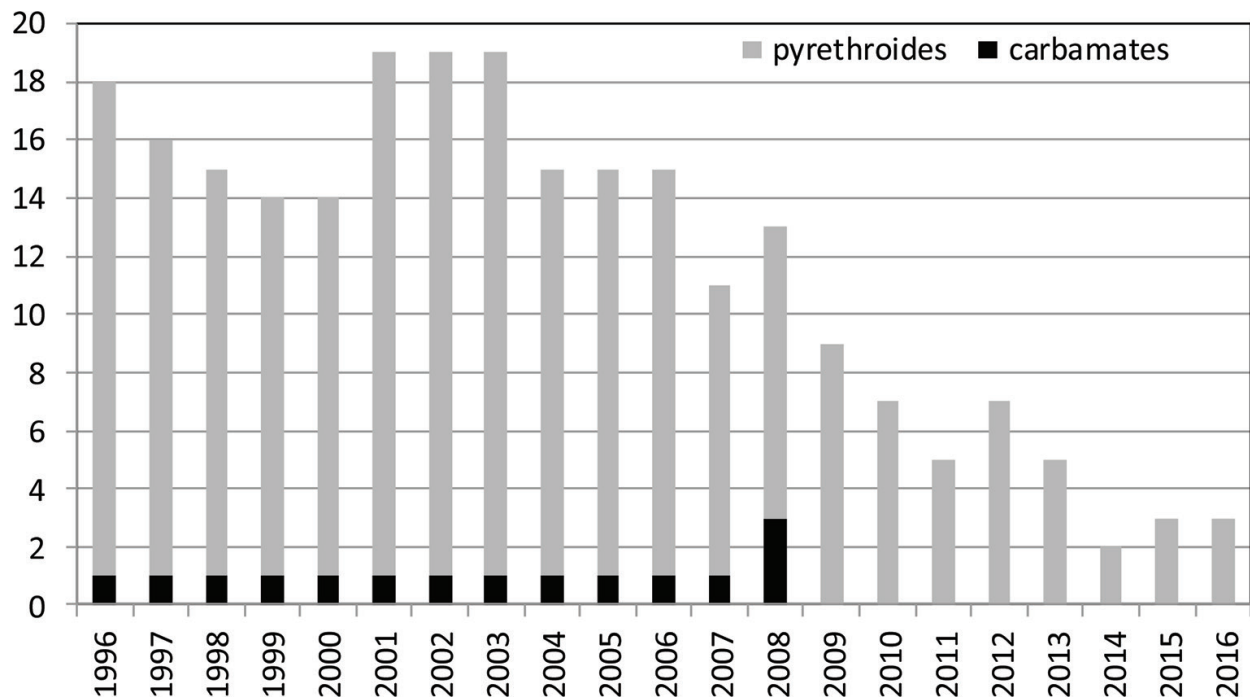


Figure 2. The use of insecticides in the protection of restock areas against weevils in Poland in years 1996–2016.

3.6. Chemical methods

Until recently, the use of insecticides was the most common method of protecting forest plantations against weevils, especially large pine weevils. However, limitation of pesticide use implemented by EU law and forest certification systems introduced by the Forest Stewardship Council (FSC) reduced the use of insecticides, particularly in young stands. The dynamics of changes in the numbers of pesticides registered for the protection of forest plantations showed an 86% reduction in insecticides that can be used against weevils (**Figure 2**). Pyrethroids are a group of insecticides most frequently used against weevils in the youngest forests. They particularly contain derivatives of cypermethrin, deltamethrin, esfenvalerate, lambda-cyhalotrin, and other compounds with *contact* and *stomach* action and repellent effects. Rose et al. [122] confirmed that *H. abietis* was able to detect the presence of lambda-cyhalotrin in multiple choice tests and feeding of food treated with this pyrethroid was significantly depressed and, in most cases, did not occur.

Carbamates were the second group of commonly used preparations to protect especially 1–2-year-old plantations. These preparations contained carbofuran and carbosulfan characterized by contact, stomach, and systemic actions. Granular formulations of carbamates applied to the soil through the roots of seedlings were particularly useful because the gradual release of active ingredients protected the tree up to two years after application [123]. These insecticides were absorbed by tree roots and showed a higher selectivity than pyrethroids. Due to toxic effects on nontarget insects (e.g., soil organisms), the use of carbamates was banned in EU countries.

The frequent use of pyrethroids can eliminate sensitive insects in the treated population. As more resistant insects are not affected, the development of insect resistance may be accelerated. Dobrowolski [124] found that *H. abietis* beetles from different populations significantly differed in their susceptibility to pyrethroids, and the author confirmed the importance of cytochrome P-450 monooxygenases in pest resistance to insecticides. To avoid the problem with resistance of *H. abietis* to pyrethroids, current research on chemical crop protection includes testing of other substances such as neonicotinoids. Rose et al. [122] observed the death of *H. abietis* weevils within three weeks after feeding on insecticide-treated Norway spruce. Similar results were obtained by Olenici et al. [125], who compared the activity of neonicotinoids and metaflumizone insecticides used against *H. abietis*. They found that beetles feeding on Scots pine twigs treated with neonicotinoids (acetamiprid, imidacloprid, thiacloprid) were either dying in three weeks or did not feed on metaflumizone-treated food.

Chemical protection of plantations against weevils includes preventive treatments consisting of dipping aboveground parts of the seedlings in the insecticides immediately before planting or the application of emergency postplanting sprays. Hereby, dipping seedlings is more effective than spraying them with the same concentration of insecticide [126, 127]. Thus, in Poland, in regions with high abundance of weevils, preplanting treatments are the most common way of plant protection.

As mentioned above, the number of insecticides registered for the protection of forests against weevils was significantly reduced because of:

- implementation of EU law (Directives of the European Parliament and of the Council 2009/128/EU and 1107/2009) for agricultural and forest practice aimed at the elimination of chemicals from the environment;
- the limited interest of chemical companies based on high costs of pesticide registrations for young forests which cover very small areas of the country compared to agricultural lands;
- the forest certification system by FSC.

As a result, in 2016, Polish foresters have the choice between three registered pyrethroids for the protection of plantations against *H. abietis* and other weevil species: Fastac Forest 15 SC with alpha-cypermethrin, Forester 100 EW, and Sherpa 100 EC, all based on cypermethrin. Currently, as threats by other species of insects have been relatively low for a number of years, chemical treatments are applied only to limit the numbers of the large pine weevil.

4. Conclusions

Curculionidae is the most important group of pest insects of forest plantations established at the clear-cut areas, which are most frequently used in Polish forests. Postcutting regeneration leads to the formation of even-age stands of poor species composition, attacked by pest insects associated with defined developmental phase of stands. Until recently chemical

plant protection was the most frequently used form of forest protection from insect pests and pathogens. Systematic decrease in number of plant protection products available in forestry as well as introduction in 2014 in the European Union of the principles of integrated plant protection calls for searching for plant protection methods using natural insect pest enemies such as pathogenic microorganisms, parasites, and predators. Therefore, contemporary forest protection requires advancement of integrated methods protecting forest plantations from insect pests through:

- studying the influence of climate warming on changes in biology of pest insects and changes in insect assemblages affecting reforestations;
- developing methods of monitoring and forecasting of forest dangers depending on site and stands characteristics;
- countering of threats caused by insect pests and pathogens within the large-scale disaster areas resulting from climate change;
- strengthening natural resistance of trees to insect pests and fungal pathogens;
- the use of natural enemies and agro-technical methods for regulation of population size of dangerous forest pests;
- evaluation of effectiveness of new plant protection products including studies intended for registration of pesticides for forestry;
- development of decision support systems as a tool facilitating introduction of integrated forest protection principles. Such support systems help to establish optimal terms for implementation of protection activities, which allows to increase their efficiency while limiting chemical pesticides to the absolute minimum.

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