Forest Ecology and Management 537 (2023) 120968

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Trap catch data are poor predictors of damage caused by pine weevil (*Hylobius abietis*) to conifer seedlings

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ARTICLE INFO

Keywords:
Forest pest management
Forest regeneration
Mechanical site preparation
Population density
Risk assessment
Site factor
Stoniness

ABSTRACT

Damage to planted conifer seedlings caused by the pine weevil *Hylobius abietis* (L.) is a severe and persistent threat to successful forest regeneration in Europe. Various countermeasures are available, which vary in effectiveness, costs and environmental impact, but none are ideal for all situations. Therefore, there is strong interest in robust assessments of damage risks, as they would enable more cost-effective and environmentally friendly forest pest management. It has been suggested that numbers of adult pine weevils caught in host-odour baited traps placed in regeneration sites may be valuable in such risk assessments. However, published studies provide at most weak support for the hypothesis that trap catch data provide adequate predictions of damage. Therefore, we conducted a two-year field study, designed to determine the relationship between weevil trap catch and subsequent damage at 10 regeneration sites in central Sweden. Site factors that might influence pine weevil feeding on seedlings were recorded and used as explanatory variables in the analysis. Stoniness was the only site factor identified as having a significant effect; damage mainly increased with increases in stoniness. No significant correlation was detected between damage to planted conifer seedlings and numbers of pine weevils trapped in the same locations. We suggest that this lack of correlation between weevil numbers and damage is due to planted seedlings only constituting a minor part of the weevils food intake and considerable between-site variation in availability of food sources other than seedlings. Therefore, assessment of pine weevil numbers appears unlikely to be useful for predicting damage risk at specific regeneration sites.

1. Introduction

Newly planted conifer seedlings on regeneration sites are frequently damaged and killed by adult pine weevils, *Hylobius abietis* (L.), feeding on their stem bark (Doležal et al. 2021). This poses a major threat to successful forest regeneration in large parts of Europe, especially where forests are managed by clear-cutting followed by planting (Björkman et al., 2015; Lalík et al., 2021). Effective countermeasures are therefore needed to ensure sufficient survival of the planted seedlings (Nordlander et al. 2011).

Insecticide treatment is currently still used for seedling protection in several European countries (Hardy et al. 2020, Galko et al. 2022, Thomas et al. 2022), despite serious concerns for the environment and health of forest workers associated with their use (Mian and Mulla 1992, Kolmodin-Hedman et al. 1995, Pisa et al. 2015, 2021). However, in Swedish forestry, protection with insecticides has been almost completely phased out and replaced by stem coatings that provide physical protection for the seedlings, and similar changes in practices can be expected in other countries (Nordlander et al. 2009, Skogsstyrelsen, 2021, Luoranen et al. 2022). To ensure a high level of protection both insecticide and stem coating treatments are commonly combined with mechanical site preparation, which enables planting of the seedlings in pure mineral soil (Petersson and Örlander 2003, Sikström et al. 2020). New pest management approaches may also be implemented in practical forestry, such as triggering of the seedlings' inducible defences against insect feeding by treating them in the nursery with the

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https://doi.org/10.1016/j.foreco.2023.120968
Received 14 February 2023; Received in revised form 20 March 2023; Accepted 22 March 2023
Available online 1 April 2023
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phytohormone methyl jasmonate (Zas et al. 2014, Chen et al. 2020). A plethora of other measures with varying apparent utility against pine weevil damage have also been tested over the years, as reviewed by Lalík et al. (2021).

The various countermeasures differ in effectiveness, costs and environmental impact, but none are ideal for all situations. Therefore, an early damage risk assessment that could be used to adjust the countermeasures to maximize their cost-effectiveness and minimize their environmental impact would be highly valuable (Wilson and Day 1994, Heritage and Moore 2001, Paraschiv 2020, Fedderwitz et al. 2022, Galko et al. 2022). However, current assessments are usually regional and based on forest owners' previous experiences. Higher resolution information, ideally for each regeneration site, could greatly enhance the cost-effectiveness of forest pest management.

It has been suggested that various site factors, as well as local pine weevil population censuses, may be useful for risk assessments (Nordlander 1987, Wilson et al. 1996, Nordlander et al. 2017b). Thus, several studies have attempted to identify site factors that affect damage risks at clear-cut sites, but only a few investigated factors have proven to influence damage levels significantly and consistently. Four factors seem to be particularly important and are commonly considered to some extent in practical forest management. One is the harvested tree species, as only coniferous tree stumps attract migrating pine weevils to a site and provide the required breeding substrate (Solbreck 1980, Nordlander et al. 1986, Björkman et al. 2015). Another is the age of clear-cuts, as the time between harvesting and planting determines the concordance between adult pine weevil population peaks at the site and availability of vulnerable seedlings (Örlander and Nilsson 1999, Moore 2004, Wallertz et al. 2016, Nordlander et al. 2017a). A third is the availability of planting spots in pure mineral soil, as planting in mineral soil rather than the humus layer considerably reduces damage (Nordlander et al. 2011, 2017b, Luoranen et al. 2017, 2023). The fourth is the climate, as a positive correlation has been found between the summer temperature sum and damage levels across a vast geographic region with a variable but relatively cool climate (Nordlander et al. 2017b).

A few other site factors have been found to be related to damage in some studies, but not in others, and some reported effects are inconsistent. For example, the amount of slash on the ground has been found to have no effect, positive effects or negative effects on damage (Örlander and Nilsson 1999, Hanssen et al. 2018, López-Villamor et al. 2019). A study in Northern Ireland including 82 sites found that only four of 45 tested explanatory variables were significant, and the only relationship not already well known was that damage decreased with increasing area of the regeneration site (Wilson et al. 1996). In a landscape comprising a small-scale mosaic of agroforestry lands in Galicia, Spain, López-Villamor et al. (2019) found that the abundance of mature coniferous forest in the vicinity of the regeneration site was positively correlated with damage. Such a relationship is, however, unlikely to be present in a landscape more dominated by coniferous forests, such as those in large parts of northern Europe.

Assessments of the populations of adult pine weevils on regeneration sites have long had suggested utility for predicting damage by the pine weevil (Nordlander 1987, Zumr and Stary 1995, Evans et al. 2004, Forest Research 2023) and some closely related species in North America (Pendrel et al. 1990, Rieske and Raffa 1993). Weevil numbers have been assessed using pieces of conifer trees (billets) on the ground (Långström 1982, Wilson and Day 1994) or host-odour baited traps placed on or in the ground (Nordlander, 1987; Lalík et al., 2019; Skrzecz et al., 2021). However, published findings regarding relationships between pine weevil catches and subsequent damage at sites vary strongly. Nordlander (1987) detected a significant correlation between damage and trap catches of weevils in August, but no significant correlation between damage and trap catches in May or June at regeneration sites in Sweden. In a study including 82 sites in Northern Ireland, Wilson and Day (1994) detected a weak but significant relationship between weevil abundance and damage. In a 6-year study in which more than 74,000 weevils were captured at sites in southern Sweden the correlations between trap catches and damage were generally poor, except that trap catches on fresh clear-cuts correlated with damage caused (by a new weevil generation) two years later (Örlander et al. 1997). Another Swedish study found a correlation only between damage in the first season and trap catches in the following season, which is clearly not a useful relationship for risk assessment (von Sydow 1997). No significant correlation between trap catches and damage was found in a recent study including 21 sites in NW Spain (López-Villamor et al. 2019).

Current interest in the use of pine weevil population assessments for forecasting damage risk is indicated by one of the authors (GN) receiving several inquiries on the subject in recent years from practitioners or researchers based in several European countries (Slovakia, Sweden, and the UK). In addition, Forest Research in the UK advocates the use of data from pine weevil trapping for predicting damage to assist the optimization of management strategies (Censis 2022, Forest Research 2023). Moreover, an 'early warning system' based on real-time monitoring of pine weevils is marketed by a private enterprise in the UK (Spotta 2023). Thus, interest and faith in the utility of population assessments of adult pine weevils persist despite the ambiguity of published results, and there is a clear need to elucidate the relationships involved more thoroughly. To aid such efforts we present here results from an old, but previously unpublished, two-year study.

The study was specifically designed to investigate the relationship between pine weevil trap catches during a limited period early in the season and subsequent damage to conifer seedlings planted on ordinary clear-cuts in a region where pine weevils are present, with varying abundance, on nearly all regeneration sites of this type. Damage to both untreated and insecticide-treated seedlings was measured in order to include two levels of damage in the study. Site factors that we assumed might influence pine weevil feeding on seedlings were recorded for use as explanatory variables in the analysis. The selection of site factors was partly based on previous studies, for instance factors related to microclimate (Christiansen and Bakke 1971), shelter for the weevils (Petersson et al. 2006), and alternative food sources (Wallertz et al. 2006). No site preparation treatments were applied in the sampling areas, so planting spots did not vary in this respect. The age of clear-cuts was also uniform within each of the two years the study was conducted. The first year the clear-cuts were fresh, with immigrant weevils (parent generation) arriving by flight some weeks before the experiment started in the middle of June. The second year overwintered parent generation weevils use to become active from late April or early May in central Sweden and remain on the clear-cuts during the season. From late July or August the second year new generation weevils start to appear (Nordenhem 1989, Nordlander et al. 2017a).

2. Materials and methods

2.1. Study sites

The correlation between trap catches of pine weevils and the feeding damage they cause to planted conifer seedlings was measured in a field experiment repeated during two consecutive years (2008 and 2009). The experiment was conducted on 10 clear-cuts (hereafter sites) in the provinces of Dalarna and Gästrikland in central Sweden (Table 1). Since the sites were situated within a relatively limited geographical region, weather conditions, and thereby general weevil activity, were assumed to be similar at all sites. Stands at these sites, mainly consisting of mixtures of mature Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.), had been harvested during the 2007/2008 winter. The sites were chosen to cover representative clear-cuts in this region (Table 1).

2.2. Experimental design

At each of the 10 sites four widely separated sampling areas

Table 1
Characteristics of sites used in the study, as described in the respective forest management plans.

Name of site	Area (ha)	Site Index[1]	GYL[2]	Altitude (m, a.s.l.)	Latitude	Longitude
Sidsjöbäcken	30.8	T21	332	230	60° 53′	16° 23′
Måcksjöbergsmasten	12.1	G21	313	340	60° 54′	16° 26′
Jädraås	4.5	T20	421	200	60° 50′	16° 28′
Hällåsen	28.9	G22	312	340	60° 50′	16° 19′
Kastjärnskorset	4.7	T22	322	200	60° 38′	16° 12′
Kann-Olles heden	43.8	G24	322	250	60° 37′	16° 14′
Skvalet	8.0	G25	322	200	60° 37′	16° 12′
Vindfröberg	48.2	T21	121	220	61° 11′	15° 27′
Finnmyren	40.1	T24	321	290	61° 5′	15° 36′
Amungsberget	27.3	T20	243	250	61° 6′	15° 39′

[1] Site Index refers to the height at the age of 100 years of dominant Scots pine (T) or Norway spruce (G) trees (Hägglund, 1973).
[2] GYL (G = bearing capacity, Y = surface structure and L = inclination) determined according to the Swedish Terrain Classification System (Berg 1982), where each factor is classified on a scale from 1 to 4.

(hereafter blocks) were established, in each of which five pine weevil traps were placed beside two groups of Norway spruce seedlings, one with 25 untreated seedlings and one with 25 seedlings treated with the insecticide cypermethrin. These were 2-year-old container seedlings planted in the first half of June in both years, i.e. all the seedlings planted in the first year were replaced with new seedlings in the second year. Seedlings were planted in a 5x5 pattern with 1 m spacing between seedlings and 2 m between the two groups. No site preparation treatment was applied within the blocks, so the seedlings were planted in undisturbed soil. The pine weevil traps (described below) were placed in a row situated 5 m beside the two groups of plants with at least 5 m between traps. Each trap was placed approximately 1 m from the nearest conifer stump, and all blocks were situated at least 15 m from the nearest forest edge.

Trap catches of pine weevils were recorded during two consecutive weeks in June during both years (12–26 June 2008 and 2–16 June 2009). The traps were placed directly after the seedlings were planted, and after the first week the traps were emptied and the attractive bait in them was replaced. The trapping period the first year started well after the peak of pine weevil immigration to the fresh clear-cuts in the region (checked at a sawmill attracting migrating weevils). Seedling damage, measured as the area of stem bark removed by pine weevils on each seedling (estimated using a millimetre grid reference), as well as whether the seedlings were alive or dead, was recorded at the end of the season (27–28 August 2008 and 19–20 October 2009).

2.3. The traps

To obtain a relative measure of pine weevil abundance we used a novel trap developed by one of the authors (HN), which can be conveniently placed on the ground without using any tools and is designed to keep the weevils alive.

Each trap consists of a cylindrical plastic jar (height 70 mm, diameter 100 mm) with a screw lid covering the top and two holes (diameter 18

Fig. 1. A pine weevil (*Hylobius abietis*) opening a flexible door when entering a trap through one of two inserted tubes. The bait, consisting of an ethanol dispenser and a piece of Scots pine, can be seen suspended from the lid.

mm) on opposite sides with their lower margin 10 mm above the bottom of the jar. A 40 mm long plastic tube (inner diameter 15 mm) is inserted into each hole. The internal surface of this tube is gently rubbed to provide a good grip for the feet of entering weevils. The inner end of the tube is cut at a 45° angle, and a piece of a flexible PVC mosquito net with 3 mm mesh size is fixed with glue to the upper margin of the sloping end of the tube (Fig. 1). The net thus forms a door entirely resting on the obliquely cut end of the tube. When a weevil enters the trap, the flexible door easily opens then immediately falls back into the closed position after the weevil has entered, preventing weevils from leaving the trap. A narrow piece of metal net folded along the lower margin of the door enhances effective closure of the door. The trap can be simply baited by placing appropriate sources of attractant odours in it, as the odours are then released to the surroundings through the entrance tubes.

2.4. Bait

To trap pine weevils during early summer we used a combination of ethanol and a piece of fresh Scots pine stem, which releases α-pinene and several other attractive monoterpenes (Nordlander et al. 1986). This combination of host volatiles is highly attractive for reproductive *H. abietis* weevils (Tilles et al. 1986, Nordlander 1987, Nordenhem and Eidmann 1991) and has known utility for monitoring pine weevils (Nordlander et al., 2003a; Lalík et al., 2019).

In the experiment reported here the traps were baited with ethanol dispensers consisting of cylindrical polyethylene containers with a hinged lid (height 30 mm, diameter 20 mm) containing 8 ml of 95% ethanol. A 4 mm diameter hole was drilled in the tightly closed lid, allowing release of approximately 3 ml of the ethanol during a 7-day period in the field. A fresh piece of Scots pine, taken from 25 to 35 mm thick branches cut into 70 mm long sections, was placed in each trap, suspended under the lid so it did not interfere with the opening and closure of the entrance door.

2.5. Trap placement

The traps were firmly placed on the ground after removing some litter or mosses on the surface by hand. This material was then used to partly cover the trap, thereby providing approaching weevils with the shelter they tend to seek (Petersson et al. 2006, Björklund 2008). The covering also probably helped to hide the traps from ravens and other birds that may have wanted to investigate and displace more visible traps.

2.6. Site and block factors

Several factors were recorded or calculated for each site at either site or block level, using field measurements when the blocks were established in June 2008 (except for the coverage of Ericaceous species and grass species, which was measured in August 2009). An overview of these factors is presented in Table 2.

Site Index values were given in the forest management plan for either Scots pine or Norway spruce, depending on the tree species composition of the previous stand (Table 1). Therefore, Scots pine-based values were converted to Norway spruce-based values (dominant heights at an age of 100 years) using a table presented by Hägglund and Lundmark (1987) to standardize them.

The forest management plans also provided data on the bearing capacity (G), surface structure (Y) and inclination (L) at each site (Table 1). Bearing capacity (ground condition) is determined by the soil type, soil moisture content and ground reinforcement in the form of rocks, boulders, stumps, tree residues etc. Surface structure (ground roughness) is determined by the height and number of obstacles that impede the progress of machines. Inclination (slope) describes the prevailing steepness of the terrain in all directions.

Temperature sum (TS), defined as the sum of the daily mean temperature above + 5 °C during one growing season, was estimated for each site according to the following model developed by Morén and Perttu (1994):

Table 2
Overview of site factors used in the study.

Level	Factor	Description
Site	Area	4.5–48.2 ha
Site	Site Index	G19-G25
Site	Bearing capacity class	1, 2, 3, 4
Site	Surface structure class	1, 2, 3, 4
Site	Inclination class	1, 2, 3, 4
Site	Temperature sum	990–1130 °C
Block	Solar radiation	800–1000 kWh/m^2 p.a.
Block	Slope direction	16: N, NNE, NE etc.
Block	Slope inclination class	0, 1, 2, 3
Block	Topography class	L, M, H
Block	Stoniness class	0, 1, 2, 3
Block	Slash class	1, 2
Block	Soil moisture class	Dry, mesic, mesic/moist, moist
Block	Broadleaf stump proportion	0–40 %
Block	Ericaceous cover in field layer	0–90%
Block	Grass cover in field layer	0–100%

$$TS = 4922.1\text{-}60.367 * \text{lat}\text{-}0.837 * \text{alt} \tag{1}$$

where lat = latitude (°N) and alt = altitude in meters above sea level (m a.s.l.).

For each block, the slope was classified in terms of direction (16 classes: N, NNE, NE etc.) and inclination (four classes from 0 = flat to 3 = steep). The topographical position of the block was classified as L (low position in the landscape), M (middle, similar to the surrounding landscape) or H (high position in the landscape). Stoniness was visually assessed and assigned to one of four classes of increasing stoniness: 0, 1, 2, 3. The amount of slash, i.e. logging residues, was assigned to classes 1 (small) or 2 (moderate). Soil moisture class was defined as dry, mesic, mesic/moist or moist according to Hägglund and Lundmark (1987). The proportion of broadleaf stumps (i.e. ratio of deciduous to total number of stumps) and the coverage of both Ericaceous species and grass species in the field layer was estimated for each block.

In addition, the total amount of solar radiation was estimated for each block based on its slope's inclination (according to the classes described above, where classes 1–5 are inclinations of 0–5, 6–10, 11–15 and 16–20°, respectively) and direction (according to the 16 classes described above). The inclination and cardinal direction values were then used to obtain estimates of the total amount of solar radiation (in kWh/m^2 per year) using the graph in Figure 2 presented by Hedén (2013), based on weather data from Jönköping (average values for the time period 1962–1990).

2.7. Statistics

The response variables used in the analysis were the proportion of seedlings attacked per block and treatment, the proportion of seedlings killed per block and treatment, and debarked area, defined as the total debarked area in cm^2 of the 25 seedlings assigned to each of the two seedling treatments in a block. We also used the total numbers of weevils trapped per block during both trapping periods each year as response variables.

The procedure used to estimate the importance of the explanatory variables (Table 2; also including year and seedling treatment) for pine weevil damage to seedlings and number of trapped weevils involved two steps. In the first step, all the explanatory variables were included in the GLMSELECT Procedure in SAS 9.4 (SAS Institute, Cary, NC, USA). The selection method used was stepwise and separate models were constructed for each response variable. Selections were made based on the Akaike Information Criterion (AIC). Some variables were removed at this early stage, including bearing capacity, surface structure, inclination, and coverage of both grass and Ericaceous species. The number of trapped weevils was tested as both an explanatory factor and a response variable. In the second step, effects of the selected variables on each response variable were analysed with a general mixed model using the Mixed Procedure in SAS 9.4. Site was set as a random variable, with both year and block nested in site according to the following model:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \delta_k + b_{(l)} + c_{(k)} + e_{ijkl} \quad (2)$$

Here: μ is the overall mean, α_i the fixed effect of seedling treatment (i = 1–2), β_j the fixed effect of selected explanatory variables (j = 1-n), δ the fixed effect of year (k = 1–2), $b_{(l)}$ the random effect of block nested within site (l = 1–4), $c_{(k)}$ the random effect of year within site (k = 1–2) and e_{ijkl} the random experimental error. When significant differences occurred, least square means were separated using the Tukey-Kramer adjustment. A significance level of 0.05 was used for all analyses.

3. Results

3.1. Trap catches

A very small proportion of the trap catches (0.3%) consisted of *H. pinastri*, which causes feeding damage to seedlings that is inseparable from damage caused by *H. abietis.* Those weevils were therefore treated as *H. abietis* in the analyses.

The numbers of pine weevils caught in each block in the two consecutive trapping periods were similar, with coefficients of correlation (Pearson correlation coefficient) between trap catches in the first and second weeks in 2008 and 2009 of 0.647 ($p < 0.0001$) and 0.585 ($p < 0.0001$), respectively (Fig. 2).

The numbers of pine weevils trapped per block during the 2-week periods ranged from 43 to 439 in the first year, and from 19 to 202 in the second year (Fig. 2). Despite the large ranges in numbers of trapped weevils and high repeatability, no significant effects of the variable on seedling damage were found so it was not selected as a possible contributor to explanation of pine weevil damage in the first step.

3.2. Factors potentially affecting damage

Only a few of the tested variables were identified as having an impact on the response variables in the selection procedure. These included: seedling treatment, year, stoniness, Site Index, area and proportion of broadleaf stumps (Table 3). Their effect and importance for the model varied depending on the response variable used. Of these variables seedling treatment and year were not among the investigated site factors (Table 2) but included in the analysis because two seedling treatments were used in parallel and the experiment was conducted in two consecutive years.

Of the tested explanatory variables, the number of trapped weevils was significantly affected by year ($p = 0.0004$), but not Site Index ($p = 0.1069$). The effects of interaction between year and Site Index were also tested, but found to be non-significant ($p = 0.1163$). The number of trapped weevils was not selected as an important variable in the models and had no effect on number of attacked seedlings, number of killed seedlings or the debarked area (Fig. 3).

3.3. Significant explanatory variables

Of all the tested explanatory variables, only three (seedling treatment, stoniness and year) had a significant effect on pine weevil damage (Table 4). Although proportions of broadleaf stumps, area and Site Index were selected for inclusion in some of the first models they had no significant effects on the response variables.

The importance of the three significant variables declined in the order seedling treatment, stoniness and year. Pine weevil damage were lower if the seedlings were treated with insecticides (Fig. 4), it increased with increases in stoniness index up to 2, and were higher in the second

Table 3
Explanatory variables selected by the GLMSELECT procedure for each response variable and model statistics including R-square, AIC, F-value and p-value for each of the selected models. The variables are presented in the order they were selected in the procedure.

Response variable	Selected variables	R-square	AIC	F value	Pr > F
Attacked seedlings	Intercept, seedling treatment, year, stoniness, area, Site Index	0.6458	1087.25	22.34	<0.0001
Killed seedlings	Intercept, seedling treatment, stoniness, year, proportion of broadleaf stumps	0.8057	1075.20	90.05	<0.0001
Debarked area	Intercept, seedling treatment, year, stoniness	0.6707	1177.21	62.73	<0.0001
Number of trapped weevils	Intercept, year, Site Index	0.6318	1481.20	43.75	<0.0001

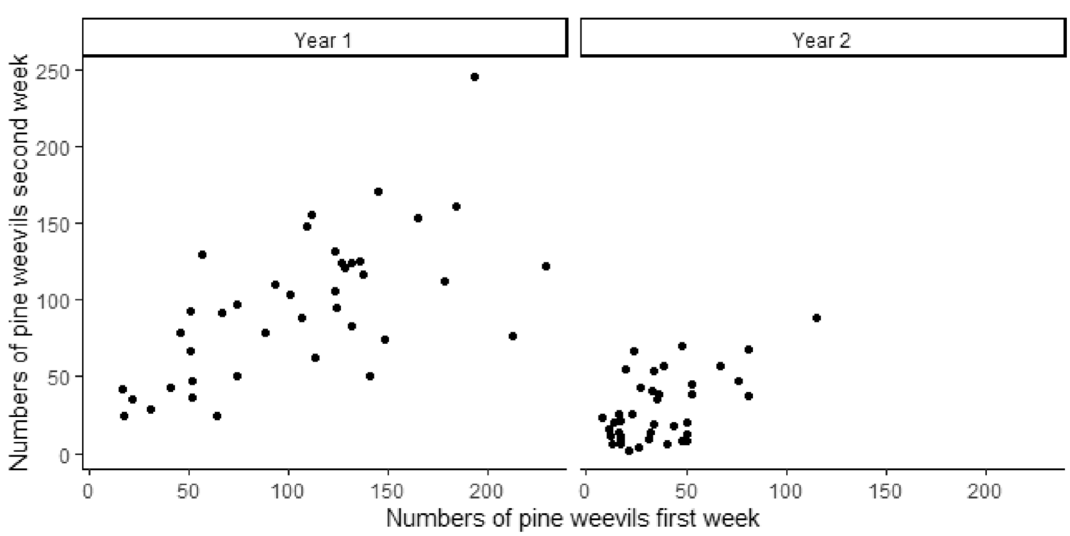

Fig. 2. Number of pine weevils trapped in each of 40 blocks during the first (x-axis) and second (y-axis) week of trapping in June in the first and second years. The coefficient of correlation was 0.647 for year 1 and 0.585 for year 2, $p < 0.0001$ for both.

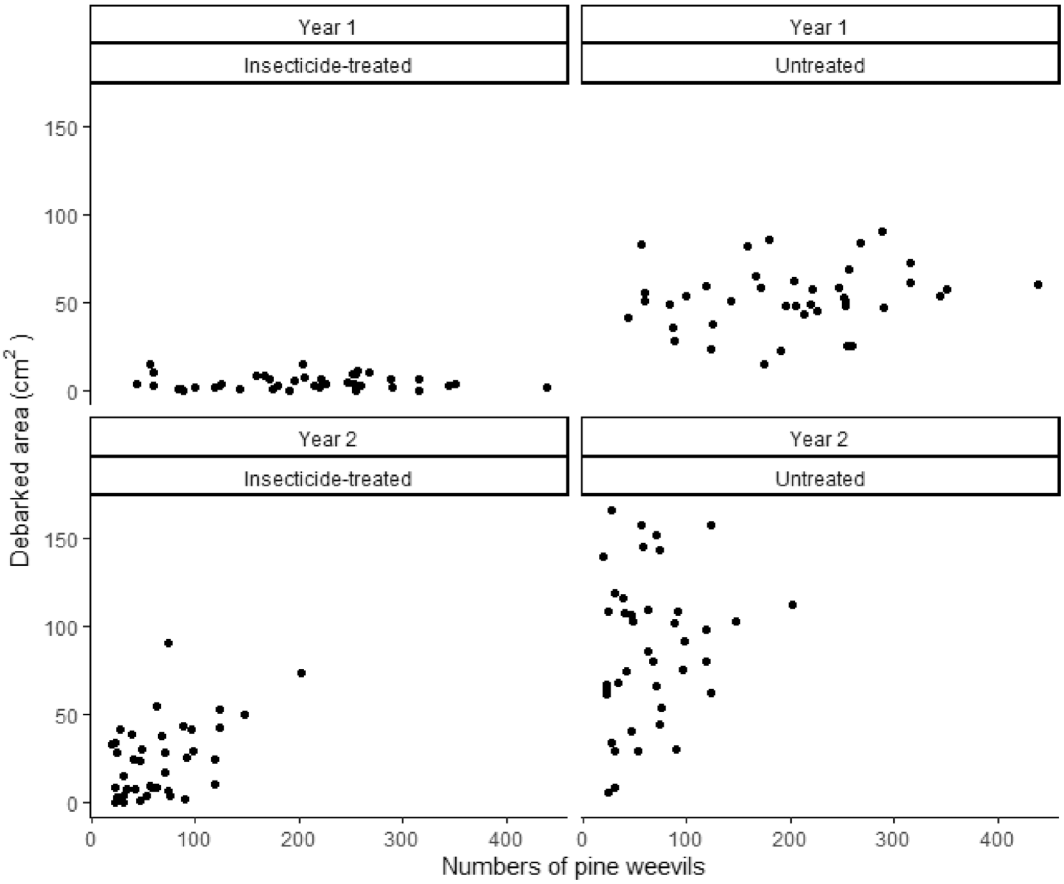

Fig. 3. Number of pine weevils trapped in relation to debarked area on untreated and insecticide-treated seedlings in each of the 40 blocks, presented separately for each year. The number of trapped pine weevils had no significant effect on the debarked area.

Table 4
Summary of results of the statistical tests of the effects of seedling treatment, stoniness and year on the response variable shown as p-values.

	Attacked seedlings	Killed seedlings	Debarked area
Seedling treatment	<0.0001	<0.0001	<0.0001
Stoniness	<0.0001	0.0003	0.0019
Year	0.0055	0.0315	0.0041

year after clear felling (2009) than in the first year (2008).

3.3.1. *Seedling treatment*

As described above, seedling treatment significantly affected all the tested response variables. Not surprisingly, seedlings treated with insecticides were less frequently attacked by pine weevils and had lower levels of damage when defined as killed by pine weevils and debarked area (Table 4). The overall mean, i.e. the mean value for all blocks and sites, was 52 % attacked seedlings among insecticide treated seedlings versus 83 % for untreated seedlings. A similar pattern was found for killed seedlings, but the difference between the treatments was even larger, as 13 % and 76 % of the insecticide-treated and untreated seedlings were killed, respectively. The average debarked area per insecticide-treated and untreated seedling were 0.3 cm^2 and 2.5 cm^2, respectively. For all tested response variables, the p-value was < 0.0001.

3.3.2. *Stoniness*

Stoniness also had a significant effect on all response variables (Table 4). With increasing amounts of stones in the ground, up to class 2, the pine weevil damage increased (Fig. 4). In class 3, the damage tended to slightly decrease again. The values for classes 1 and 2 differed significantly ($p = 0.0002$). However, there was substantial variation in the response and the data were also quite unbalanced (Fig. 4). Although it differed between years and seedling treatment, the class 2 stoniness was associated with the largest total debarked area. A similar pattern was found for the other response variables, i.e. numbers of attacked and killed seedlings.

3.3.3. *Year*

There was a clear effect of year on pine weevil damage, with significant between-year differences for the response variables attacked seedlings, killed seedlings and debarked area. In the first year, when the clear-cuts were fresh, seedlings received less damage than in the second year when the same clear-cuts were one year old.

4. Discussion

We found no significant correlation between the number of pine weevils caught in traps and damage to planted conifer seedlings (in terms of proportions attacked, proportions killed or total debarked area) at the same regeneration sites. Only one of the recorded site factors, stoniness, had a significant effect on damage according to the final model, and none of the site factors significantly affected weevil catches. The lack of significant relationships with weevil catches should not be due to unreliable trapping data since the numbers of weevils captured in each block during the first and second week of trapping were fairly well correlated. Moreover, the catch varied up to 10-fold between blocks, which should easily be sufficient to allow detection of any correlation between trap catches and damage that could be of practical value for predicting damage levels. The damage recorded the second year was probably increased by new generation weevils appearing towards the

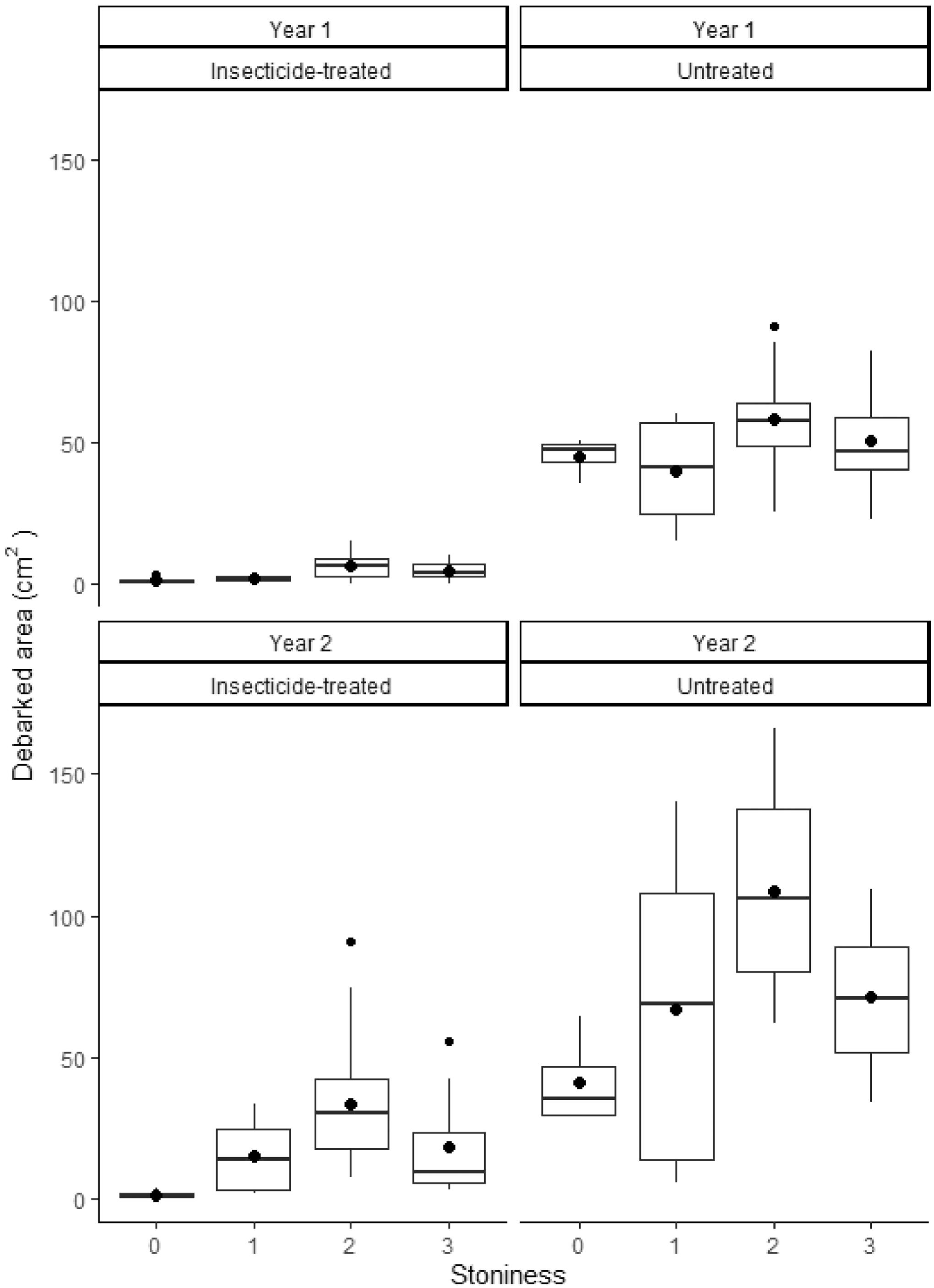

Fig. 4. Effects of seedling treatment, year and stoniness on pine weevil damage measured as total debarked area (cm^2) on 25 seedlings per block (40 blocks). For each box plot, the ends of whiskers show the minimum and maximum values, the box defines data within the first and third quartiles, the horizontal line within the box the median and the dot the mean value. Outliers are shown as dots outside the boxes.

end of that season. This may have affected the relation between catch and damage the second year, even though the numbers of new generation weevils can be expected to be related to the numbers of parent weevils on each site.

The lack of significant relationship between pine weevil catch and damage in the same season is consistent with the findings of some previous studies (Örlander et al. 1997, von Sydow 1997, López-Villamor et al. 2019). A weak correlation between weevil numbers and damage was found in a study including 82 regeneration sites, although substantial amounts of intrasite variation remained unexplained (Wilson and Day 1994). It is thus possible that data from very large numbers of sites is required to detect significant relationships between weevil catch and damage. However, such weak relationships may be of limited use for risk assessments intended to support pest management decisions.

The weak (at best) correlation between numbers of pine weevils and damage to seedlings they cause in the same places may be counterintuitive, but planted seedlings constitute a minor part of the adult weevils' diet and amounts of available food substantially vary among regeneration sites (Bylund et al. 2004, Wallertz et al. 2006). Pine weevils feed on branches of larger trees (Örlander et al. 2000) and a range of plants other than conifers (Löf et al. 2004, Toivonen and Viiri 2006). To a considerable extent they also feed on roots of mature trees, either living or recently harvested (Wallertz et al. 2006, Fedderwitz et al. 2018). In addition, the presence of coniferous shelter trees or retention trees reduces damage to planted seedlings (von Sydow and Örlander 1994, Nordlander et al. 2003a, Pitkänen et al. 2005, 2008). This is apparently because the trees provide alternative food sources, primarily roots and branches but possibly also field vegetation favoured by the presence of trees (Nordlander et al. 2003a, Pitkänen et al., 2008). For example, on adjacent regeneration sites with and without shelter trees, Nordlander et al. (2003a) found similar pine weevil population levels (measured with 100 pitfall traps) at each site, but only half as much damage to seedlings on the site with shelter trees. Strong effects of the supply of other food sources at regeneration sites on levels of weevil feeding on planted conifer seedlings have also been detected in a field experiment in which a weekly supply of fresh pine branches on the ground strongly reduced damage to seedlings (Örlander et al. 2001).

Differences in microclimatic conditions between sites are also likely to influence damage levels (Christiansen and Bakke 1971). Several site factors related to microclimate were recorded in the study reported here, but none of them significantly affected damage levels, possibly because the included regeneration sites did not differ sufficiently with respect to these factors. For instance, the calculated temperature sums varied between 990 and 1130 °C, whereas they varied between 550 and 1270 °C in a previous large-scale study that detected a significant relationship between the calculated temperature sum at each included location and pine weevil attack (Nordlander et al. 2017b). The cited survey included 292 sites throughout the northern half of Sweden, from coast to mountainous areas. However, results presented here indicate that within a more limited geographical region the variation in temperature sum between regeneration sites is likely to be too small to have practical value for predicting differences in damage risk.

Structures providing shelter for the weevils are known to increase damage to seedlings (Örlander and Nordlander 2003, Petersson et al. 2005, 2006, Luoranen and Viiri 2021). Some site factors included in this study, like field layer vegetation and slash on the ground, may provide shelter for weevils and to some extent, while the material is fresh, alternative food sources. Hence, such factors may have positive, negative or dynamically changing overall effects, depending on the relative strength of these contributory effects (Hanssen et al. 2018). However, no significant effects of the amount of slash or recorded field vegetation were detected in the present study.

Stoniness was the only site factor that significantly affected damage, which increased with the level of stoniness from class 0 to 2 but then tended to slightly decrease with a further increase in stoniness to class 3. The reasons for this are not clear, especially as the seedlings in this study were planted directly in the ground without site preparation. Hence, stoniness did not influence damage by affecting site preparation quality, as noted in other studies (Wallertz et al. 2018). However, stoniness may influence the availability of sheltering structures and increase both soil temperature and moisture content (Saini and MacLean 1967). A high level of stoniness might also be associated with low levels of alternative food sources on the ground for pine weevils. Thus, it would be valuable to evaluate effects of stoniness more thoroughly in future studies, especially as stoniness also negatively affects possibilities to create planting spots with mineral soil, which is a key measure to reduce pine weevil damage (Sikström et al. 2020).

Although the area of the clear-cut was included as a variable in the model for predicting the proportion of attacked seedlings, it was not found to be a significant explanatory variable, despite the considerable range in size of the clear-cuts (4.5 to 48.2 ha). Site area was found to be negatively correlated with damage by Wilson et al. (1996), who suggested that this may be due to the tendency for damage to decline with increasing distance from edges of clear cuts. However, in another study less damage was recorded near clear-cut edges (Nordlander et al. 2003b). The conflicting results may be at least partly due to difference in timing of the data collection, since the distribution of pine weevils on regeneration sites changes over the season (Nordlander et al. 2003a). Flying immigrant weevils arriving in fresh clear-cuts in spring initially aggregate at the edges where they feed for a while in the crowns of mature trees (Örlander et al. 2000). They subsequently spread over the clear-cut and later in the season may become more abundant in central parts (Skrzecz 2021).

The proportion of broadleaf stumps was another site factor that was initially selected but not found to be a significant explanatory variable in the present study. As the pine weevils are attracted to conifer stumps but not broadleaf stumps for reproduction, a high proportion of broadleaf stumps may putatively considerably decrease weevils' attraction to a site (Björkman et al. 2015). However, our study did not include sites with a high proportion of broadleaf stumps (at most 40 % at block level), which may explain why we detected no significant effect.

Two other explanatory variables, seedling treatment and year, significantly affected damage, and year also affected the number of weevils trapped. This was consistent with expectations, but the experiment was not designed to investigate effects of these variables. Both insecticide-treated and untreated seedlings were used throughout the study to include two levels of damage and thereby reduce risks of having only too high or too low levels of damage for the analysis. The experiment was repeated during two years on the same clear-cuts, so during each of these years all clear-cuts were of the same age (fresh in the first year and one year old in the second year). Thus, effects of clear-cut age were not investigated. However, several previous studies have shown that clear-cut age strongly affects local pine weevil population sizes and damage caused by the weevils (Moore et al. 2004, Wallertz et al. 2016, Nordlander et al. 2017a). Therefore, to predict damage risk robustly within regions with a similar climate it is essential to identify the periods in time after harvest when peaks of the adult pine weevil population coincide with the availability of recently planted seedlings (Wainhouse et al. 2014).

5. Conclusions

Assessment of pine weevil numbers appears unlikely to be useful for predicting damage risks at individual regeneration sites, because of a general lack of correlation between weevil numbers and damage. We suggest that the expected relationship between weevil abundance and damage is strongly masked because planted seedlings only constitute a minor part of the weevils̕ diet and the availability of other food sources varies considerably between sites. A site factor that warrants further attention is stoniness, since damage increased with increases in stoniness, at least up to a fairly high level. Previously well-known factors that should be considered when estimating damage risk on a local scale include age of clear-cut, and availability of planting spots with mineral soil. On a larger geographic scale, effects of climatic differences on pine weevils' life cycle, population sizes, as well as both duration and intensity of feeding activity, should be considered.

CRediT authorship contribution statement

Göran Nordlander: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Niklas Björklund:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Claes Hellqvist:** Conceptualization, Data curation, Investigation, Methodology. **Henrik Nordenhem:** Investigation, Methodology. **Mateusz Liziniewicz:** Formal analysis. **Karin Hjelm:** Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank Bergvik Skog AB for providing field sites and John Blackwell (Sees-editing Ltd.) for improving the language of the paper. This study was part of the Swedish *Hylobius* Research Program financed by the Swedish forestry sector.

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