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Year: 2022

Version: Published version

Please cite the original version:

Luoranen J., Laine T., Saksa T. (2022). Field performance of sand-coated (Conniflex®) Norway spruce seedlings planted in mounds made by continuously advancing mounder and in undisturbed soil. Forest Ecology and Management 517, 120259. https://doi.org/10.1016/j.foreco.2022.120259.

Forest Ecology and Management 517 (2022) 120259

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Field performance of sand-coated (Conniflex®) Norway spruce seedlings planted in mounds made by continuously advancing mounder and in undisturbed soil

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ARTICLE INFO

Keywords:
Picea abies
Pine weevil
Hylobius abietis
Site preparation
Physical protection

ABSTRACT

The pine weevil (*Hylobius abietis* L.) is among the worst pests of newly planted conifer seedlings in Europe. EU regulations restrict the use of insecticides, the cost of mechanical site preparation (MSP) is high, and it has even been suggested that MSP should be abandoned due to social and environmental causes. The aim of this study was to investigate i) the field performance of Norway spruce (*Picea abies* (L.) Karst.) seedlings planted in mounds made by a continuously advancing mounder (CAM) and in undisturbed soil in southern Finland, and ii) how well the physical barrier (Conniflex® sand coating) prevented pine weevil damage compared to insecticide-applied and unprotected seedlings. The quality of CAM was generally at an acceptable level. After two growing seasons, mortality, mainly caused by pine weevils, was higher and growth lower in unprotected seedlings than in Conniflex-coated or insecticide-treated seedlings. Mortality was also higher and growth lower in undisturbed soil than in mounds. Even though the quality of soil preparation after CAM was quite good, planting Norway spruce seedlings without any protection could not guarantee a successful planting result (>1500 seedlings ha^{-1}). Conniflex coating and insecticide treatment provided equal protection against serious pine weevil damage.

1. Introduction

Most Norway spruce (*Picea abies* (L.) Karst.) seedlings are planted in mounds in Finland. In mounds, the risk of damages is at a lower level, and growth is better than in disc-trenched furrows or patches in which only mineral soil is revealed (Sikström et al., 2020). In most cases, mounds are made with an excavator (Ramantswana et al., 2020). Making each mound separately is quite an expensive method, although when considering the entire regeneration chain of Norway spruce container seedlings until commercial thinning it is more economic than disc trenching in Finnish conditions (Uotila et al., 2010). However, there is pressure to reduce the cost of the reforestation chain, and especially the costs of mounding. One way is to use continuously advancing mounders (CAM) (Hallongren et al., 2014). Since this device makes mounds at even intervals without taking into account any features or obstacles at the point of the mound, the quality of the mounds may vary (Saksa et al., 2018). There is only scant research into the quality of mounds and especially the field performance of seedlings in mounds made by CAMs.

There have been demands to reduce or even prohibit the use of mechanical site preparation (MSP), at least in Finland, due to social sustainability or environmental reasons. However, MSP is an effective measure for improving seedlings' field performance (Sikström et al., 2020), and especially for reducing the risk of pine weevil (*Hylobius abietis* L.) damage in newly planted conifer seedlings (e.g. Petersson and Örlander, 2003; Nordlander et al., 2011). The pine weevil is a widespread damage-causing agent in European forests, and it causes economic losses of more than €120 million in newly planted forests (Långström and Day, 2004; Lalík et al., 2021). The protection effect of MSP against the pine weevil is based on the mineral soil around a seedling (Petersson and Örlander, 2003; Petersson et al., 2005). The risk of pine weevil damage is therefore high in poor-quality mounds (Luoranen et al., 2017; Wallertz et al., 2018) and without the use of MSP (Sikström et al., 2020).

The protection of seedlings with a chemical application (insecticides) before planting has been the most common and effective measure against pine weevil damage in Europe (Lalík et al., 2021). The risk of damage caused by pine weevils is highest when unprotected seedlings

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https://doi.org/10.1016/j.foreco.2022.120259
Received 31 January 2022; Received in revised form 22 April 2022; Accepted 26 April 2022

are planted in undisturbed soil (Petersson and Örlander, 2003; Luoranen et al., 2017). In southern Sweden, the previously used insecticide permethrin applied twice (first before planting and then sprayed in the following spring after planting) also protected seedlings well against weevil damage in undisturbed soil (Petersson and Örlander, 2003). However, the European Commission Directive on the Sustainable Use of Pesticides (European Commission, 2020) encourages a reduction in the use of pesticides, and the use of insecticides is being successively restricted or banned because of their risks to the environment or humans. In Sweden, the replacing the insecticides with physical protection has been driven by forest certification organizations (in particular FSC) and active development work of forest companies. Consequently, the use of insecticides has decreased, and physical protection of conifer seedlings increased since 2010 (Giurca and von Stedingk, 2014), and in 2020 50% of conifer seedlings used in Sweden were physically protected, only 3% were insecticide treated, and 47% were unprotected (for use in northern Sweden) (Skogsstyrelsen, 2021). In Finland, almost all conifer seedlings are treated in nurseries with insecticides before planting, except those delivered to the northernmost part of Lapland are unprotected. Only two active ingredients, lambda-cyhalotrin and acetamiprid, are in use in Finland in 2022 (Tukes).

Various coatings, shields and other physical barriers have been studied as protection methods against pine weevil (Petersson and Örlander 2003; Petersson et al., 2004; Nordlander et al., 2009; Lalík et al., 2020; Moore et al., 2021). Depending on the method and tree species for which they are used, they can be as effective as insecticides (Lalík et al., 2021), particularly for container seedlings (Nordlander et al., 2009, 2011). However, for example, in Great Britain, where bareroot seedlings are used, insecticides have been the most cost-effective method (Hardy et al., 2020), or insecticides have been more effective when the pine weevil population has been big (Moore et al., 2021). In Sweden, the physical protection against pine weevil feeding is now the main method. One of the physical barriers is the sand coating of seedlings (commercial product Conniflex®, SveaSkog, Stockholm, Sweden). In this method, fine sand (grain size = 0.2 mm) is blown onto the lower part of stems which have first received an application of water-based glue (Nordlander et al., 2009). From Sweden, we know sand coating with Conniflex done by hand can protect seedlings planted in disc-trenched furrows better than insecticide treatment (Nordlander et al., 2011), but in commercial-scale coating, no differences between Conniflex and insecticides have been found (Nordlander et al., 2009).

In Finland, field experiments in which pine weevil damage have been studied have been carried out in central Finland (e.g. Heiskanen and Viiri, 2005; Pitkänen et al., 2008; Luoranen and Viiri, 2012, 2021; Rahman et al., 2015; Luoranen et al., 2017). During recent decades, only some stump removal sites in the study of Piri et al. (2020) were in southern Finland. Some practical observations suggest that the risk of damage caused by pine weevils in southern Finland is much higher than in central Finland. The effects of different measures against the pine weevil should therefore be studied in conditions with a high probability of pine weevil damage in southern Finland.

If the quality of mounds made by CAMs is poor, or if scenarios to avoid MSP are realized, it is good to know how effective currently used insecticides are against pine weevil feeding on seedlings planted in undisturbed soil or how effective the other protection measures like physical barriers are in reducing pine weevil damage. The aim of this study was to investigate i) the field performance of Norway spruce seedlings planted in mounds made by a continuously advancing mounder (CAM) and in undisturbed soil in southern Finland and ii) how well the physical barrier Conniflex (sand coating) prevented pine weevil damage compared to insecticide-applied and unprotected seedlings. The quality of CAM was also evaluated.

2. Material and methods

2.1. Seedling material

The seedlings were 1.5-year-old Norway spruce container seedlings grown by the Vibytorps nursery of Svenska Skogsplantor in Sweden. The seeds used to raise seedlings were from seed orchards (Fp-65 Rörby in 2019 and Fp-66 Saleby in 2020) and were appropriate for use in the study sites in southern Finland. The seedlings were grown in hard plastic containers SA90 (Svepot Air 90, cell volume 90 cm^3, 45 cells per container, Svenska Skogsplantor AB, Sweden). In 2019, one third of seedlings were treated with Imprid Skog (acetamiprid), one third were treated with Conniflex sand coating (see application protocol https://www.bccab.com/products-planting/conniflex-2/) before packing, and the remaining seedlings were unprotected. The seedlings were packed in cardboard boxes on February 19, 2019 (insecticide) or March 1, 2019 (others). In 2020, one third of seedlings were sand-coated with Conniflex before packing. In the middle of November 2019, Conniflex was applied to the seedlings, and these and the unprotected seedlings were packed in cardboard boxes. The seedlings were transferred to the Suonenjoki Research Unit of Natural Resources Institute Finland (Luke) in May 2020. On May 22, 2020, half the unprotected seedlings were sprayed with Karate® Zeon (lambda-cyhalotrin) and the rest were used as unprotected seedlings without any protection application. A box contained 100 seedlings from one seedling protection treatment. There were six boxes per treatment and year, a total of 36 boxes and 3600 seedlings. Before planting, the seedlings were watered regularly.

2.2. Study sites and experimental design

The study was established in six experimental sites located in southeast Finland. Three sites were established at the beginning of June 2019, and the other three at the end of May 2020 (Fig. 1). All sites were suitable for growing Norway spruce, and they were clear-cut in the previous fall or winter, except for one in Ruotsinpyhtää a year before (Table 1). Fresh clear-cuts were selected to maximize the pine weevil feeding. Spot mounds (Fig. 1) were made using continuously working two-raw mounder attached to forwarder (Bracke M24.a with the arms articulated laterally which move aside for obstacles and create planting spots to one side) in May 2019 and 2020, a few weeks before planting. The target number of mounds was 1800 per hectare.

On each site, seedlings were planted in four blocks in different parts of the regeneration area, excluding a buffer zone of 15 m between blocks and the adjacent forest (Fig. 1). Each block consisted of 50 planted seedlings of three seedling protection treatments against pine weevil feeding: 1) Conniflex coating (Fig. 2); 2) insecticide treatment with Imprid Skog (2019) or KarateZeon (2020) (the substance was supposed to be KarateZeon in both years, but accidentally in the first year the seedlings were treated Imprid Skog); and 3) unprotected seedlings. Half of these seedlings were planted in mounds, and half in undisturbed soil, and the same seedling protection treatment in the mound and in undisturbed soil made a pair. In undisturbed soil, the seedlings were planted between the mounds (at a distance of 1 m from the mound), (Fig. 1). Treatments for subplots within a block were randomized, and each subplot consisted of each protection treatment planted in the mound and in undisturbed soil (i.e. six seedlings). Each block consisted of 150 planted seedlings, a total of 600 seedlings per site, and 3600 seedlings altogether. The seedlings were planted in the middle of the mounds or undisturbed soil to a depth of 6 cm. A separate planting tube was used for each seedling protection treatment to avoid the seedlings in other protection treatments being contaminated with insecticide. Root plugs were kept wet before planting by watering.

2.3. Measurements

In each block, site type [mesic (*Oxalis-Myrtillus* type), sub-mesic

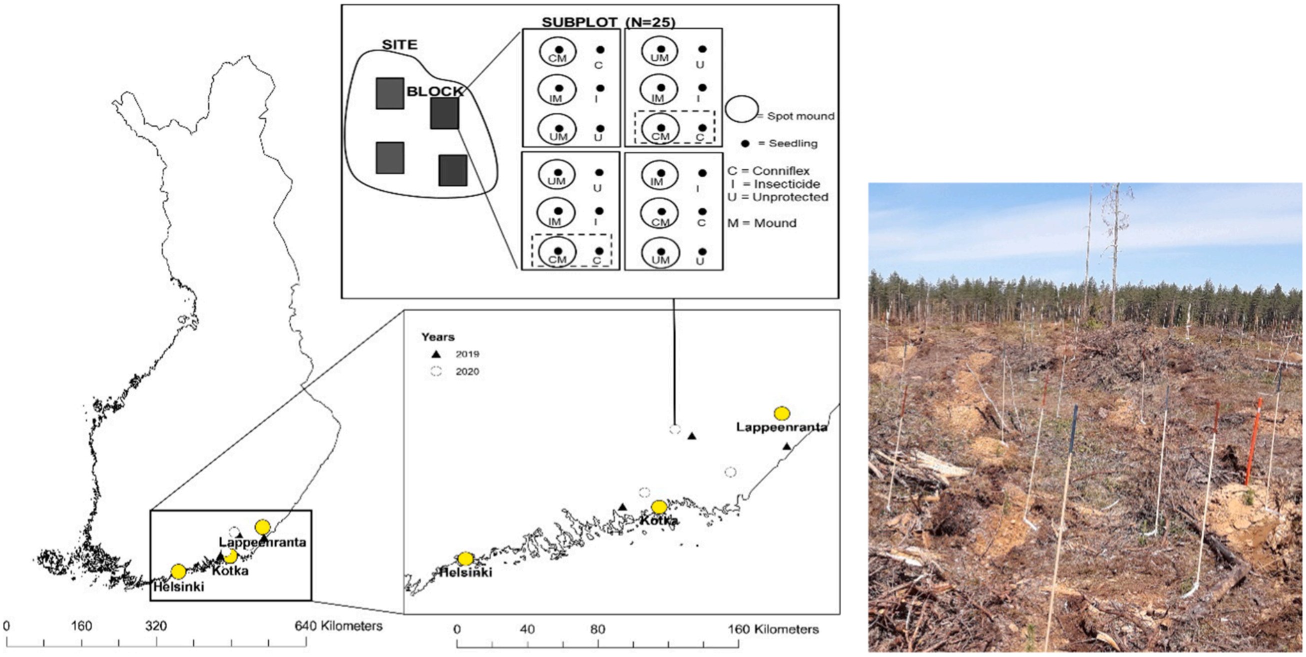

Fig. 1. Locations of experimental sites in southeast Finland and the experimental design of the study. Three pine weevil feeding protection treatments [Conniflex coating, insecticide treatment, no seedling protection (unprotected)] were planted either in mounds or in undisturbed soil. In the study design picture, it has been drawn as an example four subplots out of 25 subplots within the block. Within a subplot, dashed areas indicate a pair of seedlings with same seedling protection treatment planted in mound and unprepared soil. In the photo, mounds made by continuously advancing mounder in Kouvola site. Between mounds, seedlings planted in undisturbed soil are also marked with sticks. Photo: Juhani Salonen.

Table 1

Description of the regeneration sites. Site type classification is based on Tonteri et al., 1990 and Cajander, 1949. Soil texture type was determined based on grain size.

Location	Time of clear-cut (month/ year)	Site type	Collecting of logging residues	Soil texture type	Stoniness
Lappeenranta	02/2018	Sub-mesic (*Myrtillys* type)	Yes	Medium-coarse coarse	Few stones – normal
Luumäki	09/2018	Sub-mesic (*Myrtillys* type)	Yes	Fine – medium-coarse	Few stones
Ruotsinpyhtää	09/2017	Sub-mesic (*Myrtillys* type)	Yes	Medium-coarse	Normal
Miehikkälä	08/2019	Sub-mesic (*Myrtillys* type)	No	Medium-coarse	Few stones
Kotka	10/2019	Sub-mesic (*Myrtillys* type)	No	Fine	Few stones
Kouvola	08/2019	Sub-xeric (*Vaccinium* type)	No	Coarse	Few stones

(*Myrtillus* type), sub-xeric (*Vaccinium* type); based on Tonteri et al., 1990 and Cajander, 1949], podzol soil texture type was visually determined to be coarse mineral soil (grain size easy to evaluate with the naked eye), medium-coarse mineral soil (single grains still detectable with the naked eye, grains detached), or fine mineral soil (single soil grains undetectable with the naked eye). Soil stoniness was determined using the method devised by Viro (1952), and the distance from the block to the forest edge (m) was visually evaluated.

In the 2020 fall inventory, we also assessed the quality of site preparation made by the CAM in all sites. The area of each block was measured using the GPS device by Risutec (Nakkila, Finland). All mounds or potential mound places inside a block were counted, and the suitability of mounds or potential mound places for planting was assessed using the following categories: an unsuitable mound or place in which a mound should have been established; a suitable mound with a planted seedling; a suitable mound without a planted seedling. The reason for a suitability assessment was categorized as; i) a mineral soil mound; ii) a mineral soil mound with humus cover; iii) a humus mound (mound only from the inverted humus layer); iv) unsuitable for planting, because the mounder had made a small deformed mound (only partly inverted soil, inverted soil left up etc.); v) a patch; vi) unsuitable for planting due to a potential place for a mound, but stones, stumps, harvesting residues, or other obstacles had prevented the establishment of the mound.

After planting and at the end of the first and second growing seasons, the height (from the soil surface to the top of the apical bud, with 0.5 cm accuracy), current year height growth, and stem base diameter (2 cm above the soil surface with an accuracy of 0.1 mm) of each seedling were measured. The texture of the mineral soil on the mound surface was visually evaluated to be pure mineral soil, a mineral soil mound with some humus, or mostly humus.

The vitality of planted seedlings (1 healthy, 2 minor damage, 3 weakened, 4 nearly dead, 5 dead) and the cause of any damage (drought, frost, pine weevil, bark beetle (*Hylastes cunicularius*), vole *(Myodes glareolus*), frost heaving, field vegetation) were evaluated. Pine weevil feeding was evaluated separately using a scale of 0–4: 0) no feeding; 1) feeding <25% of the stem; 2) feeding 25–50% of the stem; 3) severely feeding more than 50% of the stem; 4) feeding around the stem of a dead or dying seedling. For further calculations, classes 3 and 4 were combined to describe serious pine weevil feeding and total pine weevil feeding of classes 1–4. All the dead seedlings were dug up, and the cause of damage was evaluated again in the laboratory. The feeding of *Hylastes* spp. in the root system was checked especially carefully (not found). In the springs of 2020 and 2021, winter damage was also evaluated in sites established in the previous year.

The target density was 1,800 planted seedlings per hectare, and the criteria for planting success (based on Pikkarainen et al., 2020) after two

Fig. 2. Conniflex-coated seedling planted in unprepared soil. Photo: Tiina Laine.

growing seasons were as follows: successful if there were more than 85% (1530) living seedlings compared to the target (1800) after two growing seasons; and poor if there were fewer living seedlings. A seedling was classified as living if the vitality class was 1–3 after two seasons. To calculate planting success in different treatment combinations, the average number of seedlings planted per hectare was used.

2.4. Weather conditions

We collected monthly temperature and precipitation data for each experimental site from the database of the Finnish Meteorological Institute. The temperature sums ($T_{sum} > +5$ °C) for each experimental site during the planting season were also calculated. The summer of 2020 was warmer than 2019 (Table 2). A period from August to October especially increased the growing season's temperature sum to more than 100 d.d than in 2019. In June and August 2019 and May 2020, precipitation sums were low, and in July 2020 quite high, especially at the Kotka and Kouvola sites.

2.5. Statistical analysis

We analyzed growth data using a linear mixed (MIXED) model in IBM SPSS Statistics 27, and the probability of total and serious pine weevil feeding, mortality, and other damage causing agents was analyzed using generalized linear mixed models (GLMM) in SAS for Windows 9.4 (SAS Institute Inc., Cary, NC, USA). In the models, fixed effects were the year of establishment (for damage and mortality data), seedling protection treatments (Conniflex, insecticide, unprotected), site preparation treatment (mounding, undisturbed) or their interactions, and random effects in the regeneration site and block within the site. The subplot effect was minimal, and it was dropped from the final models. The effect of mineral soil cover (yes or no) in a mound on the probability of serious pine weevil feeding was also analyzed between seedling protection treatments planted in mounds with GLMM. Feeding pressure (FP) was determined using the total pine weevil feeding of unprotected seedlings planted in undisturbed soil at the end of the first growing season (Luoranen et al., 2017). We tested if the time between clear-cut and planting, soil type, stoniness, distance to the nearest forest edge and its tree species, as well as the T_{sum} and precipitation sum of the first growing season predicted the probability of FP by using GLMM. The GLMM analysis was conducted with a binomial distribution, logit link function, and using adaptive quadrature (QUAD) or Laplace (for FP) estimation methods. Multiple comparisons were based on Least Significant Difference. A difference with a p-value of <0.05 was considered significant.

To clarify the quality of CAM, statistically significant differences in the number of mounds or seedlings between sites were analyzed by one way ANOVA in SPSS. In the analysis, the number of mounds/seedlings in each block was used. The homogeneity of variances was tested by Levene's statistic.

3. Results

3.1. Quality of site preparation

The CAM made an average of 2042 ± 62 (mean ± standard error) potential planting points/ha without statistically significant differences between sites ($p = 0.196$). There were 1730 ± 58 mounds/ha that were suitable for planting ($p = 0.092$). The average number of planted seedlings was 1704 ± 56 seedlings/ha ($p = 0.143$). On average, there were 312 ± 23 potential planting points/ha without a mound, or the quality of a mound was so poor that it was unsuitable for planting ($p = 0.889$). There were 15% of places where a good mound should have been established, but the CAM had been unable to make it due to an obstacle.

On average, 84% of potential planting places were mounds made up

Table 2

Monthly mean temperatures (°C; first in each cell) and precipitation sums (mm) in the planting summer on each experimental site. Temperature and precipitation sums at the end of planting seasons are also presented. Data were collected from the database of the Finnish Meteorological Institute.

	2019			2020		
Month	Lappeenranta	Luumäki	Ruotsinpyhtää	Miehikkälä	Kotka	Kouvola
May	9.7/49.3	9.8/86.2	10.2/71.5	8.6/25.6	9.1/29.1	9.2/30.0
June	17/12.5	17.3/14.8	17.2/18.2	17.4/62.8	17.8/97.8	18.1/72.7
July	15.1/82.6	15.9/59.5	16.7/60.2	15.8/89.2	16.1/92.4	16.1/118.0
August	14.7/35.9	15.4/47.6	16.1/64.1	15.6/79.2	15.8/78.4	16.1/59.0
September	9.8/51.1	10.2/83.6	10.7/69.9	12.2/62.1	12.4/55.6	12.2/59.1
October	3.8/92.2	3.9/85.3	4.7/81.4	7.5/76.1	8.0/83.2	7.4/75.8
Temperature sum, d.d.	1,297	1,365	1,416	1,452	1,495	1,518
Precipitation sum, mm	324	357	365	395	436	415

of mineral soil, either pure mineral soil or covered with a thin humus layer. In 2019, 96% of experimental seedlings were planted in mounds covered by mineral soil in all sites without statistically significant differences between seedling protection treatments within a site (p-values > 0.50). Compared to 2019, more seedlings were planted in mineral soil mounds covered by humus (4, 6, and 10% at Kotka, Kouvola, and Miehikkälä) in 2020. At Miehikkälä, the randomization of mounds to the seedling protection treatments within a plot failed, because more Conniflex-coated seedlings were planted in mounds covered with mineral soil (probability 0.97) than seedlings in the other seedling treatments (0.84 and 0.86 for unprotected and insecticide-treated seedlings; $p = 0.018$). At Miehikkälä and Kouvola, 1 and 2% of seedlings were planted in humus mounds.

3.2. *Mortality and damage*

There were statistically significant differences ($p < 0.001$) in total mortality between sites, years, site preparation, and seedling protection treatments, as well as the interactions of these effects (Table 3). At the Lappeenranta and Luumäki sites, the total mortality was lower than in the other sites (Fig. 3b). Overall mortality was higher in 2020 (predicted probability of mortality until the end of the second season 0.20) than in 2019 (0.11). The mortality of Conniflex-coated (0.06 and 0.08 in 2019 and 2020) and insecticide-treated (0.06 and 0.10) seedlings did not differ between years within a seedling protection treatment or between seedling protection treatments within site preparation treatments (Fig. 3b). However, more unprotected seedlings died in 2020 (0.62) than in 2019 (0.33), both in mounds (0.32 and 0.09) and undisturbed soil (0.85 and 0.71). Calculated as the average number of planted seedlings (1704 seedlings/ha), the average densities of living seedlings after two years were 356, 1385, and 1331 per hectare in undisturbed soil for unprotected, Conniflex-coated and insecticide-treated seedlings respectively. The corresponding values in the mounds were 1294, 1573, and 1584.

The main cause of damage and mortality was pine weevil feeding (Fig. 4). Pine weevil feeding damage was found in 22% of seedlings. Drought damaged more seedlings in 2019 (10%) than in 2020 (1%) with no statistically significant differences between treatments (Table 3). In 2020, excessive water in soil damaged seedlings more in undisturbed soil than in mounds, and in undisturbed soil, fewer unprotected seedlings were damaged by excessive water than in the other treatments. During the first winter, voles damaged 10% of seedlings planted in 2020 especially in Kotka (predicted probability 0.15), but also in Miehikkälä (0.09) and Kouvola (0.02; $p < 0.001$ for site). Voles damaged more seedlings planted in mounds than in undisturbed soil ($p < 0.001$) and more Conniflex-coated and insecticide-treated than unprotected seedlings ($p < 0.001$). Two percent of seedlings were suppressed by field vegetation, and 2% of seedlings were also damaged for other reasons (frost heaving, spring frost).

3.3. *Pine weevil feeding damage*

FP varied between sites from 0.43 to 0.91 (predicted probability of feeding). The increasing T_{sum} in the planting season slightly increased FP ($FP = -4.89 + T_{Sum} x 0.005$; $p = 0.030$).

In total, pine weevil feeding damage was at about the same level in both years (Table 3; Fig. 5), but feeding damage was more serious in 2020 than in 2019. Pine weevil feeding and serious feeding damage were more common in seedlings planted in undisturbed soil than in mounds in all seedling protection treatments. In undisturbed soil, almost all unprotected seedlings were dead after two growing seasons. The total feeding was greater in insecticide-treated seedlings than in Conniflex-coated seedlings, both in mounds and in undisturbed soil. In mounds, the total feeding of unprotected seedlings was at about the same level as it was in Conniflex-coated seedlings in undisturbed soil. In 2019, serious feeding damage was more common in insecticide-treated than in Conniflex-coated seedlings, but in 2020, there were no differences between seedling protection treatments.

Mound quality (soil cover around seedlings planted in mounds) affected differently the probability of serious pine weevil damage in different seedling treatments (Table 3). In Conniflex-coated (predicted probability of serious damage 0.02 in mineral soil, 0.11 for other surfaces) and unprotected seedlings (0.17 and 0.28) mineral soil around a seedling decreased the predicted probability of serious pine weevil feeding. In insecticide-treated seedlings (0.05 and 0.06) there were no differences in feeding damage between mound quality classes.

3.4. *Seedling growth*

There were small but not systematic differences in seedling height at planting between treatments in both establishing years (Table 4; Fig. 6). Due to the sand coating, Conniflex-coated seedlings were thicker at planting. Height at planting was used as a covariate in further analysis.

At the end of the second growing season, seedlings planted in undisturbed soil had grown less, and they were shorter and thinner than seedlings planted in mounds in all seedling protection treatments in both establishing years. In the 2019 experiment, no differences in height growth, total height, or stem base diameter were found. In 2020, insecticide-treated seedlings were thicker and taller than seedlings in other treatments, both in undisturbed soil and mounds.

4. Discussion

Successful regeneration results were achieved only in mounds by using either Conniflex coating or insecticides and these two seedling treatments had a similar protection effect against serious pine weevil damage. The equally effective protection effect of Conniflex coating and insecticide treatment against serious pine weevil feeding damage planted in mounds corresponds to the results of Nordlander et al. (2009) in the commercial-scale Conniflex coating of conifer seedlings. In our study, Conniflex coating was also done commercially.

The additive effect of seedling protection treatment and MSP against pine weevil feeding corresponds to the results of Petersson and Örlander (2003). Mineral soil cover around a seedling protects seedlings from pine weevil feeding (Petersson et al., 2005; Luoranen et al., 2017; Wallertz et al., 2018). Insecticide-treated seedlings had less serious

Table 3
Statistical significances (p-values) given by the generalized linear mixed models for the total mortality of seedlings at the end of the second season, drought damage in 2019 data, excessive water in 2020 data, total and serious pine weevil feeding damage in the whole data. P-values for the model of serious pine weevil feeding damage only for seedlings planted in mounds with the mound quality effect are also presented. Q means Quality of mound (mineral soil cover or not).

Effect	Total mortality	Drought in 2019	Excessive water in 2020	Total feeding	Serious feeding	Serious feeding –mound quality
Establishing year (Y)	0.026			0.269	0.025	0.0138
Seedling treatment (ST)	<0.001	0.796	0.101	<0.001	<0.001	<0.0001
Site preparation (SP)	<0.0001	0.363	0.004	<0.001	<0.001	
ST × SP	<0.001	0.309	0.025	<0.001	<0.001	
ST × Y	0.004			0.023	<0.001	0.0177
SP × Y	0.033			0.013	0.001	Q 0.0188
ST × SP × Y	0.513			0.758	0.651	Q × ST 0.1431

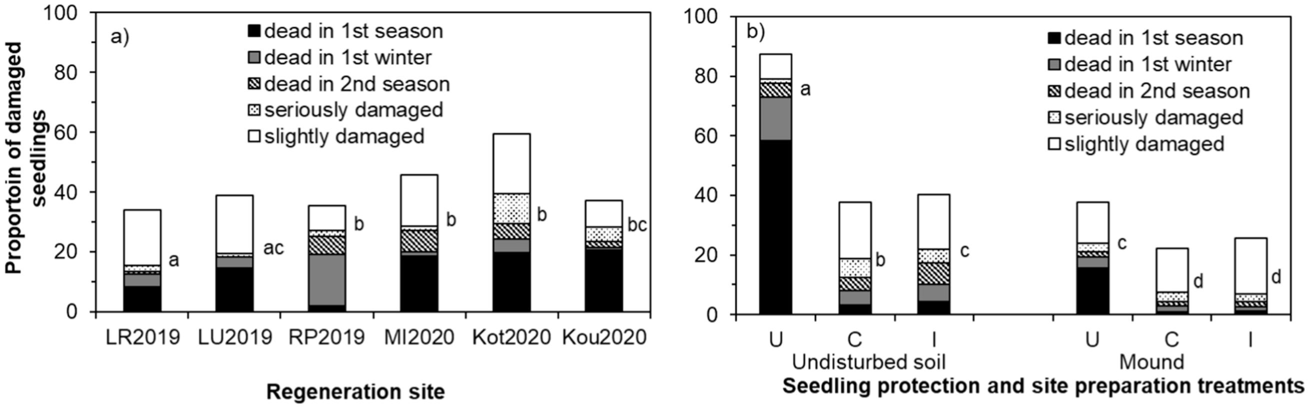

Fig. 3. Proportion of damaged (at the end of the second growing season) and dead Norway spruce seedlings during the first growing season, first winter, and second growing season in a) regeneration sites located in Lappeenranta (LR), Luumäki (LU), Ruotsinpyhtää (RP), Miehikkälä (MI), Kotka (Kot), and Kouvola (Kou) and b) in unprotected (U), Conniflex-coated (C), and insecticide-treated (I) seedlings planted either in undisturbed soil or in mounds. Seedlings were planted either in 2019 or 2020. In b) all sites were combined. Lowercase letters next to bars indicate statistically significant differences in total mortality at the end of the second growing season a) between sites and b) between seedling protection and site preparation treatments.

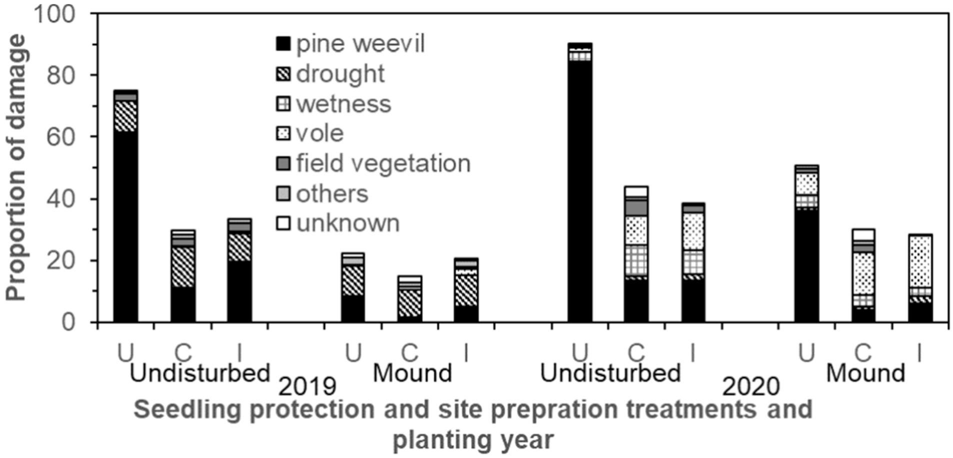

Fig. 4. Proportion of different damage-causing agents separately for seedling protection and site preparation treatments within establishing years. All sites were combined within a year. U = Unprotected seedlings, C = Conniflex-coated, I = Insecticide-treated Norway spruce seedlings.

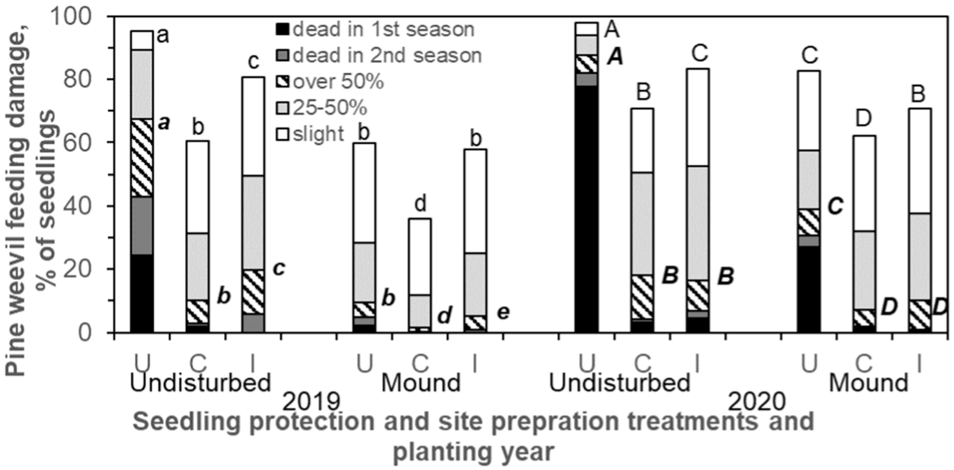

Fig. 5. Proportion of seedlings in each pine weevil feeding class at the end of the second growing season. Data of all sites within an establishing year were combined. Lowercase letters next to bars indicate statistically significant differences between treatments in 2019 and uppercase letters in 2020. Bold and italic letters indicate differences in serious pine weevil feeding (dead or more than 50% feeding), and normal letters differences in total feeding. U = unprotected seedlings, C = Conniflex-coated, I = insecticide-treated seedlings.

damage than Conniflex-coated seedlings when seedlings had been planted in surfaces other than mineral soil in mounds. In the 2020 experiment, slightly more Conniflex-coated seedlings were planted in mineral soil covered mounds than seedlings in other protection treatments. This may have affected the mortality results in mounds and made it difficult to draw decent conclusions. In any case, in order to reduce the pine weevil feeding damage, it is important to have mineral soil cover around planted seedlings.

Table 4
P-values for different predictors in linear mixed models run for total height, height growth, and diameter at planting and at the end of the second growing season. Height at planting were used as a covariate.

Source	Total height		Height growth		Diameter
	at planting	2nd year	2nd year	at planting	2nd year
Intercept	<0.001	<0.001	<0.001	<0.001	<0.001
Seedling treatment (ST)	<0.001	<0.001	<0.001	<0.001	<0.001
Site preparation (SP)	0.161	<0.001	<0.001	0.826	<0.001
ST × SP	<0.001	0.139	0.484	0.033	0.001
Establishing year (Y)	0.172	0.016	0.002	0.064	0.344
ST × Y	0.004	<0.001	<0.001	<0.001	<0.001
SP × Y	0.906	0.002	0.384	0.132	0.858
ST × SP × Y	0.019	0.399	0.703	0.656	0.909
Covariate		<0.001	0.025		

Although there were no differences between serious damage and mortality between Conniflex coating and insecticide treatment, Conniflex coating was more effective at protecting seedlings from slight pine weevil feeding than insecticide treatment. Pine weevils taste the insecticide-treated stem before they decide not to continue eating, or they find parts of the stem without insecticide (Rose et al., 2006). An individual pine weevil can cause only a small scar to a seedling treated with pyrethroid or neonicotinoid insecticide before feeding is interrupted (Rose et al., 2005,2006), but when pine weevil population level is high, the accumulated damage by several individuals can lead to serious damage and death of insecticide-treated seedlings. A sand coating prevents pine weevils from biting through the covering to feed on the bark, i.e. acting as a physical barrier in the stem (Nordlander et al., 2009). Without a harmful effect on seedlings' future development, it is possible only to coat about 60% of the lower part of the stem with sand (Nordlander et al., 2009). Pine weevils can therefore still eat the upper part of the stem, but damage in that part kills the seedling less often. Neither insecticides nor Conniflex coating can therefore completely prevent feeding damage, but they can prevent serious damage.

The mortality of unprotected Norway spruce seedlings planted in mounds was 24%. This led to a stand with 1300 living seedlings per ha two years after planting, which requires the repair planting or supplement from naturally regenerated seedlings to have a full stocked stand. Mounding alone therefore did not give sufficient protection against pine weevil. Previously, the protection effect of MSP has been better: the mortality of unprotected seedlings planted in mineral soil was 7% in central Sweden in the study of Nordlander et al. (2011) and 10% in central Finland in the study of Luoranen et al. (2017). In the synthesis report of Sikström et al., 2020 in nemoboreal and boreal conditions in Nordic countries, the mean survival of seedlings protected against pine weevil (any kind of protection treatment) was more than 80%, and when seedlings were planted in prepared soil without seedling protection, survival was 20 percentage units lower.

In undisturbed soil, the risk of damage and mortality caused by pine weevil was high, especially if seedlings were unprotected but even with both physical Conniflex coating or insecticide treatment. In our study, the damage caused by pine weevils and the mortality of seedlings planted in undisturbed soil was about the same level as it was in the studies done in southern Scandinavia (e.g. Petersson and Örlander, 2003) and much higher than observed in central Sweden and central Finland in the last 20 years. In the study of Nordlander et al. (2011), only 26% of unprotected seedlings planted in undisturbed humus and only 7% in mineral soil were damaged and killed. In the study of Heiskanen et al. (2013), pine weevils damaged 31–56% of insecticide-treated seedlings planted in undisturbed soil and 0–5% in spot mounds at two sites in central Finland conditions, and the corresponding values for mortality were 8.5–27.5 and 0–0.7%. In our study, seedlings were

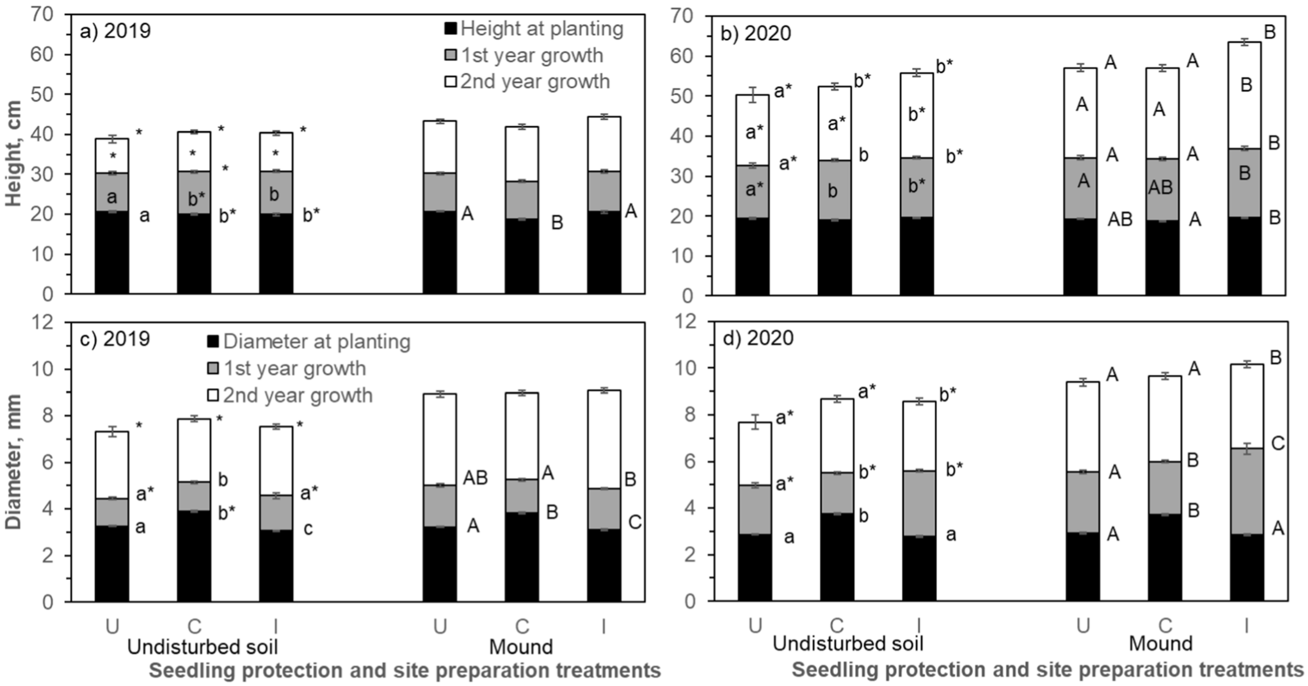

Fig. 6. a–b) Height and c–d) stem base diameter of Norway spruce seedlings that were not protected against pine weevil (U), were sand-coated with Conniflex (C) or sprayed with insecticide (I) and planted in undisturbed soil or in mounds in southeast Finland in a), c) 2019 and b, d) 2020. Each figure presents average values of three regeneration sites and 100 (due to the mortality numbers of seedlings reduced in later years) planted seedlings in each treatment combination within a site. Lowercase letters indicate statistically significant differences in height or diameter, or height growth between seedling protection treatments in undisturbed soil and uppercase letters in mounds. Asterisks indicate differences between site preparation treatments within a seedling protection treatment. Letters inside bars indicate differences in height growth, and those next to bars are for total height or diameter at planting or the end of each growing season. If there were no differences, letters are not presented.

planted in fresh clear-cuts, which may have increased the damage levels, although Heiskanen et al. (2013) also planted seedlings in fresh sites. Our study was carried out in the southern part of Finland, where pine weevil populations have been greater than in central and northern Finland and Sweden (Långström, 1982). The previously mentioned studies were carried out about ten years ago. It has been predicted that the warming climate will increase the probability of pine weevil damage (Venäläinen et al., 2020), and the effect of climate change, i.e. increased temperature sums during growing seasons, may also have already increased the pine weevil population and damage risk levels compared to the previous studies.

Different insecticides were accidentally used in different years. Based on the serious and total feeding damage levels in unprepared soil, the protection effects of acetamiprid and lambda-cyhalotrin was about the same. We did not find any studies where these two ingredients have been compared.

The mounding quality of the CAM was quite good: more than 1,700 acceptable mounds per hectare (target 1800 mounds per ha) and more than 80% of mounds were covered by mineral soil or only a thin humus layer. The results are better than in the previous study of Saksa et al. (2018), in which only 1,398 acceptable mounds per hectare were found after continuously advancing mounding. Our study's good result may explain the collecting (2019) and drying (2020) of logging residues before mounding. In the study of Saksa et al. (2018), there were more mounds per hectare when residues were collected or dried compared to sites with fresh residues. Collection of logging residues in 2019 may also explain why most mounds in 2019 were mineral soil mounds, either pure or covered by a thin humus layer, while in 2020, when residues were not collected, there were some mounds with a humus layer. One reason for heavier feeding in mounds in 2020 could be the slightly poorer quality of mounds. However, there were differences between sites, with mound quality being better in Kouvola than at the other sites planted in 2020, but the mortality of seedlings was higher at all sites in 2020 than in 2019. Therefore, some other factors than mound quality causing the differences between years are more probable.

In our study, most pine weevil feeding damage occurred in the first season, but minor feeding damage was still observed in the second growing season. The protection effect of insecticides diminished after the first growing season (Viiri et al., 2007). The effect of Conniflex coating may also have declined because the sand coating of Conniflex was also stripped from some dead seedlings during the two-year study period (personal observation of J. Luoranen in the laboratory checking of a dead seedling). It is important that the measure protects seedlings just after planting, during the establishment phase when seedlings are rooting. Well-rooted seedlings can survive better from the damage than poorly rooted ones (Wallertz et al., 2016). In the study of Wallertz and Peterrson (2011), some seedlings were first protected with physical barriers at planting, and they were then removed after a few weeks. They observed the same proportion of damage but lower mortality in seedlings protected during the early summer compared to unprotected seedlings. Correspondingly, in our study, when seedlings were probably well rooted in the first season, second-year feeding did not kill the seedlings.

Zas et al. (2017) observed differences in resistance against pine weevil between Norway spruce seedlings originating in Sweden, and one reason for the different responses between years may be the seedling origin differences between years. However, we believe that the most likely reason is weather conditions, because pine weevil feeding pressure in the experimental sites was higher with an increased temperature sum during the planting season. This is in line with previous knowledge. Warmer and longer growing seasons increase the number of pine weevils because of the enhancement of the reproduction potential, the size of weevils (Inward et al., 2012), and the lengthening of the period when pine weevils can eat seedlings. Nordlander et al. (2017) have shown that pine weevil feeding damage can be predicted by the temperature sum in northern Sweden conditions. They predicted feeding damage in different parts of northern Sweden, from the coast to mountains. In our study, the temperature sum effect can be seen even in quite a small geographical area, and this also explains the year-to-year variation. The significant effect of temperature sum on the size of the pine weevil population means that populations are probably increasing with the warming climate, and they can cause serious damage in more northern areas of the Nordic countries (Nordlander et al., 2017; Venäläinen et al., 2020). Thus far, the risk of pine weevil damage has been minimal, and seedlings are planted in prepared soil without any seedling protection before planting in most northern regions (Lapland). In future, protection measures will probably be needed in a wider geographical range.

The other factor that usually explains the feeding pressure is the number of growing seasons between a clear-cut and planting: the more growing seasons there are, the lower the pine weevil feeding pressure (Luoranen et al., 2017; Nordlander et al., 2011, 2017; Örlander and Nilsson, 1999). In our study, all the sites, apart from one in Ruotsinpyhtää located near the coast, were fresh, without any growing seasons between clear-cutting and planting, and differences in feeding pressure could not have been caused by the age of the clear-cut.

There was a trend for seedlings planted in mounds to grow more than seedlings planted in the undisturbed soil, and insecticide-treated seedlings slightly more than seedlings in other protection treatments. These results correspond to the previous results of e.g. Petersson and Örlander (2003) and Heiskanen et al. (2013). Similarly, the reduced growth of unprotected seedlings compared to protected ones corresponds to the results of Nordlander et al. (2011) and Luoranen et al. (2017). The trend that Conniflex-coated seedlings grew less than insecticide-treated ones contradicts those of Nordlander et al. (2011), who did not find any differences in height growth between insecticide-treated and Conniflex-coated seedlings. In our study, seedlings for different treatments were packed in separate boxes, and there were slight differences in seedling size at the time of planting, and the initial size of seedlings was taken into account in analysis. Greater initial diameter of Conniflex-coated seedlings was most probably caused by sand over the stem. However, the sand coating had largely dropped off during the two growing seasons, so the diameters measured at the end of the experiment were more comparable between treatments.

Increased growth of insecticide-treated seedlings either in diameter or height was observed especially in latter establishment year. Nordlander et al. (2011) speculated that increased growth of insecticide treated seedlings might be caused by their protection effect against roots (*Hylastes* spp.) or needles feeding insects. We did not find any damage caused by other insects to the seedlings in the laboratory analysis of dead seedlings and this kind of effect is possible but unlikely. The effects of seedling protection and site preparation treatments on growth may become clearer in subsequent years (Luoranen et al., 2017), and poor growth in the early years affects seedling growth, even up to ten years after planting (Johansson et al., 2013).

Drought was the main cause of damage for weakened seedlings in 2019. At the time of planting in that year, the weather was exceptionally dry, which may have affected the vitality of planted seedlings, independent of seedling protection treatment. Our results correspond to the results of Norlander et al. (2009, 2011), and we found no differences in drought damage between insecticide- and Conniflex-treated seedlings. Previously, Petersson et al. (2004) found a higher level of damage caused by other factors when seedlings were protected by other physical barriers.

Rainy weather in the middle of the summer of 2020 increased the probability of damage caused by excessive water in the planting point, especially in undisturbed soil. Our result therefore confirms the well-known fact that a higher seedling position in mounds protects seedlings from an excess of water.

During the winter of 2020–2021, there was vole damage at some sites. In our study, the probability of vole damage seemed to be lower in undisturbed soil in unprotected seedlings than in mounds or in protected seedlings. The mortality of seedlings was already high in undisturbed soil in the first growing season, and there were no longer any seedlings to eat. Our results are therefore unreliable and cannot be used to compare different treatments. Previously, Huitu et al. (2013) have speculated that mounding can protect seedlings from vole damage, but Heiskanen et al. (2013) found no differences between seedlings planted in spot mounds and undisturbed soil. There was more vole damage in Kotka than at other sites planted in 2020. In Kotka, the soil texture type was fine, whereas it was medium-coarse at other sites. Previously, Luoranen and Viiri (2012) also observed more vole damage in fine soil than in medium-coarse soils.

5. Conclusions

The risk of pine weevil feeding damage is high without any seedling protection measure. To achieve a sufficient level of protection, insecticide-treated or Conniflex-coated seedlings had to be planted in prepared soil with mineral soil cover around Norway spruce seedlings, and the quality of mounds made by CAM was good enough to attain sufficient planting success. Conniflex coating gave the same level of protection against serious pine weevil damage as insecticide treatment for seedlings planted in mounds. In addition to better survival, planting in mounds already increased seedling growth in the first years after planting.

Role of funding source

The work was undertaken in cooperation with Sveaskog (Svenska Skogsplantor), BCC, and Tornator Oyj. Svenska Skogsplantor raised the seedlings, and the experiments were established at sites owned by Tornator. However, the cooperating companies played no role in the study design, analysis, or data interpretation, in the writing of the report, or in the decision to submit the article for publication.

Funding

This work was supported by the cooperating companies and Natural Resources Institute Finland (Project 41007-00167501).

CRediT authorship contribution statement

Jaana Luoranen: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tiina Laine:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Resources, Writing – review & editing. **Timo Saksa:** Methodology, 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.

Acknowledgements

We would like to thank Sveaskog, BCC, and Tornator Oyj for their collaboration in the implementation of the research, and Juhani Salonen, Ilkka Taponen, Auli Lehtinen, and Aulis Leppänen for the establishment and measurements of the experiments. Acolad revised the English.

References

Cajander, A., 1949. Forest types and their significance. Acta For. Fenn. 56 (5) https://doi.org/10.14214/aff.7396.

European Commission 2020. Report from the Commission to the European Parliament and the Council. On the experience gained by Member States on the implementation of national targets established in their National Action Plans and on progress in the implementation of Directive 2009/128/EC on the sustainable use of pesticides. https://data.consilium.europa.eu/doc/document/ST-8238-2020-INIT/en/pdf.

Giurca, A., von Stedingk, H., 2014. FSC Pesticides Policy in Sweden. https://se.fsc.org/preview.fsc-pesticides-policy-in-sweden.a-763.pdf.

Hallongren, H., Laine, T., Rantala, J., Saarinen, V.-M., Strandström, M., Hämäläinen, J., Poikela, A., 2014. Competitiveness of mechanized tree planting in Finland. Scand. J. For. Res. 29 (2), 144–151. https://doi.org/10.1080/02827581.2014.881542.

Hardy, C., Sayyed, I., Leslie, A.D., Dittrich, A.D.K., 2020. Effectiveness of insecticides, physical barriers and size of planting stock against damage by the pine weevil (*Hylobius abietis*). Crop. Protection 137, 105307. https://doi.org/10.1016/j.cropro.2020.105307.

Heiskanen, J., Viiri, H., 2005. Effects of mounding on damage by the European pine weevil in planted Norway spruce seedlings. Northern J. Appl. For. 22, 154–161. https://doi.org/10.1093/njaf/22.3.154.

Heiskanen, J., Saksa, T., Luoranen, J., 2013. Soil preparation method affects outplanting success of Norway spruce container seedlings on till soils susceptible to frost heave. article id 893 Silva Fenn. vol. 47 no. 1. https://doi.org/10.14214/sf.893.

Huitu, O., Rousi, M., Henttonen, H., 2013. Integration of vole management in boreal silvicultural practices. Pest Manage. 69 (3), 355–361. https://doi.org/10.1002/ps.3264.

Inward, D.J.G., Wainhouse, D., Peace, A., 2012. The effect of temperature on the development and life cycle regulation of the pine weevil *Hylobius abietis* and the potential impacts of climate change. Agric. For. Entomol. 14, 348–357. https://doi.org/10.1111/j.1461-9563.2012.00575.x.

Johansson, K., Nilsson, U., Orlander, G., 2013. A comparison of long-term effects of scarification methods on the establishment of Norway spruce. Forestry 86 (1), 91–98. https://doi.org/10.1093/forestry/cps062.

Lalík, M., Galko, J., Kunca, A., Nikolov, C., Rell, S., Kunca, A., Modlinger, R., Holuša, J., 2020. Non-pesticide alternatives for reducing feeding damage caused by the large pine weevil (*Hylobius abietis* L.). Ann. Appl. Biol. 177, 132–142. https://doi.org/10.1111/aab.12594.

Lalík, M., Galko, J., Kunca, A., Nikolov, C., Rell, S., Zúbrik, M., Dubec, M., Vakula, J., Gubka, A., Leontovyč, R., Longauerová, V., Konôpka, B., Holuša, J., 2021. Ecology, management and damage by the large pine weevil (*Hylobius abietis*) (Coleoptera: Curculionidae) in coniferous forests within Europe. Central Eur. For. J. 67, 91–107. https://doi.org/10.2478/forj-2021-0005.

Långström, B., 1982. Abundance and seasonal activity of adult Hylobius-weevils in reforestation areas during first years following final felling. Communicationes Instituti Forestalis Fenniae 106, 23 p.

Långström, B., Day, K.R., 2004. Damage, control and management of weevil pests, especially Hylobius abietis. In: Lieutier, F., Day, K.R., Battisti, A., Grégoire, J.-C., Evans, H.F., Bark and Wood Boring Insects in Living Trees in Europe, a Synthesis. pp 415–444.

Luoranen, J., Viiri, H., 2012. Soil preparation reduces pine weevil (*Hylobius abietis* L.) damage on both peatland and mineral soil sites one year after planting. article id 71 Silva Fennica vol. 46 no. 1. https://doi.org/10.14214/sf.71.

Luoranen, J., Viiri, H., 2021. Comparison of the planting success and risks of pine weevil damage on mineral soil and drained peatland sites three years after planting. article id 10528 Silva Fennica vol. 55 no. 4. https://doi.org/10.14214/sf.10528.

Luoranen, J., Viiri, H., Sianoja, M., Poteri, M., Lappi, J., 2017. Predicting pine weevil risk: Effects of site, planting spot and seedling level factors on weevil feeding and mortality of Norway spruce seedlings. For. Ecol. Manage. 389, 260–271. https://doi.org/10.1016/j.forece.2017.01.006.

Moore, R., Willoughby, I.H., Moffat, A.J., Forster, J., 2021. Acetamiprid, chlorantraniliprole, and in some situations the physical barriers MultiPro® or Kvaae® wax, can be alternatives to traditional synthetic pyrethroid insecticides for the protection of young conifers from damage by the large pine weevil Hylobius abietis L. Scand. J. For. Res. 36 (4), 230–248. https://doi.org/10.1080/02827581.2021.1906313.

Nordlander, G., Nordenhem, H., Hellqvist, C., 2009. A flexible sand coating (Conniflex) for the protection of conifer seedlings against damage by the pine weevil *Hylobius abietis*. Agric. For. Entomol. 11, 91–100. https://doi.org/10.1111/j.1461-9563.2008.00413.x.

Nordlander, G., Hellqvist, C., Johansson, K., Nordenhem, H., 2011. Regeneration of European boreal forests: Effectiveness of measures against seedling mortality caused by the pine weevil *Hylobius abietis*. For. Ecol. Manage. 262 (12), 2354–2363. https://doi.org/10.1016/j.foreco.2011.08.033.

Nordlander, G., Mason, E., Hjelm, K., Nordenhem, H., Hellqvist, C., 2017. Influence of climate and forest management on damage risk by the pine weevil *Hylobius abietis* in northern Sweden. Silva Fenn. 51 (5) https://doi.org/10.14214/sf.7751.

Örlander, G., Nilsson, U., 1999. Effect of reforestation methods on pine weevil (*Hylobius abietis*) damage and seedling survival. Scand. J. For. Res. 14 (4), 341–354. https://doi.org/10.1080/02827589950152665.

Petersson, M., Örlander, G., 2003. Effectiveness of combinations of shelterwood, scarification, and feeding barriers to reduce pine weevil damage. Can. J. For. Res. 33 (1), 64–73. https://doi.org/10.1139/x02-156.

Petersson, M., Örlander, G., Nilsson, U., 2004. Feeding barriers to reduce damage by pine weevil (*Hylobius abietis*). Scand. J. For. Res. 19 (1), 48–59. https://doi.org/10.1080/02827580310019554.

Petersson, M., Örlander, G., Nordlander, G., 2005. Soil features affecting damage to conifer seedlings by the pine weevil *Hylobius abietis*. Forestry 78, 83–92. https://doi.org/10.1093/forestry/cpi008.

Pikkarainen, L., Luoranen, J., Kilpeläinen, A., Oijala, T., Peltola, H., 2020. Comparison of planting success in one-year-old spring, summer and autumn plantings of Norway spruce and Scots pine under boreal conditions. Silva Fennica 54 (1), 12. https://doi.org/10.14214/sf.10243 article id 10243.

Piri, T., Viiri, H., Hyvönen, J., 2020. Does stump removal reduce pine weevil and other damage in Norway spruce regeneration? – Results of a 12-year monitoring period. Forest Ecology and Management 465, article id 118098. https://doi.org/10.1016/j.foreco.2020.118098.

Pitkänen, A., Kouki, J., Viiri, H., Martikainen, P., 2008. Effects of controlled forest burning and intensity of timber harvesting on the occurrence of pine weevils, *Hylobius* spp., in regeneration areas. For. Ecol. Manage. 255 (3-4), 522–529. https://doi.org/10.1016/j.foreco.2007.09.024.

Rahman, A., Viiri, H., Pelkonen, P., Khanam, T., 2015. Have stump piles any effect on the pine weevil (*Hylobius abietis* L.) incidence and seedling damage? Glob. Ecol. Conserv. 3, 424–432. https://doi.org/10.1016/j.gecco.2015.01.012.

Ramantswana, M., Guerra, S.P.S., Ersson, B.T., 2020. Advances in the mechanization of regenerating plantation forests: a review. Curr. For. Rep. 6 (2), 143–158. https://doi.org/10.1007/s40725-020-00114-7.

Rose, D., Leather, S.R., Matthews, G.A., 2005. Recognition and avoidance of insecticide-treated Scots Pine (*Pinus sylvestris*) by *Hylobius abietis* (Coleoptera: Curculionidae): implications for pest management strategies. Agric. For. Entomol. 7 (3), 187–191. https://doi.org/10.1111/j.1461-9555.2005.00249.x.

Rose, D., Matthews, G.A., Leather, S.R., 2006. Sub-lethal responses of the large pine weevil, *Hylobius abietis*, to the pyrethroid insecticide lambda-cyhalothrin. Physiol. Entomol. 31 (4), 316–327. https://doi.org/10.1111/j.1365-3032.2006.00525.x.

Saksa, T., Miina, J., Haatainen, H., Kärkkäinen, K., 2018. Quality of spot mounding performed by continuously advancing mounders. Silva Fenn. 52 (2) https://doi.org/10.14214/sf.9933.

Sikström, U., Hjelm, K., Holt Hanssen, K., Saksa, T., Wallertz, K., 2020. Influence of mechanical site preparation on regeneration success of planted conifers in clearcuts in Fennoscandia – a review. Silva Fenn. 54 (2) https://doi.org/10.14214/sf.10172.

Skogsstyrelsen, 2021. Levererade skogsplantor 2020 (Forest seedlings delivered for planting 2020). Sveriges Officiella Statistik, Statistiska Meddelanden JO0313 SM 2001. https://eur03.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.skogsstyrelsen.se%2Fglobalassets%2Fstatistik%2Fstatistiska-meddelanden%2Fsm-levererade-skogsplantor-2020.pdf&data=04%7C01%7Cjaana.luoranen%40luke.fi%7C31ea09efd5ec42f960fb08da001ecd4b%7C7c14dfa4c0fc47259f0476a443deb095%7C0%7C0%7C637822430151656479%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C3000&sdata=4nljtZ9orsq8hnRwqdU3XNLXBUqzUpnZZD%2BWBzf8als%3D&reserved=0 [Accessed Mar 10, 2022].

Tonteri, T., Hotanen, J.-P., Kuusipalo, J., 1990. The Finnish forest site type approach: ordination and classification studies of mesic forest sites in southern Finland. Vegetatio 87 (1), 85–98. https://doi.org/10.1007/BF00045658.

Tukes. KemiDigi. Plant protection products register. https://www.kemidigi.fi/kasvinsuojeluainerekisteri/haku [Accessed Jan 19, 2022].

Uotila, K., Rantala, J., Saksa, T., Harstela, P., 2010. Effect of soil preparation method on economic result of Norway spruce regeneration chain. article id 146 Silva Fennica 44 (3). https://doi.org/10.14214/sf.146.

Venäläinen, A., Lehtonen, I., Laapas, M., Ruosteenoja, K., Tikkanen, O.-P., Viiri, H., Ikonen, V.-P., Peltola, H., 2020. Climate change induces multiple risks to boreal forests and forestry in Finland: a literature review. Glob. Change Biol. 26 (8), 4178–4196. https://doi.org/10.1111/gcb.v26.810.1111/gcb.15183.

Viiri, H., Tuomainen, A., Tervo, L., 2007. Persistence of deltamethrin against *Hylobius abietis* on Norway spruce seedlings. Scand. J. For. Res. 22 (2), 128–135. https://doi.org/10.1080/02827580701224113.

Viro, P., 1952. Kivisyyden määrittämisestä. Summary: on the determination of stoniness. Comm. Inst. For. Fenn. 40, 1–23.

Wallertz, K., Peterrson, M., 2011. Pine weevil damage to Norway spruce seedlings: effects of nutrient-loading, soil inversion and physical protection during seedling establishment. Agric. For. Entomol. 13, 413–421. https://doi.org/10.1111/j.1461-9563.2011.00536.x.

Wallertz, K., Hansen, K.H., Hjelm, K., Fløistad, I.S., 2016. Effect of planting time on pine weevil (*Hylobius abietis*) damage to Norway spruce seedlings. Scand. For. Res. 31, 262–270. https://doi.org/10.1080/02827581.2015.1125523.

Wallertz, K., Björklund, N., Hjelm, K., Petersson, M., Sundblad, L.-G., 2018. Comparison of different site preparation techniques: quality of planting spots, seedlings growth and pine weevil feeding damage. New Forests 49, 705–722. https://doi.org/10.1007/s11056-018-9634-8.

Zas, R., Björklund, N., Sampedro, L., Hellqvist, C., Karlsson, B., Jansson, S., Nordlander, G., 2017. Genetic variation in resistance of Norway spruce seedlings to damage by the pine weevil *Hylobius abietis*. Tree Genet. Genom 13, 12 p. https://doi.org/10.1007/s11295-017-1193-1.