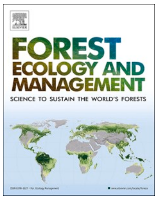
Forest Ecology and Management 566 (2024) 122053

Contents lists available at ScienceDirect

Forest Ecology and Management

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



Effect of drought and pine weevil damage on mechanically protected Norway spruce seedlings

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ARTICLE INFO

Keywords:
Seedling establishment
Drought
Mechanical protection
Regeneration
Hylobius abietis
Picea abies

ABSTRACT

Pine weevils (*Hylobius abietis* L.) pose a significant threat to conifer seedlings by feeding on the bark, thus damaging or killing seedlings. Historically, insecticides were used to suppress such damage, but were slowly phased out in Sweden due to environmental and health concerns. This study aimed to assess field performance of an alternative protection method: mechanical coating applied to the stem of planted Norway spruce (*Picea abies*) seedlings. Field trials were conducted on 14 sites in south Sweden, using four different types of mechanical protection (Cambiguard, Conniflex, Ekovax, Hylonox), standard insecticide (Merit Forest), and ambient control. Seven sites were established in the drought year of 2018 and seven more in 2019. This allowed for additional investigation of the effect of drought on seedling establishment and possible interaction with pine weevil damage. Seedlings were surveyed for survival and height after the first, second and fourth growing season. Results show drought as the main source of damage for seedlings planted in 2018, with no significant effect of insecticide or mechanical protection on survival of seedlings. However, mechanical protections performed equally well as insecticide and positively increased survival by 30 %, compared to untreated, four growing seasons after planting for seedlings planted in 2019. Seedling height was not significantly affected by planting year or any of the treatments, suggesting no adverse effects of coating application. However, a synergistic effect between pine weevil damage and drought was observed, where even low levels of pine weevil damage resulted in high mortality for seedlings planted in 2018, compared to those planted in 2019. Additionally, for seedlings planted in 2019, damage to the top of the stem did not result in significant mortality, until high damage levels were reached (40 % and above). The opposite was found for seedlings planted in a 2018 drought year, where both damage to the top and the bottom of the stem followed a linear response. In conclusion, we show that investigated mechanical protection methods can be considered a viable replacement for insecticides, but our results also highlight the importance of considering multiple environmental stressors such as drought and pest damage on seedling establishment.

1. Introduction

Pine weevils (*Hylobius abietis* L.) are a considerable source of damage to conifer seedlings in large parts of Europe (Day and Leather, 1997). They feed on the bark, eventually girdling the seedling and preventing the transport of water, which may lead to mortality. The problem is widespread in southern Sweden (Örlander and Nilsson, 1999; von Sydow, 1997; Wallertz et al., 2016) and southern Norway (Holt Hanssen and Sundheim Fløistad, 2018) where mortality of up to 60 % has been reported for unprotected seedlings. Since around 440 million seedlings are planted in Sweden annually (Skogsstyrelsen, 2024), such losses represent a significant economic setback.

Pest damage to conifer seedlings, including that by pine weevils, has historically been suppressed using chemical insecticides (Giurca and von Stedingk, 2014). Over the past few decades however, insecticides have been largely banned for use in forestry due to negative effects both on natural environment and on work environment (Giurca and von Stedingk, 2014). Nevertheless, the problem of pine weevil damage remains, and novel methods of protection are urgently needed. In recent years, mechanical protection by coating the lower part of the seedlings' stem has emerged as an alternative to chemical solutions (Nordlander et al., 2011, 2009). However, there are still many unanswered questions to be

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https://doi.org/10.1016/j.foreco.2024.122053
Received 26 March 2024; Received in revised form 31 May 2024; Accepted 1 June 2024

resolved regarding the use of these alternatives. One consideration is that mechanical coatings would constrict the stem or cover the needles of the seedlings, thus limiting growth through reduced photosynthesis, which has been shown in a greenhouse experiment (Sjöström, 2020). Their persistence in field conditions is another factor, as pine weevil exhibit an established pattern of seasonal damage over a longer period of time. The majority of pine weevil damage to seedlings occurs in the first three years after clearcutting (von Sydow, 1997; Wallertz et al., 2016), and coatings would thus have to be long lasting, covering a period of several years.

Further, pine weevils, among other insects, are not the only factor affecting seedling survival and growth (Bergquist and Örlander, 1998; Grossnickle, 2012; Jobidon et al., 2003; Langvall et al., 2001; Wallertz et al., 2018). Environmental factors such as microclimate, planting spot and weather patterns play an important role in seedling establishment, which has been widely studied over the past decades (Grossnickle, 2012; Häggström et al., 2021; Holmström et al., 2019; Nilsson and Örlander, 1995; Nordin et al., 2023; Sikström et al., 2020; Wallertz et al., 2018). With a changing climate (Christensen et al., 2001; Christensen and Christensen, 2007; May, 2008), some parts of this collective knowledge should be reconsidered, as growing conditions may have changed from when many of these silvicultural concepts were first established. Several climate models predict a warmer climate with increasingly long and severe droughts in the future, especially summers, which will surely affect forests as well (Allen et al., 2010; Krikken et al., 2019; Lindner et al., 2010; Reich and Oleksyn, 2008). The consequences of these altered growing circumstances are still poorly understood, as are our tools to adapt to them. A recent case of such a drought year was the summer of 2018, which has been widely reported as having detrimental impact on seedling survival and growth (Beloiu Schwenke et al., 2023; Lindroth et al., 2021; Schuldt et al., 2020; Sturm et al., 2022).

In multi-damage scenarios, like seedling establishment on clearcuts, interaction between different damage factors should be considered. An example of a well-studied system is the effect of drought on spruce bark beetle (*Ips typographus*) damage to mature trees (Hart et al., 2017; Netherer et al., 2022, 2021, 2019; Williams et al., 2013). Research shows that spruce bark beetles actively select trees that have previously been drought stressed, leading to great outbreaks of insect damage following a drought (Hart et al., 2017; Netherer et al., 2019). The mechanism behind selection are the weaker tree defenses, such as reduced production of monoterpenes and resin, as drought puts an additional stress on trees (Kaiser et al., 2013; Netherer et al., 2022). Such multi damage responses have been less studied in pine weevils, with most studies utilizing an artificial or semi-artificial experimental setup (Lavallée et al., 1994; Rasheed et al., 2020; Selander and Immonen, 1992; Suárez-Vidal et al., 2019). For example, Selander & Immonen (1992) reported that pine weevils selected drought stressed seedlings when enclosed in cages for 20 hours. Similarly, Suarez-Vidal et al. (2019) reported 75 % higher pine weevil damage on moderately drought stressed seedlings when enclosed together for 4 days, compared to pine weevil damage on both low and high drought stressed seedlings. However, it is also important to consider that pine weevils themselves are affected by drought and other environmental conditions. While greenhouse experiments may focus on the scale of responses to pine weevil damage, overall survival of seedlings in field conditions is still of value, as it may directly contribute to forest management decisions.

Even though many studies have been done on pine weevils with the aim of understanding and reducing the problem (Barredo et al., 2015; Nordlander et al., 2017; Örlander et al., 1997; Petersson et al., 2004; von Sydow, 1997; Wallertz et al., 2016, 2014; Zas et al., 2020), some knowledge gaps remain. For example, field observations have shown that if a seedling is damaged and girdled underneath the lowest branch, it will most likely die. However, if only the upper portion of the stem is damaged, the seedling has the potential to survive and maintain adequate transportation of water and nutrients despite the injury. This type of damage would correspond to damage from ungulate browsing, where seedlings can tolerate some damage to shoots, but still survive (Kupferschmid, 2017). However, to our knowledge, the effect of location of pine weevil damage on seedling survival has not yet been investigated in a replicated field trial. Additionally, only a few studies have examined multi-damage scenarios involving pine weevils (Lavallée et al., 1994; Rasheed et al., 2020; Selander and Immonen, 1992; Suárez-Vidal et al., 2019).

The aim of this study was to assess performance of mechanical pine weevil protection on survival and growth of planted conifer seedlings in field conditions. Owing to chance drought conditions at the start of the experiment, we expanded the aim to include assessing the impact of drought on seedlings as well as interaction between drought and pine weevil damage. We hypothesized that mechanical protection would perform equally well as insecticide, but better than untreated control. Further, we hypothesized that the damage between the two factors is synergistic, where the combined stress of drought and pine weevil damage increases overall mortality more than the sum of its parts. Additionally, we hypothesized that the damage to the bottom of the stem would have a higher impact on overall seedling survival compared to damage to the top of the stem.

2. Methods

To test field performance of mechanical protection on seedlings, seven study sites were established in south Sweden in 2018, with seven more sites established in 2019 (Fig. 1). Following a standard clearcutting procedure, 180 Norway spruce (*Picea abies*) seedlings were planted on each site, striving to plant in mineral soil. Containerized seedlings from the same nursery and batch were coated with mechanical protections, which were applied to the stem of the seedling before leaving the nursery (Fig. 2). In total four different mechanical protections were tested: Conniflex (Svenska Skogsplantor), Cambiguard (Södra Forest), Ekovax (Norsk Wax AS) and Hylonox (Organox AB), standard commercially available insecticide (Merit Forest, Bayer AB) and untreated. Each treatment was replicated 30 times in one large block (approximately 30 ×30 m) on each site, sufficiently away from the surrounding forest to avoid edge effect. Replication was systematic using Latin squares, where each treatment occurred once in each row and each column of a block.

Seedlings on each site were surveyed for survival, height, and damage for four years: immediately after planting, after one growing season, after two growing seasons, and after four growing seasons. Survival was assessed visually by characterizing seedlings as vigorous and with green needles, while height (in mm) was measured from soil surface to and including top shoot. Whenever damage was recorded, type and severity of damage was noted, whenever possible (1 = slight damage – less importance, 2 = damaged – may affect growth, 3 = severely damaged – will affect growth, 4 = probably lethal damage). If pine weevil damage was found, area of removed bark in percentage classes and location of damage (top or bottom of stem) were noted. For mechanically protected seedlings bottom was the coated area, while top was considered above the coating. For insecticide treated and untreated control, bottom was 10 cm measured from the soil, while top was above the 10 cm mark. Additionally, persistence of coating was assessed visually after the first and second growing seasons and sorted into following classes: intact (entire coating left), coating partially removed (pine weevil can damage the seedling), coating significantly removed (pine weevil can girdle and kill the seedling), no coating left.

Environmental variables, especially relating to drought conditions, were collected from SMHI open database (Swedish Meteorological and Hydrological Institute) (SMHI, 2024). These included temperature and relative humidity used to calculate vapor pressure deficit (VPD) for our sites. Additionally, we used temperature data to establish growing seasons for each site, i.e., when daily mean temperatures reached above 5 °C, roughly April-November. For each site, data from the closest weather observation station was selected, resulting in mean distance to

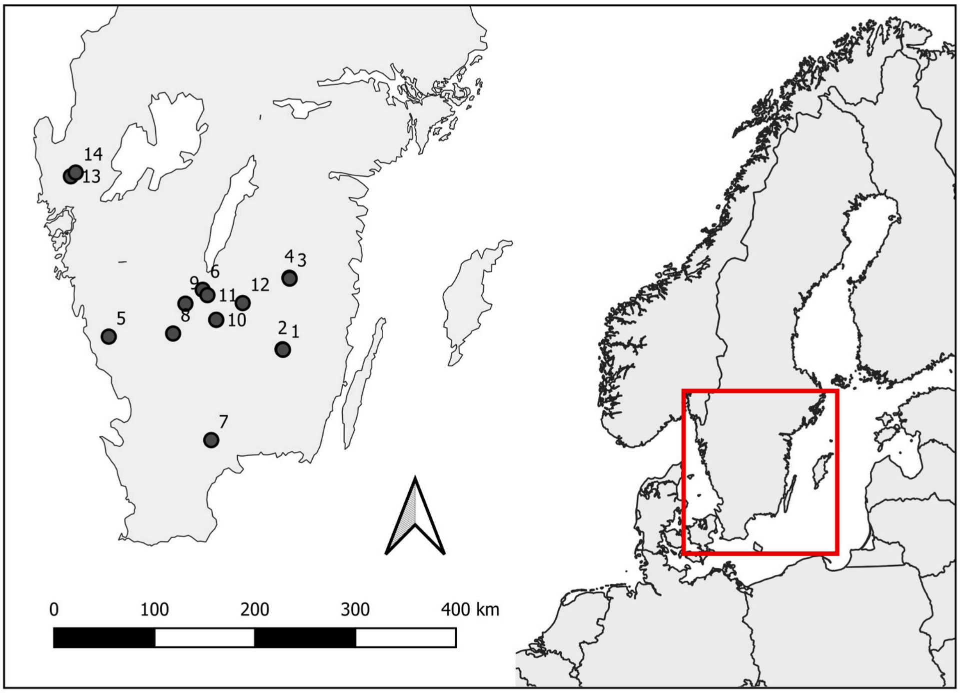

Fig. 1. Map of the 14 study sites between latitudes of 58° and 56°. The red rectangle indicates the zoomed view on the left. Scale indicates distances of the left map.

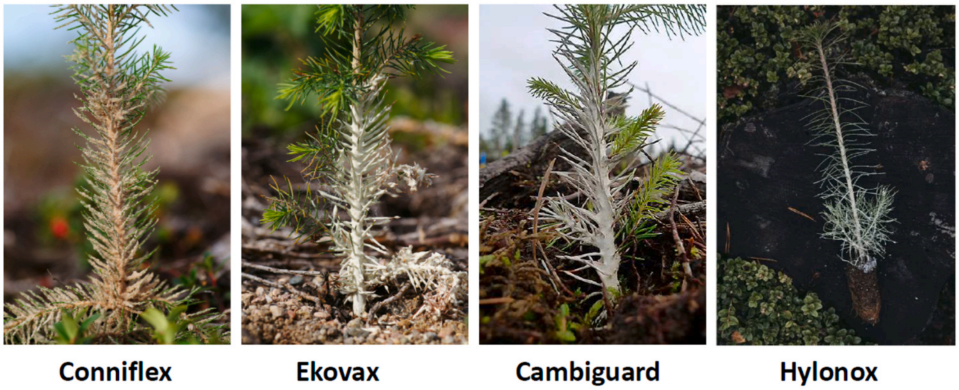

Fig. 2. Pictures of the mechanical protection coatings used in the study (photos: Claes Hellqvist and Karin Hjelm, SLU).

sites of 34.2 km. Some sites were close together and shared weather observation station, resulting in five different stations for sites 1–7 and four stations for sites 8–14. For precipitation data, more stations were available, resulting in an average distance to sites of 15.7 km, where five stations were selected for sites 1–7 and seven for 8–15.

Generalized mixed model in R (R core team, 2024) was used to determine the effect of mechanical protections, persistence of coatings, planting year, pine weevil damage and their interaction on seedling height and survival for each survey. For survival data, generalized binomial mixed model was used instead. To account for the impact of site differences, site was included as a random variable in the final model. To interpret model results, estimated marginal means in the emmeans R package were used (Lenth, 2022). This included contrast analysis, i.e., comparisons between protection methods. For easier interpretation of results, we focused on comparison of mechanical protection methods and insecticide against untreated control.

3. Results

Environmental variable calculations for the sites showed higher maximum and mean VPD (vapor pressure deficit) in 2018 compared to 2019 (Table 1), indicating that seedlings planted in 2018 may have experienced drought conditions. Maximum VPD values were between 3.5 and 4 kPa for 2018, whereas only two sites reached above 3 kPa in 2019. Additionally, mean VPD for 2018 was 50 % higher compared to 2019. There was also a 36 % decrease in precipitation during 2018 compared to 2019 for the same sites. The normal precipitation value for the area (1991–2020) of 513.29 mm indicates that while 2019 was still below average in terms of precipitation with 466.97 mm, 2018 was even lower with 343.26 mm, averaged for all sites.

During the drought conditions of 2018, except for Cambiguard, we found no significant effect of mechanical protection methods, or insecticide on survival of seedlings (Fig. 3). After four seasons in the field, average survival of mechanically treated seedlings was 68 %, while insecticide treated and untreated control had 72 % and 60 % survival, respectively. Only one treatment, Cambiguard, had a positive effect and significantly increased survival of seedlings four seasons after planting to 75 %, compared to untreated control (Table 2). For other treatments, we saw large variations in survival for every survey, especially Conniflex and untreated. Persistence of coating was not found to be a significant

Table 1
List of sites used in the study with vapor pressure deficit (VPD) (kPa) and growing season precipitation (Sum precip.) (mm) values for 2018 and 2019. Sites 1–7 were planted in 2018, while sites 8–14 were planted in 2019. Bold numbers are values during the first growing season when seedlings were planted on those sites. The normal value (1991–2020) of precipitation in the area was 513.29 mm during the growing season, roughly April-November (SMHI, 2024).

		2018			2019		
	Site	**Max VPD**	**Mean VPD**	**Sum precip.**	**Max VPD**	**Mean VPD**	**Sum precip.**
1	Kroksjövägen	**3.51**	**0.59**	**345**	2.73	0.29	347
2	Björnamossvägen	**3.51**	**0.59**	**345**	2.73	0.29	347
3	Norrhult	**3.87**	**0.70**	**351**	3.51	0.57	325
4	Snibben	**3.87**	**0.70**	**351**	3.51	0.57	325
5	Släne	**3.91**	**0.41**	**443**	2.80	0.28	674
6	Månsarp	**3.73**	**0.47**	**235**	3.26	0.36	337
7	Kullaskogen	**3.99**	**0.48**	**241**	3.34	0.36	342
8	Nennesmo	3.63	0.66	293	**2.94**	**0.42**	**483**
9	Lilla Öjhult	3.63	0.66	344	**2.94**	**0.42**	**551**
10	Siggaskog	3.63	0.66	321	**2.94**	**0.42**	**590**
11	Kränsberg	3.73	0.47	342	**3.26**	**0.36**	**474**
12	Margrevehult	3.99	0.63	309	**3.12**	**0.41**	**394**
13	Brattöns gård	3.31	0.48	470	**2.70**	**0.31**	**646**
14	Sanneskogen	3.31	0.48	417	**2.70**	**0.31**	**703**
	Mean value	3.69	0.57	343	3.04	0.38	467

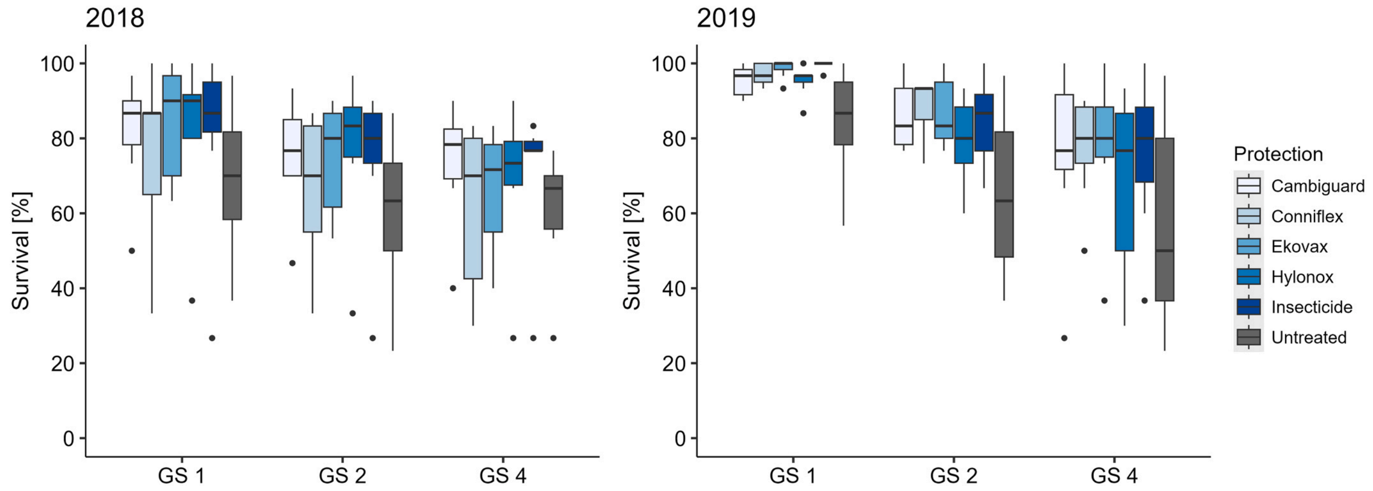

Fig. 3. Boxplots of survival of all seedlings during each survey for each of the treatments and both planting years, 2018 and 2019. GS indicates the growing season after which the survey was performed.

Table 2
Probability of seedling survival after four growing seasons in the field for each treatment method and both planting years. SE stands for standard error. P-values reported are from contrasts comparison in estimated marginal means analysis, where every treatment was compared against untreated. Significant p-values are highlighted in bold.

	2018			2019		
Treatment	**Survival**	**SE**	**p-value**	**Survival**	**SE**	**p-value**
Cambiguard	0.745	0.065	**0.030**	0.809	0.074	**0.0001**
Conniflex	0.622	0.078	0.982	0.828	0.069	**<0.0001**
Ekovax	0.672	0.074	0.562	0.823	0.071	**<0.0001**
Hylonox	0.696	0.070	0.281	0.722	0.096	0.0732
Insecticide	0.715	0.067	0.137	0.809	0.074	**0.0001**
Untreated	0.604	0.079	/	0.600	0.113	/

factor affecting survival in 2018.

In contrast, there was a positive significant effect of mechanical protection methods on survival for seedlings planted in 2019 (Fig. 3). Mechanical protection increased survival of seedlings and performed significantly better when compared to untreated control (Table 2). One exception was Hylonox, where the difference was not significant, but there was still a tendency towards higher survival than untreated control (p=0.073). There was also a lower variation in survival among treatments, especially after the first and second growing season, when mortality of the treated seedlings was relatively low. After four seasons in the field, average survival of mechanically treated seedlings, excluding Hylonox, was 82 %, while insecticide treated and untreated control had 81 % and 60 % survival, respectively. Persistence of coating was found as a significant factor affecting survival in 2019, but only for Hylonox treatment, where 35 % of all Hylonox treated seedlings planted in 2019 had no protection left after two seasons in the field. In comparison, the proportion of seedlings with no protection left for other treatments were 2 %, 5 % and 1 % for Cambiguard, Conniflex, and Ekovax, respectively.

Further, focusing on seedlings with signs of pine weevil damage, a synergistic effect was observed between pine weevil damage and drought, i.e., similar levels of pine weevil damage resulted in higher mortality in the following season for seedlings planted during the drought year of 2018 (Fig. 4A). Already at first level of damage (slight) after the first planting season, seedlings planted in 2018 had an average survival of 49 % after two growing seasons, while those planted in 2019 had a survival of 83 % at the same damage level. Moreover, seedlings planted in 2019 were able to maintain survival above 80 % until severe level of damage was reached, while seedlings planted in 2018 showed a gradual decrease in survival with increasing levels of damage. Additionally, there was greater variability in survival for the seedlings

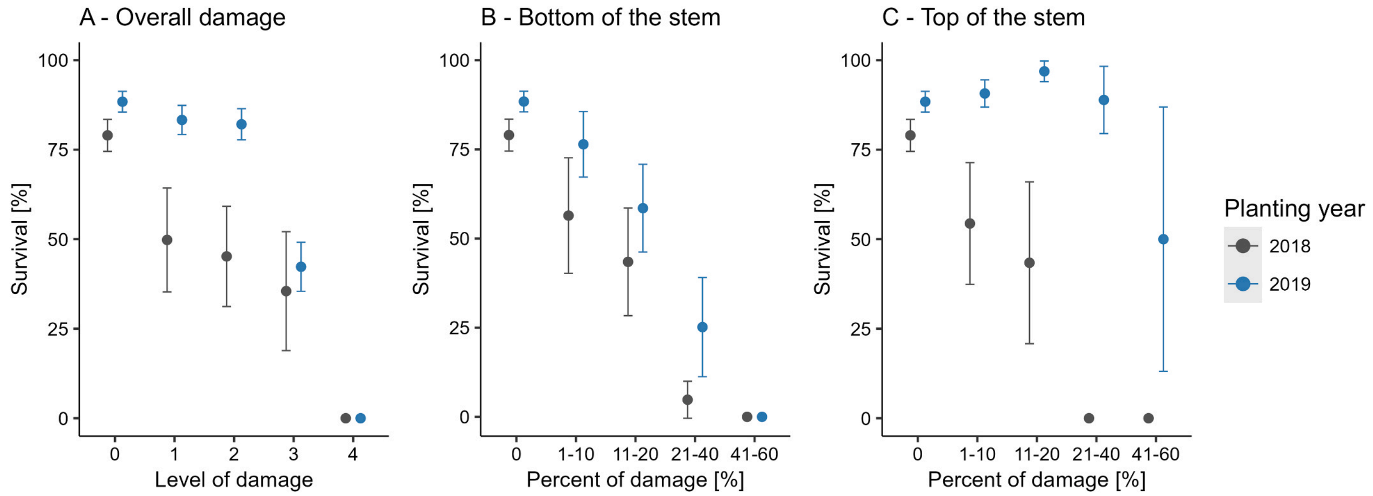

Fig. 4. Mean survival of seedlings after two growing seasons in relation to recorded pine weevil damage after one growing season. Fig. 4A shows survival in different levels of damage to whole seedling (0 – no damage, 1- slight damage, 2- damage will probably affect growth, 3- severe damage will affect growth, 4 – lethal damage). Figs. 4B and 4C show damage only to the bottom or top of the stem, respectively, expressed in percentage classes representing proportion of debarked stem. All seedlings with damage higher than 60 % died. The error bars represent standard errors.

planted in 2018 compared to those planted in 2019.

When looking at damage only to the bottom or top of the stem, similar differences were found between the two planting years (Fig. 4B & 4 C), i.e., similar damage level resulted in higher mortality to seedlings planted in 2018. Damage at the bottom of the stem shows a similar pattern to overall damage, decreasing survival with increasing damage for both planting years. However, when the damage occurred at the top of the stem, until considerable levels of damage were reached (41 % of debarked area and above), seedlings planted in 2019 had a relatively high survival of around 90 %. In comparison, damage at the top of the stem for seedlings planted in 2018 had a gradually decreasing survival, following a similar pattern as damage at the bottom of the stem.

Several damage factors affecting mortality were recorded in our study, which differed between growing seasons and planting years (Fig. 5). The greatest difference between the two planting years was for mortality during the first growing season, which was the drought season for seedlings planted in 2018. This may explain differences in mortality between the two planting years since the source of damage for the majority of damaged seedlings was unknown. While some of the damage factors were easy to identify in field conditions, like areas of pine weevil feeding, drought damage has few specific signs and is thus hard to pinpoint. Therefore, it may be that a significant portion of the unknown damage was due to drought, especially during the growing season of 2018. Moreover, after the first growing season, we recorded lower rates of pine weevil attack for the 2018 seedlings, where 13 % of seedlings showed signs of debarking, while the percentage was 20 % for seedlings planted in 2019. Despite this difference, mortality attributed to pine weevil damage in the first growing season was slightly higher for seedlings planted in 2018, suggesting synergistic effects between drought and pine weevil damage.

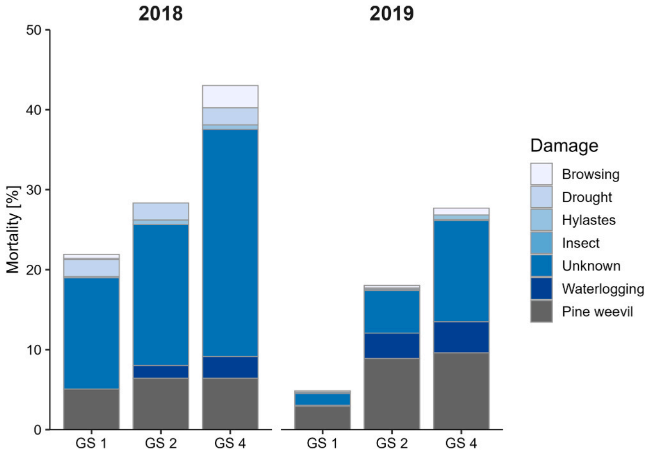

Fig. 5. Sources of mortality of all seedlings irrespective of treatment and damage level. The damage bars are cumulative over the years, presenting total damage. Browsing label refers to browsing damage by ungulates and insect damage label refers to damage by insects other than pine weevil or *Hylastes sp.* GS indicates the growing season after which the survey was performed.

There was no difference in height of seedlings between different treatment methods or planting years (Fig. 6). Additionally, estimated marginal means comparison of different methods revealed no difference in height of all seedlings treated with any mechanical protection method or insecticide compared to untreated control.

4. Discussion

Our analysis of site factors using climate data from SMHI, alongside other studies (Lindroth et al., 2021; Schuldt et al., 2020; Sturm et al., 2022), suggests that the summer of 2018 was indeed an exceptionally dry year, which had a detrimental effect on planted seedlings (Luoranen et al., 2023). This can be observed both in high VPD values as well as in the amount of precipitation during the growing season. While precipitation during the growing season of 2019 was also below average, when considering normal precipitation values for the area, it was closer than that of 2018. The detrimental impact on seedlings is also evident Fig. 5, which shows greater overall mortality in the 2018 dataset. The majority of damage was noted as unknown, which, when coupled with site factor analysis, could suggest drought related damage, otherwise difficult to pinpoint. Additionally the effect of drought is seen in Fig. 3, as the overall lower survival with higher variation for the 2018 dataset, compared to 2019.

Although one of the main goals of the study was to test field performance of mechanical protection methods on Norway spruce seedlings against pine weevil damage, coincidentally, the experiment was started during a year with an exceptional drought (Lindroth et al., 2021; Schuldt et al., 2020). This allowed for additional investigation into performance of protection methods under drought conditions as well as multi-damage scenario of seedling establishment. Our results are in line with other studies showing that drought significantly influences survival of seedlings (Grossnickle, 2012; Luoranen et al., 2023), where additional stress

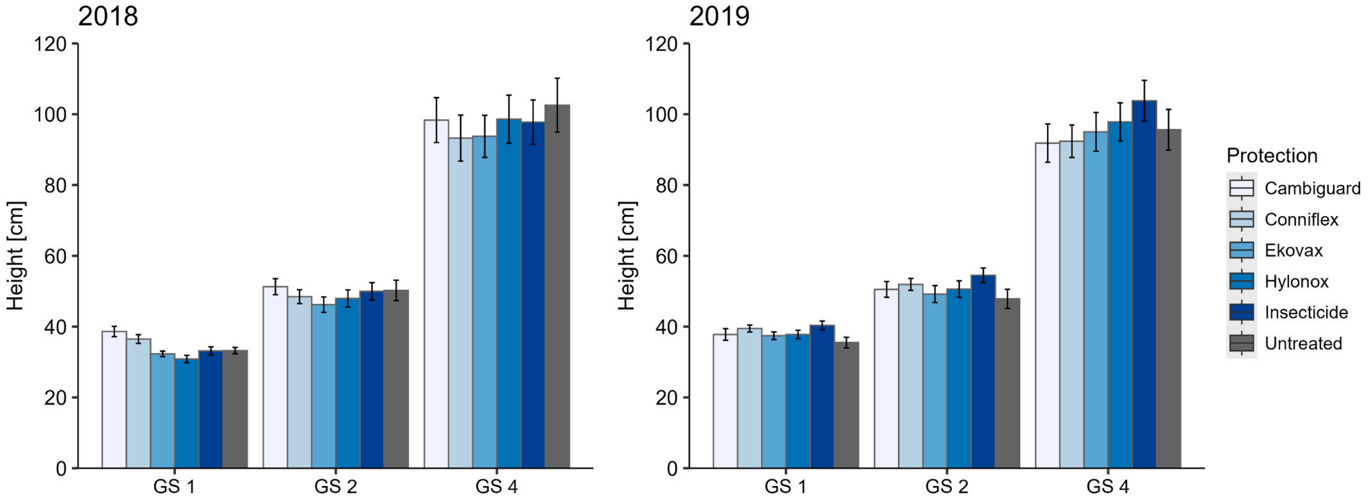

Fig. 6. Mean height of all seedlings during each survey for each of the treatments and both planting years, 2018 and 2019. The error bars represent standard errors. GS indicates the growing season after which the survey was performed.

may predispose seedlings to mortality from other damage factors (Grossnickle, 2012). This aspect is also highly relevant for the future with predictions of more frequent and severe droughts (Beniston et al., 2007; Chen et al., 2015; Spinoni et al., 2018), which may significantly impact seedling survival. For seedlings planted in the drought year of 2018, only one protection method, Cambiguard, performed significantly better than untreated. This was somewhat expected, as neither mechanical protection nor insecticide are designed to protect seedlings from desiccation or other drought related damages. Moreover, Cambiguard performed similarly to other mechanical protection methods for seedlings planted in 2019, suggesting other causes may have contributed to survival of seedlings coated with Cambiguard in 2018. However, for seedlings planted during a non-drought year, mechanical protections performed equally well as insecticide, and significantly better than untreated, indicating their potential as replacements for insecticide. This was further highlighted by the fact that insecticide did not protect seedlings significantly better than untreated when seedlings were planted during a drought year, indicating that drought was a more important factor than pine weevils in this case.

An important finding to emerge from our analysis is the persistence in the application of protective coating, which should be the focus of further development. It is important that protective coatings last sufficiently long to provide protection, as shown in the example of Hylonox. While its coating application was not significantly different from other methods for the 2018 dataset, Hylonox in the 2019 dataset had a significantly higher proportion of seedlings with no coating coverage after two seasons. While there may be other factors involved, lower amount of coating left on the seedlings could result in higher rates of pine weevil attack and help explain lower survival of seedlings treated with Hylonox in the 2019 dataset.

It is also important to consider interaction between drought and pine weevils not only in terms of seedling damage. Previous studies on pine weevils in controlled environments showed reduced feeding behavior and egg laying at air temperatures above 30 °C (Christiansen and Bakke, 1971, 1968). Unfortunately, direct effects of drought in field conditions remain a knowledge gap, since due to their sheer numbers, abundance studies are difficult to implement (Örlander et al., 1997; von Sydow, 1997). Still, it is reasonable to assume that pine weevils themselves were affected by high soil surface temperatures during the summer of 2018, potentially leading to reduced activity and feeding behavior. In our study, drought occurred in the first growing season for the 2018 dataset, which is at the beginning of a longer period of pine weevil damage, previously shown to decrease after three years (Örlander et al., 1997). Still, we wanted to focus on the first growing season, as it is the most important period of seedling establishment (Grossnickle, 2005). Fig. 5 shows comparatively little additional mortality between the first and second growing season for the 2018 dataset, with the majority of mortality occurring in the first growing season. The situation is opposite in the 2019 dataset, most likely owing to the lack of drought in the first growing season of 2019.

While pine weevil activity may have been lower in 2018, as suggested by different recorded attack rates, we still recorded significant damages and seedling mortality attributed to pine weevil damage (Fig. 5). Comparing pine weevil damage between the two planting years (Fig. 4), we saw that seedlings planted in 2019 had a higher survival than those planted in 2018 for the same damage classes, until damage became severe. It is impossible to completely separate the effect of drought and pine weevil damage in field conditions, however, it seems that the combined effect of both factors contributed to an overall lower survival. This is in line with previous research in greenhouse conditions, where seedlings were exposed to pine weevils and varying levels of drought, under controlled conditions. Suarez-Vidal et al. (2019) showed a non-linear seedling response to drought, where medium stress resulted in highest damage, later linked to lower production of defensive compounds (Suárez-Vidal et al., 2019). In varied field conditions, it may be that our study seedlings also experienced different levels of drought stress and were subsequently attacked at different rates. For example, highly drought stressed seedlings would have reduced cambium thickness, thus potentially leading to reduced attack rates. In our investigation, however, we chose to focus on evaluating overall survival rates of seedlings within the context of a regeneration process, rather than investigation into distinctions in drought stress susceptibility. Moreover, analysis of seedling height data shows no impact of drought on growth of seedlings, suggesting little gradation of drought damage. It seems that drought stress in 2018 was severe enough to push the majority of already stressed seedlings into mortality, regardless of any additional damage by pine weevils.

Location of pine weevil attack on seedlings has long been thought to play a role in overall mortality, but studies testing this in field conditions have been lacking. Logically, damage further down the stem would restrict the seedling more, as a higher portion of the stem would be deprived of water transport. Our results are in line with this, as we saw a linear response of survival to pine weevil damage on the bottom of the stem, but not the top, for seedlings planted in 2019 (Fig. 4). Contrastingly, seedlings with pine weevil damage to the top of the stem were able to retain high survival (above 80 %), until high levels of damage were reached. The situation is different for seedlings planted in 2018, where we do not see this higher tolerance for damage at the top of the steam, but instead, a response similar to when the damage occurred at the bottom of the stem. This may indicate that during a non-drought year, damage to the bottom of the stem is indeed the deciding factor of the overall survival. During a drought year, however, location of pine weevil damage to seedlings is of lesser importance to their survival, as the drought itself is either the dominant damage factor or significantly predisposes seedlings to mortality by pine weevil. Under drought conditions, careful selection of planting spots and other drought-mitigating methods could become even more important to ensure adequate seedling survival (Häggström et al., 2021; Nordin et al., 2022).

There was no effect of protection methods on measured height of seedlings, suggesting that concerns of coating constricting seedling growth or reducing transpiration and needle leaf area were unfounded, which was previously shown in a greenhouse experiment (Sjöström, 2020). Interestingly, there were also no differences between the two planting years, suggesting that seedlings that established well and survived in 2018 were no different in terms of height growth from seedlings planted in a non-drought year. This is in line with other research that suggests proper initial establishment is a key factor in survival of seedlings in field conditions (Burdett, 1990; Grossnickle, 2012, 2005; Häggström et al., 2021; Nordin et al., 2023).

5. Conclusions

We show that mechanical protection methods against pine weevil tested in this study perform well in protecting conifer seedlings when planted during a non-drought year. They increased survival of seedlings and performed similarly to insecticide treated and better than untreated seedlings. A similar height growth among all treatments indicate that no physiological restrictions could be connected to mechanical protections. Additionally, we show high survival of seedlings with pine weevil damage at the top of the stem, until high damage levels were reached. In comparison, when the seedlings were planted in a drought year, additional drought stress increased overall mortality and reduced the importance of mechanical protection. Under these conditions, the combined stress of pine weevil damage and drought significantly decreased survival, regardless of the location of damage on the stem. The findings presented here highlight the interplay between different environmental stressors on survival of seedlings in field conditions. They emphasize the necessity of tailored management strategies adapted to specific planting conditions to optimize seedling survival.

Funding

Stiftelsen Skogssällskapet, Södras Stiftelse för Forskning, Utveckling och Utbildning and Partnerskap Alnarp.

CRediT authorship contribution statement

Karin Hjelm: Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Kristina Wallertz:** Writing – review & editing, Data curation, Conceptualization. **Matej Domevscik:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation.

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

The authors would like to thank the field personnel of Asa Research station, SLU, for help with the fieldwork and data collection. We also thank Adam Flöhr for helpful suggestions on statistical analysis as well as two anonymous reviewers that have contributed to the manuscript. Additionally, we would like to thank the forest companies (Södra, Skogssällskapet, Sveaskog) and private forest owners for contributing land for experiments.

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