Effectiveness of insecticides, physical barriers and size of planting stock against damage by the pine weevil (*Hylobius abietis*).

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Abstract

A series of five trials was established in Great Britain to test the effectiveness of fourteen treatments and a control on reducing mortality and damage by pine weevil (*Hylobius abietis*) on recently replanted Sitka spruce (*Picea sitchensis*). Overall percentage mortality and damage was significantly different between trials, varying from a median of 24% to 100%. The most effective treatments in reducing mortality were insecticides and physical barriers, with insecticides being most cost effective. Low volume applications of insecticides were found to be as effective as higher doses. Using larger trees did not reduce mortality compared to the control, nor did application of a controlled release fertiliser. At Auchencairn, the trial where mortality was highest no treatment provided protection and so there is a need to develop an effective and integrated approach to reducing damage by pine weevil.

Keywords:

Hylobius, control measures, conifer plantation, seedling damage, *Picea sitchensis*

1. Introduction

In the UK, pine weevils (*Hylobius abietis*) are one of the most damaging pests on recently planted conifer restock sites (Willoughby *et al.,* 2017) and the only insect pest where routine preventative measures are taken (Leather at al. 1999). Maturation feeding by adult weevils damages the young trees, through chewing of the bark on the lower stem, causing girdling and death (Willoughby *et al.,* 2017). Without some form of intervention, in the UK mortality of young trees averages 50% (Willoughby *et al* 2017) ranging between 30% and 100% (Leather *et al.,* 1999). The pine weevil also feeds on branches of mature trees and can be a vector of damaging fungal pathogens (Leather *et al.,* 1999).

Despite pine weevil being recognised as a serious pest since the beginning of the last century (Leather et al 1999) it remains a highly damaging agent to commercial forestry in the UK (Willoughby *et al.,* 2017). There are no recent assessments of the cost of this damage but it was estimated in the late 1990s that pine weevil cost the forestry sector £4 million per year, for direct control measures alone, not including the replacement of killed trees (Leather *et al.,* 1999). Furthermore, future damage from pine weevil is likely to increase due to the heightened temperatures predicted as a result of climate change (Inward *et al.,* 2012).

The pine weevil is an important pest elsewhere in Europe (Leather et al., 1999), and a wide range of approaches have been adopted or are being investigated to control damage. These can be grouped into nine broad categories: (1) chemical control (Luoranen & Viiri,, 2005), (2) biological control

(Williams et al., 2013), (3) physical barriers (Petersson *et al.,* 2004), (4) site preparation (Wallertz *et al.* 2018), (5) use of larger (Thorsen *et al.* 2001, Nordlander et al., 2011) or smaller planting material (Petersson *et al.,* 2008), (6) delayed planting (Moore 2004), (7) use of antifeedants (Unelius *et al*., 2018), (8) enhanced plant defences (Lundborg *et al.,* 2016, Zas *et al*. 2014) and (9) genetic improvement (Zas *et al.,* 2017). There have also been attempts to develop systems that predict the risk of damage to the young trees through characterisation of sites (Heritage & Moore 2000, Nordlander *et al.,* 2017, Lopez-Villamor *et al.,* 2019) and population monitoring systems have also been developed (Wainhouse *et al.,* 2007, Forest Research 2019). There has been interest in combinations of these approaches to create an integrated pest management system for pine weevil in the UK (Evans *et al.,* 2003). The trials that this paper reports were focused on chemical treatments, physical barriers, the use of larger plantings stock and fertiliser. These treatments in combination have not been formally compared before in the UK and other than one treatment, the polymer, the methods used could all be adopted currently to protect trees on planting sites.

Use of insecticide treated trees has been shown to be a cost effective and practical approach to reducing damage. In 2016 it was used to protect 40% of trees planted in the EU (Norsk Wax, 2016). Leather *et al.,* (1999) describe the ideal insecticide for pine weevil as one that is systemic and kills the adults but also masks or alters attractive host volatiles. Some insecticides have these two attributes; a study by Rose *et al.,* (2005) showed that application of either a pyrethroid or a neonicotinoid insecticide to young Scots pine (*Pinus sylvestris*) trees inhibited feeding on them by pine weevil.

While insecticides are effective and cheap, there is pressure to minimise the use of pesticides in forestry (Willoughby *et al.,* 2004), while under the UK Woodland Assurance Scheme the use of pesticides, biological control measures and fertilisers are to be reduced (UKWAS, 2018). There are also international influences encouraging reduction of pesticide use in forests, such as forest certification (FSC, 2019) and regional policies such as the 2009 European Commission Directive on the Sustainable Use of Pesticides (European Commission, 2019).

Three insecticides are currently used in the UK to treat stock in the nursery, prior to planting to protect it from pine weevil damage. These are alpha cypermethrin and two neonicotinoid pesticides: imidacloprid, marketed as Merit Forest and acetamiprid, marketed as Gazelle (The Advisory Service for Weed & Pest Control in Forestry & Amenity, 2018). For top up spraying in the forest two insecticides are used: cypermethrin, marketed as Forester and Gazelle (The Advisory Service for Weed & Pest Control in Forestry & Amenity, 2018). In a trial in Sweden, Merit Forest was shown by Petersson *et al.,* (2006) to be less effective than cypermethrin as a pre-planting treatment with significantly higher losses in the second year. Evidence shows that Gazelle is potentially much less harmful than alpha cypermethrin (Willoughby *et al.,* 2017).

An alternative to using chemicals are physical barriers to pine weevil. Various guards have been tested and design is known to affect their efficacy. Petersson *et al.,* (2004) tested two broad types of guards, ones with a collar (a structure at the top of the guard preventing weevils from climbing up and over the guard) and ones without a collar. They found those with a collar to be effective at controlling damage by pine weevil. A later piece of research by Petersson *et al.,* (2006) in Sweden showed Clipstop, a collared guard to be as effective as permethrin over three years.

Clipstops were tested in informal trials in the UK in 2005 but did not reduce damage (Leslie & Liddon, 2017) and other barriers have been tried including paper guards and those fabricated from ladies' stockings but none have been successful (Leslie & Liddon, 2017). Despite this unpromising experience, there are other guards available in the UK, including plastic Biosleeves, Multipro Sleeves and Weenets (Willoughby *et al.,* 2017).

A different approach involves the application of protective coatings on the lower part of the stem of young trees. These include Flexcoat, a polysaccharide coating (Harlin and Eriksson, 2010), and Conniflex, a sand and glue based coating (Nordlander *et al.,* 2009). Conniflex has proved to be effective in protecting Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) against pine weevil damage in a trial in Sweden (Nordlander *et al.,* 2009) and to date has protected 320 million container grown stock trees (Svenska-Skogsplantor ,2019). Another treatment, Norsk Wax has been developed in Scandinavia (Norsk Wax 2016). Field trials in Sweden of this product were encouraging with 1.3% of treated trees being killed compared with 29% of those unprotected (Ohrn & Nordlander, 2015). The use of protective coatings has largely replaced the use of insecticides in Sweden with an intention that 2020 will be the last year where insecticides will be applied (Sveriges Lantbruksuniversitet, 2018).

Larger trees have been shown to be less attractive to pine weevil and to exhibit lower mortality (Nordlander *et al.,* 2011). Thorsen *et al.* (2001) identified a threshold basal diameter of greater than 8mm and scarification around the planting position were needed for high seedling survival of Norway spruce (*Picea abies*) in Sweden. However, a study (Petersson *et al.,* 2008) showed mini-trees, 10 week old containerised seedlings of Norway spruce to be less damaged (3.5% vs 55%) than conventional planting stock. When the mini-trees were damaged by pine weevil they released larger concentrations of limonene, a chemical known to be repellent to pine weevil, while conventional planting stock released the attractant alpha-pinene.

In April 2017 Maelor Forest Nurseries Ltd. in collaboration with Scottish Woodlands, Flintshire Woodlands Ltd and Tilhill Forestry established a series of five trials across Great Britain with the aim of testing the effectiveness of fifteen treatments (including a control) in reducing the mortality and damage by pine weevil on newly planted Sitka spruce (*Picea sitchensis*). The treatments included chemical control measures, physical barriers and planting materials that had greater girth and greater height than standard planting material. Specifically, the aims of the trials were to:

1. Identify the most effective control measures in reducing mortality and damage

2. Relate the effectiveness of the control measures to their cost

3. Compare effectiveness of treatments across sites.

4. Relate the characteristics of the sites to damage from pine weevil

An analysis of results at two years is presented in this paper and recommendations made for future work. The cumulative damage over two growing seasons, rather than one was used as it gives a better indication of the effects of treatments on damage and mortality over the establishment period.

2. Material and Methods

2.1 Site descriptions

Five trials were established in April 2017 in the uplands of the UK, with four located in south west Scotland and the fifth, Cwm Henog, in southern Wales. The locations are described in Table 1 with details on the climate and suitability for Sitka spruce as generated by the Ecological Site Classification (Forest Research 2020). Sitka spruce was selected as it is the most common species in commercial softwood forestry plantations in the UK (Forestry Commission, 2019). Heritage and Moore (2000) identified site characteristics that strongly influenced damage by pine weevil and the sites are compared against these factors. All comprised stands of monoculture Sitka spruce or stands with a preponderance of Sitka spruce which had been clear felled recently. Furthermore, the sites were not close to areas of serious windthrow, the crop had not been thinned within six years previously, however all had older trees within 1-2km distance, and all had standing trees nearby. There was exposed mineral soil around the trees on all sites, reducing risk but conversely the brash and other harvesting residues had not been burned and stumps had not been removed. Characteristics that differed between the trials are described in Table 2.

2.2 Treatments

We tested 14 treatments and a control. For Auchencairn, Cwm Henog, Newton Stewart and Ramshaw Rig sites, Sitka spruce came from A12 Seed Orchard material. For Lamloch, vegetatively propagated Sitka spruce was used from PF80, a full sib family with material vegetatively propagated. All trees were bare root and were graded for size and quality before being treated. There were four broad categories of treatment: physical barriers, chemical insecticides, size of planting stock and application of controlled release fertiliser.

The physical barriers comprised four treatments. Biosleeves (Greenerpol Ltd, UK) and Multipro sleeves (Svenska Skogplantor, Sweden) were commercially available protection, fitted around the stems of the young trees at the nursery. Multipro sleeves were made of waxed cardboard and are known to be biodegradable. Biosleeves, which are no longer available were made from an experimental biodegradable plastic, with an estimated lifetime in the forest of 2-5 years. The other two barrier treatments used an experimental polymer, applied to the tree stem in the nursery, covering either 85% or 50% of the stem. Application was carried out by dipping plants into a container of liquid polymer, taking care to avoid contact with roots or branches of the plant. The plants were then left to air dry for 1 hour before packing. Roots were regularly misted with water to prevent them drying out.

The chemical treatments used three insecticides: Gazelle (Nisso Chemical Europe GmbH: 0.037g per tree acetamiprid), Alpha C6 ED (Techneat Ltd: 0.006g per tree alpha-cypermethrin) and Coragen (Dupont: 0.013g per tree chlorantraniliprole). Coragen is not currently used on an operational scale to control pine weevil damage in Great Britain. The Alpha C 6 ED treatment was applied using an Electrodyn machine (Techneat Engineering Ltd.), which applies electrically charged insecticide accurately to individual root collars of trees. The trees are earthed in the machine by passing over an earthing wire, ensuring that the insecticide is attracted to exactly the right location on the plant. The treatments of Coragen and Gazelle were applied using ultra low volume (ULV) application nozzles in bundles of ten trees but is now applied to individual trees using a purpose built machine. Due to the low volumes of water used in this process, the plants could be packed immediately after treatment. Conventional application was by knapsack sprayer to trees laid out on a clean, protected ground surface. Trees were turned over during the process to ensure good coverage. The trees were left to air dry for one hour before being packed. Roots were regularly misted with water to prevent them drying out.

For all trials except Lamloch, seed orchard PSI A12 material was planted. Four treatments using larger trees than conventional planting stock (1 +1, 30-50 cm tall, 5mm root collar diameter) were tested in the trials. Planting stock of 2+1 (30-50cm tall, 6mm root collar diameter), with a larger girth and 2+1 50-70cm with a larger girth (8mm root collar diameter) and height were included. At Lamloch, vegetatively propagated (PF80) planting stock was planted. The 1+1 treatment was replaced by S+1 (25-50cm tall, 5.5mm root collar diameter), while the 2+1 treatment was replaced by a S+2 (25-50cm tall, 6.5mm root collar diameter) and the 2+1 50-70cm with a larger girth treatment was replaced with S+2 (50-70cm tall, 8.5mm root collar diameter).

For each of two larger tree treatments and for the standard sized trees there were trees with and without application of Treeboost, a controlled release fertiliser (CRF) developed by Maelor Forest Nurseries Ltd. This contains the following elements at the following concentrations: 13%N, 11% P, 8% K + 2% CaO, 0.10% B, 0.015% Cu, 0.20% Fe, 0.08% Mn and 0.025% Zn. A summary of the treatments is described in Table 3.

For each plot 25 trees were packed into an individual labelled plastic bag. Four bags of the same treatment type were then packed into a larger bag which was then sealed. These bags were then kept in a cold store at approximately -2° C until point of planting.

2.3 Experimental Design and Measurements

The trials were established using a randomised complete block design with 15 treatments and four replicates. Each plot contained 25 trees in a 5 tree by 5 tree layout. Stocking density was the commercial stocking rate used in the UK of 2,700 stems ha^{-1}. Assessments were made in July 2017, November 2017 and July 2018. For each plot each individual tree was scored using the following five categories:

A = Undamaged

B = Damaged by weevil, but tree likely to survive

C = Tree dead/dying due to weevil damage

D = Tree dead for reasons other than weevil damage

X = Tree missing

Damage was attributed to pine weevil if the characteristic damage to the bark of the stem of the young tree was present. It is the 2018 assessment that is reported on in this paper.

Statistical analysis

Percentage mortality and percentage damaged by pine weevil per plot were combined and calculated by:

$$Percentage\ mortality\ and\ damaged = \frac{100 \cdot (B + C)}{(A + B + C)}$$

Originally damage and death were to be analysed separately. However, these two variables were combined for two reasons. The first was that it has been shown that damage by pine weevil reduced subsequent survival and growth (Leather *et al*., 1999) and second separating damage and mortality for analysis presented confusing results. For example, a trial with high mortality may have low damage, because there are few trees alive to be damaged. This was particularly notable at Auchencairn, the trial with the highest mortality.

The unstandardised residuals for percentage mortality and damaged were tested for normality. For the treatments a Shapiro Wilkes test was used due to the small number of observations per treatment, whereas for the comparison between trials, the larger number of observations for each treatment meant a Kolmogorov- Smirnov test was used. For the data for all trials the residuals from mortality and damage data before and after an Arcsine transformation did not conform to normality so non-parametric Kruskal Wallis tests have been used to test significance of differences. For the mortality and damage date for individual trials all but Auchencairn were normally distributed but the variances were unequal for all trials except Cwym Henog. Non-parametric Kruskal Wallis tests were therefore used to test significance of differences.

To identify which treatments were significantly different a post-hoc Dunn's test was employed with pairwise comparison applying the Bonferroni adjustment for multiple comparisons. This approach was applied to the comparison of death and damage between trials. However, this is overly conservative when applied to large numbers of comparisons (McDonald, 2015) such as when testing significance between the 15 treatments. In this case, the Benjamini-Hochberg procedure was applied, accepting a potential false-positive rate of one in ten (McDonald, 2015).

3. Results

3.1 Overview of Results

The results of damage by the five damage categories assessed are presented in Figure 1 for the trials and Figure 2 for the treatments. The percentage of trees killed by agents other than pine weevil was as much as 25%, but the percentage of trees missing was low at 10% or less. Detailed results of damage and mortality are described in the following sections.

3.2 Mortality and damage by trial

There were significant differences ($p<0.001$) in the median percentage mortality and damage between trials (Figure 3). Level of damage and mortality at Lamloch (median = 35%), Ramshaw Rig (median =36%) and Newton Stewart (median =24%) were lower than the other trials and not significantly different. There was a high level of damage and mortality at Cwym Henog (median=72%) and complete mortality and damage at Auchencairn (median = 100%).

3.3 Mortality and damage by treatment

Figure 4 (a-e) describe the death and damage caused by pine weevil for each of the treatments. Results from Auchencairn are not shown as death and damage for all treatments was 100%. Combining the data from all trials including Auchncairn (Figure 4e) showed significant differences between treatments ($p<0.00001$) and that chemical treatments and barriers were as effective as Gazelle, the exception being the 50% polymer treatment. Larger planting stock and larger planting stock with controlled release fertiliser were no more effective than the control. Highly significant differences between treatments were found at all trials, except Auchencairn (Lamloch p=0.003, Ramshaw Rig p=0.008, Newton Stewart p=0.0001 and Cwym Henog p=0.007). Despite the variation in overall levels of death and damage between trials the general findings were that chemicals and barriers were most effective and that larger plants, with or without fertiliser were no more effective than the control. The efficacy of even the effective treatments was much reduced in trials where overall damage was high, such as Cwym Henog (Figure 4a) and Auchencairn, where all treatments exhibited 100% dead or damaged.

4. Discussion

There were significant differences in the level of damage and mortality between trials. The highest level of mortality was at Auchencairn and the next highest was at Cwym Henog. The percentage mortality and damage was significantly different between these trials and between them and the other three trials (Figure1, Figure 3). At Auchencairn the previous Sitka spruce stand was felled over a protracted period, which may have allowed damaging populations of pine weevil to build up on the site. Also, there was heavy grass growth on that site, which is known to increase pine weevil damage (Orlander and Nordlander, 2003). Furthermore, the new trees were 'hot planted' immediately after harvesting and the extended harvesting of the previous crop may have acted to attract pine weevil onto the site through a continuous supply of fresh stumps and brash. Lamloch was the only site where vegetatively propagated material was planted and this has been shown to be less attractive to pine weevil than seedling stock (Kennedy et al., 2006). Lamloch was the trial site that sustained least mortality and damage from pine weevil and using vegetatively propagated stock could be a factor. The treatments that were effective at reducing mortality and damage at other trials were also effective at Lamloch.

Using the data pooled from all five trials, significant differences in percentage mortality were detected between treatments. Broadly, the treatments can be divided into two groups, those that effectively protected the young trees and those that were ineffective (no better than the control).

Chemical treatments and the physical barriers provided by the Multipro sleeves, Biosleeves and the 85% polymer treatment proved effective in reducing damage and death. The Multipro sleeves and Biosleeves provided excellent protection but their effectiveness was compromised by poor installation in some cases, allowing access to trees' stems by the pine weevils. The fitting of Multipro sleeves and Biosleeves onto trees was labour intensive, and relatively slow compared to other treatments which adds to their cost (Table 3, Figure 5). However, the additional cost of the guards may be offset by the need in some cases for top up spraying on insecticide treated trees. Application of guards was hindered by bigger branches on larger seedlings which reduced clearance for the sleeve. Proper burial of the lower part of the sleeve base was impeded by stony ground on some sites, allowing weevils to access the tree from the base. Furthermore, on exposed sites, it has been observed that movement of the tree shifted the position of the sleeve on the stem, allowing access by pine weevils. Weevils that were found inside sleeves were observed to cause significant damage to the tree.

The novel polymer barrier treatment gave mixed results, with death and damage for the 85% stem coverage treatment being significantly different from the control using pooled data from all trials. In contrast, death and damage using the 50% stem coverage was not significantly different from the control. It was only at Cwym Henog, a trial with high levels of damage that the difference in death and damage is significantly lower for the 85% stem coverage treatment than the 50% treatment. The mixed performance of the polymer may be due to poor adhesion to the stem in some cases, reducing its protection to the young tree. The success of stem coatings in Scandinavia in reducing pine weevil damage (Norsk Wax, 2016) and their widespread use (Sveriges Lantbruksuniversitet, 2018) suggests this is an approach worth further investigation. However, problems were experienced in trials in the UK with the protective wax cracking and exposing the stem to damage (Leslie and Liddon ,2017). The cost of the experimental polymer was not known but is assumed to be similar to that of Norsk Wax, which costs €0.05 (£0.04) to €0.09 (£0.08) per tree (Norsk Wax, 2016) (Table3, Figure 5).

Using greater stem coverage, such as in the 85% treatment may have drawbacks over the 50% treatment as research in Sweden showed that greater coverage of the stem and needles reduced growth (Norsk Wax, 2016) and the importance of protection higher up the stem is not clear as weevils prefer to feed on the lower part of the stem where there is more cover (Nordlander *et al.,* 2005). In these trials, mortality from causes other than pine weevil was greater in the 85% treatment than others (Figure 2) which suggests extensive covering of the stem reduces survival in addition to growth.

Using the pooled data from all trials and those from individual trials, chemical treatments and physical barriers were both effective in terms of their reduction in damage and mortality, with Gazelle, Gazelle ULV, Electrodyne, Coragen and Coragen ULV ranked highly, except at Cwym Henog. Chemical treatments were also more cost effective (Table 3, Figure 5) than the physical barriers. However, there is a global aim to reduce the use of chemicals used in forestry, driven by concerns about the toxic effect of insecticides on animals and by encouragement to reduce pesticide use by certification bodies (FSC, 2019). Coragen is less toxic to non-target organisms than Gazelle (Roubos et al., 2014) but is currently not used on an operational scale in Great Britain to control pine weevil. The results were promising. Two treatments, the Gazelle ULV and the Coragen ULV applied insecticide at much lower volumes. The lower volume applications were as effective as those applied at conventional volumes.

Across all trials, using larger planting stock did not reduce damage and mortality. Thorsen *et al.* (2001) found that larger stock with a root collar diameter of 8mm on scarified sites and 10mm on other sites showed negligible damage in Scandinavia. The root collar diameter of the larger planting stock employed in this trial was at 8 to 8.5mm. Populations of pine weevil are higher in the UK than in Scandinavia (Willoughby *et al.,* 2017) and it may be that using larger trees would be an effective strategy at lower population densities, if this could reliably be predicted. However, using larger trees was not a successful control measure at the two trials with low overall damage and mortality and use of the seedling planting stock; Newton Stewart and Ramshaw Rig and so based on these data it is not an effective strategy to reduce mortality and damage.

Applying controlled release fertiliser did not influence death and damage from pine weevil, compared to the same sized planting stock without fertiliser applied. This contrasts with the findings of Zas et al. (2006) who found fertiliser application increased damage by pine weevil.

The lack of complete protection from any of the treatments when under high levels of damage, such as at Auchencairn is an encouragement for the development of an integrated pest management system for pine weevil. There are methods for predicting the population size of pine weevil, such as that devised by Nordlander *et al.,* (2017) in Sweden and the Hylobius Management Support System (Willoughby *et al.,* 2017) from the UK but these will need to be combined with an effective means of protection at high population densities.

5. Conclusions

The five trials tested the success of fourteen treatments against a control in reducing damage and mortality from pine weevil. While there were significant differences in the damage and mortality caused by pine weevil across the sites, overall the following conclusions can be made:

At these trials, insecticides and physical barriers were equally effective. However, physical barriers have been known to be less effective when used in certain site conditions.

Ultra low volume insecticide treatments were as effective as using higher volume applications.

The new insecticide Coragen was as effective as Gazelle and alpha cypermethrin.

Planting larger trees did not reduce mortality and damage.

Application of fertiliser in the field did not reduce mortality and damage.

At Auchencairn, where there were extreme levels of damage and mortality, none of the treatments were effective and this supports the need to develop an integrated solution to pine weevil.

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Table 1 Location of trials. Climatic data and suitability for Sitka spruce generated by the Ecological Site Classification v4 (Forest Research 2020). AT = Accumulated temperature above 5°C, MD = moisture deficit and DAMS = exposure index where 3 is sheltered and 22+ is too exposed for productive forestry.

Site	**Latitude**	**Longitude**	**AT (day degrees above 5°C)**	**MD (mm)**	**DAMS**	**Species suitability**
Auchencairn	55° 13′ 50.82″ N	003° 39′ 14.65″ W	1103	75	17	Suitable
Cwm Henog	52° 07′ 12.99″ N	003° 43′ 55.94″ W	1057	54	17	Suitable
Lamloch	55° 14′ 41.17″ N	004° 20′ 14.62″ W	1179	79	16	Suitable
Newton Stewart	55° 01′ 16.79″ N	004° 40′ 06.86″ W	1387	107	17	Marginal
Ramshaw Rig	55° 15′ 55.83″ N	003° 18′ 39.04″ W	1022	66	15	Marginal

Table 2 Description of trials addressing the main factors influencing pine weevil damage as described in Heritage and Moore (2000).

Site name	Auchencairn	Cwym Henog	Lamloch	Newton Stewart	Ramshaw Rig
Site management					
Month site was clearfelled	February 2016-March 2017	April - July 2015	May 2015-November 2015	March-August 2016	July 2016-December 2016
Period between clearfell and planting (months)	0-11	18-21	17-23	8-13	4-8
Exposed mineral soil around plants? (Y/N)	Yes	Yes	Yes	Yes	Yes
Site burned after clearfell? (Y/N)	No	No	No	No	No
Stumps removed or destroyed? (Y/N)	No	No	No	No	No
Vegetation, woody? (light/moderate/heavy)	light	Light regen of willow / rowan	moderate	Light	light
Vegetation grasses? (light/moderate/heavy)	heavy	Light – moderate	light	Moderate	light
Plant Details					
Nursery code	PSI A12	PSI A12	PF80	PSI A12	PSI A12
Type	seedling	seedling	vegetatively propagated	seedling	Seedling
Size	30-50	30-50	25-50	30-50	30-50

Table 3 Details of treatments (* based on cost of Norsk Wax, a similar coating (Norsk wax 2016)).

Treatment name	Details	Additional Cost per tree
Control	No treatment applied to the tree.	None
Electrodyne	alpha-cypermethrin – applied by electrodyne	£0.11
Gazelle spray	Nisso Chemical Europe GmbH Gazelle - Applied by knapsack sprayer.	£0.11
Gazelle ULV	New ULV nozzles, improved machine.	£0.11
Coragen spray	Dupont coragen - Applied by knapsack sprayer.	£0.11
Coragen ULV	New ULV nozzles, improved machine.	£0.11
Multipro Sleeves	Multipro cardboard sleeve fixed around the stem of the tree before planting.	£0.30
Biosleeves	Biosleeve (biodegradable plastic) fitted around the stem of the tree before planting.	£0.35
Polymer barrier 50 %	A new polymer applied to 50% of the lower length of the stem.	£0.06*
Polymer barrier 85 %	A new polymer applied to 85% of the lower length of the stem.	£0.06*
1+1 stock + CRF	1+1 stock, 10g Treeboost controlled release fertiliser applied to roots before heeling in.	£0.05
2+1 stock	2+1 stock (greater girth)	£0.06
2+1 stock + CRF	2+1 stock, 10g Treeboost controlled release fertiliser applied to roots before heeling in.	£0.11
50-70cm 2+1 stock	50-70cm tall, 2+1 stock (greater height + girth).	£0.06
50-70cm 2+1 stock + CRF	50-70cm tall, 2+1 stock (greater height + girth)10g Treeboost controlled release fertiliser applied to roots before heeling in.	£0.11

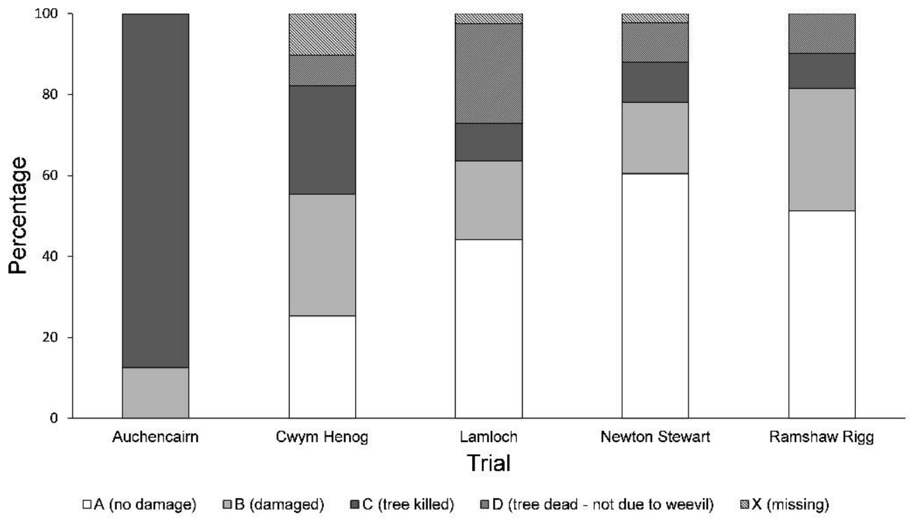


Figure 1 Percentage of trees in each of the five damage categories in each of the trials.

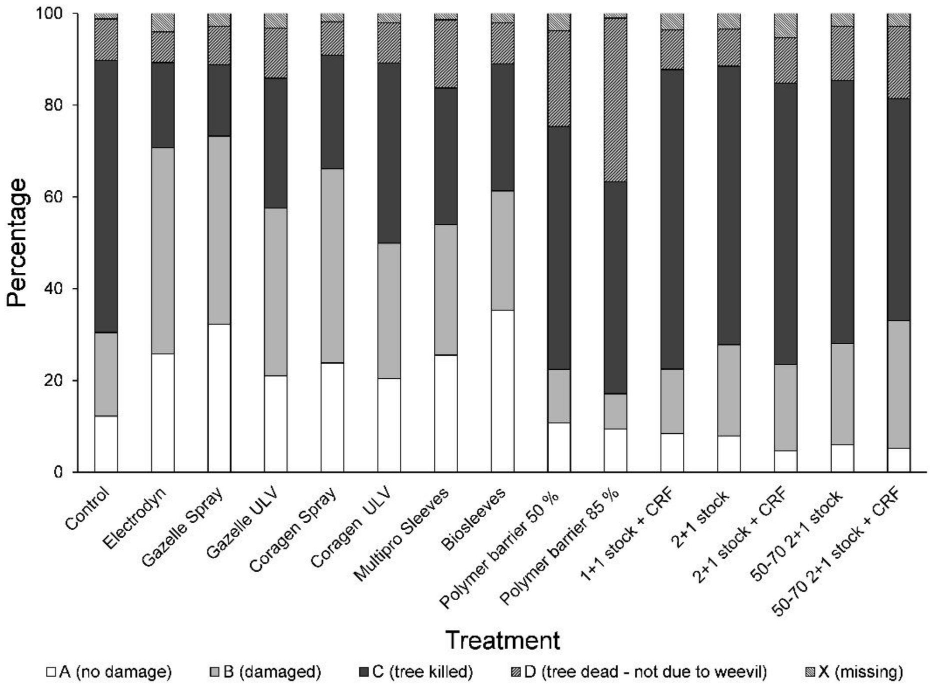


Figure 2 Percentage of trees in each of the five damage categories for each treatment.

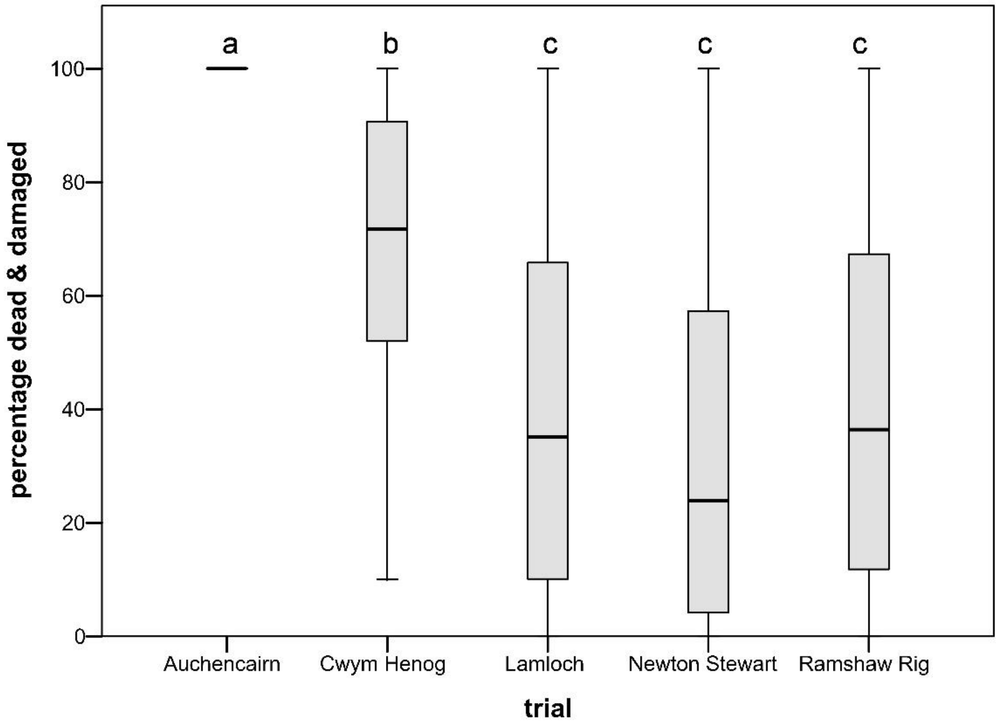
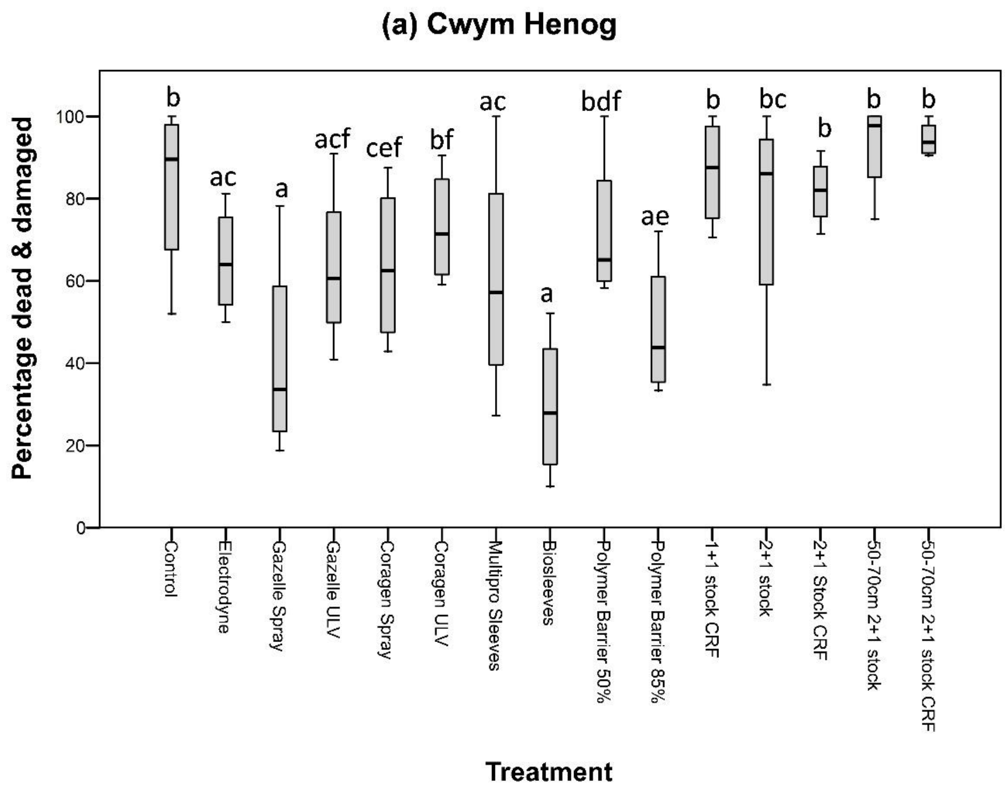
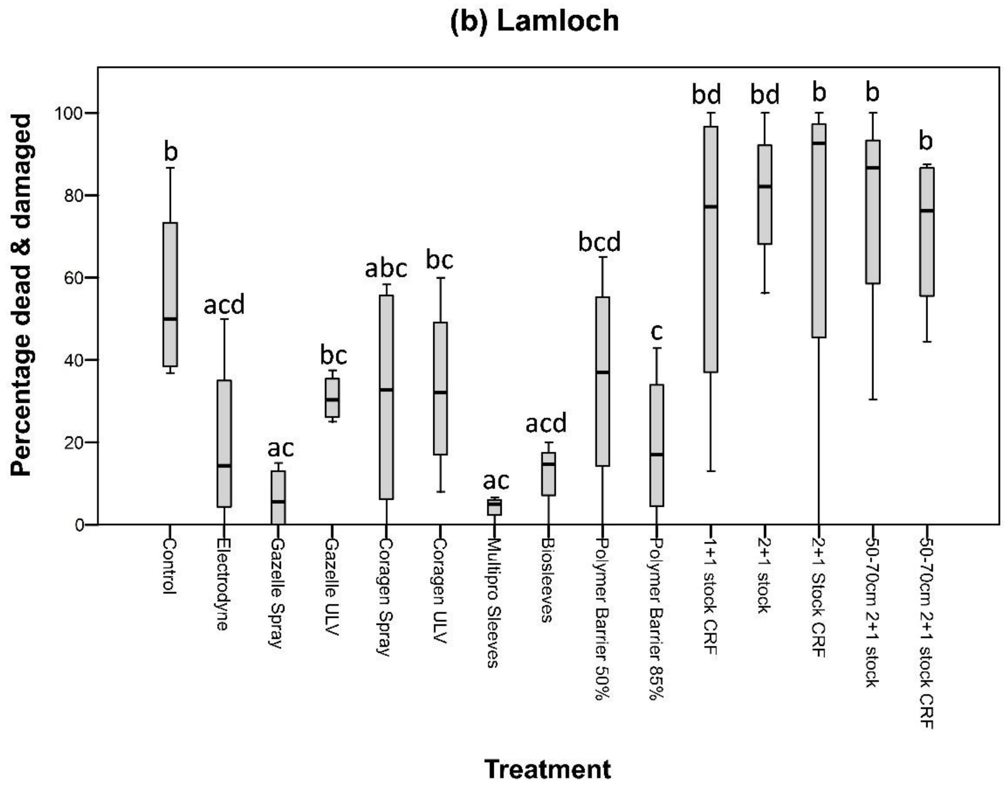


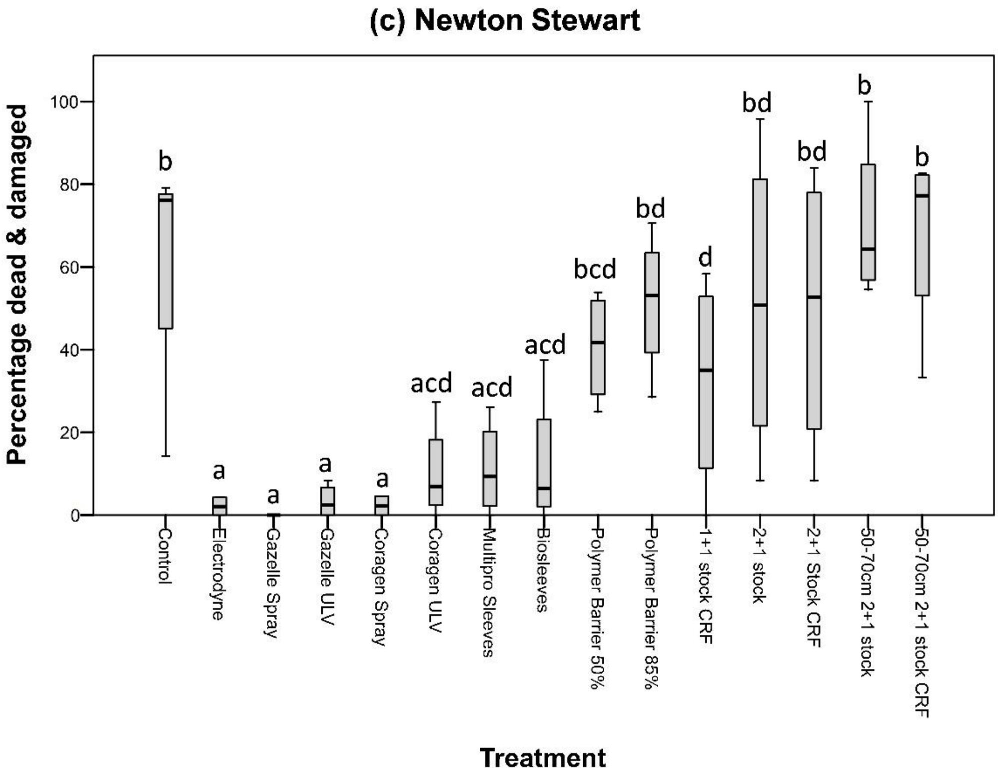
Figure 3 Median percentage mortality and damage by trial. The same letter above the bars denote groupings of sites with no significant difference. Boxplots show the median values as the dark horizontal lines; 25th and 75th percentiles as the top and bottom of the boxes. The vertical lines show the maximum and minimum values, excluding outliers shown as a circle.

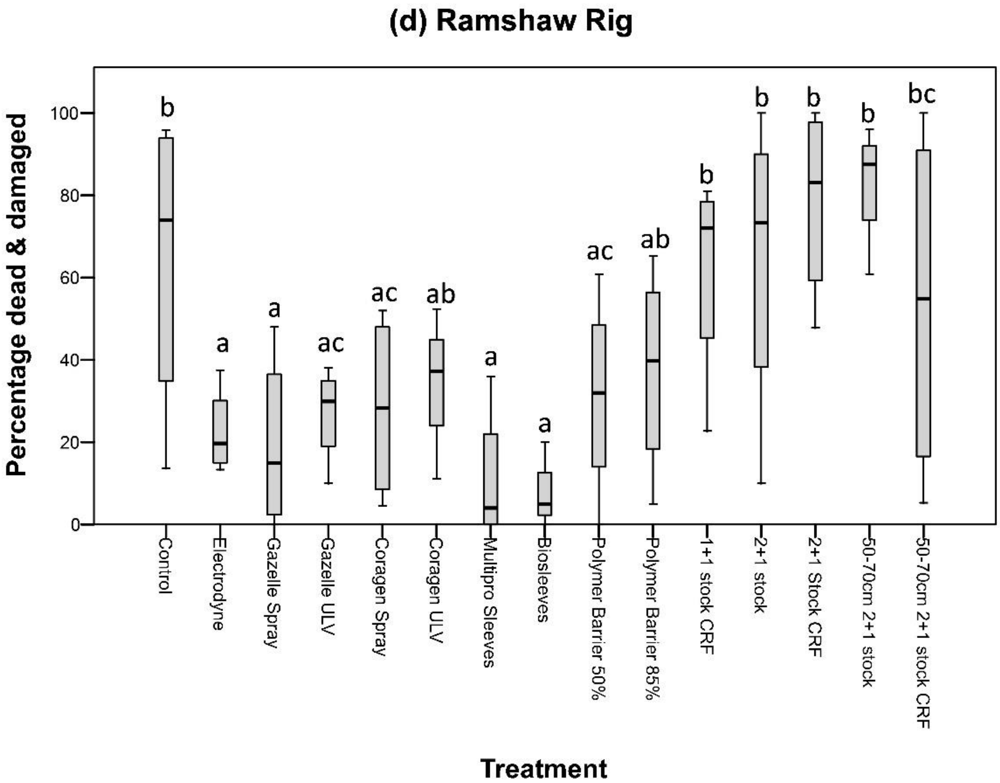


(a) Cwym Henog
Percentage dead & damaged
0
20
40
60
80
100
b
ac
a
acf
cef
bf
ac
a
bdf
ae
b
bc
b
b
b
Control
Electrodyne
Gazelle Spray
Gazelle ULV
Coragen Spray
Coragen ULV
Multipro Sleeves
Biosleeves
Polymer Barrier 50%
Polymer Barrier 85%
1+1 stock CRF
2+1 stock
2+1 Stock CRF
50-70cm 2+1 stock
50-70cm 2+1 stock CRF
Treatment



(b) Lamloch
Percentage dead & damaged
0
20
40
60
80
100
b
acd
ac
bc
abc
bc
ac
acd
bcd
c
bd
bd
b
b
b
Control
Electrodyne
Gazelle Spray
Gazelle ULV
Coragen Spray
Coragen ULV
Multipro Sleeves
Biosleeves
Polymer Barrier 50%
Polymer Barrier 85%
1+1 stock CRF
2+1 stock
2+1 Stock CRF
50-70cm 2+1 stock
50-70cm 2+1 stock CRF
Treatment


(c) Newton Stewart
Percentage dead & damaged
0
20
40
60
80
100
b
a
a
a
a
acd
acd
acd
bcd
bd
d
bd
bd
b
b
Control
Electrodyne
Gazelle Spray
Gazelle ULV
Coragen Spray
Coragen ULV
Multipro Sleeves
Biosleeves
Polymer Barrier 50%
Polymer Barrier 85%
1+1 stock CRF
2+1 stock
2+1 Stock CRF
50-70cm 2+1 stock
50-70cm 2+1 stock CRF
Treatment


(d) Ramshaw Rig
Percentage dead & damaged
0
20
40
60
80
100
b
a
a
ac
ac
ab
a
a
ac
ab
b
b
b
b
bc
Control
Electrodyne
Gazelle Spray
Gazelle ULV
Coragen Spray
Coragen ULV
Multipro Sleeves
Biosleeves
Polymer Barrier 50%
Polymer Barrier 85%
1+1 stock CRF
2+1 stock
2+1 Stock CRF
50-70cm 2+1 stock
50-70cm 2+1 stock CRF
Treatment

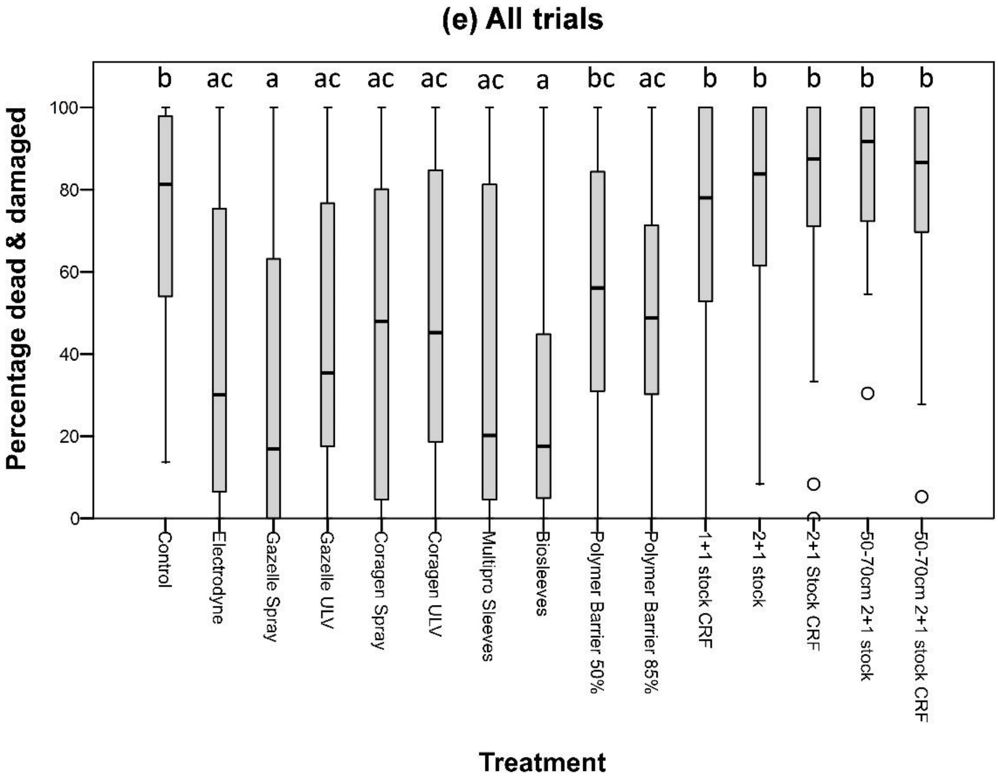


Figure 4 Median percentage mortality and damage by treatment. The same letter above the bars denote groupings of treatments with no significant difference. Boxplots show the median values as the dark horizontal lines; 25th and 75th percentiles as the top and bottom of the boxes. The vertical lines show the maximum and minimum values, excluding outliers shown as a circle.

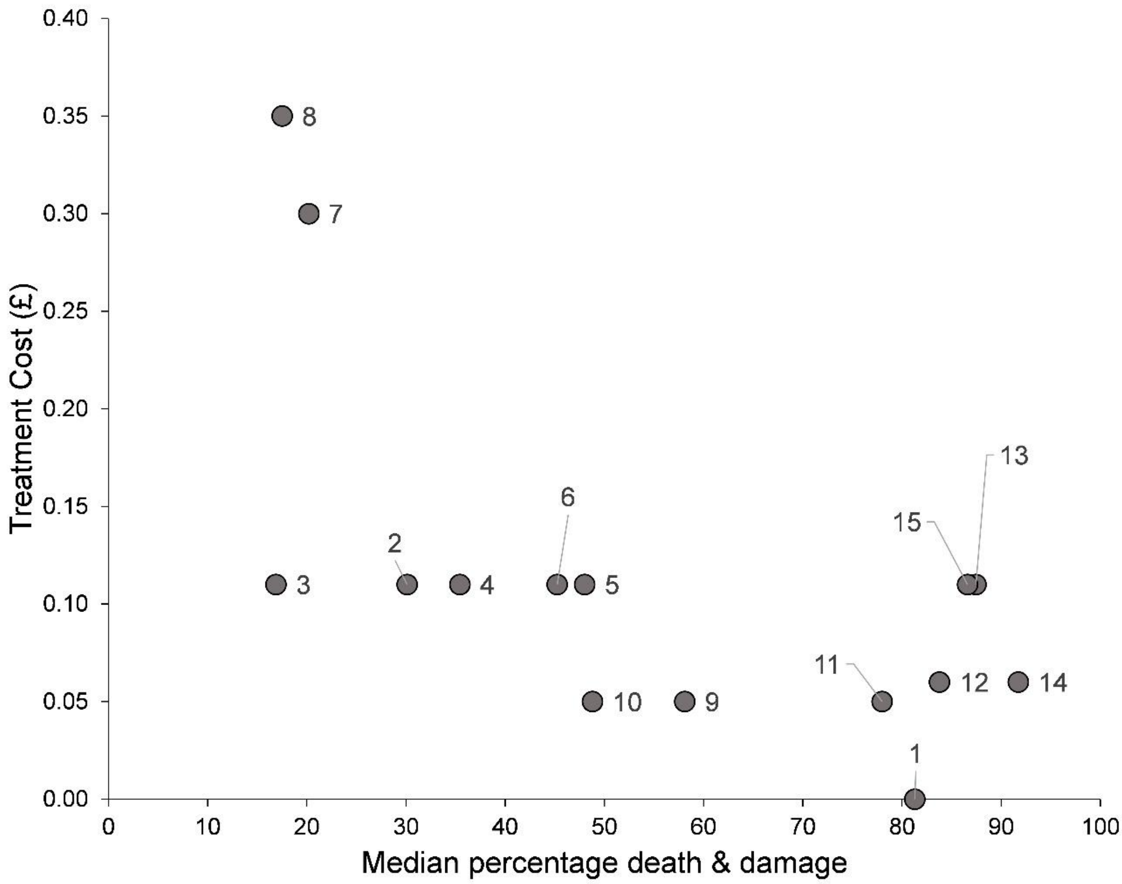


Figure 5 Comparison of treatments by cost (£) and median percentage damage. 1=control, 2=Electrodyne, 3=Gazelle spray, 4=Gazelle ULV, 5=Coragen spray, 6=Coragen ULV, 7=Multipro sleeves, 8=Polymer barrier 50%, 9=Polymer barrier 85%, 10=Biosleeves, 11=1+1 stock + CRF, 12=2+1 stock, 13=2+1 stock+CRF, 14=50-70 2+1 stock and 15=50-70 2+1 stock+CRF