

Effectiveness of repellents for reducing damage to eucalypt seedlings by browsing mammals

Alison M. Miller^{1,2}, Julianne M. O'Reilly-Wapstra^{1,3}, Hugh P. Fitzgerald^{1,3}, Stephen C. Paterson³, Lee Stam⁴, Andrew Walsh⁴, Tim Wardlaw^{3,4} and Brad M. Potts^{1,3}

¹School of Plant Science, University of Tasmania, Private Bag 55, Hobart, Tasmania 7001, Australia

²Email: Alison.Miller@utas.edu.au

³Cooperative Research Centre for Forestry, Private Bag 12, Hobart, Tasmania 7001, Australia

⁴Forestry Tasmania, GPO Box 207B, Hobart, Tasmania 7001, Australia

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Summary

Marsupial herbivores cause significant damage to seedlings in forestry operations. Damage can lead to changes in tree form, reduced growth rates and seedling death. Non-lethal tactics, as a component of an integrated browsing management strategy, are currently sought to assist in reducing this damage. One such tactic involves making seedlings deterrent or unpalatable through the application of chemical repellents.

We investigated the effect of three chemical repellents, Plant Plus, Sentree and Hot Shot, upon browsing of *Eucalyptus nitens* seedlings by two marsupial herbivores known to browse newly established plantations in Tasmania: the common brushtail possum and the red-bellied pademelon. One repellent was designed to deter herbivores through an unpleasant odour (Plant Plus), one to be unpalatable (Hot Shot), and the third to be both deterrent and unpalatable (Sentree). We ran a combination of paired feeding trials (one repellent + control) and cafeteria trials (all three repellents at once with no control) with captive possums and pademelons, for three nights per trial. Both species consumed significantly more foliage from control seedlings than those treated with Plant Plus or Sentree repellents. Pademelons also preferred controls to Hot Shot treated seedlings but, interestingly, possums consumed significantly more foliage from seedlings treated with Hot Shot than from control seedlings. The most effective repellent against both herbivores was Sentree, and the marked reduction in browsing indicates that further testing in the field is warranted.

Keywords: seedlings; browsing damage; repellents; marsupials; pademelon; possum; *Eucalyptus nitens*

Introduction

Browsing in newly established plantations has become an issue of economic importance in south-eastern Australia (Coleman *et al.* 1997) through its impact on seedling growth rate and survival, and on tree form (Wilkinson and Neilsen 1995; Bulinski and McArthur 1999). Methods for controlling Tasmanian native herbivores, such as the common brushtail possum (*Trichosurus vulpecula*), red-bellied pademelon (*Thylogale billardierii*) and Bennett's

wallaby (*Macropus rufogriseus*), and the introduced European rabbit (*Oryctolagus cuniculus*) have mostly been lethal, using the poison compound 1080 and shooting. Non-lethal methods have not been widely adopted because they offer only partial protection (repellents) or are expensive and subject to theft (tree guards and fencing).

The application of repellents to newly planted seedlings is a relatively inexpensive and, when used as a component of an integrated browsing management strategy, potentially effective option to reduce browsing damage. Such a strategy would incorporate repellents with a variety of complementary methods, such as natural resistance, nursery fertiliser regime and physical barriers, and aim to reduce browsing more than any one method used in isolation. Repellents generally act by deterring the herbivore from approaching the seedling (due to an unpleasant odour), or by making the seedling unpalatable to the herbivore. Repellents have been proven to deter mammalian herbivores such as deer, elk, possums, rabbits, wallabies and beaver from feeding on a range of plants, including plantation trees, fruit trees, vegetables and ornamental plants (e.g. Gillingham *et al.* 1987; Epple *et al.* 1993; Andelt *et al.* 1994; Marks *et al.* 1995; Woolhouse and Morgan 1995). Commonly used repellents have active ingredients including carnivore urine or faeces, egg, bitter-tasting compounds and capsaicin. It has been suggested that the wide variety of chemical repellents can be categorised into four modes of action based on their active ingredients: fear (odours indicating predator activity), irritants (products such as capsaicin or ammonia which irritate mucous membranes), taste (commonly bitter) and aversive conditioning (learning to associate illness with consumption) (Beauchamp 1997; Mason 1997). Wagner and Nolte (2001) tested 20 repellents representing these modes against black-tailed deer (*Odocoileus hemionus*), and found that repellents using fear as the mode of action were generally the most effective.

The first step in incorporating chemical repellents into an integrated browsing management strategy is to determine which most effectively protect tree seedlings against the target herbivore species. This study builds on a University of Tasmania BSc (Honours) project (Witt 2002) that demonstrated that a repellent,

Sentree (formally WR-1), was effective at reducing browsing damage by red-bellied pademelons on *Eucalyptus globulus* seedlings. This study extends that research to test the effectiveness of Sentree and two additional repellents in reducing browsing damage of *E. nitens* seedlings, the dominant hardwood plantation species in Tasmania, against the common brushtail possum and the red-bellied pademelon.

We predicted that all repellent-treated seedlings would receive less damage than control (untreated) seedlings, and that Sentree would be the most effective of the three as it incorporates both deterrence and unpalatability (i.e. it uses both fear and taste modes of action). We had no a priori expectations of repellent effectiveness on pademelons versus possums.

Methods

In order to test the effectiveness of three chemical repellents for reducing browsing on *E. nitens* seedlings by native mammalian herbivores, we ran a combination of paired feeding trials (one repellent + control) and cafeteria trials (all three repellents at once with no control) with captive common brushtail possums and red-bellied pademelons.

Seedlings

Eucalyptus nitens seedlings were provided by Forestry Tasmania's tree nursery, located at Perth, Tasmania. They were grown in Lannen trays (104 cells per tray, each 41 mm wide × 73 mm deep, with side slots allowing air-pruning of lateral roots). The seedlings, when dispatched from the nursery, were 8 mo old and an average of 25 cm tall. Prior to the trial, seedlings were kept in an open-air enclosure measuring about 5 m × 10 m, at the University of Tasmania, Hobart. Seedlings were watered under automatic sprinklers for 20 min twice daily before and over the course of the trials.

Repellent treatments

The repellents tested were Sentree, Plant Plus and Hot Shot. Sentree is an egg-based repellent sprayed onto seedlings, with a sandy grit (carborundum) sprinkled onto the egg base. It acts as both an odour repellent (the egg odour) and a palatability repellent (the grit). Carborundum is a hard, non-toxic grit which replicates naturally-occurring silica found in plants. This wears down the animals' teeth, and is something the animal naturally avoids when encountered in high concentrations (Delbridge and Lutze 1998). Sentree (as WR-1) has been shown to be repellent to captive European rabbits, swamp wallabies (*Wallabia bicolor*) and red-bellied pademelons (Marks *et al.* 1995; Harman 1996; Delbridge and Lutze 1998; Witt 2002). It is not harmful to humans or animals and does not affect plant growth (Marks *et al.* 1995; Johnston *et al.* 1998; Witt 2002).

Plant Plus (Roe Koh and Associates Pty Ltd 2000) is a pink liquid that smells like predator (dog) urine. It is easily sprayed onto seedlings and has no harmful effects on humans or animals and has no adverse effects on plant growth and development. The predator smell deters the herbivore from approaching and feeding on the plant. Numerous studies have shown that herbivores avoid predator odours (Pfister *et al.* 1990; Sullivan *et al.* 1990; Swihart *et al.* 1991; Boag and Mlotkiewicz 1994), and that it is not necessary for the animal to recognise the predator for it to be effective (Weldon *et al.* 1993; Nolte *et al.* 1994; Woolhouse and Morgan 1995). Plant Plus has been shown to successfully reduce browsing damage by European rabbit, brushtail possums, brown hare (*Lepus europaeus*) and swamp wallaby (Morgan and Woolhouse 1998; Roe Koh and Associates Pty Ltd 2000) and to influence behaviour of the parma wallaby (*Macropus parma*) and the red-necked pademelon (*Thylogale thetis*) (Ramp *et al.* 2005).

Hot Shot is a non-toxic gel-based repellent that has demonstrated promising results on New Zealand native plants (S. Hix, Connovation Ltd, 2006, *pers. comm.*). The active ingredient is natural oleoresin capsaicin. Capsaicin is a secondary metabolite present in large quantities in the seeds and fleshy fruits of plants in the genus *Capsicum*, and is the active component of chilli peppers. It is an irritant for mammals, and produces a sensation of burning in any tissue with which it comes in contact. It is applied sparingly to the leaves of the seedlings. It is not harmful to humans or animals and does not affect plant growth if every leaf is not painted. There are no published reports of the effectiveness of Hot Shot, but a number of other repellents based on capsaicin have been tested with a range of animals, with varying results (Montague *et al.* 1990; Andelt *et al.* 1992, 1994; Marks *et al.* 1995).

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Captive feeding trials

Animal husbandry

Feeding trials were undertaken in the University of Tasmania Animal Compound in Hobart, Tasmania, which has facilities suitable for housing both species of animals used in these trials. Six brushtail possums (*Trichosurus vulpecula*; mean 3.06 ± 0.19 kg se), and six red-bellied pademelons (*Thylogale billardierii*; mean 7.74 ± 1.21 kg se) were used in the trials, represented by three adult females and three adult males of each species. Brushtail possums were captured in Mascot traps in the greater Hobart area in the three weeks prior to the trials. The possums were housed in sheltered pens measuring 4.3 m × 1.7 m × 2.5 m. Pens had concrete floors, wire mesh walls and ceiling, and polycarbonate roofing. Each possum had fresh water, a wooden nest box and climbing poles provided. Pademelons were selected from a captive population maintained in the University of Tasmania Animal Compound. They were housed in open wire netting pens with earth floors and measuring 4 m × 8 m. A roofed shelter with bedding straw and fresh water was provided in each pen. All animals were fed once a day and weighed regularly to monitor condition.

Basal diets used as animal feed

Prior to the trials, brushtail possums were introduced to a freshly prepared diet (basal diet) consisting of silver beet, carrot, apple, lucerne and sugar. Possums were fed basal diet to ensure body weight was maintained and all individuals were feeding well. Basal diet was offered at 50% maintenance on the nights seedlings were presented to the possums in the first three trials. No basal diet was offered with seedlings for the fourth trial. Possums were offered 150% basal diet on the night immediately following trial night 3, and 100% basal diet thereafter until the next trial began.

Pademelons were fed pasture replacement stock feed pellets manufactured by Monds and Affleck, Carrick, Tasmania (their normal daily maintenance diet). The basal diet was offered based on body weight, and was supplemented with silver beet, carrot and apple on non-trial days. Pademelons were offered 100% basal diet pellets on non-trial nights, 50% basal diet pellets during the first three trials, and no basal diet during the fourth trial.

Trial design

Four separate repellent trials were conducted over four consecutive weeks during November and December 2006. Animals were given at least one week to acclimate to pens or cages before commencing trials. The first three trials were paired feeding trials, where one repellent was tested against control (untreated) seedlings over three nights. The fourth trial was a cafeteria-style feeding trial, where all three repellents were offered simultaneously over three nights with no control seedlings, to determine any preferences among treatments. Repellents were applied to seedlings, as per manufacturer's instructions, on Mondays, and the seedlings were placed in 81-cell Lännen trays and sat in shallow dishes of water to keep the roots moist over subsequent days of the trial. Control seedlings for each week's trial were kept in similar conditions. Seedlings were offered to animals on Tuesday, Wednesday and Thursday afternoons each week. Trays were removed and scored the following morning; fresh seedlings were used for each day of the trial. Possums received one tray containing 15 control seedlings and another tray containing 15 treatment seedlings (total 30 seedlings plus 50% basal diet) each night for the first three trials, and three trays, each containing 15 of one treatment (total 45 seedlings with no basal diet) each night during the fourth trial. Pademelons received 8 control and 8 treatment seedlings (total 16 seedlings plus 50% basal diet) each night for the first three trials, and 8 of each treatment (total 24 seedlings with no basal diet) each night during the fourth trial. Tray positions were alternated each day to reduce any position effects. Based on previous studies, these amounts were considered *ad libitum* for both species (Miller *et al.* 2006b).

Data collection

Before being offered to animals, all seedlings were inspected to ensure there was no damage. After each trial night, seedlings were removed from the pens and scored for browsing damage. Damage was assessed in two parts; whether the apical bud was removed, and the amount of foliage removed. The latter was scored as percentage foliage removed on a scale from 0–6: 0 = 0%, 1 = 1–5%, 2 = 6–25%, 3 = 26–50%, 4 = 51–75%, 5 = 76–95%, 6 = 96–100%. The same observer was used for each assessment to ensure consistency.

Statistical analysis

Three variables were examined for each trial: the percentage of seedlings browsed, the percentage of foliage removed from seedlings, and the percentage of seedlings with apical buds removed. To calculate the percentage of foliage removed, or browsing severity, browsing scores were converted to median values of percentage foliage removed by mammals (e.g. a score of 2 = 15.5%). Results were then averaged for each treatment

by animal and day. The percentage of seedlings browsed and the percentage of seedlings with apical buds removed were calculated as the number of seedlings with damage, divided by the total number of seedlings. Data from the four trials and two herbivore species were analysed separately. For all statistical tests, residuals were checked for homoscedasticity and normality; no transformations were required (Zar 1996). All analyses were conducted in SAS 9.1 (SAS Institute Inc. 2004).

For each experiment, a linear mixed model was fitted to the day mean or proportion data with animal (df = 5) and animal × treatment (df = 5, or in the case of Trial 4 df = 10) treated as random effects, and day, treatment and their interaction treated as fixed effects. The random animal × treatment interaction term was used to test the fixed treatment effect. This model was fitted with Proc Mixed procedure of SAS using REML. Where significant ($P < 0.05$) treatment effects were found, pairwise comparisons were made using the Tukey–Kramer adjustment for multiple comparisons. Unless stated otherwise, there was no significant effect of day or day × treatment interaction.

Results

Trial 1: Plant Plus vs control

Brushtail possums

Possums showed a preference for control seedlings over those treated with Plant Plus (Fig. 1), removing significantly more foliage from control seedlings ($F_{1,5} = 7.9$; $P = 0.038$). There was also a trend toward browsing a higher proportion of control seedlings ($F_{1,5} = 6.5$; $P = 0.051$), and removing more apical buds from control than from Plant Plus-treated seedlings ($F_{1,5} = 6.6$; $P = 0.051$). Apical buds were removed from almost all seedlings that were browsed.

Pademelons

Pademelons also showed a preference for control seedlings, but there was a much greater difference between treatments than seen

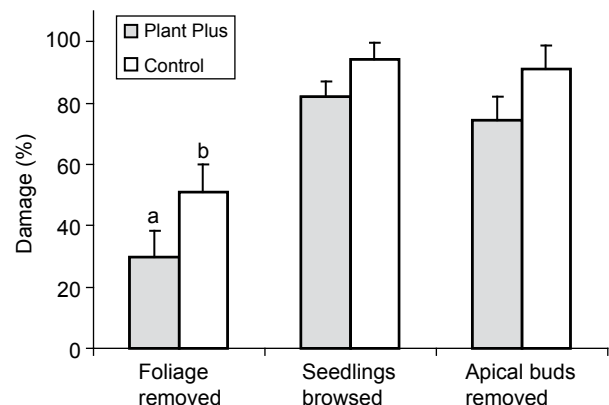


Figure 1. Damage to *E. nitens* control and Plant Plus-treated seedlings by possums in Trial 1. The difference between treatments within each group of columns is significant when the associated letters are different ($P < 0.05$).

with possums (Fig. 2). Pademelons removed significantly more foliage from control seedlings than from those treated with Plant Plus ($F_{1,5} = 36.0$; $P = 0.002$). They browsed the same percentage of control seedlings as possums (94%), but only 51% of seedlings treated with Plant Plus, compared with 82% for possum ($F_{1,5} = 24.8$; $P = 0.004$). They also removed twice as many apical buds from controls ($F_{1,5} = 10.4$; $P = 0.024$). There were significant day \times treatment interactions for the percentage of seedlings browsed ($F_{2,20} = 9.08$; $P = 0.002$), and apical buds removed ($F_{2,20} = 4.8$; $P = 0.019$). The former was due to the number of Plant Plus-treated seedlings browsed being significantly different to the number of control seedlings browsed only on Days 1 and 3, while the latter was because the percentage of Plant Plus treated seedlings with apical buds removed was lowest on Day 1, when removal from control seedlings was highest.

Trial 2: Hot Shot vs control

Brushtail possums

Unexpectedly, possums showed a preference for seedlings treated with Hot Shot over controls (Fig. 3). They removed significantly

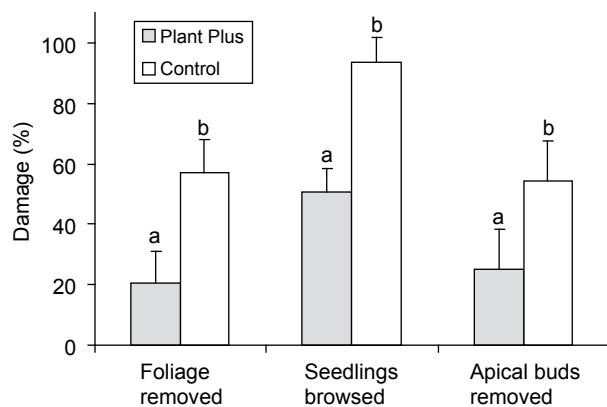


Figure 2. Damage to *E. nitens* control and Plant Plus-treated seedlings by pademelons in Trial 1. The difference between treatments within each group of columns is significant when the associated letters are different ($P < 0.05$).

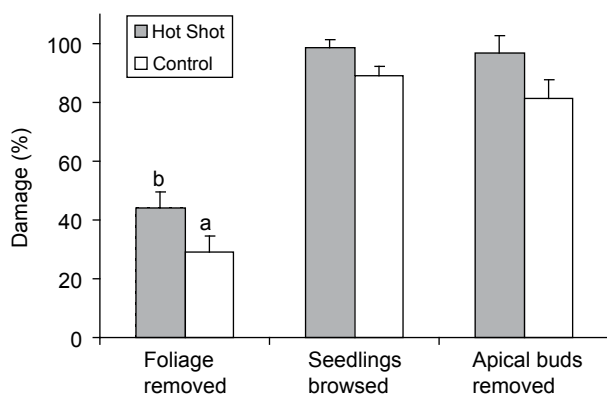


Figure 3. Damage to *E. nitens* control and Hot Shot-treated seedlings by possums in Trial 2. The difference between treatments within each group of columns is significant when the associated letters are different ($P < 0.05$).

more foliage ($F_{1,5} = 7.8$; $P = 0.039$) from Hot Shot-treated seedlings, and there were trends toward browsing more Hot Shot-treated than control seedlings ($F_{1,5} = 5.7$; $P = 0.062$), and removing more apical buds from these ($F_{1,5} = 5.9$; $P = 0.059$). Once again, almost all seedlings that were browsed had their apical buds removed. There were also significant day effects for the amount of foliage removed ($F_{2,20} = 3.5$; $P = 0.049$) and the percentage of seedlings browsed ($F_{2,20} = 4.5$; $P = 0.024$), due to increasing severity and extent of browsing over the three days.

Pademelons

Pademelons preferred control seedlings to Hot Shot-treated seedlings (Fig. 4). Pademelons removed almost three times more foliage from control than from treated seedlings, and this difference was significant ($F_{1,5} = 10.0$; $P = 0.025$). They also removed significantly more apical buds from controls ($F_{1,5} = 7.6$; $P = 0.040$), and tended to browse more control than Hot Shot-treated seedlings ($F_{1,5} = 6.3$; $P = 0.054$). There were significant day \times treatments interactions for all variables (foliage removed: $F_{2,20} = 6.7$; $P = 0.006$; seedlings browsed: $F_{2,20} = 6.6$; $P = 0.007$; and apical buds removed: $F_{2,20} = 5.5$; $P = 0.013$), due to much lower browsing of Hot Shot on Day 2.

Trial 3: Sentree vs controls

Brushtail possums

Possums showed a marked preference for control seedlings over Sentree-treated seedlings (Fig. 5). They removed 14 times more foliage from control seedlings ($F_{1,5} = 42.6$; $P = 0.001$) than from treated seedlings. Every control seedling was browsed (100%), while significantly fewer Sentree-treated seedlings were browsed ($F_{1,5} = 14.8$; $P = 0.012$). Apical bud removal again mirrored that of percentage seedlings browsed ($F_{1,5} = 15.2$; $P = 0.011$).

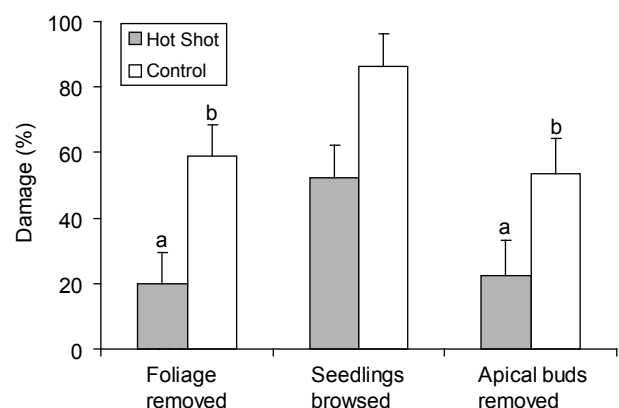


Figure 4. Damage to *E. nitens* control and Hot Shot-treated seedlings by pademelons in Trial 2. The difference between treatments within each group of columns is significant when the associated letters are different ($P < 0.05$).

Pademelons

Pademelons showed a highly significant preference for control seedlings over Sentree-treated seedlings (Fig. 6). They removed 79% of control seedling foliage compared with just 1% of treated seedling foliage ($F_{1,5} = 102.8$; $P < 0.001$). Pademelons browsed over six times more control seedlings ($F_{1,5} = 701.0$; $P < 0.001$), and removed significantly more apical buds from these ($F_{1,5} = 28.5$; $P = 0.003$).

Trial 4: Repellent cafeteria

Brush-tail possums

When offered no alternative to treated seedlings (that is, no control seedlings), possums showed a clear preference for Hot Shot-treated seedlings, followed by Plant Plus- and then Sentree-treated seedlings (Fig. 7). These were all significantly different in the amount of foliage removed ($F_{2,10} = 26.3$; $P < 0.001$) and the percentage of apical buds removed ($F_{2,10} = 25.7$; $P < 0.001$). There was no significant difference in the number of Plant Plus- and

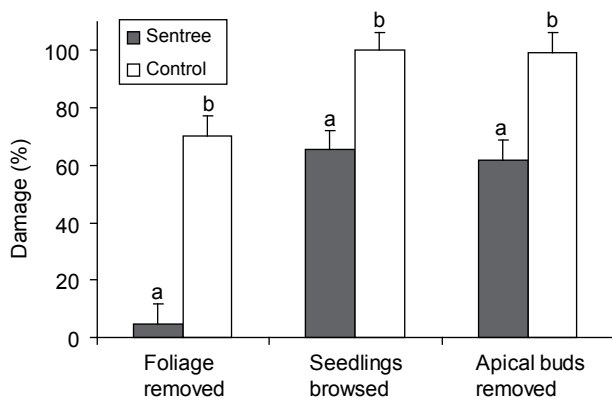


Figure 5. Damage to *E. nitens* control and Sentree-treated seedlings by possums in Trial 3. The difference between treatments within each group of columns is significant when the associated letters are different ($P < 0.05$).

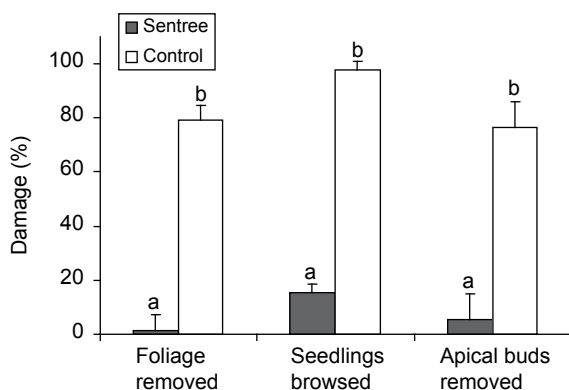


Figure 6. Damage to *E. nitens* control and Sentree-treated seedlings by pademelons in Trial 3. The difference between treatments within each group of columns is significant when the associated letters are different ($P < 0.05$).

Hot Shot-treated seedlings browsed, but these were significantly greater than the number of Sentree-treated seedlings browsed ($F_{2,10} = 24.7$; $P < 0.001$). When offered in combination with the other repellents, possums attacked markedly fewer Sentree-treated seedlings than when offered with controls (Trial 3). The percentage of foliage removed from Sentree-treated seedlings was, however, similar in both trials. There was a significant day \times treatment interaction in the percentage of seedlings browsed, due to an increasing number of Sentree-treated seedlings attacked each day ($F_{4,30} = 3.5$; $P = 0.019$).

Pademelons

When offered together, pademelons consumed significantly more foliage from Plant Plus-treated seedlings than from Sentree-treated seedlings; Hot Shot-treated seedlings were not significantly different from either ($F_{2,10} = 7.5$; $P = 0.010$). They browsed significantly more Plant Plus-treated seedlings than Hot Shot- or Sentree-treated seedlings ($F_{2,10} = 13.2$; $P = 0.002$). There was also a trend for more apical buds to be removed from Plant Plus-treated seedlings than Sentree-treated seedlings ($F_{2,10} = 4.1$; $P = 0.051$). There were significant day \times treatment interactions for the number of seedlings browsed ($F_{4,30} = 7.3$; $P < 0.001$) and apical buds removed ($F_{4,30} = 4.3$; $P = 0.007$); these were due to seedlings treated with Plant Plus being damaged significantly more than Hot Shot-treated seedlings on Day 3 only. The preference in this cafeteria trial of pademelons for Plant Plus over Hot Shot (Fig. 8) contrasts with results from the paired-choice trials, where pademelons consumed a similar amount of foliage from seedlings treated with Plant Plus (Trial 1) and Hot Shot (Trial 2) repellents when offered with controls (Figs 2 and 4).

Discussion

Type of seedling damage

On average, possums consumed more *E. nitens* foliage than pademelons and the type of damage to seedlings was quite different between the two herbivores. The amount of apical buds removed from seedlings was notably different between species. Possums always removed a higher proportion of apical buds from seedlings, and this was actually similar to the percentage of seedlings browsed, showing that almost all seedlings that were browsed had their apical bud removed. This was not the case for pademelons, who on average removed apical buds from only half to two-thirds of seedlings browsed. This preference of possums for apical buds and pademelons for older leaves has also been reported by McArthur *et al.* (2000), and more recently by Loney *et al.* (2006). It is important to distinguish between loss of foliage and apical bud loss, even though the apical bud accounts for a small proportion of seedling biomass. Apical bud removal can lead to poor growth form, such as the development of multiple leaders and tree malformation (Volker and Orme 1988; Bulinski and McArthur 1999).

All three measures (% foliage removed, % seedlings browsed and % apical buds removed) showed the same pattern with regard to the preferences of both animal species in all trials. Any of these measures could therefore be used in isolation in order to judge simple preferences. Results suggest that animals were deterred (or attracted in the case of possums and Hot Shot) by the repellents

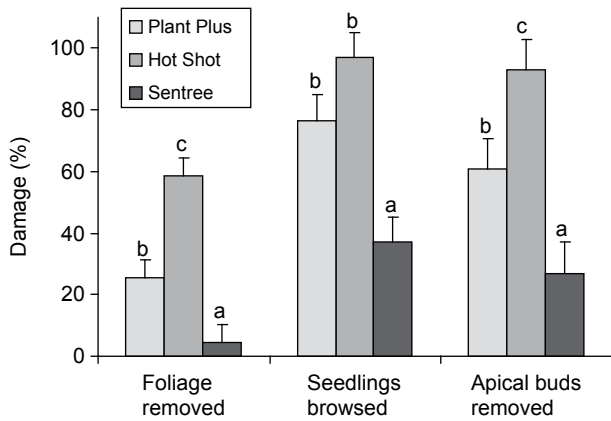


Figure 7. Damage to *E. nitens* seedlings treated with one of three repellents by possums in Trial 4. The difference between treatments within each group of columns is significant when the associated letters are different ($P < 0.05$).

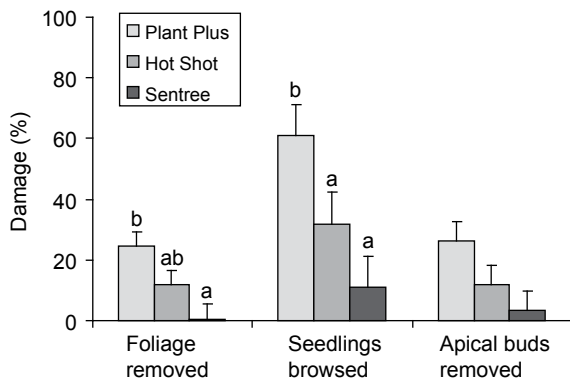


Figure 8. Damage to *E. nitens* seedlings treated with one of three repellents by pademelons in Trial 4. The difference between treatments within each group of columns is significant when the associated letters are different ($P < 0.05$).

before tasting seedlings. If animals had to taste seedlings in order to be repelled, then one would expect the percentage of control versus repellent-treated seedlings browsed to be similar, with preferences only showing up in the percentage of foliage removed, which was not the case.

Repellent effectiveness

While all repellents tested proved to be effective in reducing browsing of *E. nitens* seedlings by pademelons, only two of the three repellents were effective against possum. Interestingly, the third repellent, Hot Shot, was effective only against pademelon, and was actually an attractant to possum. As predicted, Sentree was the most effective repellent against both species, with only 4.9% of foliage removed by possums and 1.5% by pademelons in the paired-choice feeding trials. Similarly, in the cafeteria trial, Sentree was convincingly the most effective repellent. The preference for control over Sentree-treated seedlings in Trial 3 is much greater than that reported by Witt (2002), where in paired-choice trials with *E. globulus*, pademelons consumed only

eight times more foliage from control than from Sentree-treated seedlings — compared with 53 times more here.

The superior effectiveness of Sentree is likely due to its dual mode of action, i.e. it acts as both an odour deterrent and a palatability reducer (or uses both fear and taste modes of action). The effectiveness of a range of repellents based solely on egg odour (e.g. Big Game Repellent, Liquid Shotgun and Treepel) has been demonstrated against a range of herbivores (Montague *et al.* 1990; Andelt *et al.* 1991, 1992; Woolhouse and Morgan 1995). It would be interesting to compare Sentree to those repellents to determine the relative effectiveness of the egg odour versus the grit. Although Sentree repellent has a two-step application process, its marked effectiveness outweighs the greater effort required to apply it when compared to Plant Plus repellent. It is arguably easier to apply than the gel-based Hot Shot repellent.

Hot Shot proved very effective in preventing pademelon browsing, reducing browsing to one-third of that of untreated seedlings, but fell somewhat short of expectations as far as possums are concerned. There are many cases where capsaicin-based repellents have failed to deter animals. For example, chilli powder did not deter rabbits from feeding on *Pinus radiata* or *E. regnans* (Marks *et al.* 1995). However, there are no examples in the literature of capsaicin being an attractant to mammals. It is unclear what properties of the repellent made it attractive to the possums. It is possible that Hot Shot may have been repellent to possums if the concentration of capsaicin was higher. Andelt *et al.* (1994) reported a decrease in the consumption of apple twigs by mule deer with an increase in the concentration of capsaicin applied.

While Sentree was the most effective repellent in this study, the effectiveness of repellents can be animal specific. For example, Andelt *et al.* (1992) conducted a comparable trial with captive elk and alfalfa cubes, comparing coyote urine odour, egg odour (in the form of chicken egg and Big Game Repellent, which is 37% putrescent egg solids) and capsaicin-based (Hot Sauce) repellents. They found urine to be most repellent to elk, followed closely by egg odours, with significantly more capsaicin-based repellent treated food consumed. All repellent-treated foods were consumed significantly less than controls. This pattern differs from those observed here with pademelons and possums, and highlights the importance of species variability to repellent effectiveness. Although previous work has shown that it is not necessary for the animal to recognise the predator for it to be effective, animals such as elk that are commonly preyed on by canids could perhaps be more sensitive to repellents based on predator odours (which are usually canid-based) than our local Tasmanian herbivore species, which are generally not subject to such predation. Alternatively, the superior effectiveness of Sentree in this trial could simply be due to its dual mode of action.

Shortcomings of repellents

It should be noted that in each case the repellent treatments were not as effective in protecting the apical buds as the rest of the seedling. The loss of the apical bud can lead to serious growth form damage to the seedling, producing stunting, double leaders and poor sawlog trees, particularly if the bud is repeatedly removed. Loss of these buds could be due to them being

preferentially browsed by the animals, particularly in the case of possums that frequently eat seedlings from the top down (Loney *et al.* 2006). However, we noted that the application of the repellents often missed these small tips of the seedlings, and this is another possible explanation why such heavy damage was sustained by the apical buds. Alternatively, such a small surface area can receive only a small application of repellent — sufficiently small perhaps for a browser to try before the repellent is detected. The bud may be subsequently spat out, but the damage to the seedling remains the same.

Unlike some other seedling manipulation strategies, for example the use of more resistant seedling stock (O'Reilly-Wapstra *et al.* 2002, 2004), repellents have a limited life-span. All repellents tested here are contact repellents, protecting only foliage coated in repellent. This means that new growth is unprotected, and these repellents can be washed off plants by heavy rain. Plant Plus was recently tested in a small-scale field trial and, although it initially reduced browsing relative to controls, new, unprotected growth began to emerge after just three weeks, after which repellent effectiveness significantly declined (Miller *et al.* 2006a). Therefore, in order to maintain effectiveness, repellents must either be regularly re-applied until seedlings are past the stage where they are vulnerable to browsing, or be used in combination with other methods. For example, repellents could be used to protect seedlings immediately after planting and provide a window of protection to enable browsing monitoring to determine whether additional control is needed.

Recommendations

While all repellents tested proved to be effective to some extent against pademelons, only two of the three proved effective against the brushtail possum. Results suggest that Sentree is the best repellent to use to prevent browsing by brushtail possums and pademelons. No matter which repellent is used, particular care should be taken to coat the apical buds to ensure these are not targeted by the browsers. We did not note a strong smell associated with the egg-base application of Sentree, and considered the carborundum grit as possibly the main deterrent to browsing. It would therefore be interesting to apply the grit to the Plant Plus repellent to see if it increased its effectiveness. Further trials are required to test the long-term effectiveness of these repellents, especially to determine the feasibility of re-application in the field and, if feasible, how often the repellent needs to be re-applied. Additionally, studies investigating any potential long-term damage from the applications would be beneficial.

While we have focused on a Tasmanian situation, *E. nitens* is a common plantation species throughout south-eastern Australia and, although the pademelon species tested occurs only in Tasmania, brushtail possums are Australia-wide. Therefore, results from this study could be extrapolated to other areas where there are problems of possum feeding on *E. nitens* plantations. Repellents work by influencing feeding behaviour, and therefore our results should also be applicable across the range of mammalian herbivores that affect plantation establishment, including wallaby, rabbit and deer.

Now that the superior effectiveness of Sentree has been revealed, the next step is to work on incorporating Sentree repellent into an

integrated browsing management strategy. Studies have shown repellent effectiveness to be dependent upon an animal's level of hunger (Andelt *et al.* 1992), so repellents are unlikely to be effective in isolation on sites with high browsing pressure (i.e. high animal numbers). Future work should therefore include testing repellents in combination with other control methods, for example shooting to reduce browsing pressure, or in combination with more resistant stock, which may help protect plant parts not covered with repellent.

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References

- Andelt, W.F., Burnham, K.P. and Manning, J.A. (1991) Relative effectiveness of repellents for reducing mule deer damage. *Journal of Wildlife Management* **55**, 341–347.
- Andelt, W.F., Baker, D.L. and Burnham, K.P. (1992) Relative preference of captive cow elk for repellent-treated diets. *Journal of Wildlife Management* **56**, 164–173.
- Andelt, W.F., Burnham, K.P. and Baker, D.L. (1994) Effectiveness of capsaicin and bitrex repellents for deterring browsing by captive mule deer. *Journal of Wildlife Management* **58**, 330–334.
- Beauchamp, G.K. (1997) Chemical signals and repellency: problems and prognosis. In: Mason, J.R. (ed.) *Repellents in Wildlife Management: Proceedings of a Symposium*. National Wildlife Research Centre, Denver, Colorado, pp. 1–10.
- Boag, B. and Mlotkiewicz, J.A. (1994) Effect of odor derived from lion faeces on behaviour of wild rabbits. *Journal of Chemical Ecology* **20**, 631–637.
- Bulinski, J. and McArthur, C. (1999) An experimental field study of the effects of mammalian herbivore damage on *Eucalyptus nitens* seedlings. *Forest Ecology and Management* **113**, 241–249.
- Coleman, J. D., Montague, T.L., Eason, C.T. and Statham, H.L. (1997) *The Management of Problem Browsing and Grazing Mammals in Tasmania*. Landcare Research Contract Report LC9596/106, Lincoln, New Zealand.
- Delbridge, J. and Lutze, M. (1998) *An Evaluation of the Effectiveness of WR-1 Repellent for Browsing Control in HEMS Forest*. Forests Service, Department of Natural Resources and Environment, Melbourne, Victoria, 12 pp.
- Epple, G., Mason, J.R., Nolte, D.L. and Campbell, D.L. (1993) Effects of predator odors on feeding in the mountain beaver (*Aplodontia rufa*). *Journal of Mammalogy* **74**, 715–722.
- Gillingham, M.P., Speyer, M.R., Northway, S. and McLaughlin, R. (1987) Feeding preference and its relation to herbivore repellent studies. *Canadian Journal of Forest Research* **17**, 146–149.
- Harman, V. (1996) Wallaby repellent trials. Silviculture Section, Commercial Forestry Branch, Department of Natural Resources and Environments, Melbourne, *Native Forest Silviculture News*, pp. 11–12.
- Johnston, M.J., Marks, C.A., Moore, S.J., Fisher, P.M. and Hague, N. (1998) WR-1 and AD-3 browsing repellents: a journey from problem to product. In: Pickles, G. (ed.) *Eleventh Australian Vertebrate Pest Conference*. Programme and proceedings. Bunbury, Western Australia, 3–8 May. Promaco Conventions Pty Ltd, Perth, WA, Australia, pp. 305–311.

- Loney, P.E., McArthur, C., Potts, B.M. and Jordan, G.J. (2006) How does ontogeny in a *Eucalyptus* species affect patterns of herbivory by brushtail possums? *Functional Ecology* **20**, 982–988.
- McArthur, C., Goodwin, A. and Turner, S. (2000) Preferences, selection and damage to seedlings under changing availability by two marsupial herbivores. *Forest Ecology and Management* **139**, 157–173.
- Marks, C.A., Fisher, P., Moore, S. and Hague, N. (1995) Techniques for the mitigation of plantation seedling damage by the European rabbit (*Oryctolagus cuniculus*) and swamp wallaby (*Wallabia bicolor*). In: Statham, M. and Buggy, K. (eds) *Tenth Australian Vertebrate Pest Control Conference*. Proceedings. Department of Primary Industry and Fisheries, Hobart, Tasmania, pp. 155–160.
- Mason, J.R. (1997) Vertebrate repellents: mechanisms, practical applications, possibilities. In: Wagner, K.K. and Nolte, D.L. (eds) *Wildlife Damage Management for Natural Resource Managers*. United States Department of Agriculture, Animal and Plant Health Inspection Service, Olympia, Washington, USA.
- Miller, A.M., McArthur, C. and Smethurst, P.J. (2006a) Characteristics of tree seedlings and neighbouring vegetation have an additive influence on browsing by generalist herbivores. *Forest Ecology and Management* **228**, 197–205.
- Miller, A.M., McArthur, C., Smethurst, P.J. and Wang, S.F. (2006b) Preferences of two mammalian herbivores for tree seedlings and potential cover crops in plantation forestry. *Australian Forestry* **69**, 114–121.
- Montague, T.L., Pollock, D.C. and Wright, W. (1990) An examination of the browsing animal problem in Australian eucalypt and pine plantations. In: Davis, L.R. and Marsh, R.E. (eds) *Fourteenth Vertebrate Pest Conference*. University of California, Sacramento, California, pp. 203–208.
- Morgan, D.R. and Woolhouse, A.D. (1998) Predator odors as repellents to brushtail possums and rabbits. In: *Repellents in Wildlife Management*. Proceedings of a symposium. National Wildlife Research Centre, Denver, Colorado, pp. 241–252.
- Nolte, D.L., Mason, J.R., Epple, G., Aronov, E. and Campbell, D.L. (1994) Why are predator urines aversive to prey? *Journal of Chemical Ecology* **20**, 1505–1516.
- O'Reilly-Wapstra, J.M., McArthur, C. and Potts, B.M. (2002) Genetic variation in resistance of *Eucalyptus globulus* to marsupial browsers. *Oecologia* **130**, 289–296.
- O'Reilly-Wapstra, J.M., McArthur, C. and Potts, B.M. (2004) Linking plant genotype, plant defensive chemistry and mammal browsing in a *Eucalyptus* species. *Functional Ecology* **18**, 677–684.
- Pfister, J.A., Muller-Schwarze, D. and Balph, D.F. (1990) Effects of predator fecal odors on feed selection by sheep and cattle. *Journal of Chemical Ecology* **16**, 573–583.
- Ramp, D., Russell, B.G. and Croft, D.B. (2005) Predator scent induces differing responses in two sympatric macropodids. *Australian Journal of Zoology* **53**, 73–78.
- Roe Koh and Associates Pty Ltd (2000) Plant Plus Animal Repellent: Product Profile. Melbourne.
- SAS Institute Inc. (2002) *SAS/STAT User's Guide*. SAS Institute, Cary, North Carolina, USA.
- SAS Institute Inc. (2004) *SAS 9.1.2*. SAS Institute, Cary, North Carolina, USA.
- Sullivan, T.P., Crump, D.R., Wieser, H. and Dixon, E.A. (1990) Comparison of release devices for stoat (*Mustela erminea*) semiochemicals used as montane vole (*Microtus montanus*) repellents. *Journal of Chemical Ecology* **16**, 951–957.
- Swihart, R.K., Pignatello, J.J. and Mattina, M.J.I. (1991) Aversive responses of white-tailed deer, *Odocoileus virginianus*, to predator urines. *Journal of Chemical Ecology* **17**, 767–777.
- Volker, P.W. and Orme, R.K. (1988) Provenance trials of *Eucalyptus globulus* and related species in Tasmania. *Australian Forestry* **51**, 257–265.
- Wagner, K.K. and Nolte, D.L. (2001) Comparison of active ingredients and delivery systems in deer repellents. *Wildlife Society Bulletin* **29**, 322–330.
- Weldon, P.J., Graham, D.P. and Mears, L.P. (1993) Carnivore fecal chemicals suppress feeding by alpine goats (*Capra hircus*). *Journal of Chemical Ecology* **19**, 2947–2952.
- Wilkinson, G.R. and Neilsen, W.A. (1995) Implications of early browsing damage on the long term productivity of eucalypt forests. *Forest Ecology and Management* **74**, 117–124.
- Witt, A. (2002) Effects of repellents on seedling growth and herbivory. Honours thesis, University of Tasmania, School of Zoology, Hobart.
- Woolhouse, A.D. and Morgan, D.R. (1995) An evaluation of repellents to suppress browsing by possums. *Journal of Chemical Ecology* **21**, 1571–1583.
- Zar, J.H. (1996) *Biostatistical Analysis*, 3rd edn. Prentice-Hall, Upper Saddle River, New Jersey.