Effects of an aerial 1080 possum poison operation using carrot baits on invertebrates in artificial refuges at Whirinaki Forest Park, 1999–2002

R.G. Powlesland[1*], I.A.N. Stringer[1] and D.I. Hedderley[2,3]

[1]Research, Development & Improvement Division, Department of Conservation, P.O. Box 10-420, Wellington, New Zealand

[2]Statistics Research & Consulting Centre, Massey University, Private Bag 11-222, Palmerston North, New Zealand

[3]Present address: Crop & Food Research, Private Bag 11-600, Palmerston North, New Zealand

*Author for correspondence (E-mail: rpowlesland@doc.govt.nz)

Abstract: The effects of an aerial 1080 possum poison operation using carrot baits on invertebrates in Whirinaki Forest Park are described from an un-replicated study of artificial refuges attached to tree trunks. Auckland tree weta (*Hemideina thoracica*), cave weta (*Pharmacus* sp. and *Isoplectron* sp.), cockroaches, spiders and harvestmen, and leaf-veined slugs (*Athoracophorus bitentaculatus*) were the most frequent occupants, but snails, millipedes, centipedes, flatworms, lepidopteran larvae, glowworm larvae (*Arachnocampa luminosa*), peripatus, slaters and beetles were also present occasionally. Invertebrate numbers were monitored every second or third month for a year before the poison operation, and for two years afterwards. Numbers of tree weta, cave weta, cockroaches, spiders and harvestmen, and leaf-veined slugs did not decline substantially in refuges in the treatment area relative to those in the non-treatment area immediately after the poison operation. Our results, and those from two other similar studies, suggest that aerial 1080 poison operations are unlikely to have a detrimental effect on invertebrates that occupy cavities above ground.

Keywords: 1080; artificial refuges; invertebrate monitoring; New Zealand; sodium monofluoroacetate; vertebrate pest control.

Introduction

The introduced brushtail possum (*Trichosurus vulpecula*) is a serious pest to both indigenous forests and agriculture in New Zealand. Their effects as browsers in forest ecosystems are well documented, and include changing the composition of some plant communities (Atkinson *et al*., 1995; Nugent *et al*., 2000; Payton, 2000; Cowan, 2001). Possums are also predators that may seriously affect native invertebrate and bird populations (Meads *et al*., 1984; Innes *et al*., 1995; Sadleir, 2000; Veltman, 2000; Powlesland *et al*., 2003). As a result, increasing efforts have been made to reduce the numbers of possums by trapping and poisoning them. The main method used over the last 30 years, especially for large areas or where access is difficult because of steep terrain, was aerial broadcasting of carrot or cereal baits containing compound 1080 (sodium monofluoroacetate). This can achieve a reduction in possum numbers of greater than 90% in populations at equilibrium density (Morgan *et al*., 1997; Veltman and Pinder, 2001).

Such 1080 poison operations can also result in high mortality of other introduced pest mammals, including predators, such as ship rats (*Rattus rattus*), stoats (*Mustela erminea*), and feral cats (*Felis catus*), through secondary poisoning (Innes *et al*., 1995; Gillies and Pierce, 1999; Murphy *et al*., 1999). A variety of invertebrates also eat carrot and cereal baits used in 1080 poison operations in indigenous forests, as well as the carcasses of poisoned animals (Hutcheson, 1989; Notman, 1989; Eason *et al*., 1993; Sherley *et al*., 1999; Shrubshall, 1999; Spurr and Drew, 1999; Lloyd and McQueen, 2000), so some invertebrates are poisoned (Notman, 1989; Eisler, 1995; Booth and Wickstrom, 1999). Sherley *et al*. (1999) reported a significant but short-term (6 days) reduction in the numbers of a few species of invertebrates that were observed on toxic baits compared to non-toxic baits, and noted that the effect extended for less than 20 cm from the toxic baits. Other studies comparing the numbers of invertebrates caught in pit-fall traps before and after a 1080 poison operation suggest that any negative effect may be short-lived (Meads, 1994;

Spurr, 1994; Spurr and Powlesland, 1997). Hutcheson (1996, 1999) reported that the greatest species richness and abundance of beetles caught in Malaise traps was associated with areas where mammals had been controlled intensively by aerial 1080 over 3–7 years. However, these effects were lost after two years when control stopped.

Recently, artificial refuges attached to tree trunks were used to monitor the effects of aerial 1080 operations on cavity-dwelling invertebrates, particularly tree weta (Orthoptera: Anostostomatidae). C. Robertson (Department of Conservation, Hokitika, N.Z., *pers. comm.*) reported substantially greater numbers of Wellington tree weta (*Hemideina crassidens*) in a treatment area that was monitored three months after poisoning compared with numbers in a non-treatment area. In contrast, Spurr and Berben (2004), found that a simulated 1080 bait operation had no significant effect on the numbers of *H. crassidens*, a cave weta (*Isoplectron* sp., Orthoptera: Rhaphidophoridae), slugs, spiders or cockroaches in artificial refuges. Their investigation used a BACI (Before-After/Control-Intervention) design (McDonald *et al.*, 2000) with replication.

In the present paper, we investigate how the numbers of invertebrates in artificial refuges changed in relation to an aerial 1080 poison operation to control possums in Whirinaki Forest. The poison operation was part of an experimental investigation into the effects of an aerial application of 1080 poison baits on kaka (*Nestor meridionalis*) and kereru (*Hemiphaga novaeseelandiae*) over an area of 1880 ha, with a non-treatment area of similar habitat of *c.* 3000 ha nearby (Powlesland *et al.*, 2003). It provided the opportunity to obtain further information on the immediate effects of such an operation on the numbers of invertebrates occupying artificial refuges. However, the cost involved in applying poison to the large area required for studying such mobile birds as kaka and kereru limited the experimental design to a comparison between two areas. Hence, it was not possible to replicate the treatment and non-treatment areas.

The experimental design consisted of counting the invertebrates present in well-established, artificial refuges in both areas during one year prior to and during two years after the poison operation. This is a BACI design without replication. However, there was an erratic relationship between the numbers of invertebrates found in refuges in the two areas during the pre-poison period so occupancy of refuges in the non-poisoned area could not be compared usefully with occupancy in the poisoned area following the poison operation. Instead, differences in occupancy between the two areas were compared directly, although it was inappropriate to apply formal statistical tests in relation to the effects of the poison operation because this would have involved pseudoreplication (Hurlbert, 1984). Artificial refuges are used commonly for monitoring weta, and such monitoring is often done following mammal control in non-replicated situations similar to the present study where there is a single treatment area and a single non-treatment area (Waipapa Ecological Area (H. Speed, Department of Conservation, Pureora, N.Z., *pers. comm.*), Boundary Stream (B. Christensen, Department of Conservation, Rotorua, N.Z., *pers. comm.*). We present our results here to encourage further investigation and publication of similar studies to see whether they produce a common pattern, and whether an effect, or lack of effect, is shown by meta-analysis.

Methods

Study areas

Two areas, Oriuwaka (3000 ha) and Otupaka (1880 ha), in Whirinaki Forest were the non-treatment and treatment (aerial 1080 possum poison operation) study areas, respectively. They are separated by about 4 km at their nearest points, have a nearly continuous cover of dense podocarp or podocarp-hardwood forest, and both have a mainly undulating to moderately steep topography, although Otupaka has a higher elevation (600–900 m a.s.l vs 475–600 m a.s.l.). For a description of the main canopy species in each study area, see Powlesland *et al.* (2003).

Artificial refuges

Artificial refuges made of untreated *Pinus radiata* timber (Fig. 2 *in* Trewick and Morgan-Richards, 2000) were used to monitor cavity-dwelling invertebrates. Each was 0.65 m long and contained 10 cavities, including one large cavity at the top to accommodate harems of Auckland tree weta (*Hemideina thoracica*). The refuges were used previously in Pureora Forest Park from May 1997 to August 1998, and were attached to trees in Whirinaki Forest Park during February–April 1999: 39 in the non-treatment study area and 37 in the treatment area. Refuges were placed non-randomly, in groups of 2–5 within 50 m of each other on tree species with natural cavities, such as the holes made by larvae of *Aenetus virescens*. The median height to the top of the refuges was 1.5 m in both areas (treatment area, range = 1.1–1.9 m, SD = 0.18 m; non-treatment area, range = 1.1–1.7 m, SD = 0.16 m; Mann-Whitney Rank Sum test, $P = 0.599$). Median height of the trees to which the refuges were attached was significantly lower in the non-treatment area (median = 5.0 m, range = 4.0–7.0, SD = 0.72) than in the treatment area (median = 6.0 m, range = 4.0–7.0, SD = 0.89; Mann-Whitney Rank Sum test, $P = 0.009$).

Refuges were attached to the trunks of 30 canopy-forming and nine understorey trees in the non-treatment area, and 19 canopy-forming and 18 understorey trees in the treatment area. In the non-treatment area, 26 refuges were attached to putaputaweta (*Carpodetus serratus*), eight to wineberry (*Aristotelia serrata*), and one each to wheki (*Dicksonia squarrosa*), karamu (*Coprosma robusta*), kahikatea (*Dacrycarpus dacrydioides*), pate (*Schefflera digitata*) and a dead wineberry. In the treatment area, 16 refuges were on putaputaweta, 10 on wineberry, five on pepperwood (*Pseudowintera colorata*), four on mahoe (*Melicytus ramiflorus*), and one each on kaikomako (*Pennantia corymbosa*) and a dead wineberry.

The cavities in each refuge were numbered, and counts of the invertebrates in each cavity were made during the day with the aid of a torch. Most invertebrates were identified to order or family as follows, although a few were identified to species: flatworms (Turbellaria), peripatus (Onychophora), slaters (Isopoda), centipedes and millipedes (Myriapoda), cockroaches (Blattodea: Blattidae), cave weta (*Pharmacus* sp., *Isoplectron* sp.; Orthoptera: Rhaphidophoridae), Auckland tree weta (*Hemideina thoracica*; Orthoptera: Anostostomatidae), beetles (Coleoptera), caterpillars (Lepidoptera), glowworm larvae (*Arachnocampa luminosa*; Diptera: Keroplatidae), spiders and harvestmen (Arachnida: Araneida & Opiliones), leaf-veined slugs (*Athoracophorus bitentaculatus*; Gastropoda: Stylommatophora), and snails (Gastropoda: Pulmonata). Counts were carried out every second or third month, except that there were monthly counts before and after the May 2000 poison operation.

Aerial 1080 operation

Non-toxic, pre-feed carrot baits (not dyed green or cinnamon lured) were aerially broadcast on 1 May 2000 at a rate of 5 kg ha^{-1} over the treatment area. Toxic (1080 at a nominal concentration of 0.08% weight for weight) carrot baits (6–9 g baits), dyed green and cinnamon lured, were spread at 10 kg/ha on 17–18 May 2000. Three samples of bait assayed by gas chromatography by Animal Control Products Ltd, Wanganui, contained 0.073, 0.087 and 0.089% 1080. Baits were distributed from helicopters using differential global positioning systems to ensure they were evenly spread and not dropped in sensitive areas or outside the treatment area. Baits had been screened to remove all fragments of carrot less than 0.5 g before they were coated with toxin.

Statistical analyses

Genstat, 7th edition (VSN International Ltd, Hemel Hempstead, UK, 2003), was used to fit generalised linear models with Poisson distributions and log link functions (Dobson, 1990) to the numbers of Auckland tree weta, cave weta, cockroaches, spiders and harvestmen, and leaf-veined slugs found in refuges during September 1999, November 1999, February 2000 and April 2000 (i.e. pre-poisoning), October 2000, December 2000, February 2001 and April 2001 (i.e. 1 year after poisoning), and October 2001, November 2001, February 2002 and April 2002 (i.e. 2 years after poisoning). Explanatory factors in the model were Area (Treatment, Non-treatment), individual Refuge, Month (September/October, November/December, February, April), Year (Before Poisoning, 1 Year After, 2 Years After), Level (Canopy, Understorey) and Tree Species (Putaputaweta, Wineberry or Other). A number of overall environmental effects were fitted before testing the effects of interest; Area × Year (i.e. whether the patterns over the three years differed between Treatment and Non-treatment areas) and its interaction with Month, Level, and Tree Species. Effects were tested using likelihood ratio tests (Dobson, 1990), which compare the change in deviance ($\Delta = -2 \times$ log-likelihood) with the number of degrees of freedom of the effect. Because the Area × Year × Level and Area × Year × Tree Species terms were not orthogonal, each was tested allowing for all other terms.

Changes in the numbers of invertebrates over time in the treatment and non-treatment areas were compared by plotting means with 95% confidence intervals (± 95% C.I.).

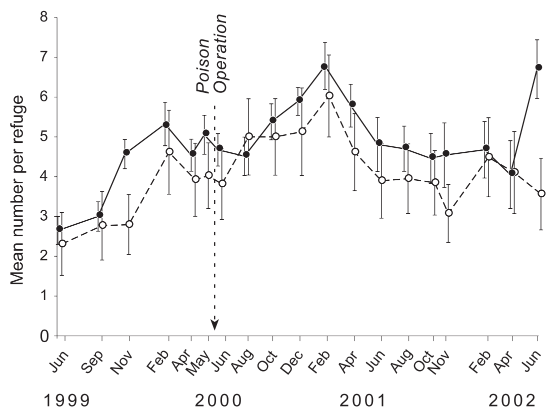

Figure 1. Mean number of cave weta (*Pharmacus* sp. and *Isoplectron* sp.) per artificial refuge (± 95% C.I.) in artificial refuges in 1080-poison treated (37 refuges, •) and non-treated (39 refuges, o) study areas, Whirinaki Forest Park, June 1999–June 2002.

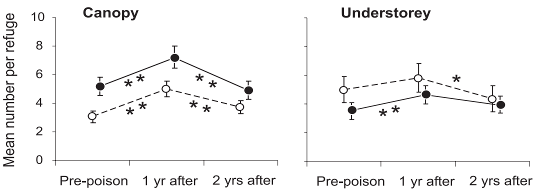

Figure 2. Mean number (± 95% C.I.) of cave weta (*Pharmacus* sp. and *Isoplectron* sp.) in artificial refuges attached to the trunks of canopy and understorey trees in 1080-poison treated (•) and non-treated (o) study areas during three time periods: pre-poison (counts in September and November 1999, and February and April 2000), one year after poisoning (October and December 2000, and February and April 2001), and two years after poisoning (October and November 2001, and February and April 2002). Asterisks denote significance levels between successive time periods: * = $P < 0.05$, ** = $P < 0.01$.

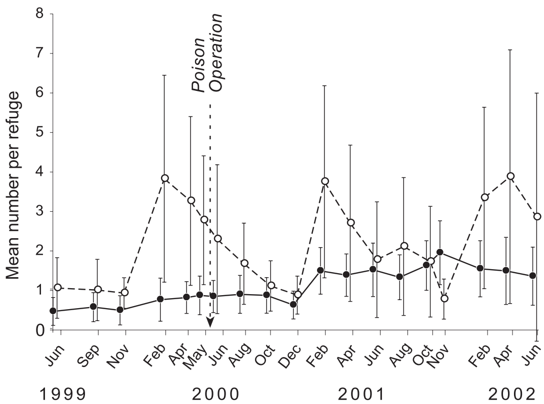

Figure 3. Mean number per refuge (± 95% C.I.) of cockroaches in artificial refuges in 1080-poison treated (37 refuges, •) and non-treated (39 refuges, o) study areas, Whirinaki Forest Park, June 1999–June 2002.

Results

Invertebrates found most frequently in artificial refuges were cave weta (50.0% of all 12 031 invertebrates counted), cockroaches (18.2%), tree weta (*Hemideina thoracica*, (13.8%), spiders and harvestmen (9.2%), and slugs (5.4%). Appendix 1 shows results for the other invertebrates, which comprised fewer than 5% of the total numbers found.

Cave weta

The numbers of cave weta followed similar patterns in both study areas from year to year (Area × Year, Δ = 0.64, d.f. = 2, $P = 0.727$), and there was no significant difference between their numbers in the two areas except in November 1999, before the poison operation, and in June 2002 at the end of the study (Fig. 1). There was, however, a significant difference in the changes in mean numbers in refuges attached to canopy trees compared to those on understorey trees (Area × Year × Level, Δ = 7.62, d.f. = 2, $P = 0.027$). In both study areas, cave weta numbers in the refuges on canopy-forming trees increased significantly during the first year after the poison operation ($P < 0.01$), and then declined to pre-poison levels during the second year ($P < 0.01$) (Fig. 2). Likewise, in refuges on understorey trees, cave weta numbers increased during the first year after the poison operation, but the increase was significant only in the treatment area ($P < 0.01$). Both areas experienced a decline in cave weta numbers in the second year after poisoning, although it was significant only in the non-treatment area ($P < 0.05$).

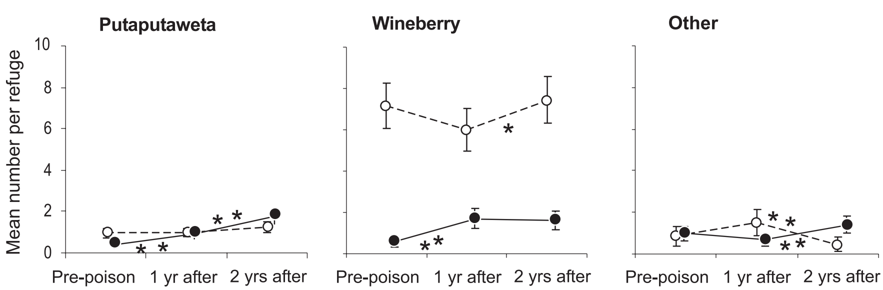

Figure 4. Mean number (± 95% C.I.) of cockroaches in artificial refuges attached to putaputaweta, wineberry, and other trees in 1080-poison treated (•) and non-treated (o) study areas during three time periods (see Fig. 2). Asterisks denote significance levels between successive time periods: * = $P < 0.05$, ** = $P < 0.01$.

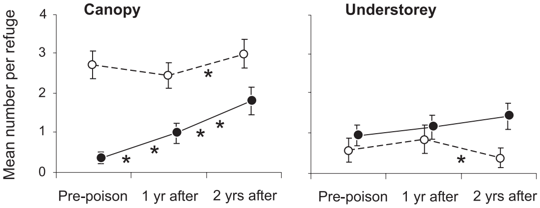

Figure 5. Mean number (± 95% C.I.) of cockroaches in artificial refuges attached to the trunks of canopy and understorey trees in 1080-poison treated (•) and non-treated (o) study areas during three time periods (see Fig. 2). Asterisks denote significance levels between successive time periods: * = P <0.05, ** = P <0.01.

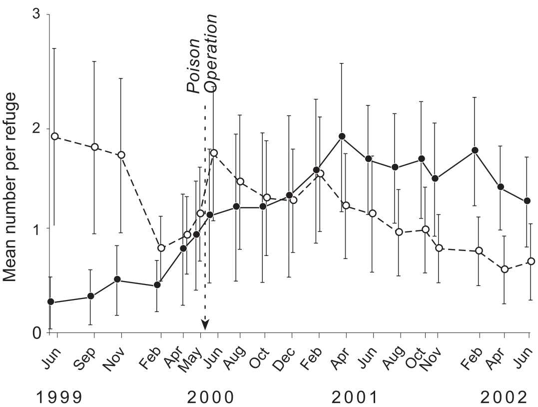

Figure 6. Mean number per refuge (± 95% C.I.) of Auckland tree weta in artificial refuges in 1080-poison treated (37 refuges, •) and non-treated (39 refuges, o) study areas, Whirinaki Forest Park, June 1999–June 2002.

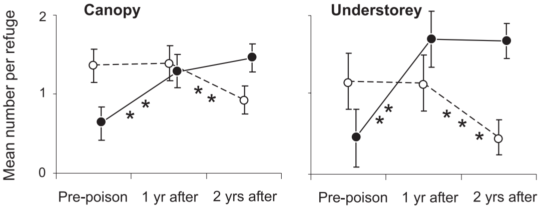

Figure 7. Mean number (± 95% C.I.) of Auckland tree weta in artificial refuges attached to the trunks of canopy and understorey trees in 1080-poison treated (•) and non-treated (o) study areas during three time periods (see Fig. 2). Asterisks denote significance levels between successive time periods: * = P <0.05, ** = P <0.01.

Cockroaches

Although no significant difference in the numbers of cockroaches was found in the two areas on each sample occasion (Fig. 3), there was a significant difference in their seasonal patterns overall (Area × Year × Month, Δ = 16.38, d.f. = 6, P = 0.012). Thus, cockroaches in the treatment area showed a gradual increase in numbers over time, whereas those in the non-treatment area showed marked seasonal fluctuations (Fig. 3). When considered overall, the numbers of cockroaches in the two study areas also showed a significant year-to-year difference (Area × Year, Δ = 32.42, d.f. = 2, P <0.0001). In addition, a significant difference in the number of cockroaches occupying refuges attached to different tree species was found in both study areas (Fig. 4) (Area × Year × Tree species, Δ = 21.88, d.f. = 4, P = 0.0002), and between those attached to canopy-forming and understorey trees (Fig. 5, Area × Year × Level, Δ = 6.74, d.f. = 2, P = 0.035). Cockroach numbers in refuges on putaputaweta trees increased significantly during the first (P <0.01) and second years after the poison operation (P <0.01) in the treatment area, but there was no substantial change in numbers in either year for the non-treatment area (Fig. 4). On wineberry trees in the treatment area, cockroach numbers increased significantly in the first year after the poison operation (P <0.01), then remained at high levels during the second year (Fig. 4). In contrast, cockroach numbers in refuges on wineberry trees in the non-treatment area remained at the same approximate level during the first year, and increased during the second (P <0.05) (Fig. 4).

The numbers of cockroaches found in refuges on canopy trees in the treatment area increased significantly each year (P<0.01), whereas they only increased in the second year in the non-treatment area (P<0.05) (Fig.5). Their numbers remained approximately constant over the two years on understorey trees, except for a decline during the second year in the non-treatment area (P <0.05).

Auckland tree weta

The mean number of tree weta per refuge in the non-treatment area declined by 68% during the study, except for an increase in May–June 2000, and in January–February 2001 (Fig. 6). In contrast, there was a marked rise in numbers through to April 2001 in the treatment area, followed by a slight decline. There were significantly more weta present in refuges in the treatment area than the non-treatment area one year after the poison was applied (Fig. 6). The tree species to which refuges were attached appeared to have no influence on the number of tree weta found in refuges (Area × Year × Tree species, Δ = 2.78, d.f. = 4,

Table 1. Percentages of immature and adult Auckland tree weta (*Hemideina thoracica*) in artificial refuges in treatment and non-treatment study areas each June from 1999 to 2002. Also shown is whether adults were solitary, paired, or members of a harem (1 male with 2 or 3 females) in a cavity.

	Number of weta	Immature (%)	Adult (%)	Solitary (%)	Paired (%)	Harem (%)
Treatment						
1999	11	90.9	9.1	100.0	-	-
2000	42	95.2	4.8	100.0	-	-
2001	62	62.9	37.1	52.2	34.8	13.0
2002	47	8.5	91.5	23.3	27.9	48.8
Non-treatment						
1999	74	95.6	5.4	100.0	-	-
2000	66	87.9	12.1	100.0	-	-
2001	45	37.8	62.2	32.1	14.3	53.6
2002	27	40.7	59.3	25.0	12.5	62.5

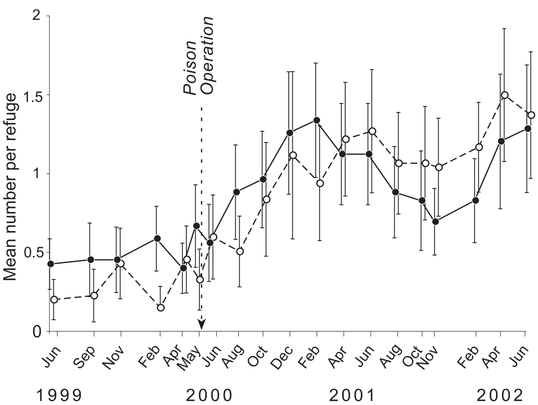

Figure 8. Mean number per refuge (± 95% C.I.) of spiders and harvestmen in artificial refuges in 1080-poison treated (37 refuges, •) and non-treatment (39 refuges, o) study areas, Whirinaki Forest Park, June 1999–June 2002.

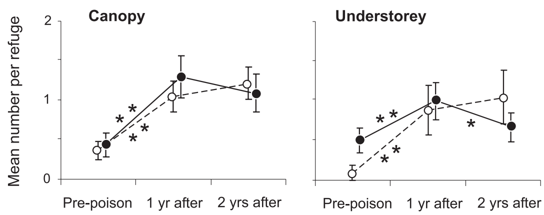

Figure 9. Mean number (±95% C.I.) of spiders and harvestmen in artificial refuges attached to the trunks of canopy and understorey trees in 1080-poison treated (•) and non-treated (o) study areas during three time periods (see Fig. 2). Asterisks denote significance levels between successive time periods: * = P <0.05, ** = P <0.01.

P = 0.595). However, the numbers of tree weta found in refuges on the trunks of canopy trees versus understorey trees showed different patterns of change (Fig. 7). Both the increase in numbers in the treatment area one year after the poison operation, and the fall in numbers in the non-treatment area in the second year after the poison operation were greater for weta in refuges on understorey trees than for those on canopy trees (Area × Year × Level, Δ = 0.33, d.f. = 2, P = 0.006).

Adults generally comprised fewer than 10% of tree weta in artificial refuges in both the treatment and non-treatment areas in June 1999 and June 2000, and usually only one adult was found per cavity (Table 1). However, the proportion of adults increased to 37% and 62% in refuges in the treatment and non-treatment areas, respectively by June 2001 when 48% (treatment) and 68% (non-treatment) of adults were paired or in harems (male + 2 or 3 females). By June 2002, the proportion of adults had further increased to 91% and 59% in the treatment and non-treatment areas, respectively (Table 1), with 76% (treatment) and 75% (non-treatment) of adults paired or in harems.

Spiders and harvestmen

The mean number of spiders and harvestmen in refuges in both study areas showed no significant differences, except on one occasion in February 2000 (Fig 8). They remained approximately even prior to the poison operation (May 2000), then increased gradually until

February 2001 (Fig. 8). However, there was a significant overall difference in their annual patterns because relative abundances reversed after April 2001 (Fig. 8; Area × Year, $\Delta = 22.17$, d.f. = 2, $P < 0.0001$). Numbers of arachnids found in refuges on canopy trees followed similar annual patterns in treatment and non-treatment areas, with a significant increase during the first year after the poison operation ($P < 0.01$), and high numbers during the second year (Fig. 9). Numbers of spiders and harvestmen in refuges on understorey trees increased significantly in both study areas during the first year ($P < 0.01$), remained high in the non-treatment area in the second year, but declined significantly in the treatment area ($P < 0.05$) (Fig. 9). Overall, numbers of spiders and harvestmen found differed appreciably between refuges on canopy and understorey trees in the two study areas (Area × Year × Level, $\Delta = 9.63$, d.f. = 2, $P = 0.008$).

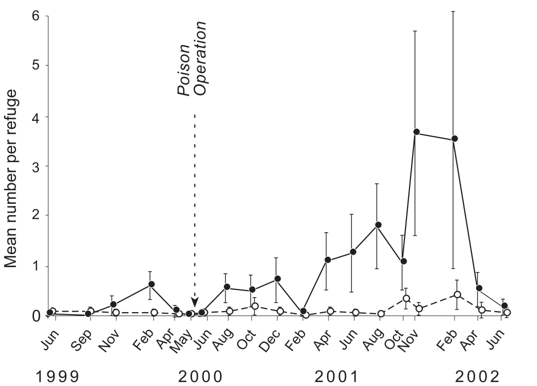

Figure 10. Mean number per refuge (± 95% C.I.) of leaf-veined slugs in artificial refuges in 1080-poison treated (37 refuges, •) and non-treated (39 refuges, ○) study areas, Whirinaki Forest Park, June 1999–June 2002.

Slugs

The number of leaf-veined slugs found in refuges increased in both treatment and non-treatment study areas during the study, but the increase was greatest in the treatment area (Fig. 10). Usually, there were significantly more slugs in refuges in the treatment area during summer. The numbers of slugs in both areas declined each year during late summer and autumn, but the timing of the decline varied from year to year (Fig. 10). Most of the variation in the numbers of slugs could be accounted for by environmental effects (either affecting slug numbers in both treatment and non-treatment areas, or applying in one area both before and after the poison operation ($\Delta = 1067.36$, d.f. = 63, $P < 0.0001$)), and by differences between individual refuge locations ($\Delta = 576.63$, d.f. = 38, $P < 0.0001$).

Significant increases occurred in the numbers of slugs after the poison operation but this varied depending on the species of tree to which the refuges were attached. Increases were also more marked in the treatment area than the non-treatment area (Fig. 11) (Area × Year × Tree species, $\Delta = 10.12$, d.f. = 4, $P = 0.039$).

All but two of the 654 slugs found were native leaf-veined slugs. The exceptions were introduced tiger slugs (*Limax maximus*) that were present in the non-treatment area, one in September 2000 and the other in February 2002. Relatively few (71) of the leaf-veined slugs were found in refuges in the non-treatment area. A total of 23 egg clusters were present in the refuges from April 2001 to June 2002. We assumed that any egg cluster present in the same cavity on two or more successive surveys was the same one, and if so some of them were present for up to five months. Only one egg cluster was seen in the non-treatment area, but the total number of clusters found varied little with season: six in spring 2001, five in summer, seven in autumn 2002, and nine in winter.

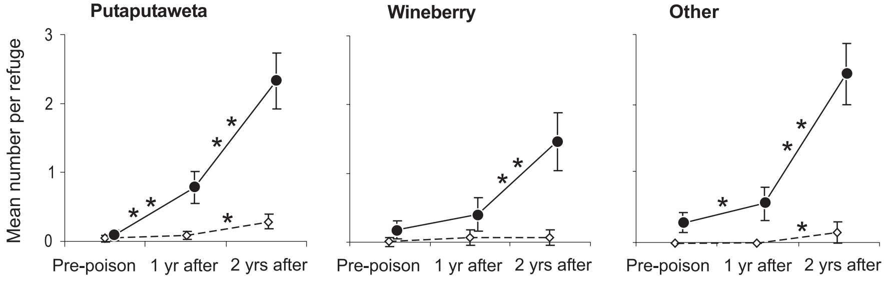

Figure 11. Mean number (± 95% C.I.) of leaf-veined slugs in artificial refuges attached to putaputaweta, wineberry, and other trees in 1080-poison treated (•) and non-treated (○) study areas during three time periods (see Fig. 2). Asterisks denote significance levels between successive time periods: * = $P < 0.05$, ** = $P < 0.01$.

Discussion

Other authors have reported cave weta, cockroaches, tree weta, spiders, slugs, beetles, millipedes, centipedes and even peripatus occurring in varying numbers in artificial refuges (Ordish, 1992; Trewick and Morgan-Richards, 2000; Spurr and Berben, 2004), but glowworm larvae have not been reported previously. Glowworms are common throughout New Zealand in sheltered humid places where small flying insects are plentiful. They often occur under banks in forest along streams and road cuttings, but are seldom found more than a few centimetres from rock or soil (see reviews by Pugsley, 1983; Meyer-Rochow, 1990).

Cave weta, cockroaches, tree weta, spiders and harvestmen, and slugs were the most numerous occupants of the artificial refuges in the present study, and each apparently responded differently to the 1080 poison operation. They are each discussed in more detail below.

Cave weta

The numbers of cave weta (*Pharmacus* sp. and *Isoplectron* sp.) in refuges appeared to be unaffected by the aerial 1080 poison operation in this unreplicated study, even though several species reportedly have been observed on 1080 baits (Spurr and Berben, 2004), and to have ingested the toxin (Lloyd and McQueen, 2000). Spurr and Berben (2004) also found no significant change in the numbers of *Isoplectron* sp. in refuges during the four months after a simulated aerial 1080 operation. The apparent lack of benefit to the cave weta population in the treatment study area at Whirinaki may be due to unknown differences between the two habitats, or it may indicate that the level of predation by stoats and ship rats [which are both known to eat cave weta (Best, 1969; Rickard, 1996)] was insufficient to have a noticeable effect on the cave weta population. The latter might in part be due to cave weta having a more pronounced escape response than tree weta when in areas where mammalian predators occur (Bremner *et al*., 1989).

Cockroaches

No change in the numbers of cockroaches found in refuges could be attributed to the 1080 operation. Cockroaches were consistently more abundant in refuges in the non-treatment area than the treatment area at Whirinaki, both on a seasonal and yearly basis. Similarly, Spurr and Berben (2004) found no significant differences in the numbers of cockroaches occupying artificial refuges in their treatment and non-treatment areas before and after a simulated aerial 1080 operation. Cockroaches were reported to feed on 1080 baits on the ground, but only in low numbers by Sherley *et al*. (1999), Lloyd and McQueen (2000) and Spurr and Berben (2004). Possibly, carrot and cereal baits are not particularly attractive to cockroaches, or perhaps those that shelter in cavities in trees rarely forage on the ground. Cockroaches may also have an effective escape response to the approach of mammalian predators (Bremner *et al*., 1989), and so may not be affected by the presence or absence of mammals.

The marked increases in cockroach numbers in the non-treatment refuges between December and February each summer at Whirinaki (Fig. 3) were largely derived from the same three refuges, all attached to wineberry trees (Fig. 4). These refuges accounted for 60.8%, 58.6% and 45.7% of all cockroaches in the 39 non-treatment refuges in February 2000, 2001 and 2002, respectively. Why these three refuges were particularly attractive as shelters for cockroaches is unknown; there were five other refuges on wineberry trees that few cockroaches occupied.

Auckland tree weta

Our study indicates that an aerial 1080 possum operation could have two effects on tree weta. First, there was no indication of increased mortality of tree weta in refuges in the treatment area after the poison operation. By comparison, their numbers tended to increase following the poison operation but not in the non-treatment area (Fig. 6). In contrast, Spurr and Berben (2004), reported that a simulated 1080 bait application (cereal baits at 5 kg ha^{-1}, 0.15% w/w 1080) had no significant effect on the numbers of *H. crassidens* found in artificial refuges. Captive tree weta are known to feed on 1080 baits and die in the laboratory (Hutcheson, 1989), and *Hemideina* spp. do feed on carrot and cereal baits on the ground (Brown, 1993; Sherley *et al*., 1999; Spurr and Drew, 1999; Lloyd and McQueen, 2000; Spurr and Berden, 2004). It seems likely that few tree weta will be affected by an aerial poison operation because they probably come into contact with the baits rarely. Few aerially-spread baits become lodged in trees and shrubs, where they would be more likely to be eaten by tree weta (Shrubshall, 1999), which seldom go onto the ground, except to oviposit (Moller, 1985). There is even evidence that tree weta become more arboreal when mammalian predators are present (Rufaut, 1995).

Secondly, our study suggests that the poison operation might benefit tree weta in the medium term, as there were markedly more weta in the treatment area than in the non-treatment area two summers after the poison operation (Fig. 6). Likewise, C. Robertson (Department of Conservation, Hokitika, N.Z., *pers. comm.*) found significantly more *H. crassidens* in artificial refuges within a treatment area than within a non-treatment area after an aerial 1080 operation (cereal baits at 4 kg ha^{-1}, 0.15% w/w 1080, April 1998) at Ryan Creek, West Coast. That increase was observed three months after the operation, and so was a more rapid response than we found in the present study at Whirinaki. Both possums (Cowan and Moeed, 1987; Rickard, 1996) and ship rats (Best, 1969; Miller and Miller, 1995; Rickard, 1996) are predators of tree weta, so a likely reason for the increase in weta numbers in the treatment area at Whirinaki was that few of either mammal remained after the poison operation, and in fact abundance indices for both species remained low for over 21 months afterwards (Figs 2 and 3 in Powlesland *et al*., 2003). However, the numbers of mice, which also prey on weta (Ruscoe, 2001), remained high at Whirinaki until November 2000, so the lag in the apparent recovery of the tree weta population in the treatment area may have been a consequence of mouse predation. Certainly, the period when markedly more tree weta were found in the treatment area than the non-treatment area was when mouse abundance declined (R.G. Powlesland, *unpubl. data*). Another possible reason for such a delay is that few tree weta eggs hatch during winter-spring (Stringer, 2001). Just how long the benefits of the poison operation remained for tree weta is not know, but it may not have lasted long after the conclusion of this study in June 2002 because tree weta numbers were declining during February–May 2002 in the treatment area (Fig. 6) when there were moderate increases in the abundance indices of mice and rats.

The increase in the proportion of adult tree weta in artificial refuges during the study, and the increase in numbers of adult weta that were found paired, or in a harem, in the second and third years (Table 1) probably relates mainly to two factors. Firstly, late instar and adult tree weta (*Hemideina* spp.) are relatively site-specific and often occupy the same cavities for extended periods (Field and Sandlant, 2001). Thus, artificial refuges are more likely to be occupied first by early instars of *H. thoracica*, and casual observation suggested this was the case in the present study. Secondly, *H. thoracica* probably takes 1–2 years to mature, as does *H. crassidens* (Stringer and Cary, 2001), and this may explain the delay of about two years after the refuges were set out in April 1999 before pairs and harems of adults were found in them.

Groups of Auckland tree weta were found only in the single large cavity at the top of each of the 76 refuges during the present study. If we assume that this cavity is the only one large enough to accommodate a male and one or more females, then 14.5% and 21.1% of these cavities contained aggregations of adult weta in June 2001 and June 2002, respectively. These values are similar to the 20.8% of natural cavities reported to be occupied by aggregations of *H. crassidens*, but much lower than the 53.6% reported for cavities occupied by *H. femorata* (Field and Sandlant, 2001). Such variation in the occurrence of aggregations of adult tree weta in cavities may be related to species differences, to time of year (assuming that adult mortality peaks in autumn-winter), and/or the suite and density of predators, particularly introduced mammals, that are present.

Spiders and harvestmen

The aerial 1080 possum poison operation had no apparent effect on spider and harvestmen numbers in the refuges. Although there was a substantial difference in the annual numbers of spiders and harvestmen occupying the refuges in both areas during the three-year study, there was no obviously large decline in numbers after the operation in the treatment area, and numbers were greater in the non-treatment area during the third year. Spiders and harvestmen both prey on other invertebrates and they have been found on 1080 baits (Sherley *et al*., 1999; Lloyd and McQueen, 2000). Thus, if their numbers do decline after a 1080 operation, this should result from feeding on invertebrates that had ingested 1080. No studies to date have recorded a decline in populations of these two groups immediately after 1080 operations, whether from monitoring numbers in either refuges (Spurr and Berben, 2004) or pitfall traps (Spurr, 1994, 1996; Sherley *et al*., 1999).

Spiders and harvestmen seem to be favoured foods of ship rats (Rickard, 1996) and mice (Pickard, 1984; Miller and Miller, 1995; Miller, 1999). Thus, it was expected that spider and harvestmen populations would benefit from the Whirinaki 1080 operation that poisoned most rodents. However, this was not apparent in the treatment area, even though rat abundance indices were below 10% (i.e., mean percentage for 10 lines of tracking tunnels per study area containing rat foot-prints, with each line consisting of 10 tunnels at 50-m spacings) for over 18 months (Fig. 3 in Powlesland *et al*., 2003). As discussed above, one possible reason for the absence of an effect was that mouse predation replaced that of rats initially, and subsequently predation by the combined rat and mouse populations was sufficient to suppress any spider and harvestmen population recovery.

Leaf-veined slugs

Although slugs (and snails) have been found on 1080 baits (Sherley *et al*., 1999), we obtained no indication that leaf-veined slugs might be affected by the 1080 operation. Even though there were four to eight times more slugs in the treatment refuges than the non-treatment ones, particularly during the third year of the study (Fig. 10), this difference was most likely due to environmental effects. The most pertinent environmental variable that may favour slugs is probably moisture, and it is possible that the treatment area received either more rainfall, or more mist because it is at c. 200 m higher altitude than the non-treatment area. This may have enabled slugs in the treatment area to remain more active during summer and autumn than those in the non-treatment area where the forest often became dry. Spurr and Berben (2004) and Spurr (1996) also found that 1080 operations had no effect on the numbers of slugs found, respectively, in artificial refuges or in pitfall traps.

Slugs are eaten by ship rats (Best, 1969; Innes, 1990), and because leaf-veined slugs are relatively large (up to 40 mm in length) and slow-moving, a significant increase in their numbers was expected in the treatment area. The slugs were certainly abundant in some refuges in the treatment area (one refuge hosted 44 slugs). It is possible that rodents have little effect on slugs that reside up trees.

Conclusions

It does seem likely that the aerial 1080 possum poison operation using carrot bait at Whirinaki had no detrimental effect on the numbers of cave weta (*Pharmacus* sp. and *Isoplectron* sp.), cockroaches, Auckland tree weta, spiders and harvestmen, and leaf-veined slugs found in artificial refuges attached to tree trunks. Similarly, no detrimental effects were found in two other studies that monitored invertebrates in artificial refuges within forest (Spurr and Berben, 2004; C. Robertson, Department of Conservation, Hokitika, N.Z., *pers. comm.*). In the present study, the poison operation reduced abundance indices for ship rats (% of tracking tunnels with foot-prints) and possums (captures 100 trap-nights^{-1}), substantially, their indices remaining below 10% for at least 12 months afterwards, whereas indices in the non-treatment area stayed at c. 30 captures 100 trap-nights^{-1} for possums and 19–75% tracking for rodents during the same period (Powlesland *et al*., 2003). There was, however, an indication that the tree weta population might benefit from such an extended period of reduced predator abundance after an initial lag because of the long developmental time of tree weta. In addition, the apparent lack of response shown by many invertebrate populations to a reduction in the numbers of mammalian predators may indicate that predation by mammals on tree-dwelling invertebrates in New Zealand forests is low, and that many invertebrates that shelter in tree cavities seldom go onto the ground (Sherley *et al*., 1999; Spurr and Drew, 1999) where they would be more likely to be eaten by mammals.

Also, we obtained evidence that environmental differences between the two study sites probably affected the numbers of invertebrates found in refuges. The treatment area was probably more moist than the non-treatment area, and this may have been responsible, for example, for the marked differences in seasonal patterns of cockroach numbers between the two areas.

From the few studies that have been carried out on the effects of aerial 1080 poison operations on invertebrates in refuges [this study, that on Wellington tree weta at Ryan Creek, West Coast (C. Robertson, Department of Conservation, Hokitika, N.Z., *pers. comm.*), and that by Spurr and Berben (2004)], it appears that such operations have little effect on invertebrates that shelter in trees. Aerial 1080 poison operations are, however, quite variable with regard to bait type, bait size, amount of bait distributed per hectare, and toxin concentration. Hence, comparable studies are warranted in different forest types before it can be concluded that there is little likelihood of 1080 operations having a detrimental effect on invertebrates that live both on the ground and in trees.

Acknowledgements

We thank the staff of the Rangitaiki Area Office for the support they provided for this study, in particular John Sutton, Andy Blick and Rod Warne; to the kaumatua and runanga of Ngati Whare, the kaumatua of Ngati Manawa, and the tangata whenua of Whirinaki Forest Park for endorsement of the aerial 1080 possum control operation and interest in the project; to Dave Wills, Claude August and Andrew August for assistance with mammal population monitoring; to Phil Sirvid for glowworm larva identification, to Gary Barker for slug identification, and Steve Trewick for cave weta identification; to Fletcher Challenge Forests for access along their roads through its forests; to Chris Edkins for the preparation of the figures; and to Eric Spurr, Steve Trewick, Duane Peltzer and two anonymous referees for improvements to drafts of this paper.

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Appendix 1. Number of each uncommon invertebrate type in artificial refuges in treatment (TT) and non-treatment (NT) study areas at Whirinaki Forest Park during 19 monitoring sessions from June 1999 to June 2002.

		Monitoring sessions																		
		Jun 1999	Sep 1999	Nov 1999	Feb 2000	Apr 2000	May 2000	Jun 2000	Aug 2000	Oct 2000	Dec 2000	Feb 2001	Apr 2001	Jun 2001	Aug 2001	Oct 2001	Nov 2001	Feb 2002	Apr 2002	Jun 2002
Snail	TT	1	0	1	6	0	0	5	7	13	5	6	14	9	4	2	1	3	3	8
	NT	0	4	0	2	1	0	0	0	2	5	6	19	5	4	6	0	8	5	12
Myriapoda	TT	3	1	1	4	6	7	6	5	0	3	6	2	2	3	2	3	3	8	6
	NT	5	1	3	0	4	1	3	2	10	6	3	3	4	3	7	8	6	1	5
Flatworm	TT	0	0	0	1	0	3	0	1	2	0	0	0	1	3	2	2	2	4	2
	NT	0	0	0	0	0	1	0	1	1	3	0	0	1	0	0	0	2	2	2
Caterpillar	TT	0	0	0	0	1	0	1	0	2	1	2	6	4	1	0	2	1	3	1
	NT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Glowworm	TT	0	1	0	0	0	0	0	2	3	5	0	0	2	2	5	5	1	0	1
	NT	0	0	0	0	0	0	0	2	3	4	0	0	1	6	8	8	3	0	6
Peripatus	TT	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	NT	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
Slater	TT	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
	NT	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Beetle	TT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	NT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0