Effects of removal of *Tradescantia fluminensis* on *Powelliphanta traversi* and other invertebrates

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ABSTRACT

This study was initiated owing to concern that removal of the invasive ground cover weed *Tradescantia fluminensis* may adversely effect the rare giant predatory land snail *Powelliphanta traversi*. From field trials using hand removal and herbicide spraying, it was considered that graduated control of *Tradescantia* with concomitant replacement of native ground cover could be of benefit to *P. traversi* and other ground-dwelling invertebrates. Grazon® herbicide (active ingredient triclopyr) appears suitable for controlling *Tradescantia* at sites where *P. t. traversi* occurs, since the effects of triclopyr on ground-dwelling invertebrates in the field and first generation *P. t. traversi* in the laboratory were minimal. However, possible effects of triclopyr on subsequent *P. t. traversi* generations remain untested, and evidence from the literature suggests that there could be some detrimental effects. Similarly, the effects of triclopyr on the presumed earthworm prey of *P. t. traversi* remain untested.

Keywords: ground-dwelling invertebrates, pitfall trapping, side effects, *Tradescantia fluminensis*, triclopyr, weed control

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1. Introduction

Weed control measures constitute a significant disturbance to communities, and any benefits they offer need to be weighed up against potential side effects and the estimated impact of continued weed invasion in the event of no weed control (Hobbs & Mooney 1993). *Tradescantia fluminensis* is an invasive weed that constitutes a significant threat to native forest regeneration in New Zealand (Esler 1978; Meurk 1996). Currently, herbicides are considered the only practical means of controlling large infestations of *Tradescantia* (McCluggage 1998), where environmental costs to native flora (e.g. Kelly & Skipworth 1984a; Brown & Rees 1995) are generally accepted in the light of the perceived benefits. Grazon® (active ingredient triclopyr) is used by reserve managers in the Horowhenua district for controlling *Tradescantia* (T. Guard, Wellington Regional Council; J. Davis, Palmerston North City Council; G. Scott, Manawatu District Council). Manual removal is considered suitable for removing small infestations (Porteous 1993), while the effects of hand weeding on native flora are unknown. The effects on native fauna of herbicide use or hand weeding for control of *Tradescantia* remain untested.

The aims of this study were to test the effect on ground-dwelling invertebrates, using pitfall traps, of *Tradescantia* removal by herbicide application, or by hand weeding in a lowland forest remnant. Invertebrates were selected because they play important roles in forest ecosystem functioning (e.g. litter decomposition, nutrient cycling, pollination) and have been considered useful indicator species in studies of habitat disturbance, e.g. spiders (Main 1987a,b), ants (Andersen 1980), mites and collembola (Yeates & Lee 1997), and beetles (Harris & Burns 2000). Pitfall traps were used because they trap ground-dwelling invertebrates, which are most likely to be affected by *Tradescantia* and its removal, and also because they are inexpensive and their limitations are well studied (Marshall et al. 1994).

The response of invertebrates to disturbance is likely to differ among taxa. In this study, weed removal is the last of a number of disturbances to the site, that mostly include habitat fragmentation, habitat modification and weed invasion. The less resilient invertebrates are likely to have already become locally extinct (Harris & Burns 2000). Moreover, invertebrate groups which respond positively to invasion by *Tradescantia* may be among those which respond most negatively to its removal. There are no studies of the effects of triclopyr on terrestrial gastropods, so we determined the effect of a single application of a 1.4% Grazon® solution to *Powelliphanta traversi traversi* in the laboratory. The concentration of Grazon® used is approximately double that used in the field trials, but equivalent to the highest concentration that has been used to control *Tradescantia* (McCluggage 1998).

2. Methods

2.1 FIELD TRIALS

The study site was a roadside forest remnant in Awahuri, lower North Island (NZMS 260 S23 261 035). This small (< 1 ha) podocarp/ broad-leaved forest remnant is situated on a floodplain bordered on one side by farmland, and on the other by a road which separates it from a larger (10 ha) forest remnant. The canopy mainly consists of titoki (*Alectryon excelsus*), mahoe (*Melicytus ramiflorus*) and tawa (*Beilschmiedia tawa*), with a few emergent kahikatea (*Dacrycarpus dacrydioides*). Kawakawa (*Macropiper excelsum*), supplejack (*Ripogonum scandens*) and small-leaved shrubs (e.g. *Streblus heterophyllus*, *Hoheria populnea* var. *lanceolata*) occur in the understorey. *Tradescantia* forms a thick carpet throughout the forest remnant; in the few patches where *Tradescantia* does not occur, ground cover is provided by litter and forest seedlings.

Where *Tradescantia* carpeted the ground, we established 30 contiguous, 5 m × 10 m experimental plots. To compare herbicide application and hand weeding for control of *Tradescantia*, and the effect that season of initial removal had on control success, we divided the plots into five blocks, then randomly assigned initial season of removal (summer (S) or winter (W)) to sets of three plots within each block. The treatments (herbicide application (HB), hand weeding (HW) or non-treatment (NT)) were randomly assigned to plots within seasonal blocks for the first 15 plots, and the assignment was repeated for the second 15 plots. There were five replicates of each treatment. The first summer treatment was applied on 26 February 1997 and re-applied on 24 July 1997 and 13 January 1998. The first winter treatment was applied on 24 July 1997 and re-applied on 13 January 1998 and 31 August 1998. We used Grazon® herbicide (active constituent 600 g/L triclopyr; DowElanco (NZ) Ltd, New Plymouth) on the basis of its successful control of *Tradescantia* in previous trials (Brown & Rees 1995; McCluggage 1998). Using a knapsack, the herbicide was applied to the foliage, at a concentration of 100 mL per 15 L water and at a volume of 6–9 L per plot (equivalent to 1200–1800 L/ ha), depending on the depth of the mat of *Tradescantia* within the plot. Herbicide spraying was carried out on days with no cloud cover and minimal wind. Hand weeding entailed rolling up the *Tradescantia* like a carpet (Porteous 1993) and collecting the remaining fragments, on the day prior to each herbicide application.

Prior to treatment, and at two, nine and 20 weeks post-treatment, soil samples to a depth of 10 cm were collected from herbicide-treated plots and analysed for triclopyr residue by gas chromatography at the National Chemical Residue Laboratory, Upper Hutt, New Zealand. One soil core was collected randomly from each herbicide plot ($n = 5$), and these were mixed together and stored at −20°C pending analysis.

Prior to the initial summer treatment, we randomly selected three replicate plots of each treatment and set up three pitfall traps, 2 m apart and centred within each plot. Each trap was a plastic container 10.5 cm in diameter and 10 cm deep, sunk into the ground so that the rim was level with the soil surface.

Gault's preservative solution (Walker & Crosby 1988) was used. Each trap was covered with a plastic plate 25 cm in diameter, set on two plastic rulers slotted together and fastened with a wire frame. The covers prevented litter and rain from entering the traps, and the plastic rulers slightly increased the perimeter of the traps, increasing the likelihood of an invertebrate encountering and falling into the trap (Luff 1975). Traps were opened for eight days on 5 March 1997 (one week after initial treatment) and again on 17 April 1997 (seven weeks after initial treatment). We recorded rainfall and temperature data at the site using Tinytag® data loggers (Gemini data loggers (UK) Ltd, West Sussex, UK) throughout the invertebrate collection period, since both could influence invertebrate activity (Moeed & Meads 1985).

Invertebrates were sorted to taxonomic levels of Order, Class or Family, with two exceptions. Insect larvae were lumped, and the Hymenoptera were sorted into Formicidae (ants) and others (bees and wasps). Invertebrate abundance and taxonomic richness among treatments, and also abundance of individual taxa among treatments, were analysed using repeated-measures ANOVA (SYSTAT, SPSS Inc. 1996).

2.2 LABORATORY TRIALS

Ten *P. t. traversi* (Shannon Heights form) were collected from Shannon Forest (cf. p. 3) on 22 June 2000. Snails were individually housed in 44 L plastic tanks in a controlled- temperature room (14–17°C), with a light cycle of 11:13 hours (light:dark). Each tank contained a layer of gravel covered with soil and native leaf litter collected from Bledisloe Park, Palmerston North, and were kept damp with distilled water emitted from an atomiser. Snails were acclimatised for 43 days before the experiment began.

To test the effects of exposure of *P. t. traversi* to Grazon® herbicide*,* each tank was randomly assigned to a treatment or non-treatment group. Five tanks containing *P. t. traversi* were sprayed with a 1.4% Grazon® solution (i.e. approximately double the concentration used in the field trial) using a knapsack sprayer (treatment group). Five tanks containing snails were sprayed with tap water, although one snail died just prior to the start of the experiment, reducing the sample size in this group by one (control group). Snails were not sprayed directly, but were present under the leaf litter, which was sprayed until saturated.

The snails' weight, maximum shell length (ML) and maximum shell width (MW) were measured each week for 22 weeks after treatment. Prior to weighing and measurement, each snail was placed in a 2 L plastic container with some leaf litter for two consecutive nights and presented with at least two garden earthworms. After treatment, the reproductive output (number of eggs laid) was noted for each snail, and eggs were weighed. The effect of Grazon® exposure on *P. t. traversi* was tested by comparison of treatment and non-treatment groups using one-factor ANOVA in SYSTAT (SPSS Inc. 1996). Since shell measures were not independent, ML data were selected for the test, and log (x + 1) transformed prior to analysis. A second test of egg weight included the weight of the laying adult as a covariate.

3. Results

3.1 FIELD TRIALS

Triclopyr was not detected in soil samples collected prior to herbicide application. The amounts of triclopyr detected in soils sampled at two, nine and 20 weeks post-herbicide application were: 0.70 ± 0.03, 0.49 ± 0.19 and 0.12 ± 0.03 mg/kg soil respectively (values are means (± SE) across summer and winter treatments).

The mean (± SE) temperature for the collection period 5–12 March 1997 was 14.9 ± 0.2°C, with a range of 11.4–20.1°C, while that for the collection period 17–24 April 1997 was 10.5 ± 0.2°C, with a range of 6.4–14.6°C. Total rainfall for these periods was 34 and 36 mm respectively.

In total, 6630 invertebrates were caught in the two weeks of pitfall trap sampling across experimental treatments. Most of these taxa were rare, constituting less than 1% of the total catch, namely slaters (Isopoda), centipedes (Chilopoda), millipedes (Diplopoda), bugs (Hemiptera), terrestrial snails (Gastropoda), grasshoppers and weta (Orthoptera), moths (Lepidoptera), cicadas, hoppers, etc. (Homoptera) and thrips (Thysanoptera). Mites (Acari) were the most common taxa caught, constituting 36% of the total catch, followed by springtails (Collembola) (31%), sandhoppers (Amphipoda) (9%), flies (Diptera) (4%), beetles (Coleoptera) (4%), spiders (Araneae) (3%) and bristletails (Meinertellidae) (2%). The remainder constituted 1–2% of the total catch, namely harvestmen (Opiliones), false scorpions (Pseudoscorpiones), bees and wasps (Hymenoptera excluding Formicidae), ants (Formicidae) and insect larvae (mostly Coleoptera, Diptera and Lepidoptera). Slightly more invertebrates were caught one week post-treatment (57% of total catch) than at seven weeks post-treatment (43% of total catch; Table 1).

There was no significant difference in the total abundance of invertebrates among treatments at either sampling time (Table 2A), despite a pulse in invertebrate abundance in hand-weeded plots one week after treatment. The magnitude of change between HW plots one week and seven weeks post-treatment was greatest for the following taxa, in decreasing order: bristletails, sand hoppers, false scorpions, beetles, insect larvae, ants, bees and wasps, mites and spiders, of species comprising >1% of total catch (Table 1). There were significantly more bristletails recorded in HW plots at one week post-treatment than in HB or NT plots: $F_{2,6} = 9.66$, $P = 0.013$ (treatment); $F_{1,6} = 6.19$, $P = 0.047$ (time); $F_{2,6} = 11.51$, $P = 0.009$ (time × treatment). There were no other significant differences in abundance of individual invertebrate taxa among treatments, or within treatments between times. The richness of invertebrate taxa differed significantly among treatments (HW > HB = NT), and the interaction between time and treatment indicates that the difference among treatments was more apparent at one week than at seven weeks post-treatment (Table 2B). The pulse in invertebrate taxonomic richness of HW plots was due to an increased catch of a suite of taxa common to all treatments, rather than the appearance of new taxa (Table 1).

TABLE 1. ABUNDANCE OF INVERTEBRATE TAXA CAUGHT IN PITFALL TRAPS SET UP IN EXPERIMENTAL *TRADESCANTIA* PLOTS ONE WEEK (1) AND SEVEN WEEKS (2) FOLLOWING HERBICIDE APPLICATION (HB), HAND WEEDING (HW) AND NON-TREATMENT (NT). DATA ARE SUMS OF THREE PLOTS × THREE TRAPS EXCEPT FOR HW2 FOR WHICH THERE IS ONE TRAP MISSING.

TAXA	HB1	HW1	NT1	HB2	HW2	NT2
Mites (Acari)	333	760	483	359	291	184
Springtails (Collembola)	281	370	198	280	635	271
Sandhoppers (Amphipoda)	101	188	80	131	27	87
Flies (Diptera)	26	56	27	55	36	75
Beetles (Coleoptera)	22	86	58	21	19	28
Spiders (Araneae)	30	89	20	29	26	0
Bristletails (Meinertellidae)**	7	123	5	2	7	3
Harvestmen (Opiliones)	10	29	30	21	14	16
False scorpions (Pseudoscorpiones)	0	47	4	2	9	4
Bees & wasps (Hymenoptera excl. Formicidae)	8	16	17	25	5	17
Ants (Formicidae)	28	30	16	15	7	6
Insect larvae	10	43	8	11	9	8
Slaters (Isopoda)†	8	16	2	12	3	1
Centipedes (Chilopoda)†	0	5	1	0	1	0
Millipedes (Diplopoda)†	6	19	11	6	11	6
Bugs (Hemiptera)†	1	11	2	8	9	1
Terrestrial snails (Gastropoda)†	0	4	1	2	1	5
Grasshoppers & weta (Orthoptera)†	1	7	1	1	4	4
Moths (Lepidoptera)†	1	5	1	1	2	2
Cicadas, hoppers, etc. (Homoptera)†	2	24	14	0	24	1
Thrips (Thysanoptera)†	0	0	0	8	0	0
Total abundance	875	1928	979	989	1140	719
Taxonomic richness	17	20	20	19	20	18

† denotes taxa comprising <1% of total catch; **significant at P<0.01 (see text for details).

TABLE 2. REPEATED-MEASURES ANOVA OF INVERTEBRATE ABUNDANCE (A) AND INVERTEBRATE TAXONOMIC RICHNESS (B) IN HERBICIDE-TREATED, HAND-WEEDED AND NON-TREATMENT PLOTS.

A	BETWEEN SUBJECTS—SOURCE					WITHIN SUBJECTS—SOURCE			
	SS	D.F.	*F*	*P*		SS	D.F.	*F*	*P*
Treatment	15139	2	3.66	0.092	Time	7785	1	3.63	0.106
Error	12419	6			Time × treatment	11385	2	2.65	0.15
					Error	12887	6		
B	**BETWEEN SUBJECTS—SOURCE**					**WITHIN SUBJECTS—SOURCE**			
	SS	D.F.	*F*	*P*		SS	D.F.	*F*	*P*
Treatment	30.22	2	9.66	0.013	Time	6.53	1	6.19	0.047
Error	9.38	6			Time × treatment	24.28	2	11.51	0.009
					Error	6.33	6		

TABLE 3. RESPONSE OF *P. T. TRAVERSI* TO GRAZON® AND WATER (NON-TREATMENT). % CHANGE = (FINAL-INITIAL/INITIAL × 100%) ROUNDED TO NEAREST WHOLE NUMBER, NEGL. = <1% CHANGE.

SNAIL	TREATMENT	INITIAL WEIGHT (G)	% WEIGHT GAIN	INITIAL ML (MM)	% CHANGE (ML)	INITIAL MW (MM)	% CHANGE (MW)
1	Grazon®	7.66	21	36.8	4	30.92	3
2	Grazon®	16.02	3	45.71	negl.	37.45	negl.
3	Grazon®	15.30	20	43.68	4	35.07	2
4	Grazon®	16.83	20	45.01	9	36.78	negl.
5	Grazon®	19.50	10	49.35	1	40	negl.
6	Water	4.34	54	26.59	17	21.74	15
7	Water	18.45	4	48.49	negl.	39.60	negl.
8	Water	10.71	3	41.33	negl.	33.72	negl.
9	Water	17.07	17	44.82	5	36.77	3

3.2 LABORATORY TRIALS

No deaths occurred in the treatment or control group after the snails had been sprayed with herbicide. After having been sprayed, all snails gained weight over the period, but not all grew in length or width (Table 3). Changes in ML were not different between treatment and non-treatment groups ($F_{1,7}$ = 0.009; P = 0.928). Snails did not feed every night when worms were presented to them. Despite this, a gain in weight was nearly always observed for all the snails after they had been placed overnight in the smaller containers to feed. This may have been due to water uptake or the consumption of other invertebrates, such as amphipods that were also present in the leaf litter.

Two snails in the non-treatment group produced a total of ten eggs, and three snails produced a total of 11 eggs after being sprayed with Grazon®. The size and weight of the eggs produced varied within and among snails. Egg weight did not vary with treatment but was positively related to the weight of the laying adult: $F_{1,18}$ = 1.72, P = 0.206 (treatment); $F_{1,18}$ = 17.63, P = 0.001 (adult weight). The mean (± SE) egg weight was 0.41 ± 0.02 g. The mean (± SE) egg length (9.84 ± 0.19 mm) and width (8.12 ± 0.13 mm) were within the range of egg size reported for *P. t. tararuaensis* (O'Connor 1945).

4. Discussion

4.1 FIELD TRIALS

The most significant effect of *Tradescantia* removal on ground-dwelling invertebrates was a pulse of activity immediately after hand weeding, which returned to 'normal' (i.e. similar to non-treatment) levels by seven weeks after weed removal. Surprisingly, there was no detectable effect of herbicide application on ground-dwelling invertebrates, as shown by comparison of invertebrate abundance and richness in treated and non-treated plots, at the taxonomic classification levels used. Pitfall trapping is most effective for assessing the effect of weed removal on mobile invertebrates with restricted dispersal (e.g. springtails, sandhoppers, bristletails) rather than those that can move easily between experimental plots (e.g. spiders, flies, predatory beetles, ants, bees and wasps), although it is difficult to group taxa in this manner as there are sure to be exceptions (e.g. wingless flies sampled in this study).

There are two likely explanations for the greater catch of invertebrates one week after removal of *Tradescantia* by hand weeding. Firstly, the difference may be an artefact of the method (Greenslade 1964). Bare soil was all that remained after hand removal of *Tradescantia*, and this may lead to an increase in invertebrate mobility in comparison with non-treatment plots or herbicide-treated plots where a layer of dead and/or partially dead *Tradescantia* remained. However, bare soil remained in hand-weeded plots seven weeks post-treatment when invertebrate activity was similar across all treatments. Secondly, disturbance due to hand weeding may lead to the release of resources (i.e. nutrients) which can be used by either the organisms surviving the disturbance or ones entering the community (Sousa 1984; van der Maarel 1993). For example, bristletails may have increased their foraging in response to an increase in algal growth which is likely to have occurred following the increase in available light upon weed removal, or as vegetable and invertebrate debris became more readily accessible, all of which are components of their diet (Watson & Smith 1991). Similarly, the remaining invertebrates which showed increased activity post-disturbance, including detritivores (e.g. sand hoppers, some mites) and predators (e.g. false scorpions, some beetles, ants, some mites and spiders), were probably responding to an increase in the availability of their foods.

The rate of triclopyr breakdown at our study site (half-life c.11 weeks) was less than its average breakdown in soil (half-life c.4 weeks: Dow Chemical Co. 1988), but was almost completely degraded by 20 weeks. We found no impact of triclopyr on the activity of ground-dwelling invertebrates at one week and seven weeks post-treatment, despite its presence in the soil at these times. It has been shown that triclopyr has minimal impacts on aquatic insects (Kreutzweiser et al. 1994, 1998) and aquatic benthic macroinvertebrates, probably owing to its short residence time in water (< 11 hours: Maloney 1995). There is little information on triclopyr toxicity to terrestrial invertebrates, except for a study of adult leaf-eating beetles which found no impact of triclopyr amine, used at 12 kg/ha (compared with 6 kg/ha used in this study), on survival and fecundity or the ability of third instar larvae to pupate (Lindgren et al. 1998).

In all treatments, invertebrate activity was greater during the warmer sampling period. This was particularly true for spiders and cicadas, hoppers, etc., and also mites, ants, harvestmen and beetles, comparing non-treatment plots. These data are insufficient to draw correlations, but it is worth noting that increased activity with temperature has been reported for spiders, mites, harvestmen and beetles in mixed broadleaved-podocarp forest (Moeed & Meads 1985). Springtail activity did not correlate with temperature, but this is not surprising as their activity is likely to be primarily affected by rainfall (McColl 1975) and is not ubiquitously correlated with temperature (Moeed & Meads 1985). Similarly, fly activity is not ubiquitously correlated with temperature (Moeed & Meads 1985).

Removal of *Tradescantia* within 50 m^2 plots by hand weeding or herbicide spraying does not lead to any major impacts on the ground-dwelling invertebrate community. Invertebrate abundance and taxonomic richness were similar in hand-weeded, herbicide-treated and non-treated plots seven weeks post-treatment. There was no increase in the abundance or taxonomic richness of decomposers (e.g. springtails, sandhoppers, slaters, bristletails) despite the presence of a large mat of dead *Tradescantia* in herbicide treated plots soon after treatment. However, others (Neuman 1991; Whelan 1995; French & Eardley 1997) have recognised, as we have, that it is difficult to predict changes to a collection of highly diverse unrelated taxa, which makes interpretation of such studies difficult. A more focused study on the effect of *Tradescantia* removal on groups of related taxa warrants consideration. Beetles would be a good choice, since they represent a large component of New Zealand's insect species (Watt 1982), have representatives in all trophic groups, are relatively well studied (e.g. Hutcheson 1990; Crisp et al. 1998; Harris & Burns 2000), and have yielded information on response to disturbance (Neuman 1991; Abensperg-Traun et al. 1996; Crisp et al. 1998; Harris & Burns 2000). Malaise traps are regarded as the best method for representative sampling of beetle communities (Hutcheson 1990; Hutcheson & Kimberley 1999) within a c.20 m^2 area (R. Harris, pers. comm.).

Effects on the invertebrate community may be more significant when *Tradescantia* is removed from a large area (i.e. a forest remnant). If using either of these removal methods for the control of *Tradescantia*, we recommend removing sections of *Tradescantia* over time to minimise disturbance to ground-dwelling invertebrates by ensuring some adjacent vegetative cover was always available. Integration of herbicide application and/or hand weeding with revegetation to improve canopy cover, may further minimise disturbance, since the need for continual weed control involving repeated habitat destruction will be less likely.

4.2 LABORATORY TRIALS

None of the five *P. t. traversi* died or showed any ill effects in the 22 weeks after they were sprayed with a 1.4% solution of Grazon® herbicide in the laboratory, and there were no significant adverse effects to the reproductive output of snails exposed to triclopyr. In contrast, exposure of herbivorous garden snails, (*Cantarues aspersus* (Müller), to a 1.4% solution of Grazon® herbicide in the laboratory resulted in a high mortality compared with a non-treatment group (S. Bennett, unpubl. data).

The exposure to Grazon® that *P. t. traversi* endured in the laboratory was greater than the exposure these snails are expected to experience in *Tradescantia* in the field. Firstly, lower concentrations of Grazon® are used to control *Tradescantia* effectively in the field (Brown & Rees 1995; McCluggage 1998). Secondly, Grazon® is applied to *Tradescantia* foliage, and triclopyr residues are typically reduced before they reach the leaf litter, due to processes such as translocation by plants, photodegradation, volatilisation and metabolism (Norris et al. 1987). Lastly, triclopyr is degraded by soil microbes at a rate determined by moisture content and soil temperature (Dow Chemical Co.

1988). In our laboratory experiment, soil microbe activity was probably limited by temperature, since it was below optimum, and perhaps by the density of soil microbes within the soil samples.

It has been shown that the concentration of, and exposure to triclopyr determine the magnitude of its effect (Kreutzweiser et al. 1994). Triclopyr caused delayed lethal effects in fish and aquatic insects, with greater toxic effects resulting from long duration of exposure (Kreutzweiser et al. 1994). Similarly, it was shown that long-term continuous exposure to glyphosate (Roundup®) has a delayed effect on growth, development and hatching of an aquatic snail at the third generation (Tate et al. 1997). Thus, *P. t. traversi* could show an effect of triclopyr exposure in subsequent generations, or from repeated exposure, such as that resulting from the repeated sprayings usually required for long-term control of *Tradescantia* (G. Scott, pers. comm.). Finally, although Grazon® does not appear to represent a direct threat to first-generation *P. t. traversi*, indirect effects need to be considered. These snails are carnivorous and so will not ingest treated plant material. Earthworms are their staple food (Meads et al. 1984) and it has been shown that several herbicides (triclopyr not considered), when used at high rates for completely suppressing plant growth, are toxic to earthworms (Lee 1985).

There are methods to reduce the potential impact of herbicide on *Powelliphanta* and other invertebrates, which include reducing the amount of spray needed and choosing an appropriate season for application. Less herbicide spray is required to control *Tradescantia* if its bulk is reduced prior to spraying (Kelly & Skipworth 1984b). Grazon® is best applied during periods of active plant growth (Dow Chemical Co. 1988), which in the case of *Tradescantia* occurs in summer (Maule et al. 1995; Standish 2001). However, spraying in summer could be both advantageous and disadvantageous for *P. t. traversi*. These snails are typically more active following wet periods, so the chance of snails being active and moving over contaminated soils could be reduced if spraying were to be carried out during dry periods. There would also be less contamination of the soil by rain-transported residues, and degradation of triclopyr may be nearly twice as rapid in summer as compared with autumn applications (Moseman & Merkle 1977 cited in Norris et al. 1987). On the other hand, removal of *Tradescantia* during drier months could increase snail mortality through desiccation or predation if there is no suitable additional habitat. Overall, the risk posed to *P. traversi* from the loss of *Tradescantia* habitat may actually be greater than the risk of herbicide spray.

Our results indicate that the effects of triclopyr on first generation *P. t. traversi* are minimal, and that Grazon® herbicide appears suitable for the control of *Tradescantia* in sites where *P. t. traversi* occur. However, the effects of triclopyr on subsequent *P. t. traversi* generations remain untested, and evidence from the literature suggests that these effects could be detrimental. Similarly, the effects of triclopyr on earthworm prey remain untested. Moreover, at heavily infested sites there is evidence to suggest that *Tradescantia* removal would be disadvantageous for *P. t. traversi* unless a simultaneous effort was made toward providing alternative native habitat (Standish et al. 2002).

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