Experimenting with methods to control *Tradescantia fluminensis,* an invasive weed of native forest remnants in New Zealand

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Abstract: *Tradescantia fluminensis*, commonly referred to as 'tradescantia', is an invasive weed of canopy-depleted forest remnants. Previous research suggests that a reduction of tradescantia biomass to ~80 gm^{-2} (~40% cover) is compatible with native forest regeneration. I assessed herbicide application, hand weeding and artificial shading as methods for the control of tradescantia in two lowland podocarp/broad-leaved forest remnants in the lower North Island of New Zealand. Herbicide spray and hand weeding, applied to separate experimental plots, did not prevent re-growth of tradescantia after three successive treatments. Re-growth of tradescantia and invasion of other weeds were positively related to light availability, which increased in the more canopy-depleted areas, and negatively related to native forest regeneration measured two years after initial treatment. Artificial shading was the most effective method of control. The biomass of tradescantia was significantly reduced in artificially-shaded plots (2–5% full light; 81.3 ± 10.6 gm^{-2}) relative to non-shaded plots (15–27% full light; 597.6 ± 6.6 gm^{-2}; $t_4 = 17.38$, $P < 0.001$) after 17 months. Native sub-canopy species were planted into tradescantia to achieve natural shading over large areas of forest. After 2.5 years, 61% of the saplings planted had emerged from the surrounding tradescantia.

Keywords: hand weeding; herbicide; invasive weed; light availability; native forest regeneration; shade; triclopyr; weed control.

Introduction

Tradescantia fluminensis (Commelinaceae), wandering Jew, commonly referred to as 'tradescantia', is an invasive, ground-smothering perennial herb capable of preventing native forest regeneration by inhibiting the growth of seedlings (Kelly and Skipworth, 1984a; Standish *et al.*, 2001a). A native of South America (Esler, 1978), it occurs in forest remnants in New Zealand (Kelly and Skipworth, 1984a), eastern Australia (Dunphy, 1991) and Florida (Wunderlund, 1998). In New Zealand, tradescantia has spread through the dumping of rubbish and naturally via streams (Esler, 1978). Fragments as small as 1cm in length can successfully establish new plants by vegetative reproduction (Kelly and Skipworth, 1984a). It has not been known to set seed in New Zealand (Healy and Edgar, 1980). Available light is the primary factor limiting the spread and biomass accumulation of tradescantia (Kelly and Skipworth, 1984a; Maule *et al.,* 1995; Standish *et al.,* 2001a) which, in turn, determines its impact on native forest regeneration (Standish *et al.,* 2001a). Tradescantia's greatest impact occurs in those parts of forest remnants where canopy cover is reduced and at the forest margins as these sites are where it grows most vigorously. Previous work indicates that a decrease of tradescantia will lead to an increase in the abundance and species' richness of native forest seedlings (Standish *et al.,* 2001a). Several weed control options have been considered.

Currently, chemical control is considered the only practical means of controlling large infestations of tradescantia (McCluggage, 1998; T. McCluggage, Department of Conservation, Whangarei, New Zealand, *pers. comm.*; C. Buddenhagen, Department of Conservation, Wellington, New Zealand, *pers. comm.*). Manual weed removal is considered suitable for small infestations (Porteous, 1993; C. Buddenhagen, *pers. comm.*) provided care is taken to remove every last piece. A combination of these removal methods has been used successfully in a lowland podocarp/broad-leaved forest remnant in Feilding (Manawatu), but repeated efforts have been required to ensure continued control (Anon., 1995). An alternative method of suppressing tradescantia that has been suggested but not trialed is shading by artificial or natural means (i.e., by planting native species into damaged forest remnants to enhance natural vegetation cover) (Kelly and Skipworth, 1984b; Stockard, 1991; Maule *et al.,* 1995; Standish *et al.,* 2001a). While native plantings have been used to restore degraded natural habitats (Ashby, 1987; Lamb, 1993; Saunders *et al.*, 1993; Reay and Norton, 1999; Yates *et al.*, 2000), their specific use for weed control within natural habitats is uncommon (Eliason and Allen, 1997; Swarbrick and Hart, 2000).

The aims of this study were, first, to compare the success of herbicide application and hand weeding as methods for the control of tradescantia, and second, to compare the native regeneration after weed removal by these methods. To test whether shading was an effective method of control, I artificially shaded tradescantia in the field and measured its response. An advantage of chemical control is its cost-effectiveness, and a disadvantage its detrimental impact to native flora (e.g. Kelly and Skipworth, 1984a; Brown and Rees, 1995). Hand weeding is time consuming but probably has less impact on native flora. In heavily infested forest remnants, gaps left by manual or chemical removal of tradescantia are likely to be filled by other invasive species (Hobbs and Mooney, 1993). Conceivably, artificial shading might require less follow-up treatment than chemical and manual control methods, reduce invasion of other weeds and have minimal impact on established native flora. However, it would be impractical for controlling large areas of weed. Therefore, in an attempt to impose shade on the scale of a forest remnant, I planted native sub-canopy trees into swards of tradescantia and measured their initial survival and growth.

Materials and methods

Experiment 1. Herbicide application v. hand weeding for tradescantia control

The study site was a road-side forest remnant in Awahuri, lower North Island, New Zealand (40°14.9' S, 175°32.5' E). This small podocarp/broad-leaved forest remnant (< 1 ha) on a flood plain was bordered on one side by farmland, and was separated by a road from a larger (10 ha) forest remnant. The canopy was mainly 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. small-leaved milk tree (*Streblus heterophyllus*), long-leaved lacebark (*Hoheria sexstylosa*)] comprised the understorey. Tradescantia formed a carpet up to 90 cm deep throughout the forest remnant and in the few patches where tradescantia did not occur, ground cover was provided by litter and woody seedlings.

Where tradescantia carpeted the ground, I established 30 contiguous, 5 × 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, I split the plots into five blocks, then randomly assigned initial season of removal (summer or winter) to sets of three plots within each block. Treatment (herbicide application, hand weeding or non-treatment) was randomly assigned to plots within seasonal blocks for the first 15 plots and the same assignment repeated for the second 15 plots. Thus, there were five replicates of each treatment. The first summer herbicide treatment was applied on 26 February 1997 and re-applied to patches of re-growth on 24 July 1997 and 13 January 1998. Similarly, the first winter herbicide treatment was applied on 24 July 1997 and re-applied on 13 January 1998 and 31 August 1998. I used Grazon® herbicide (active constituent 600g l^{-1} triclopyr; DowElanco (NZ) Ltd, New Plymouth) on the basis of its successful control of tradescantia in previous trials (Brown and Rees, 1995; McCluggage, 1998) and its wide use within the North Island for controlling tradescantia (e.g. T. Guard, Wellington Regional Council, Wellington, New Zealand, *pers. comm.*; J. Davis, Palmerston North City Council, Palmerston North, New Zealand, *pers. comm.*; G. Scott, Manawatu District Council, Feilding, New Zealand, *pers. comm.*; T. McCluggage, *pers. comm.*), though it can kill native adult trees and their seedlings (Brown and Rees, 1995; G. Scott, *pers. comm.*; C. Buddenhagen, *pers. comm.*).

The herbicide was applied, 100 ml per 15 l water, to the foliage using a knapsack and sprayer, at a volume of 6–9 l per plot (or 1200–1800 l ha^{-1}), depending on the depth of the mat of tradescantia within the plot. On the days of herbicide spraying, there was no cloud cover and minimal wind. The triclopyr residue in the soil, measured before treatment and at two, seven and twenty weeks post-treatment, had almost degraded by 20 weeks (Standish *et al.*, 2001b). For the initial hand weeding treatment (on 25 February 1997 and 23 July 1997), I rolled the tradescantia up like a carpet (Porteous, 1993) and collected the remaining fragments. Fragments of tradescantia re-growth were collected from the hand-weeded plots before treating the herbicide plots for the second and third time.

I designated the central 3 × 8 m plot of each experimental plot for recording: percentage cover of tradescantia (monthly or bi-monthly), percentage cover of other recolonizing weeds (monthly or bi-monthly) and survival of established native flora (i.e., individuals > 0.5 m tall at the start of the experiment were mapped and checked every six months). This allowed for some interference of neighbouring treatments (e.g., spread of tradescantia from non-treatment plots, herbicide drift) without affecting the data collected. The number and identity of all native seedlings with at least two true leaves were recorded in a 1 × 8 m strip within each herbicide treated and hand weeded plot, two years after the initial treatment. In addition, I made integrated measurements of incident radiation using simple photosensitive paper light meters (Friend, 1961), which were calibrated as described in Standish *et al.* (2001a). I fastened the light meters on top of 0.5 m wooden stakes in the centre of each plot and left them for one week (15–22 March 1999). Simultaneous readings were taken in an adjacent open field to obtain estimates of full light for the period. Final light values are expressed as a percent of full light.

Experiment 2. Response of tradescantia to artificial shading

The second study site was Monro's Bush (40°23.3' S, 175°36.7' E), a 2 ha lowland podocarp/broad-leaved forest remnant heavily infested with tradescantia. The site is described fully in Kelly and Skipworth (1984a). I set up three large shade houses to cover tradescantia on 6 November 1998, and adjacent to each, I marked out an unshaded tradescantia plot of similar area. Each shade house consisted of a horizontal metal frame 2.8 × 2.8 m, supported by 1 m high legs at each corner, and a sloped roof with an apex of 2 m to prevent the accumulation of forest litter. The frame was covered by three layers of 70% shade cloth secured with plastic cable ties. Light levels were assessed as in the first experiment. Existing forest interior light levels were mostly between 7 and 16% full light. I aimed to decrease light levels to ~1% full light in the shade houses; at best I achieved 2% full light in one shade house, and 4 and 5% full light in the others ($n = 2$ light meters per plot, recorded during 16–23 March 1999). These levels are similar to those in well-shaded areas of closed-canopy New Zealand podocarp forests (2–30% full light; Ebbett and Ogden, 1998). The light levels in the adjacent unshaded plots varied from 15–27% full light.

In each plot, I measured the growth (± 0.1 cm) of five non-bifurcating and flowerless tradescantia stems over a period of six months. I laid a ladder across two saw-horses to gain access to the tagged stems, to avoid crushing the tradescantia during measurement. A tradescantia biomass estimate, using percent cover and standing height as predictors (Standish *et al.,* 2001a), was taken before and 17 months after the initiation of the experiment.

Experiment 3. Planting into tradescantia

I selected four shade-tolerant shrub and tree species, karamu (*Coprosma robusta*), mahoe, lowland ribbonwood (*Plagianthus regius*) and long-leaved lacebark (*H. sexstylosa*), for planting into ground covered by dense tradescantia at Monro's Bush. These species were selected because they were present in the understorey or sub-canopy at the site and available as 0.5 m saplings grown from locally sourced seed. Plants less than 0.5 m high are unlikely to survive in competition with tradescantia (Esler, 1962). Karamu and mahoe are known for their fast growth rates and tolerance of most environments, and their fleshy fruits are attractive to birds, which may promote forest regeneration (Porteous, 1993). Lowland ribbonwood and long-leaved lacebark are often used for revegetation in New Zealand (Bulloch, 1991; Stewart and Woods, 1991; P. van Essen, Massey University, Palmerston North, New Zealand, *pers. comm.*). Lowland ribbonwood has a preference for fertile soils such as those at Monro's Bush (Ogle and Lovelock, 1989; Ravine, 1995). I cleared tradescantia from an area 1 m in diameter around half of the saplings at the time of planting. Twenty saplings of each species were planted, in a completely randomized block design with respect to sapling species and clearing treatment, on 1 September 1997, with a 2 m spacing between each. There were ten blocks; blocks two, three and four were contiguous, as were blocks six and seven, and nine and ten, while the other blocks were between 4 m and 20 m from the next block. Survival and height of the saplings were measured at six months, one year, 1.5 years and 2.5 years. Insect herbivore damage (low = 10%, high = 90% and intermediate = 10–90%, of leaves damaged) was estimated after six months.

I determined light availability and relative soil fertility at each of the planting sites. I used light meters (as for experiment 1, from 24 September–1 October 1997) to record light levels at the planting sites. Soil fertility was measured by means of a bioassay in which brown top (*Agrostis capillaris*), chosen for its ability to respond to a wide range of soil fertilities (Lee and Fenner, 1989), was grown for a period of ~11 weeks in soil taken from each planting site. Three cores of soil (5.4 cm diameter × 8 cm depth) were collected from each planting site on 26 August 1997, and stored at 4°C until 28 August 1997 when they were sieved (using a 5 mm sieve), mixed, and placed into black plastic pots (10 × 10 × 10 cm). Brown top seed (0.7 g) was added to each, and the pots were randomly ordered on a table in a glasshouse and watered daily. On 14 November 1997 the grass shoots were harvested, then oven-dried and weighed. The yield (g) per soil sample was taken as a measure of the relative soil fertility of the planting sites.

Statistical analyses

For experiment 1, a repeated measures, fixed effects ANOVA was used to test for differences between hand weeding and herbicide application treatments, and the effect of season of treatment (SYSTAT, SPSS Inc., 1996). Data, percentage cover of tradescantia approximately six months after treatment and repeat treatments were applied, were log transformed (x + 1) prior to analysis and available light was included as a covariate. Non-treatment plots were excluded as tradescantia cover remained unchanged at 100%.

To determine the effect of shading on tradescantia, I used a repeated measures ANOVA for growth data and an independent pooled variance t-test for tradescantia biomass data. I used a repeated measures, fixed effects ANOVA to test for differences in the relative growth rate (RGR) of planted trees at six months, one year, 1.5 and 2.5 years after planting. Light availability, soil fertility and herbivore damage were included as covariates in the analysis. These data were log transformed before analysis.

Results

Experiment 1

While herbicide application and hand weeding reduced the percentage cover of tradescantia from the initial 100% cover, removal was incomplete and remaining fragments continued to re-grow after each successive treatment (Fig. 1). Hand weeding was more successful than herbicide application (Fig.1), although the significant tradescantia cover × treatment interaction indicated that the differences between treatments were less marked at time three (Table 1). Also, the interaction between tradescantia cover, treatment, and season

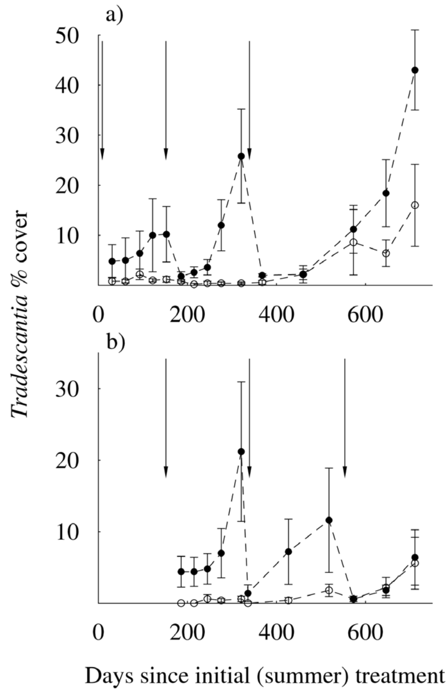

Figure 1. Response of tradescantia percentage cover to herbicide application (filled symbols) and hand weeding (clear symbols) in summer (a) and winter (b) in experimental plots at Awahuri road-side remnant. Values are means ± SE (*n* = 5 plots). Vertical arrows indicate the timing of herbicide applications and hand weeding efforts. Cover in non-treatment plots (not shown) remained at 100% throughout.

Table 1. Repeated measures ANOVA of the effect of herbicide application and hand weeding treatments, applied to experimental plots in summer and winter, on percentage cover of tradescantia at Awahuri road-side remnant (n = five plots per treatment; Experiment 1). Percent full light was a covariate. Huynh-Feldt Epsilon-*P* values quoted for within-treatment tests.

Between treatments — Source	SS	df	*F*	*P*
Treatment	17.82	1	16.75	0.001
Season	0.84	1	0.79	0.387
Treatment × season	0.85	1	0.80	0.386
Light	17.27	1	16.23	0.001
Error	15.96	15		
Within treatments across repeated measures — Source				
Tradescantia cover (repeated measure)	0.97	2	0.8	0.459
Tradescantia cover × treatment	6.58	2	5.39	0.010
Tradescantia cover × season	2.11	2	1.73	0.195
Tradescantia cover × treatment × season	6.91	2	5.66	0.008
Tradescantia cover × light	0.82	2	0.67	0.520
Error	18.31	30		

indicated that differences between treatments were less marked for winter plots than for summer plots. Overall, the season of treatment application did not affect the outcome of either control method. Tradescantia percentage cover increased with available light (Fig. 2a), which explained almost as much of the variation in tradescantia re-growth as treatment (Table 1). The percent cover of other colonizing weeds was also positively related to light (Fig. 2b).

The numbers of established native plants > 0.5 m in height that died during the 20 months after the initiation of the experiment were as follows: 13 (herbicide treated plots); 4 (hand-weeded plots) and 2 (non-treatment plots). All were saplings < 1m in height except for two trees in non-treatment plots.

Native regeneration (i.e. seedling abundance) decreased with increasing light levels (Fig. 2c) because of the increasing cover of tradescantia and other weeds (Figs. 2a, b). There was no effect of tradescantia control treatment or season of treatment on the abundance of native seedlings ($F_{1,15} = 0.02$, $P = 0.901$ (treatment); $F_{1,15} = 0.02$, $P = 0.892$ (season) and; $F_{1,15} = 11.46$, $P = 0.004$ (light)). Species richness of native seedlings was similarly unaffected ($F_{1,15} = 0.001$, $P = 0.978$ (treatment); $F_{1,15} = 1.16$, $P = 0.298$ (season) and $F_{1,15} = 10.28$, $P = 0.006$ (light)). Across plots, there were 2.47 ± 0.46 (mean ± SE) seedlings per m^2, and species richness was 8.15 ± 0.67 (mean ± SE). Kawakawa (*Macropiper excelsum*) seedlings were the most abundant (57% of the total), followed by seedlings of *Cordyline australis* (11%) and lowland ribbonwood (*Plagianthus regius*) (5%) (Appendix 1).

Experiment 2

Shading had a significant effect on the growth of tradescantia (Table 2; $F_{1,4} = 52.62$, $P = 0.002$ (treatment); $F_{1,4} = 23.35$, $P = 0.008$ (time) and; $F_{1,4} = 4.78$, $P = 0.094$ (time × treatment)). After 17 months in 95–98% shade, the biomass of tradescantia was massively and significantly reduced (81.3 ± 10.6 gm^{-2}, equivalent to ~40% cover), relative to tradescantia biomass in unshaded plots (597.6 ± 6.6 gm^{-2}, equivalent to 100% cover; $t_4 = 17.38$, $P < 0.001$).

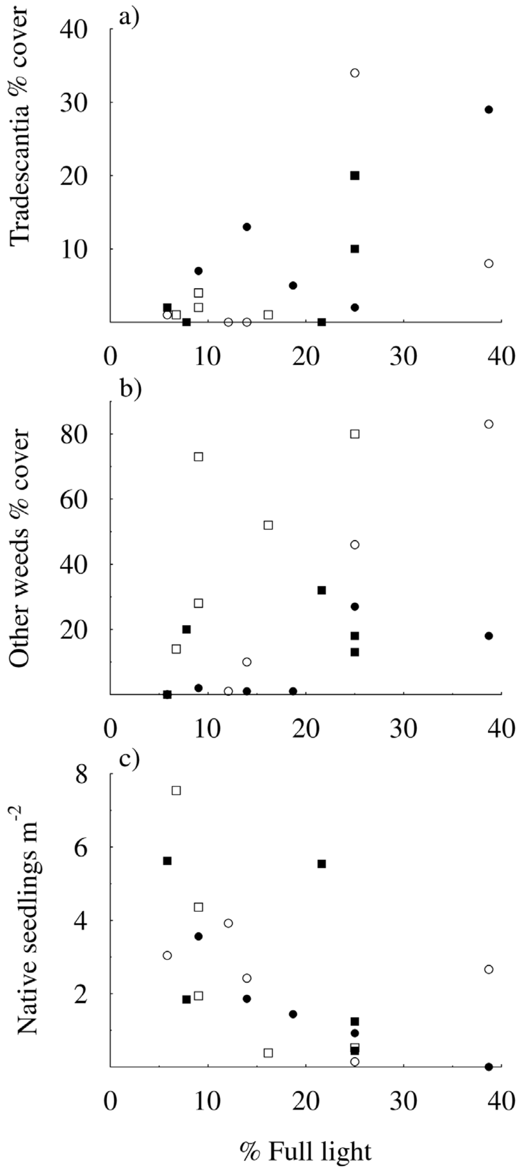

Figure 2. Relationship of available light to: % cover of tradescantia (a; $R^2 = 0.35$, $F_{1,18} = 11.21$, $P < 0.01$); % cover of other weeds (b; $R^2 = 0.14$, $F_{1,18} = 4.16$, $P = 0.056$) and; abundance of native seedlings (c; $R^2 = 0.26$, $F_{1,18} = 7.83$, $P < 0.05$), two years after initial treatment (filled symbols = herbicide application, clear symbols = hand weeding, circles = summer application, squares = winter application) in experimental plots at Awahuri road-side remnant.

Table 2. The effect of artifical shading on the growth (cm/ day) of tradescantia at Monro's Bush (Experiment 2). Values are means ± SE, three and six months after the experiment was initiated (n = 3 plots per treatment).

Treatment	3 months	6 months
Shaded	0.10 ± 0.016	0.02 ± 0.004
Non-shaded	0.14 ± 0.049	0.19 ± 0.034

Experiment 3

Overall, 61% of saplings planted into tradescantia at Monro's Bush survived to 2.5 yrs (Table 3). Of the four species, mahoe had more, and karamu fewer, individuals remaining at 2.5 yrs ($\chi^2 = 8.58$, df = 3, $P < 0.05$) and clearing tradescantia made no difference to the survival of the saplings ($\chi^2 = 1.32$, df = 1, $P = 0.25$).

Table 3. Number of surviving saplings 2.5 years after planting into tradescantia at Monro's Bush (Experiment 3). A set of ten saplings of each species was planted into ground cleared of tradescantia, and a further set was planted directly into tradescantia.

Species	Cleared	Non-cleared
Karamu	4	4
Lowland ribbonwood	7	5
Mahoe	10	7
Long-leaved lacebark	6	6
Total	27	22

The mean ± SE, and maximum heights for each species (across cleared and non-cleared treatments) at 2.5 yrs were: karamu 2.33 ± 0.33 m, 4.0 m; mahoe 1.72 ± 0.12 m, 2.8 m; long-leaved lacebark 1.45 ± 0.14 m, 2.2 m and; lowland ribbonwood 1.39 ± 0.77 m, 1.8 m. The species varied significantly in relative growth rates, with karamu consistently scoring the highest mean growth rate (Table 4; Fig. 3). Overall, sapling growth in cleared and non-cleared treatments were similar, although the interaction term indicated that some species showed better overall growth in cleared treatments (i.e. long-leaved lacebark; Fig. 3) although this was not consistent over time (growth × species × treatment interaction). Available light and soil fertility significantly affected the growth of the saplings, whereas insect herbivore damage did not (Table 4). The individual species' responses to light availability and soil fertility varied, with karamu and long-leaved lacebark responding positively to increased light availability, and no relationship between growth and light availability in mahoe and lowland ribbonwood. There were weak negative relationships between growth and soil fertility for karamu and lowland ribbonwood, and no relationship for mahoe and long-leaved lacebark.

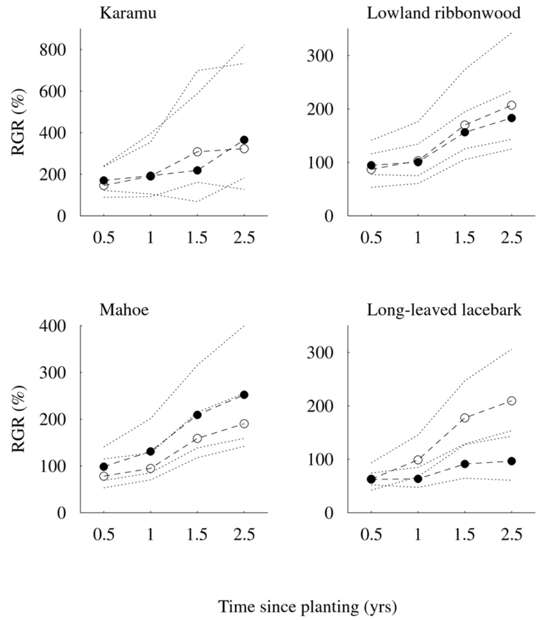

Figure 3. The relative growth rates of four species planted as saplings into cleared (clear symbols) and non-cleared (filled symbols) tradescantia at Monro's Bush. Values are means (back-transformed) and 95% CIs. Note different scale on Y-axes.

Discussion

The most effective method for sustained control of tradescantia, without invasion of other weeds, was artificial shading. Efforts to control tradescantia by repeated herbicide application or hand weeding resulted in the re-growth of tradescantia and invasion by other weeds that appeared to hinder native forest regeneration. Re-growth of tradescantia and invasion by other weeds was extreme in plots with increased available light. While it is too early to determine whether or not planted trees will overshadow tradescantia, 61% of saplings were able to emerge clear of the tradescantia sward within 2.5 yrs of planting, and release from tradescantia at the time of planting made no difference to survival and growth within this period.

Grazon® affects native seedlings, yet native regeneration (in terms of seedling species richness and abundance) did not differ between herbicide-treated and hand-weeded plots. Native seedlings first appeared in a hand-weeded plot two (winter plots) to three (summer plots) months after tradescantia's removal. Seedlings did not appear in herbicide-treated plots until four (winter plots) to six (summer plots) months after the first application of Grazon®. The emergence of seedlings in herbicide treated plots roughly corresponded with the degradation of triclopyr residues in the soil. The second and third applications of Grazon® to plots were patchy in comparison with the first blanket spray and so probably had less effect on the seedlings. While the repeated spray regime was designed to mimic that which reserve managers might follow, another option would be to follow up the initial spray treatment with manual removal to reduce the risk of non-target effects.

Table 4. Repeated measures ANOVA in the relative growth rate of four native tree species planted into cleared and non-cleared tradescantia at Monro's Bush (Experiment 3). Percent full light, soil fertility and insect herbivore damage were covariates. Huynh-Feldt Epsilon-*P* values quoted for within-treatment tests.

Between treatments — Source	SS	df	*F*	*P*
Species	13.18	3	9.2	< 0.001
Treatment (cleared or non-cleared)	0.06	1	0.12	0.737
Species × treatment	5.13	3	3.58	0.023
Light	3.07	1	6.42	0.016
Soil fertility	2.39	1	5.01	0.031
Insect herbivore damage	1.15	1	2.4	0.129
Error	18.14	38		
Within treatments across repeated measures — Source				
Growth (repeated measure)	0.59	3	5.14	0.002
Growth × species	0.6	9	1.75	0.085
Growth × treatment	0.64	3	5.65	0.001
Growth × species × treatment	1.01	9	2.95	0.004
Growth × light	0.08	3	0.66	0.577
Growth × soil fertility	0.004	3	0.04	0.991
Growth × herbivore damage	0.09	3	0.82	0.488
Error	4.32	114		

Overall, the native species that emerged following the removal of tradescantia were representative of those at the Awahuri study site and/or across the road at Kitchener Park (Esler and Greenwood, 1967). Despite its small size and poor condition, Awahuri road-side remnant has retained the capacity to regenerate on removal of tradescantia. Conspicuous by their absence as seedlings were *Podocarpus totara*, tawa and the small-leaved milk tree. Pigeonwood (*Hedycarya arborea*) and *Pittosporum crassifolium* were not present as mature specimens at the site or at Kitchener Park (Esler and Greenwood, 1967), but were recorded as regenerating seedlings (Appendix 1). Ferns are not expected to appear until quite a few years after the disturbance (i.e. weed removal in this case) (P. Williams, Landcare Research, Nelson, New Zealand, *pers. comm.*). The dominance of kawakawa (*Macropiper excelsum*) seedlings reflected its dominance in the understorey at the study site. Experience at Kitchener Park indicates that ongoing monitoring and removal of tradescantia is required for native seedlings to establish (Anon., 1995), at least until plants are 0.5 m high.

Imposing shade (2–5% full light) reduced tradescantia biomass to ~80 gm^{-2} (~40% cover), which is compatible with the germination and establishment of some native seedlings (Standish *et al.,* 2001a). Individual species can vary in their ability to tolerate tradescantia. In a group of commonly occurring native woody species, kohekohe (*Dysoxylum spectabile*) is the most tolerant, kawakawa the least tolerant, and pigeonwood, mahoe*,* titoki and pukatea (*Laurelia novae-zealandiae*) are moderately tolerant (Standish *et al.,* 2001a). The ability to tolerate tradescantia seems to relate to shade tolerance, and so other shade-tolerant native seedlings should be able to germinate and establish in ~80 gm^{-2} of tradescantia (~40% cover). Clearly, light-demanding forest species will not establish under shade imposed to reduce tradescantia biomass, but nor will they establish in high light environs (10–30% full light) affected by tradescantia (Standish *et al.*, 2001a).

Although karamu showed the fastest growth rates of the species trialed, its tendency to form spindly shrubs that fell over and became overgrown by tradescantia made it an unsatisfactory choice for this project. Its ability to respond to increased light, within the range 3–18% full light, is evidence of shade intolerance. On the other hand, mahoe was a good choice because it tended to grow in a bushy form. At 2.5 yrs it had started to shade the tradescantia directly beneath it and its survival was greatest. Neither mahoe nor lowland ribbonwood showed a response to increased light (between 5–15% full light), although lowland ribbonwood is not as shade tolerant as mahoe (Williams and Buxton, 1989). Long-leaved lacebark showed an ability to respond to elevated light levels, within the range 5–16% full light, indicating that it is somewhat light-demanding (i.e. shade intolerant). At 2.5 yrs, long-leaved lacebark provided less shade than mahoe, but more than lowland ribbonwood.

The period between planting and canopy closure is likely to be dependent on site conditions (e.g. soil fertility, light availability), the species planted and their rate of growth, the spacing of plants and aftercare (this study; Porteous, 1993). I estimate that it would take ~6 yrs for karamu to reach its mature height (5 m) in the Manawatu region, based on the average annual height increment in the first 2.5 yrs, 0.72 m, which is greater than the annual height increment of 0.48 m for this species grown in the northern South Island, New Zealand (Wardle, 1991). The average annual height increment for mahoe was the same as that reported for this species in the northern South Island, New Zealand (Wardle, 1991), and at this rate I estimate it would take ~20 yrs to reach the sub-canopy (10 m). The average annual height increment for long-leaved lacebark was lower than that for lacebark (*H. populnea*) grown south of its natural range (0.38-0.79 cm yr^{-1}; Wardle, 1991), which suggests that this species is not responding well to conditions at this site. Based on its growth in the first 2.5 yrs, long-leaved lacebark will take ~14.5 yrs to reach its mature height (6 m). Similarly, lowland ribbonwood will take an estimated 40 yrs to reach the sub-canopy (15 m). Ultimately, grouping plants beneath canopy gaps and minimizing space between plants, rather than using the blocked design and 2 m spacing of Experiment 3, may facilitate faster growth and more effective canopy closure.

There are only a few documented successes where tradescantia has been controlled with current chemical and manual techniques [e.g. Kitchener Park, N.Z. (Anon., 1995), Wingham Brush, New South Wales, Australia (Stockard *et al.*, 1985) and Stephens Island, N.Z. (C. Buddenhagen, *pers. comm.*)]. Numerous forest remnants throughout New Zealand would benefit from tradescantia control. This study is the first in New Zealand to document the response of the native plant community after removal of tradescantia. Imposing shade is a novel approach for successful control of this persistent forest weed. It remains to be seen whether trees planted into tradescantia will overshadow the weed and allow native regeneration to proceed. The ultimate measure of success would be the eventual regeneration of light-demanding native seedlings.

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References

Anon. 1995. The battle for Kitchener Park. *New Zealand Geographic 26:* 9-12.

Ashby, W.C. 1987. Forests. *In:* Jordan III, W.R.; Gilpin, M.E.; Aber, J.D. (Editors), *Restoration ecology: a synthetic approach to ecological research*, pp. 89-108. Cambridge University Press, Cambridge, U.K.

Brown, D.; Rees, D. 1995. Control of *Tradescantia* on Stephens Island. *Ecological Management 3:* 6-9.

Bulloch, B.T. 1991. The native plant option for soil conservation. *In:* Smale, M.C.; Meurk, C.D. (Compilers), *Proceedings of a workshop on scientific issues in ecological restoration*, pp. 58-61. Landcare Research, Lincoln, N.Z.

Dunphy, M. 1991. Rainforest weeds of the big scrub. *In:* Phillips, S. (Editor), *Rainforest remnants: proceedings of a workshop on rainforest rehabilitation*, pp. 85-93. New South Wales National Parks and Wildlife Service, Sydney, Australia.

Ebbett, R.L.; Ogden, J. 1998. Comparative seedling growth of five endemic New Zealand podocarp species under different light regimes. *New Zealand Journal of Botany 36:* 189-201.

Eliason, S.A.; Allen, E.B. 1997. Exotic grass competition in suppressing native shrubland re-establishment. *Restoration Ecology 5:* 245-255.

Esler, A.E. 1962. The Banks Lecture: forest remnants of the Manawatu lowlands. *New Zealand Plants and Gardens 4:* 255-268.

Esler, A.E.; Greenwood, R.M. 1967. *Kitchener Park: plan for replanting*. Unpublished report to Feilding Borough Council, Feilding, N.Z.

Esler, A.E. 1978. *Botany of the Manawatu*. Government Printer, Wellington, N.Z.

Friend, D.T.C. 1961. A simple method of measuring integrated light values in the field. *Ecology 42:* 577-580.

Healy, A.J.; Edgar, E. 1980. *Flora of New Zealand, Volume III*. Government Printer, Wellington, N.Z.

Hobbs, R.J.; Mooney, H.A. 1993. Restoration ecology and invasions. *In:* Saunders, D.A.; Hobbs, R.J.; Ehrlich, P.R. (Editors), *Nature conservation 3: the reconstruction of fragmented ecosystems*, pp. 127-133. Surrey Beatty and Sons, Chipping Norton, New South Wales, Australia.

Kelly, D.; Skipworth, J.P. 1984a. *Tradescantia fluminensis* in a Manawatu (New Zealand) forest: I. Growth and effects on regeneration. *New Zealand Journal of Botany 22:* 393-397.

Kelly, D.; Skipworth, J.P. 1984b. *Tradescantia fluminensis* in a Manawatu (New Zealand) forest: II. Management by herbicides. *New Zealand*

Journal of Botany 22: 399-402.

Lamb, D. 1993. Restoration of degraded forest ecosystems for nature conservation. *In:* Moritz, C.; Kikkawa, J. (Editors), *Conservation biology in Australia and Oceania*, pp. 101-114. Surrey Beatty and Sons, Chipping Norton, New South Wales, Australia.

Lee, W.G.; Fenner, M. 1989. Mineral nutrient allocation in seeds and shoots of twelve *Chionochloa* species in relation to soil fertility. *Journal of Ecology 77:* 704-716.

McCluggage, T. 1998. *Herbicide trials on* Tradescantia fluminensis. Conservation Advisory Science Notes No. 180. Department of Conservation, Wellington, N.Z.

Maule, H.G.; Andrews, M.; Morton, J.D.; Jones, A.V.; Daly, G.T. 1995. Sun/shade acclimation and nitrogen nutrition of *Tradescantia fluminensis*, a problem weed in New Zealand native forest remnants. *New Zealand Journal of Ecology 19:* 35-46.

Ogle, C.; Lovelock, B. 1989. *Methods for the control of wandering Jew (*Tradescantia fluminensis*) at "Rangitawa", Rangitikei District, and notes on other aspects of conserving this forest remnant.* Science and Research Internal Report No. 56. Department of Conservation, Wellington, N.Z.

Porteous, T. 1993. *Native forest restoration: a practical guide for landowners*. Queen Elizabeth the Second National Trust, Wellington, N.Z.

Ravine, D.A. 1995. *Manawatu Plains Ecological District: survey report for the Protected Natural Areas Programme*. Department of Conservation, Wanganui, N.Z.

Reay, S.D.; Norton, D.A. 1999. Assessing the success of restoration plantings in a temperate New Zealand forest. *Restoration Ecology 7:* 298-308.

Saunders, D.A.; Hobbs, R.J.; Ehrlich, P.R. 1993. Reconstruction of fragmented ecosystems: problems and possibilities. *In:* Saunders, D.A.; Hobbs, R.J.; Ehrlich, P.R. (Editors), *Nature conservation 3: the reconstruction of fragmented ecosystems*, pp. 305-313. Surrey Beatty and Sons, Chipping Norton, New South Wales, Australia.

SPSS Inc. 1996. SYSTAT Version 6.0 for windows. SPSS Inc., Chicago, U.S.A.

Standish, R.J.; Robertson, A.W.; Williams, P.A. 2001a. The impact of an invasive weed *Tradescantia fluminensis* on native forest regeneration. *Journal of Applied Ecology 38:* 1253-1263.

Standish, R.J.; Bennett, S.J.; Stringer, I.A.N. 2001b. Effects of *Tradescantia fluminensis* removal on *Powelliphanta traversi* and other invertebrates. Science for Conservation 195B: 27-39, Department of Conservation, Wellington, N.Z.

Stewart, G.H.; Woods, D. 1991. A second generation at Matawai Park. *In:* Smale, M.C.; Meurk, C.D. (Compilers), *Proceedings of a workshop on scientific issues in ecological restoration*, pp. 62-63. Landcare Research, Lincoln, N.Z.

Stockard, J. 1991. Rainforest rehabilitation at Wingham Brush. *In: Rainforest remnants: proceedings of a workshop on rainforest rehabilitation*, pp. 94-100. New South Wales National Parks and Wildlife Service, Sydney, Australia.

Stockard, J.; Nicholson, B.; Williams, G. 1985. An assessment of a rainforest regeneration program at Wingham Brush, New South Wales. *The Victorian Naturalist 103:* 84-93.

Swarbrick, J.T.; Hart, R. 2000. Environmental weeds of Christmas Island (Indian Ocean) and their management. *Plant Protection Quarterly 16:* 54-57.

Wardle, P. 1991. *Vegetation of New Zealand*. Cambridge University Press, Cambridge, U.K.

Williams, P.A.; Buxton, R.J. 1989. Response to reduced irradiance of 15 species of native and adventive shrub and tree seedlings from eastern Canterbury. *New Zealand Journal of Ecology 12:* 95-101.

Wunderlund, R.P. 1998. *Guide to the vascular plants of Florida.* University of Florida Press, Gainesville, Florida, U.S.A.

Yates, C.J.; Hobbs, R.J.; Atkins, L. 2000. Establishment of perennial shrub and tree species in degraded *Eucalyptus salmonophloia* (salmon gum) remnant woodlands: effects of restoration treatments. *Restoration Ecology 8:* 135-143.

Appendix 1. Native seedlings regenerated 2 (summer) and 1.5 (winter) years after initial tradescantia control. n = Σ 5 plots per treatment.

Species	Herbicide treated plots		Hand-weeded plots	
	Summer	Winter	Summer	Winter
Macropiper excelsum	274	275	372	473
Cordyline australis	1	274	-	9
Plagianthus regius	5	8	66	47
Muehlenbeckia australis	11	35	11	36
Dacrycarpus dacrydioides	9	29	22	30
Melicytus ramiflorus	29	35	1	20
Passiflora tetrandra	11	22	22	27
Hedycarya arborea	19	6	9	45
Hoheria sexstylosa	4	-	50	-
Coprosma areolata	1	1	10	19
Alectryon excelsus	6	7	10	6
Pennantia corymbosa	4	2	19	-
Pittosporum crassifolium	6	7	1	11
Parsonsia heterophylla	1	14	1	-
Sophora microphylla	5	2	2	6
Prumnopitys taxifolia	1	8	1	-
Haloragis sp.	1	-	8	-
Melicope (*simplex*?)	-	-	-	7
Solanum aviculare	1	4	-	-
Unidentified (Sp. A)	-	3	-	1
Ripogonum scandens	-	-	3	-
Coprosma sp.	-	2	1	-
Total	389	734	609	737