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Efficacy of herbicides for selective control of an invasive liana, old man's beard (*Clematis vitalba*)

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Abstract

Old man's beard is a woody liana that has become an invasive weed in many areas of its introduction, through its vigorous spread and negative impacts on the tree hosts it climbs. Control techniques that improve precision and reduce non-target damage are increasingly preferred for weed control yet have not been compared in published research for use against old man's beard. Field experiments in New Zealand were conducted to: (i) assess targeted herbicide techniques for control of this weed's climbing stems when growing among trees and (ii) assess foliar herbicides for control of creeping stems in ruderal sites. For climbing stems, triclopyr in oil was applied around the circumference of woody stems near their base, which was compared with cutting the stems and applying concentrated glyphosate gel (45% ai) to each cut end. Herbicides were applied in autumn directly to individual stem bases of the weed, thereby protecting tree hosts and other non-target vegetation. The basal application of triclopyr to intact stems was highly effective (>95% mortality) with no damage to nearby trees noted. The glyphosate gel applications to cut stems were less effective (56% mortality by 2 yr after treatment). For creeping stems in grass-dominated ruderal sites, selective foliar herbicide sprays had not been previously juxtaposed to compare control of old man's beard. Three selective sprays that do not damage existing grass cover were applied in autumn at their recommended rates: (i) metsulfuron; (ii) triclopyr; and (iii) a mixture of triclopyr, picloram, and aminopyralid. All herbicide treatments provided effective control, although metsulfuron had a negative effect on grass vigor, which might allow new establishment of old man's beard seedlings by competitive release. These results provide effective options that reduce non-target damage for control of both climbing and creeping old man's beard stems.

Introduction

Increasing awareness of herbicide persistence and non-target effects on the environment have contributed to a focus on the use of less persistent chemicals, lower rates of herbicide use, and the use of alternative chemical control techniques (Alavanja and Bonner 2012; Rolando et al. 2015; Simberloff 2009; Ward et al. 1999). This is especially important when invasive species are associated with valuable natural ecosystems, aquatic environments, and other habitats where methods for control may be limited as a result of environmental sensitivity and government regulations (Baillie et al. 2015; Hamilton et al. 2003; Raal and Timmins 2018; Rolando et al. 2015).

Native to warm temperate regions in western, central, and southern Europe, northern Africa, and western Asia (Tutin et al. 1964; USDA-ARS 2003), old man's beard is a naturalized liana species in northern and eastern Europe (Danielewicz and Wiatrowska 2014; Fitter 1978; Möllerová 2005), North America (USDA-NRCS 2006), Australia (Biosecurity Queensland 2016), and New Zealand (Allan 1940). Despite extensive ongoing efforts to control it, old man's beard remains one of the most problematic invasive plant species in New Zealand, where it climbs and smothers trees, depriving its hosts of light, eventually causing tree collapse. In areas where no trees or other supports are available, old man's beard creeps along the ground and sprawls over grasses and other vegetation, developing dense, weblike networks of stems (Jarvis-Lowry 2023). Old man's beard is recognized as a threat to native plant diversity and abundance, as well as native forest structure (Environmental Protection Authority 2018; Ogle et al. 2000; Redmond and Stout 2018). It is also an increasing problem in production forestry and agricultural riparian plantings.

Selective herbicides currently used in New Zealand for the control of woody vines like old man's beard include pyridine-derivative herbicides picloram, triclopyr, and aminopyralid, which work by translocating throughout the plant and disrupting the balance of hormones in active growth regions (Monaco et al. 2002); and metsulfuron, a sulfonylurea that inhibits plant growth by preventing branched-chain amino acid biosynthesis. Glyphosate, which inhibits biosynthesis of aromatic amino acids, has also been used. As a nonselective herbicide, it is likely to damage any vegetation that it contacts, although careful, directed placement can accomplish selectivity.

Picloram does not break down quickly in plant tissues or in the soil and is characterized as highly mobile to very highly mobile in soil (Chu and Chan 2000; Liu et al. 1997; Rao et al 1985). Because of its mobility, it can easily leach into groundwater or run off into water bodies (Tu et al. 2001; Vencill 2002). Since the early 2000s, picloram in a concentrated gel form has been increasingly used in New Zealand to treat woody weeds with the cut-stem method, in which herbicide is applied directly to both sides of a cut stem (Ward and Henzell 2000, 2003, 2004). Gels are valued as easy and ready to use, and the technique is advantageous, because its direct application on individual stems reduces damage to nearby non-target species, allows complete avoidance of spray drift, and reduces chances of herbicide runoff at the time of application (Ward et al. 1999). Active ingredient concentrations are usually higher for herbicides applied directly to stems, as opposed to a foliar spray, but the overall amount of herbicide product used is often smaller for the cut-stem method (Miller 2016). However, because its residues persist and thus could affect nearby desired species through root uptake, alternatives to picloram gel have been sought by New Zealand's Department of Conservation (Raal and Timmins 2018).

Glyphosate is strongly adsorbed by soil, and therefore has very low mobility (Feng and Thompson 1990; Newton et al. 1984; Okada et al, 2019). Campbell et al. (2021) reported 100% control of *Cereus uruguayanus* Ritt. ex Kiesl. cacti 42 mo after treatment with 360 g L^{-1} glyphosate in water plus a penetrant. In New Zealand, cut-stem treatment on grey willow (*Salix cinerea* L.) with 10% glyphosate gel was 95% effective 24 mo after treatment when applied at 0.3 m above ground, and 75% effective at 1 m above ground (Ward and Henzell 2004). Yet, other researchers have observed vigorous regrowth from stems of woody species treated with various formulations of glyphosate (DiTomaso and Kyser 2007; Ward and Henzell 2000). No data are publicly available on their efficacy of cut-stem treatment with glyphosate gel at concentrations higher than 10%, although a New Zealand company specializing in gel formulations of herbicides currently markets several concentrations of registered glyphosate gel products and claims that they effectively control shrubs, trees, and vines (120 g ae L^{-1}, 240 g ae L^{-1}, 400 g ae L^{-1}) (Landman Limited, Waiheke Island, Auckland, NZ),

Triclopyr's targeted use in basal-bark applications is recognized by researchers as highly effective against a wide variety of woody plants (DiTomaso and Kyser 2007; Nelson et al. 2006), and likewise cut-stem applications of triclopyr on old man's beard (Bierzychudek 2020). Triclopyr is closely related to picloram but breaks down more quickly in soil (Ferrell et al. 2006; Jotcham et al. 1989; Monaco et al. 2002). Triclopyr's soil residual activity is between 10 and 100 d after treatment (Cox 2000), although its half-life in plant tissues can be up to 291 d (Newton et al. 1990). In comparison, picloram's soil residual activity is between 90 d and 3 yr (Fryer et al. 1979; Jotcham et al. 1989; MacDiarmid 1975; Scifres et al. 1971), and its half-life in plant tissue is >3 yr (Abramova et al. 1977; Harrell and Sheets 1984). Even so, triclopyr is increasingly bound to soil over time, and adsorption increases with increasing levels of organic matter (Buttler et al. 1993; Ghassemi et al. 1981). Basal-bark applications involve spraying herbicide plus penetrant completely around the basal circumference of a woody stem. The New Zealand Department of Conservation uses this basal-bark method, with an ester formulation of triclopyr [butoxy ethyl ester (BEE); 120 g ae L^{-1}] in an oil carrier and a nontoxic biodiesel as a penetrant; a low-pressure spray is applied to saturation (but not runoff) to individual stems (Raal and Timmins 2018). The basal-bark method is somewhat more expeditious than the gel technique, as it does not require the extra step of stem cutting before treatment.

Directed techniques like cut-stem and basal-bark methods are inappropriate when a target weed is spread extensively over an area, as is the case with old man's beard in many New Zealand riparian zones and in ruderal sites such as roadsides from where the wind-blown seeds can be dispersed to areas with trees. These areas are often populated by grasses and other weedy species. Healthy grass cover can help prevent old man's beard and other weeds establishing from seed (Jarvis-Lowry 2023). However, when old man's beard does establish in such areas, it tends to spread rapidly via vegetative growth of its branching stems. In these situations, broadcast spraying of herbicides from the ground can be the best method for control, using as much precision as possible to avoid contamination of waterways and damage to desirable vegetation. Here, it is important to leave grasses intact, which can help protect against recolonization by old man's beard seedlings or other weedy species.

The herbicides most widely used by regional councils around New Zealand for such sites include triclopyr, metsulfuron, and a combination of picloram, triclopyr, and aminopyralid (Jack Keast, Horizons Regional Council, personal communication, March 25, 2021). Aminopyralid structurally resembles picloram and is likewise persistent in plant tissue and soil, with high soil mobility (Ferrell et al. 2006; Kline et al. 2005; MacBean 2010). These pyridine herbicides are commonly mixed together to achieve improved control of brush weeds (Campbell et al. 2021; Gawn et al. 2013; Moore et al. 2010; Tran et al. 2015; Webb and Harrington 2005). Although metsulfuron can be highly mobile in some soils (Thompson et al. 1992; USDA-ARS 1995), studies have shown it to have relatively low residual soil activity, from 5 to 63 d after treatment (Harrington et al. 2017; Ismail and Lee 1995; Trabue et al. 2006; Tran et al. 2015). Low persistence notwithstanding, metsulfuron has been shown to damage some grass species, such as perennial ryegrass (*Lolium perenne* L.) and Yorkshire fog (*Holcus lanatus* L.) (Harrington et al. 2017; Harrington and He 2010), despite being labeled for selective broadleaf weed control.

The first objective of the current research was to compare the efficacy of different targeted basal-stem herbicide application techniques on woody old man's beard stems to replace the use of picloram gel, using two different herbicides, i.e., the basal-bark method using a triclopyr-plus-oil mixture, and the cut-stem technique using concentrated glyphosate gel. The second objective was to determine the efficacy of several selective herbicides used widely in New Zealand as foliar sprays on sprawling old man's beard, while also considering the effect on grass cover.

Materials and Methods

Basal Treatments

Three rural sites along the Manawatu River in the Tararua District, New Zealand, were chosen for the study, with a minimum of 4 km

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Table 1. Ready-to-use herbicides evaluated following basal application to old man's beard (*Clematis vitalba* L.) plants at three riparian sites along the Manawatu River in the Tararua District, New Zealand in 2020[a]

Herbicide	Trade name[a]	Commercial formulation/rates of active ingredient	Application dosage
Glyphosate gel	Cut'n'Paste Glimax Professional	450 g ae L^{-1} glyphosate isopropylamine salt with 0.5% alkyl polyglucoside surfactants	3- to 5-mm layer per cut-stem end
Triclopyr	X-Tree® Wet & Dry	120 g ae L^{-1} triclopyr butoxyethyl ester and 620 g ae L^{-1} methyl and ethyl esters of fatty acids	2.5 mL × 2 per stem up to 2 cm diam + 2.5 mL for each additional cm increase in diameter

[a]Manufacturers: Landman Ltd., Waiheke Island, NZ (Glimax); UPL, Auckland, NZ (X-Tree®).

between them: (i) Kaitoki (40.2401° S, 176.1145° E); (ii) Tamaki (40.2527° S, 176.0672° E); and (iii) Hopelands (40.3613° S, 175.9604° E). All three sites were largely unmanaged riparian zones infested by old man's beard, both on the ground and in the tree canopy. Kaitoki was an open, grassy site, dominated by tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.], perennial ryegrass (*Lolium perenne*), tall oat grass [*Arrhenatherum elatius* (L.) P. Beauv.ex J. Presl & C. Presl], and cocksfoot (orchard grass; *Dactylis glomerata* L.), with tradescantia (*Tradescantia fluminensis* Vell.), blackberry (*Rubus fruticosus* L. agg.), hemlock (*Conium maculatum* L.), and various other weeds scattered throughout the site, as well as occasional willow (*Salix* spp.), tōtara (*Podocarpus totara* G. Benn. ex D. Don var. totara), and mataī [*Prumnopitys taxifolia* (Banks & Sol. ex D. Don) de Laub.] trees. Horses were occasionally allowed to graze at Kaitoki. Sites Tamaki and Hopelands were much more densely inhabited by trees, and neither one was used for grazing. At Tamaki, 95% of the trees were willow (*Salix* spp.), with an occasional radiata pine (*Pinus radiata* D. Don), or tree lucerne [*Chamaecytisus palmensis* (Christ) F.A. Bisby & K.W. Nicholls] in the understory. Groundcover/vine species at Tamaki consisted mainly of high densities of tradescantia, grasses (mostly cocksfoot and perennial ryegrass), three-cornered garlic (*Allium triquetrum* L.), and great bindweed (*Calystegia sylvatica* ssp. *disjuncta* Brummit), along with lower densities of periwinkle (*Vinca major* L.), blackberry, and montbretia [*Crocosmia* × *crocosmiiflora* (G. Nicholson) N.E. Br.]. At Hopelands, willow species also dominated the canopy, with some large, impenetrable clumps of Oldham's bamboo (*Bambusa oldhamii* Munro); occasional māhoe (*Melicytus ramiflorus* J.R. Forst. et G. Forst.), and tree lucerne were found in the understory. Tradescantia, periwinkle, and cocksfoot were the most abundant groundcover/vine species at Hopelands, with blackberry, great bindweed, ivy (*Hedera helix* L.), and montbretia somewhat less abundant.

Across the three sites, 48 circular plots, each in a radius around a central cluster of climbing old man's beard stems, with a minimum buffer of 3 m separating them, were classified in one of three levels of infestation (low, medium, high). The infestation levels were based on the approximate number of old man's beard stems in the plot given its size (between 3 m and 8 m diam). A group of four plots at each classification level comprised a single experimental block (12 blocks total). With infestation levels distributed as equally as possible between them, half of the blocks were assigned for treatment in 2020, and the other half in 2021.

To simplify cut-stem relocation for post-treatment assessment, all treatments were made at 1 m above ground (following Ward and Henzell 2000). Four treatments were assigned randomly to each stratified block (herbicide details listed in Table 1): (i) an untreated control ("Control"); (ii) basal-bark application of triclopyr, by chemically ring-barking stems ("Ring"; 120 g ae L^{-1} of triclopyr butoxyethyl ester plus 620 g ae L^{-1} methyl and ethyl esters of fatty acids derived from canola oil and hydrocarbon liquids in a ready-to-use formula); (iii) cut stump with application of concentrated glyphosate isopropylamine salt (IPA) gel ("Paste"; 450 g ae L^{-1}); and (iv) cut stump with no herbicide application ("Cut"), a control treatment for Paste. For the "Paste" treatment, both upper and lower cut-stem surfaces were immediately covered with a 3- to 5-mm layer of glyphosate gel––the lower for translocation to the root system, the upper to prevent re-rooting, should the stem fall to the ground. For the "Ring" treatment, a 20-mL Forestry Spotgun (modified drench gun, similar to that described by Porter (1979); ChemAgro, Auckland, NZ) with a solid-cone nozzle (GG 4.3W; Spraying Systems, Auckland, NZ), calibrated to release 2.5 mL of solution with each pull of the trigger, was used at low pressure to thoroughly wet stems (volume 5 mL per stem up to 2 cm diam, with another 2.5 mL for each additional centimeter increase in diameter) with the triclopyr-plus-oil product. The technique allowed the herbicide to encircle the whole stem when applied from two sides, without runoff. Treated stems varied in size from approximately 5 mm to 10 cm diam. Treatments were made in autumn 2020 and autumn 2021.

Treatment effects were assessed at 1 and 2 yr after the 2020 treatment (2020.1yr, 2020.2yr), and at 1 yr after the 2021 treatment (2021.1yr), on six stems per plot. Stems were selected for assessments using a systematic approach, in which the plot was divided into six equal sectors, and a stem in each sector was randomly chosen. The following data were collected at each time of assessment:

- proportion of nodes producing active growth;
- total number of live shoots produced on the stem up to 1 m;
- old man's beard as an estimated proportion of the groundcover.

Foliar Treatments

Two unmanaged riparian sites along the Manawatu River, NZ, were selected for this experiment: (i) Kaitoki (40.2401° S, 176.1145° E), a site also used in Experiment 1; and (ii) Awapuni (40.3861° S, 175.5858° E). Soil at both locations was a well-drained fluvial type. Old man's beard was prevalent in both locations, with extensive networks of creeping stems sprawling over the grass, other low-lying vegetation, and fallen trees. Old man's beard was also present in the tree canopy, although plots in this study did not include any trees, and only creeping stems were treated. The Awapuni site was slightly more densely populated with willow trees than Kaitoki, but also had large open areas in which the groundcover/vines consisted mainly of the grass species tall fescue, tall oat grass, and cocksfoot, with great bindweed, German ivy (*Delairea odorata* Lem.); occasional cleavers (*Galium aparine* L.) and blackberry shrubs also present. No grazing animals were present at Awapuni.

The heterogeneity of old man's beard infestation at each site was accounted for by creating circular plots with a 5-m radius (78.5 m^2)

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Table 2. Herbicides evaluated following foliar application to old man's beard (*Clematis vitalba* L.) plants at two riparian sites along the Manawatu River in Tararua District and Palmerston North, New Zealand.[a]

Herbicide	Trade name[a]	Commercial formulation	Knapsack sprayer product RR[b]	Rates of active ingredient	Treatment abbreviation
Metsulfuron	Agpro Meturon	600 g ai kg^{-1} metsulfuron-methyl	5 g 10 L^{-1}	30 g ai 100 L^{-1}	met
Triclopyr	Grazon	600 g ae L^{-1} triclopyr butoxyethyl ester	6 mL L^{-1}	0.36 kg ae 100 L^{-1}	tri
Triclopyr/picloram/ Aminopyralid	Tordon Brushkiller XT	100 g ae L^{-1} picloram, 8 g ae L^{-1} aminopyralid, 300 g ae L^{-1} triclopyr butoxyethyl ester	6 mL L^{-1}	60 g ae 100 L^{-1} picloram + 48 g ae 100 L^{-1} aminopyralid + 0.18 kg ae 100 L^{-1} triclopyr	tri/pic/amino

[a]Manufacturers: AgPro, Auckland, NZ (Meturon); Dow AgroSciences, New Plymouth, NZ (Tordon, Grazon).
[b]Abbreviation: RR, label recommended rate.

and a minimum buffer of 5 m between them and classifying them in one of two levels of infestation (by dividing plots into four sections, estimating the density of old man's beard cover in each section, and taking the average of the four densities): Level 1 old man's beard density was 40% to 60% groundcover, Level 2 was >60% to 80%. A group of four plots at each level composed a single experimental block, two at each site. In addition to estimated old man's beard cover, other groundcover species were identified, and percentage groundcover density was recorded in each plot section measured at 1 m above ground, using the Canopeo App for Android phones (Patrignani and Ochsner 2015) (area approx 1.73 m^2 per Canopeo image). Along with one control treatment, three herbicide treatments were assigned randomly to each block: metsulfuron-methyl ester ("met"; 600 g ai kg^{-1} of water-dispersible methyl ester granules); a triclopyr/picloram/aminopyralid mixture ("tri/pic/amino"; 300 g ae L^{-1} triclopyr as an emulsifiable concentrate as BEE, 100 g ae L^{-1} picloram, and 8 g ae L^{-1} aminopyralid, both as amine salts); and triclopyr ("tri"; 600 g ae L^{-1} BEE as an emulsifiable concentrate).

In late March 2021 (autumn), treatments at the recommended rates for woody plants plus an organosilicone surfactant (Boost Penetrant; Dow Agrosciences, New Plymouth, NZ) and a blue marker dye (FIL Done That; GEA Farm Technologies, Mt Maunganui, NZ) were applied with 15-L knapsack sprayers (Swissmex SW503), using a fan nozzle (TeeJet XR 11004-VP) (Table 2). To ensure that all old man's beard stems in the plots were covered, the spray mix (a total of 10 L per plot) was broadcast uniformly over each 78.5-m^2 plot to the point of runoff. Weather conditions at both sites at the time of treatment were dry, sunny, with light winds (Awapuni: up to 17 km h^{-1}; Kaitoki <10 km h^{-1}), and a maximum temperature of 25 C. No precipitation occurred at either site for at least 48 h after treatment.

Plots were assessed 8 mo after treatment (late November 2021) for herbicide efficacy. To mitigate interference with results by potential spread of old man's beard from outside the treated area into plots, measurements were limited to the central-most 2.5-m radius area. All measurements were made in each of four equal sections of the plot. To compare with density before treatment, percentage groundcover density was again documented (Canopeo App). Major grass species were identified, and as a measure of relative grass health, average height of grasses in the plots was recorded. Additionally, old man's beard biomass in the plot was measured by removing all aboveground plant parts within four random 50-cm by 50-cm quadrat samples and taking the weight of the samples after drying them over a 3-d period in a 60 C oven.

Analysis

All analyses were made using R statistical software (R Core Team 2022). Plots for all analyses were made using the following packages: magrittr, iNZightPlots, ggplot2, ggpubr, and patchwork (Bache and Wickham 2022; Elliot et al. 2022; Kassambara 2020; Pedersen 2022; Wickham 2016).

For the basal-treatment experiment, the analysis was carried out in two stages. First, a comparison of live stems across all treatments was made by using the data for the proportion of active nodes per stem. These data did not meet the assumptions for linear regression, nor could they be satisfactorily transformed, as determined by the following packages: broom, rstatix, tidyverse, and bestNormalize (Kassambara 2021; Peterson 2021; Robinson et al. 2022; Wickham et al. 2019). Hence, separate Kruskal-Wallis tests were performed on ranked data for each of the three efficacy assessments (2020.1yr, 2020.2yr, 2021.1yr), followed by pairwise comparisons of the treatments using Wilcoxon rank sum tests. To control the false discovery rate, the Benjamini-Hochberg P value adjustment method was utilized.

Second, an analysis of the vigor of surviving stems (number of shoots produced by each stem) was made by fitting a Poisson model to the treatment pairs––that is, the herbicide treatments and their controls (Control/Ring; Cut/Paste)––as well as a separate model for the pair of herbicide treatments alone (Ring/Paste). Negative binomial models were used when data were over-dispersed, and treatment block was used as a random variable in each model, except when its inclusion resulted in a singular matrix. Packages used for Poisson model fitting, diagnostics, and data sub-setting were: lme4, DHARMa, dplyr (Bates et al. 2015; Hartig 2022; Wickham et al. 2022).

For the foliar herbicide experiment, the effect of herbicide treatments on the groundcover layer other than old man's beard was quantified by determining the change in groundcover density from pre- to post-treatment, as well as the relative height of the grasses in the plot post-treatment. Groundcover density change and grass height were each analyzed with separate two-way ANOVAs and Tukey multiple comparisons of means post hoc tests, using the car, broom, and tidyverse packages (Fox and Weisberg 2019; Robinson et al. 2022; Wickham et al. 2019). Independent variables for both ANOVAs were treatment and site. The old man's beard dry-weight data did not meet assumptions for a linear model, nor could they be satisfactorily transformed, given that the median was zero. These were analyzed with a Scheirer-Ray-Hare test, an extension of the Kruskal-Wallis test, with treatment and site again used as independent variables (Sokal and Rohlf 1995). The variance and distribution of dry-weight data for Control treatment plots was clearly substantially different from that of all other treatments. Because treatment was the sole

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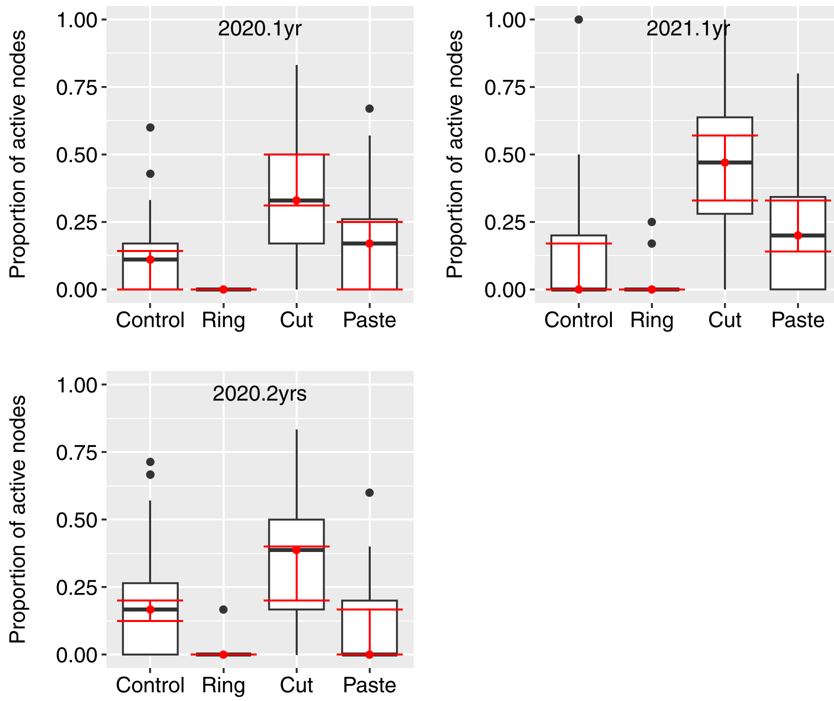

Figure 1. Observed proportion of active nodes per old man's beard stem by treatment [Control, untreated stems; Cut, stems severed at 1 m above ground; Paste, stems severed at 1 m above ground and treated with 45% glyphosate gel; Ring, stems chemically ringbarked with triclopyr in oil (basal-bark method)] in three different assessments (2020.1yr, 1 yr after treatment in autumn 2020; 2020.2yrs = 2 yr after treatment in autumn 2020; 2022.1yr = 1 year after treatment in autumn 2021). Bootstrapped confidence intervals around median in red.

statistically significant predictor from the Scheirer-Ray-Hare test, and to avoid drawing invalid inferences from post-hoc tests on the complete dataset, the Control data were removed, and an additional Kruskal-Wallis test was run on the remaining treatments. In addition to the aforementioned packages, the rcompanion, FSA, and dplyr packages (Mangiafico 2022; Ogle et al. 2022; Wickham et al. 2022) were used in the dry-weight analysis.

Results and Discussion

Basal Treatments

Of the stems treated with triclopyr (Ring), no more than 4.8% were producing active growth from any nodes at any of the three assessments (>95% mortality) (Figure 1). In comparison, 58.3% (2020.1yr), 66.7% (2021.1yr), and 44.4% (2020.2yr) of stems treated with the cut-and-paste method (Paste) had active nodes (42%, 33.3%, and 55.6% mortality, respectively; Supplementary Table S1). Differences between treatments were consistent across all assessments in the three main treatment pairs of interest, Control/Ring, Cut/Paste, and Paste/Ring (Table 3), and stems in the Ring treatment produced a smaller proportion of active nodes than any other treatment ($P < 0.001$). These results agree with previous research reporting successful woody-plant control using the basal-bark method with triclopyr ester on other species (DiTomaso and Kyser 2007; Langeland and Meisenburg 2009; Nelson et al. 2006).

In contrast, stems in the "Cut" treatment had a larger proportion of active nodes than any other treatment ($P < 0.01$). Also, although active nodes in any treatment commonly produced multiple shoots, cut stems with no herbicide applied produced especially vigorous multiple shoots per node. Cut stems produced more shoots per live stem than those pasted with glyphosate after being cut ($P < 0.001$; Figure 2; Supplementary Table S2). The extra vigor of the cut-only stems may be explained by the removal of apical dominance brought on by the cut, and simultaneous shift of translocating sugars to new sinks below the cut (Kebrom 2017). The cut-only treatment was certainly beneficial to host trees, in that it immediately caused old man's beard stems in the canopy to die back and deprived the remaining parts of new photosynthates from above, weakening the stems overall. That cut stems treated with glyphosate had significantly fewer live stems and produced significantly fewer shoots per live stem than those that were cut-only, indicates that the gel treatment substantially undermined the growth that would have been stimulated by the cut.

Although stem node activity was used as an indicator of stem survival, in the case of Control stems, whereas there was still more activity than on Ring stems, relatively few nodes on Control stems were active, and the untreated stems had fewer active nodes at 1 m and below than Cut stems. This can be attributed to the suppression of lower nodes by the apical meristem's dominance (Kebrom 2017; Monaco et al. 2002).

As a further indication of triclopyr efficacy in the basal-bark method, both Control and Paste stems produced more shoots than Ring stems ($P < 0.001$), except in the first-year comparison of plots treated in 2020. These models produced very large standard errors, demonstrating that the estimates were not robust, almost certainly because no shoots were found on any Ring stems in that assessment (as compared to at least one shoot on Ring stems in the 2020.2yr and 2021.1yr assessments).

Mixed-effect models showed some variance between treatment blocks, but the effect was not consistent. Thus, although block conditions did have some impact on the outcome, given the consistent differences between the treatments, it is clear the random variable did not influence the outcome to a large degree.

Manufacturer labels for both the basal-bark technique using X-Tree® Wet & Dry (triclopyr ester) and the cut-and-paste

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Table 3. P value results from three assessments of pairwise Wilcoxon rank sum tests with continuity correction, showing differences between old man's beard (*Clematis vitalba* L.) stem treatments in proportion of active nodes per stem. Benjamini-Hochberg P value adjustment method used.[a]

	2020.1yr			2020.2yr			2021.1yr		
	Control	Cut	Paste	Control	Cut	Paste	Control	Cut	Paste
Cut	<0.001			0.005			<0.001		
Paste	0.141	<0.001		0.040	<0.001		0.014	0.005	
Ring	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a]Abbreviations: 2020.1yr, 1 yr after treatment in autumn 2020; 2020.2yr, 2 yr after treatment in autumn 2020; 2022.1yr, 1 yr after treatment in autumn 2021; Control, untreated stems; Cut, stems severed at 1 m above ground; Paste, stems severed at 1 m above ground and treated with 45% glyphosate gel; Ring, stems chemically ringbarked with triclopyr in oil (basal-bark method).

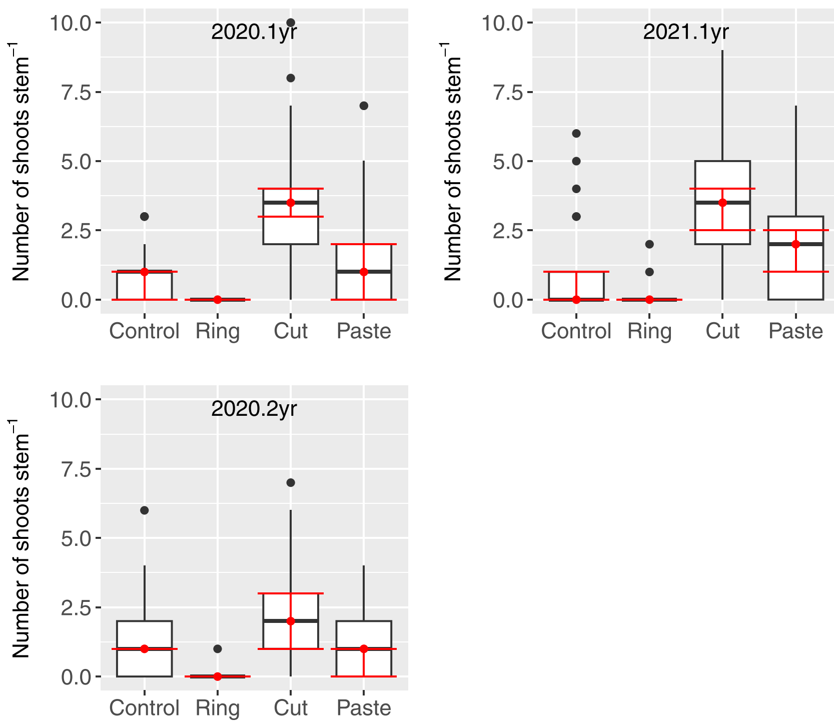

Figure 2. Observed number of shoots per old man's beard stem by treatment [Control, untreated stems; Cut, stems severed at 1 m above ground; Paste, stems severed at 1 m above ground and treated with 45% glyphosate gel; Ring, stems chemically ringbarked with triclopyr in oil (basal-bark method)] in three different assessments (2020.1yr, 1 yr after treatment in autumn 2020; 2020.2yrs, 2 yr after treatment in autumn 2020; 2022.1yr, 1 yr after treatment in autumn 2021). Bootstrapped confidence intervals around median in red.

technique using Glimax Professional (glyphosate gel) recommend treating stems at the base, including the root collar, or very close to the base. However, for this study, all stems were treated at 1 m above ground (after Ward and Henzell 2000), to ensure that cut stems could be identified for efficacy assessments 1 and 2 yr later and to minimize the risk of contacting non-target plants in the crowded groundcover zone. When cutting and pasting with 10% glyphosate gel, Ward and Henzell (2004) indicated that grey willow was controlled better when applying the treatment at 0.3 m as opposed to 1 m. Certainly, given the label recommendations, treatment lower on the stem with 45% glyphosate may likewise improve effectiveness of control for old man's beard, yet Ring stems treated at the same height showed much higher mortality, notwithstanding the lack of adherence to label guidelines.

Treatments were applied in autumn, during the period when translocation of carbohydrates is increasingly directed toward increasing root reserves for winter dormancy (Loescher et al. 1990). Although the autumn application of the triclopyr ester was highly effective, the glyphosate gel was less so. In a previous cut-stem study on old man's beard in New Zealand (Ward and Henzell 2000), late-spring applications of picloram gel on cut stems were highly effective, more effective than winter applications, and in lower concentrations. This result is likely due to active phloem movement toward growing tips and reproductive tissues in spring, which facilitates active elongation and photosynthesis (Loescher et al. 1990). The application of glyphosate using the cut-stem method may be more effective during spring.

Old man's beard infestations appear, at least in part, to be driven by vegetative growth from extensive, branching lateral networks of stems (Jarvis-Lowry 2023). Measuring the effect of different herbicide techniques on individually treated climbing stems was the focus of this experiment. Yet, during efficacy assessments, both 1 and 2 yr after treatment, there appeared to be no good correlation between treatment efficacy and the presence of healthy old man's beard stems in a plot's tree canopy. That is, although the basal-bark method was more than 95% effective on treated stems, the effect was not necessarily reflected in the canopy, particularly at 2 yr post-treatment; in most Ring plots, all visible stems in the plot were completely brittle, with no active nodes, though the canopy was full of old man's beard. Additionally, old

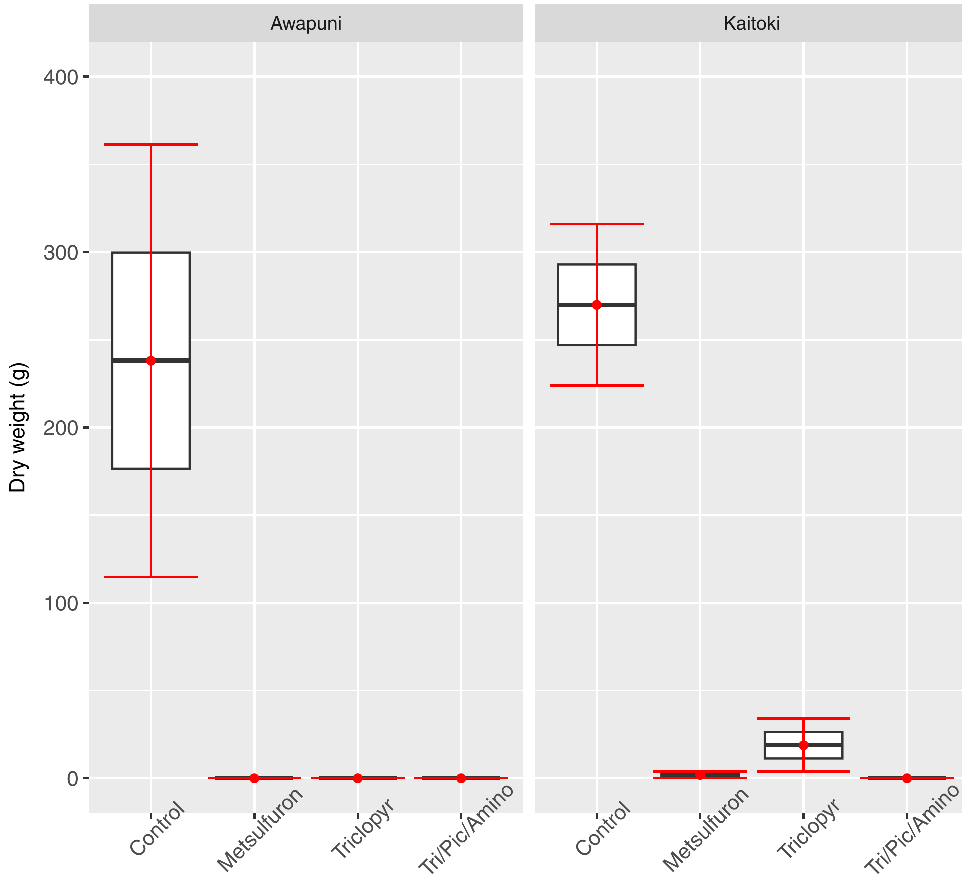

Figure 3. Measured dry weight of old man's beard remaining in plots 8 mo after foliar spray herbicide treatment (Control, untreated; Metsulfuron, metsulfuron-methyl; Triclopyr; Tri/Pic/Amino––a combination of triclopyr, picloram, and aminopyralid). Range of measurements in red.

man's beard density in the groundcover remained largely unchanged. This suggests that the quick recolonization of the canopy occurred from (a) untreated, smaller diameter climbing stems; (b) missed climbing stems; (c) stems regenerating from below the treated area; and/or (d) untreated creeping stems, both in the plot understory and outside of it. Also, dead climbing stems remained intact, acting as convenient, expeditious trellises for living stems to climb. Ward and Henzell (2000) noted the difficulty of finding and individually treating 100% of old man's beard stems without follow-up work, observing that 10% to 40% of stems in research plots were missed. Furthermore, Clay and Dixon (2000) reported that following effective control of old man's beard in the center of small, infested areas (with a foliar spray of imazapyr), peripheral stems had thoroughly recolonized them within a year. This research corroborates those findings and suggests that the vigor of old man's beard stems and its weblike lateral networks prevent anything more than a temporary setback to infestations if all climbing and creeping stems are not comprehensively treated.

Picloram gels are widely used in New Zealand to control old man's beard but are likely to have undesirable effects in some sites. The aim of the basal herbicide experiment was to identify the least environmentally persistent herbicide that can effectively control individually treated old man's beard stems, using selective techniques that protect tree hosts and other non-target vegetation. For stems treated 1 m above ground in autumn, the basal-bark method using triclopyr ester in oil plus biodiesel was highly effective (>95% mortality), even though stems were treated higher up than recommended. The cut-stem method using a 45% glyphosate gel formulation was less effective (56% mortality 2 yr after treatment) at the same stem height.

The basal herbicide stem treatments tested in this research are well suited for situations where old man's beard density is not high and can be implemented without damaging high-priority trees and shrubs. However, due to the lateral-stem network old man's beard develops, an infestation cannot be controlled by solely focusing on climbing stems, nor would it be practical to treat individual stems where old man's beard is widespread, as basal herbicide methods are labor intensive. To effectively manage both climbing and creeping stems while simultaneously minimizing non-target damage, separate approaches are necessary for each. Directed foliar herbicide spraying can be used to supplement basal methods.

Foliar Treatments

The foliar herbicide treatments proved highly effective on creeping old man's beard plants. Eight months post-treatment, old man's beard remained healthy and vigorous in all Control plots, at both sites; a random square meter of old man's beard plant parts in a Control plot yielded between 115 and 360 g of dry matter (median at Awapuni 238 g m^{-2}, at Kaitoki 269 g m^{-2}; Figure 3). In contrast, little to no old man's beard was visible within the 2.5-m diam inner circle of any plots other than Control plots at either site ($H3, 8 = 11.25$, $P = 0.01$; Supplementary Table S3). At Kaitoki, one met and both tri plots did have a small amount of old man's beard remaining (<35 g m^{-2}), though median dry weight of old man's beard in tri plots was 19 g m^{-2} as opposed to >260 g m^{-2} in Control

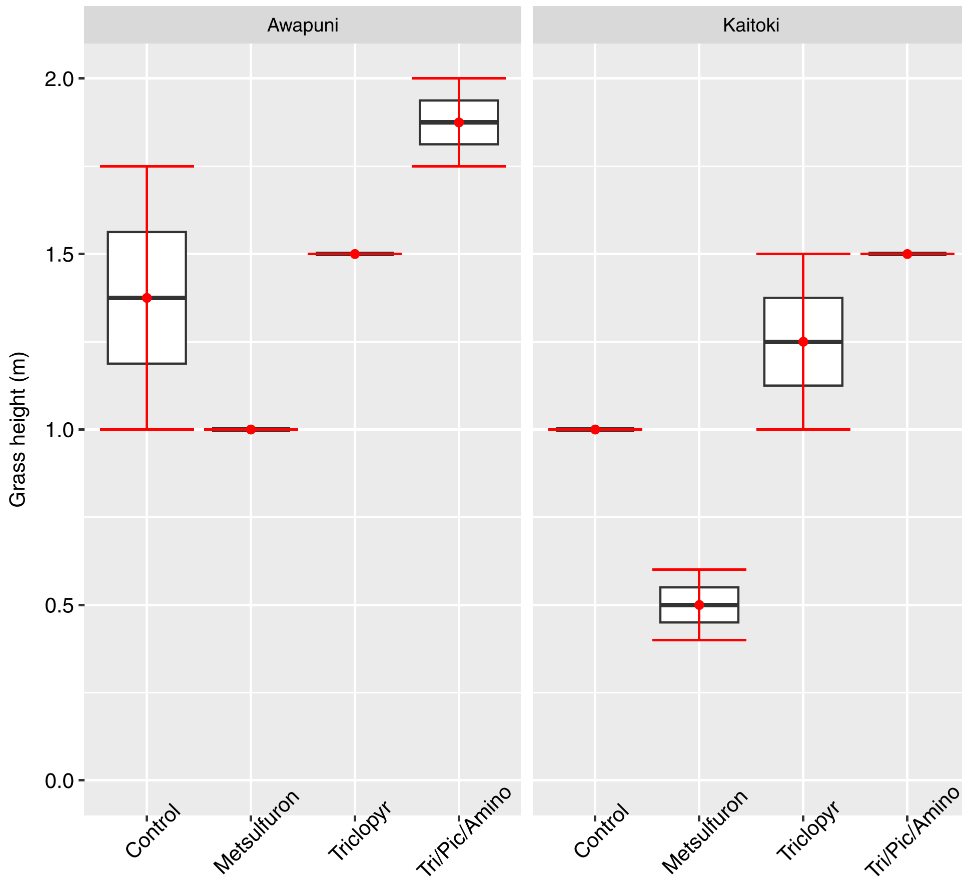

Figure 4. Measured height of plot grasses by foliar spray herbicide treatment (Control, untreated; Metsulfuron, metsulfuron-methyl; Triclopyr, Tri/Pic/Amino––a combination of triclopyr, picloram, and aminopyralid) and site (Awapuni, Kaitoki) 8 mo after treatment. Range of measurements in red.

plots at Kaitoki, showing biomass in the tri plots was approximately 7% that in the Control plots, an undeniably consequential reduction. Among the three other treatment groups, no significant difference was detected ($\chi^2 = 2.386$; $P = 0.303$). Still, any remaining old man's beard is a source from which the infestation can re-establish itself. Thus, in some situations, spot-spraying may be necessary following broadcast spraying, to get more complete control.

Likely as a result of occasional horse grazing, the groundcover density at Kaitoki was more uneven and less dense than at Awapuni throughout the study. Regarding the change in groundcover density over time, no treatment, nor site, nor their interaction had a more detrimental or beneficial effect than any other (P = 0.711, 0.195, 0.128, respectively, Supplementary Table S4).

Grass height measurements at assessment suggest that metsulfuron did more lasting damage to the grasses than all other treatments, including Control, in which the presence of old man's beard would have suppressed the grasses (Figure 4). Both treatment and site influenced average plot grass height at 8 mo ($F_{3,8} = 10.747$, $P = 0.004$; $F_{1,8} = 9.836$, $P = 0.014$, respectively), but no interaction effect was detected. Whole-plot recovery and grass height were not as strong in the met plots as in the tri plots ($P = 0.025$; Supplementary Table S5) or the tri/pic/amino plots ($P = 0.002$), suggesting that metsulfuron reduced grass vigor at both sites, more than triclopyr or the triclopyr/picloram/aminopyralid mix, but more so at Kaitoki.

This result is consistent with that of other studies that have reported sensitivity of some grass species to metsulfuron (Harrington et al. 2017; Harrington and He 2010). The main grass species present at Kaitoki included perennial ryegrass, tall fescue, tall oat grass, and cocksfoot. Tall fescue, tall oat grass, and cocksfoot were also present at Awapuni, but perennial ryegrass was not among the dominant species there. Although no attempt was made in this study to determine the proportions of each grass species present in the research plots, metsulfuron's stronger effect at Kaitoki could be partly attributed to its impact on perennial ryegrass there. It is also worth noting that in the metsulfuron plots at Kaitoki, old man's beard had been controlled but was being replaced by great bindweed, indicating a shift in dominance from one invasive species to another. Gawn et al. (2013) have shown that metsulfuron is not effective against great bindweed.

The results of the foliar herbicide study support previous work demonstrating that mixtures with triclopyr and picloram or with triclopyr, picloram, and aminopyralid, are highly effective as foliar applications against other woody species (Campbell et al. 2021; Gawn et al. 2013; Webb and Harrington 2005). However, the evidence in this study was not strong that the mixture was much more effective against old man's beard than triclopyr alone, or metsulfuron, which are less persistent in the environment. Despite its effectiveness against old man's beard, the drawback to using metsulfuron is that it can severely damage some grass species, such as perennial ryegrass, increasing the chances of recolonization from old man's beard or colonization from other weeds through the weakened grass cover (Tran 2013). Also, because metsulfuron is not effective against great bindweed, it is not a suitable choice for control of old man's beard when great bindweed is also present, as it could release great bindweed from old man's beard competition and encourage its growth.

Practical Implications

Individual stems of old man's beard can be effectively treated with triclopyr in oil, using the basal-bark method, which is especially valuable as a precision technique that avoids damage to nearby non-target vegetation, such as trees hosting climbing old man's beard. Triclopyr also has lower relative environmental persistence than commonly used picloram. However, quick recolonization of the canopy by untreated stems and creeping stems from outside plots demonstrate the need to treat the entire infestation for successful control.

Preserving the grass cover is valuable when clearing infestations from waste areas or riparian zones being prepared for native plantings, as it can help suppress recolonization by old man's beard and colonization by other weeds. Infestations of creeping stems can be treated by broadcasting a foliar spray, ideally one that preserves existing grasses, such as triclopyr or a combination of triclopyr, picloram, and aminopyralid. Native or other broadleaf vegetation must be shielded from the spray, although other research has shown that *Pinus radiata* (the species most grown in production forests) is tolerant to these pyridine herbicides (Tran et al. 2016). Once the infestation has been reduced, following up with spot spraying may be necessary.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wet.2023.40

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