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Technical Report 82

# CONTROL OF FIRETREE (*Myrica faya* AITON) WITH HERBICIDES IN HAWAII VOLCANOES NATIONAL PARK

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# INTRODUCTION

Firetree or faya tree (*Myrica faya* Aiton), a native of the Azores, Madeira, and the Canary Islands, was introduced to the Hawaiian Islands prior to 1900, probably by Portuguese immigrants for use as an ornamental, a source of fruit for wine-making, or for firewood (Wagner *et al.* 1990). The tree has also been used for reforestation in Hawai'i and in the 1920s was planted in 10 forest reserves on three islands (Skolmen 1979).

Firetree varies in appearance in different habitats: in dry or mesic open vegetation, it is a multi-trunked, shrubby tree; in wet forests it is typically single-trunked and may reach heights greater than 16 m (50 ft). Leaves are narrow, dark green, shiny, and usually toothed on the margins. Firetree bears relatively inconspicuous, unisexual flowers, typically on separate trees. Fruits are small, reddish to black, waxy drupes with a hard endocarp enclosing one to five seeds; they are dispersed by birds, particularly several alien species (LaRosa *et al.* 1987; Woodward *et al.* 1990).

By the 1980s, firetree had infested more than 34,000 ha (83,980 a) in the State, primarily on the island of Hawai'i, but also on the islands of Maui, Lāna'i, O'ahu, and Kaua'i (Whiteaker and Gardner 1985). One of the major firetree infestation sites on the island of Hawai'i is in Hawaii Volcanoes National Park (HAVO) and the adjacent Volcano Village and Volcano Golf Course subdivision. Firetree was first reported from the Park in 1961, when one plant was noted at Kilauea Military Camp (Fosberg 1966). Within five years, approximately 90 ha (225 a) in HAVO were infested with it, and by 1977, the area of the Park invaded had increased to 3,640 ha (9,000 a) (Smathers and Gardner 1979). By 1985 more than 12,200 ha (30,130 a) in HAVO had been invaded by firetree (Whiteaker and Gardner 1985).

Firetree is recognized as one of the most serious alien plant problems in HAVO (National Park Service 1988). The species is capable of invading essentially intact ecosystems and forms dense, monotypic stands with little or no ground cover (Smith 1985). Because it is a nitrogen-fixer, firetree is able to occupy nutrient-poor recent volcanic substrates, where its litter adds four times more nitrogen to the soil than is derived from all other natural nitrogen sources (Vitousek *et al.* 1987). Added nitrogen alters the nutrient balance of invaded ecosystems and may encourage the invasion of other alien plants that would not otherwise be able to thrive in nitrogen-poor Hawaiian soils (Vitousek, in press).

Control of firetree in HAVO was initiated by the National Park Service Resources Management Division in the early 1970s and was concentrated first in the 'Āinahou and Nāulu/Kalapana Trail areas. Subsequent emphasis was in areas near Hawaiian Volcano Observatory and in the vicinity of Kīpuka Puaulu. By 1979-80, firetree had become too widespread to control parkwide with existing funding levels. Management was abandoned until 1985, when resource managers focused their eradication efforts on the most intact and biologically diverse regions of the Park, Special Ecological Areas (Tunison *et al.* 1986). As of 1989, firetree was controlled in approximately 5,460 ha (13,490 a) of the Park with a 5% solution of the herbicide Tordon 22K applied to cut stumps of shrubby trees and Tordon RTU applied to continuous-frill cuts on large single-trunked trees. Tordon is not an ideal herbicide for use in natural areas, because of the possibility of leaching from the roots of treated plants and movement through the soil to nontarget species. Also, Tordon 22K may be removed from sale in the future in Hawai'i. These two problems led to the initiation of research to find an effective herbicide substitute that would be safe to use on firetrees surrounded by native plants.

## STUDY AREA

Two sites invaded by firetree with different native vegetation and climatic components were chosen (Fig. 1). The first is a wet forest east of Thurston Lava Tube; it is dominated by tall, closed-canopy 'ōhi'a (*Metrosideros polymorpha* Gaud.) with native trees, shrubs, and tree ferns, and alien shrubs in the understory (Jacobi 1980). The elevation at the Thurston site is 1,200 m (3,940 ft), mean annual rainfall is 2,540 mm (100 in.) (HAVO records), and the substrate is silt loam soil (Sato *et al.* 1973). The second site, on the western border of Kīpuka Kahali'i at 890 m (2,920 ft) elevation, has dry vegetation of very scattered 'ōhi'a with alien grasses, and native and alien shrubs in the understory (Jacobi 1982). Mean annual rainfall is 1,854 mm (73 in.) (HAVO records), and the substrate is very rocky sandy loam (Sato *et al.* 1973) with a recent overlay of volcanic cinder. These sites, both representative of firetree-infested vegetation types in the Park, were used to determine if site variation (predominantly moisture availability) would influence treatment effectiveness, as was indicated in previous work (Zabala 1969; Nicholls *et al.* 1971; Motooka *et al.* 1982).

## METHODS

The seven treatments tested were: glyphosate (undiluted Roundup*); imazapyr (Chopper, 9% v/v in water); imazapyr, (Chopper, 9% v/v in citrus oil (Cidekick)); triclopyr (Garlon 3A, 10% v/v in water for cut stump treatments, and 50% v/v in water applied to frilled trees); metsulfuron methyl (Ally or Escort, 2.8% w/w in water); crop or citrus oil (Cidekick); and water as a control. (Percentages refer to product dilutions, not active chemical ingredient.)** Imazapyr and glyphosate are strongly adsorbed to soils, whereas triclopyr and metsulfuron tend to be more mobile

*Reference to a company or product name does not imply endorsement of that product by the National Park Service.

**Chemical names of herbicides used are: glyphosate, {N-(phosphonomethyl) glycine}; imazapyr, {(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl-5-oxo-1H-imidazol-2-yl]-3- pyridinecarboxylic acid}; triclopyr, {[(3,5,6- trichloro-2-pyridyl)oxy]acetic acid}; and metsulfuron, {2[[[[4-methoxy-6- methyl-1,2,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl] benzoic acid}.

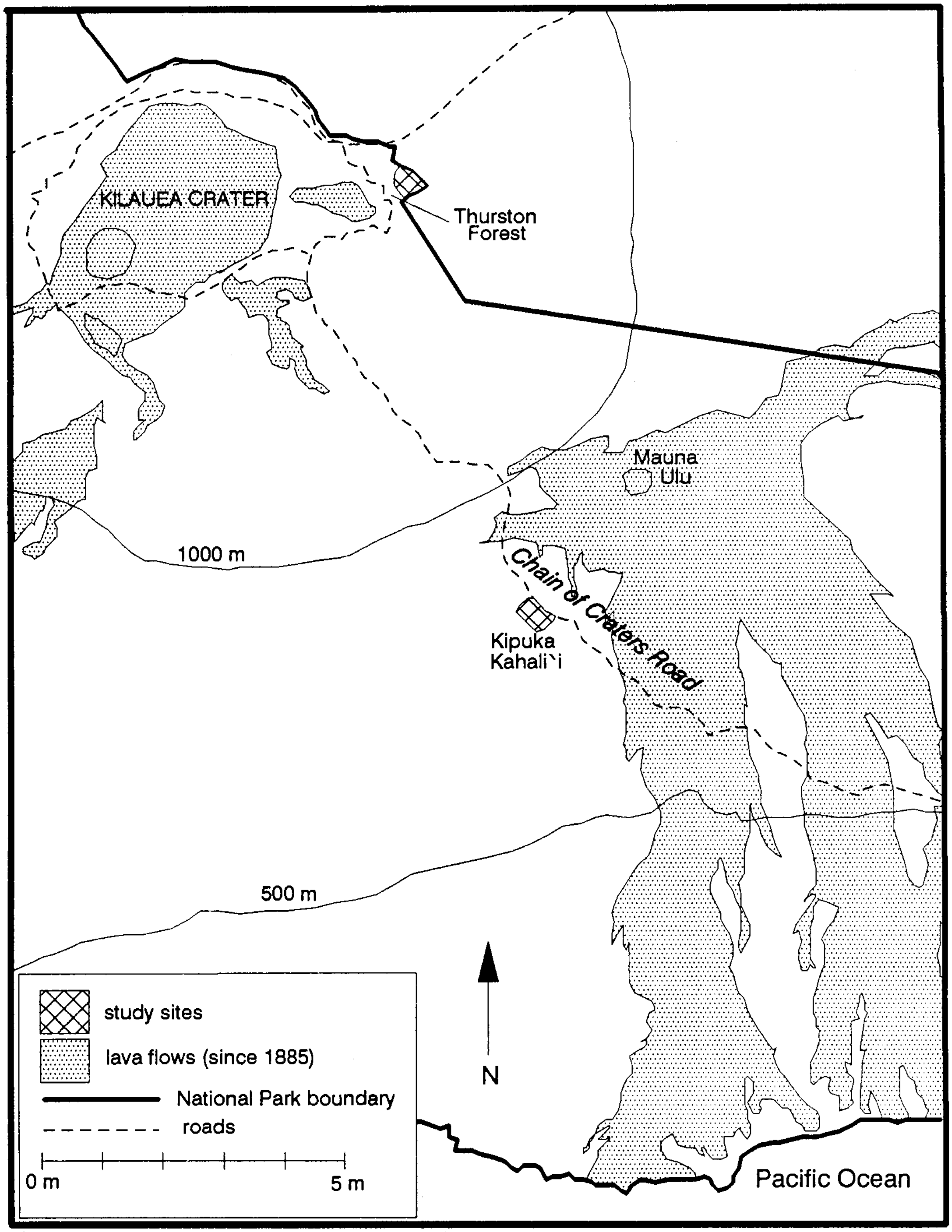


Figure 1. Wet and dry study sites (Thurston Forest and Kipuka Kahali'i) chosen for herbicide tests on firetree (*Myrica faya*) in Hawaii Volcanoes National Park.

under certain conditions. Imazapyr, glyphosate, and metsulfuron have especially low toxicity to wildlife (Humburg *et al.* 1989).

## Sample Selection and Treatment Technique

In June and July of 1987, 420 trees were selected from the two sites: 280 near Thurston Lava Tube (140 for cut stump and 140 for frill application treatments), and 140 in Kīpuka Kahali'i. Trees were selected on parallel transects running perpendicular to a fence or road. The location of the first transect was chosen at random, with subsequent transects spaced at regular intervals (approximately 50 m) from the first. Trees of two size classes were used: 3-9 cm basal diameter ("small") and ≥ 9.5 cm basal diameter ("large"). Sample size was 10 trees per size class per treatment (20 trees total) for the cut stump test; 20 "large" trees were used for the frill test. All trees were of good vigor at the beginning of the test. Pretreatment data collected on each firetree included: basal diameter, estimated height, vigor (excellent or good), location (ground or epiphytic), phenology, and whether the tree had single or multiple trunks.

Trees along the transects that met the size class and vigor criteria were used except when rare native plants were growing within 1 m of the trunk base. One of the seven treatments, selected at random, was applied to the first 10 trees of each size class encountered along the transect. Once a size class was filled in a treatment, subsequent trees of that size were used for the next treatment. The number of trees used per transect varied, as transects at Thurston were located between the Park boundary and an area where firetree had been previously removed; Kīpuka Kahali'i transects were between a road and an area of very low firetree density. The same treatment was applied to consecutive trees to preclude the possibility of cross contamination of plots or target trees. This was a concern because three of the herbicides used (imazapyr, triclopyr, and metsulfuron methyl) can be root-absorbed. Persistence averages for the three herbicides were 90-730, 46, and 7-42 days in temperate soils (Humburg *et al.* 1989). The three herbicides have only low to moderate adsorption to clay and organic matter fractions and are thus available to the surrounding plants.

A chainsaw was used to fell trees in the cut stump test; the final cut on the stump was level and as close to the ground as possible. Each treatment was immediately applied to the cut surface, using a 1,200-ml hand-pressurized sprayer to deliver a coarsely atomized spray. Because application was immediate, the herbicide was drawn deeply into the stump (Hay 1956).

In the frill test, overlapping cuts were made around the trunk with a hatchet, creating a continuous frill. The cut was sufficiently deep to sever the phloem and penetrate into the xylem. The herbicide was squirted into the frill with a hand sprayer set to deliver a solid stream. Approximately 1 ml of solution was applied per 3 cm trunk diameter.

## Monitoring

The cut stump and frill tests were monitored at 3-month intervals in the first year, and subsequently every 6 months. Data collected included: resprout number category, tallest resprout height, resprout vigor, and cambium color. An estimate of canopy defoliation was also included in the frill test.

The number of resprouts per tree was categorized as "low" (1-9), "medium" (10-50), or "high" (>50). The height of the tallest resprout per tree was measured in centimeters. Resprout vigor was estimated as: "excellent" -- leaves dark green and of normal appearance, full turgidity in stem and leaves, no chlorosis; "good" -- leaves green and normal, full turgidity in stem and leaves, some chlorosis (<10% of leaf area); "fair" -- leaves light green with some stunting or abnormalities, flaccidity in stem and leaves, chlorosis more pronounced and widespread (10-50% of leaf area), with some necrosis; "poor" -- leaves and stem stunted, deformed, severely chlorotic and flaccid, usually with widespread necrosis; and "dead" -- leaves and stem fully necrotic.

Mean resprout growth rate was calculated using the sum of the resprout height increases of the tallest resprout on each stump for two successive monitoring periods (*e.g.*, 3 and 6 months) divided by the number of resprouting trees and the interval duration (months). If no resprouts were observed on a tree at a monitoring period but were seen at the subsequent monitoring, 0 height was used for that resprout's previous height in calculating increase.

In both the cut-stump and the frill tests, the cambium of treated firetree stumps was examined and cambium color was recorded as green, yellow, or brown (in descending order of estimated vigor and viability). In the frill test, canopy defoliation or overall loss of leaves was estimated as "light" (<10%), "moderate" (10-50%), or "heavy" (>50%).

Native plants were monitored in circular plots of 1 m radius centered on each treated firetree. In each plot, the number, size, and vigor of native plants were recorded before treatments were applied to firetree, and plots were remonitored 3, 6, and 12 months after treatment. Height classes used to categorize native plants were <0.1 m (seedlings), 0.1-0.5 m, >0.5-1 m, >1-2 m, >2-3 m, >3-5 m, >5-10 m, and >10 m. (Trees from 0.1 to 1.0 m tall are considered saplings in this paper.) Native plant vigor was estimated as excellent, good, fair, poor, or dead. "Excellent" plants were those with good color, new growth, and no insect or other visible damage. "Good" plants were those that seemed typical for their species. Plants were rated "fair" if they exhibited a moderate degree of discoloration, wilting, dry leaves, or other damage; and "poor" if such visible impairments were severe. The "dead" rating was given to plants that had dropped all leaves and otherwise appeared dead.

## Data Analysis

Data collected on the number of resprouts and their heights were analyzed using the microcomputer version (6.03) of the Statistical Analysis

System (SAS) (Statistical Analysis System 1985). When the sample size was equal among treatments, the analysis of variance procedure was used, and Duncan's multiple range test was employed to separate treatment means. When the sample size for a variable was unequal among treatments, the general linear models procedure was specified for analysis of variance, and Tukey's studentized range test was used instead of Duncan's.

Using a SAS frequency procedure that computed chi-square, cambium vigors (color) of firetree were analyzed by comparing the number of stumps with brown or green cambium in any treatment with the equivalent numbers in the water or citrus oil controls. If the herbicide was mixed with water, the cambium data were compared with the water control data; for the imazapyr-oil treatment, the comparison was with the citrus oil control. Because yellow cambium often turned brown by the end of the study, the yellow and brown categories were combined and compared with the green category in this chi-square analysis. Chi-square values reported here were corrected for continuity (Snedecor and Cochran 1971).

Data collected on native plants in the 1-m radius plots centered on each treated firetree were also analyzed with SAS. The change in number of individuals greater than 0.1 cm in height over 12 months was analyzed for each native species with representatives in each treatment. As the sample sizes of native plants were unequal in the different treatments, the general linear models procedure was used for the analysis of variance, and Tukey's test was used to further separate the means among treatments. Additionally, t-tests were conducted on native plant data, pairing treatment results.

# RESULTS
## Kīpuka Kahali'i Cut Stump Treatments

### Treatment Efficacy

At 24 months post treatment, all five herbicide treatments inhibited both the initiation and further development of resprouts from firetree stumps. An analysis of variance indicated a highly significant difference ($p < 0.01$) among all treatments for both the number of resprouts ($F = 14.96$) and resprout height ($F = 3.85$). All five herbicides were significantly better ($p = 0.05$) at resprout suppression than were the controls (water and citrus oil). Among the five herbicide treatments, the imazapyr/water and triclopyr/water treatments were significantly more effective ($p = 0.05$) at suppressing resprouting than imazapyr/citrus oil (Table 1).

For the treatments that had resprouts at 24 months, triclopyr/water was more effective at inhibiting growth (represented by height) than were the controls or any herbicide tested except glyphosate. No significant difference in resprout height among imazapyr/oil, glyphosate, metsulfuron, citrus oil, or the water control was detected. More detailed results of the herbicide treatments on cut stumps of firetree at Kīpuka Kahali'i may be found in Table I of the Appendix.

Table 1. Mean number of resprouts in firetree (*Myrica faya*) treatment groups at Kīpuka Kahali'i site, Hawaii Volcanoes National Park, compared with Duncan's multiple range test.

| Cut-stump Treatment | Mean No. Resprouts | Duncan Group* | |
|---|---|---|---|
| Citrus Oil | 41.5 | A | |
| Water | 40.0 | A | |
| Imazapyr/Oil | 15.0 | B | |
| Glyphosate | 9.0 | B | C |
| Metsulfuron/Water | 7.5 | B | C |
| Triclopyr/Water | 0.5 | | C |
| Imazapyr/Water | 0 | | C |

*Treatments with different letters are significantly different at the 95% confidence level.

**Imazapyr/Water**. The imazapyr/water treatment resulted in the death of all 20 stumps by 18 months post treatment. This treatment had the lowest mean resprout height (7 cm at 6 months), and the smallest number of resprouting stumps (Appendix, Table I). Three of the four resprouting stumps were in the large-diameter class (>9.5 cm), and all eventually died. Resprouts were all deformed and stunted, and resprout leaves were severely chlorotic and small (1-3 cm long, versus 5-10 cm for normal leaves), with involute margins. Leaf venation was an abnormal red.

Cambium vigor of imazapyr/water stumps declined over 1.5 years. Brown cambium was seen on three stumps at the 3-month monitoring, and on all 20 stumps by 18 months. The number of imazapyr/water-treated stumps with dead cambium at 24 months was significantly higher ($p < 0.01$) than in the water control stumps (Table 2).

**Triclopyr/Water**. Treatment of firetree with triclopyr/water killed 18 of 20 stumps by 24 months. Only six triclopyr-treated stumps resprouted during the 2-year study, and five of these were of large diameter (>9.5 cm). These few stumps produced normal, healthy resprouts 3-6 months after treatment, then abnormal, less vigorous resprouts, followed by death by 24 months. Abnormal resprouts were slightly to moderately chlorotic, with involute leaves.

Cambium response was a darkening 3-6 months after treatment and death at 12 months. Of the two stumps surviving at the end of the study, one had green cambium and vigorously growing resprouts; the other stump had no detectable live cambium, and the late-appearing resprouts were stunted and deformed. The number of triclopyr-treated stumps showing dead cambium at 24 months was significantly greater ($p < 0.01$) than the number dead in the water control (Table 2).

Table 2. Summary of chi-square analyses of cambium vigor on herbicide-treated firetrees (*Myrica faya*) compared with that on control trees (water or citrus oil). (p = probability, $X^2$ = chi-square.)

| | Site/Application Method | | | | | |
|---|---|---|---|---|---|---|
| | Kīpuka Kahali'i/ cut-stump | | Thurston/ cut-stump | | Thurston/ frill | |
| Herbicide | $X^2$ | p | $X^2$ | p | $X^2$ | p |
| Glyphosate | 18.6 | <0.001 | 6.6 | 0.011 | 23.4 | <0.001 |
| Imazapyr/Water | 18.6 | <0.001 | 16.4 | <0.001 | 29.2 | <0.001 |
| Imazapyr/Oil | 8.2 | 0.004 | 7.7 | 0.006 | 1.4 | 0.230 |
| Triclopyr/Water | 15.4 | <0.001 | 13.3 | <0.001 | 36.1 | <0.001 |
| Metsulfuron | 6.4 | 0.011 | 13.3 | <0.001 | 36.1 | <0.001 |
| Citrus Oil | 0 | 1.000 | 1.6 | 0.205 | 26.2 | <0.001 |

**Glyphosate.** The glyphosate treatment killed 17 of 20 stumps by 18 months post treatment. The early response of firetree to glyphosate was medium resprouting (10-50 per stump) on 14 stumps by 3 months. Resprout vigor at 3 months was fair to good, with some foliar chlorosis, stunting, and deformity. Deformed resprouts were tightly clustered on swollen tissue masses at the perimeter of cut stumps. Between 3 and 18 months, the number of stumps bearing live resprouts declined, and overall resprout vigor deteriorated to poor. Mean resprout growth rate ranged from 3 to 5 cm/mo in the first year. By 18 months, resprouts had died on all but three stumps. At 24 months post treatment, the same three stumps survived and bore healthy resprouts that were growing at 11.9 cm/mo, apparently unaffected by the glyphosate.

The number of glyphosate-treated stumps with green cambium decreased steadily after 3 months, until all but the three survivors had dead cambium. At 24 months, the number of stumps with dead cambium was significantly higher ($p < 0.01$) in the glyphosate treatment than in the water control (Table 2).

**Imazapyr/Oil.** Sixteen of 20 stumps treated with imazapyr/oil died within 18 months. Firetree response to the imazapyr/oil treatment was moderate resprouting on 11 of 20 stumps by 3 months. The early resprouts were of good vigor and were clustered on swollen tissue on the bark of the stumps. The number of imazapyr-treated stumps with live resprouts decreased between 6 and 18 months and leveled off at four live firetrees at the end of the study.

The overall vigor of resprouts (including those that subsequently died) declined from good to poor during the study, with some showing early stunting and foliar deformities similar to those observed in the imazapyr/water treatment. Resprouts on the four surviving stumps were of good to excellent vigor, with no visible herbicide damage. The mean growth rate of live resprouts increased throughout the 2-year monitoring period from 3.5 to 12.9 cm/mo.

At 3 months, live cambium was detected on 19 stumps, but at 24 months only the four resprouting survivors had green cambium. The number of stumps with dead cambium in the imazapyr/oil treatment was significantly higher ($p = 0.004$) than in the citrus oil control (Table 2).

**Metsulfuron/Water.** The metsulfuron/water treatment killed 15 of 20 stumps by 24 months post treatment. At 3 months post treatment, four stumps had resprouted, and resprouts appeared normal and healthy. The number of stumps with resprouts decreased slightly by 6 months, then increased to five by 24 months. This final observation included new resprouts on one stump, which had appeared dead throughout the test. Seven of the eight stumps that resprouted during the test were in the large-diameter class, including the surviving stumps.

Resprout vigor was fair to good during the 2-year study, with some moderate stunting observed. The mean growth rate of live resprouts was only 3.3 cm/mo at first, but doubled by the 12-month monitoring and continued to increase to 20 cm/mo.

Cambium was live on most stumps after 3 months, but the color was yellow instead of the normal green. The number of stumps with live cambium decreased by 6 months, and between 12 and 24 months only the few resprouting stumps had green cambium. At 24 months, the number of stumps with dead cambium was significantly greater ($p = 0.011$) in the metsulfuron treatment than in the water control (Table 2).

**Citrus Oil and Water Control.** The citrus oil treatment killed 2 of 20 stumps by 24 months post treatment. All 20 of the stumps resprouted at some time during the test. Resprouts were of good to excellent vigor with no abnormalities; only one large stump, which died at 18 months, had severely chlorotic resprouts. The growth rate of resprouts ranged from 7 to 14 cm/mo over the two-year period.

None of the 20 firetree stumps treated with water died during the test. Resprouting was observed on all stumps, with mean monthly growth rates ranging from 8 to 13 cm over 24 months. Resprout vigor was good to excellent, with no deformities noted. All control stumps exhibited green cambium until the end of the study, when a few had yellow cambium.

## Effects on Native Plants

Natural vegetation at the Kīpuka Kahali'i study site is an open 'ōhi'a woodland with relatively low species diversity. In addition to scattered 'ōhi'a trees, several native shrubs and sedges are common in the area. Few alien plant species, other than firetree, are found at the site; the most abundant of these is broomsedge (*Andropogon virginicus* L.), which has a patchy distribution on the cinder substrate. Most of the sedges and woody plants, including firetree, are found beneath 'ōhi'a trees. This association is due to dispersal of firetree seeds by birds using 'ōhi'a tree branches as perches and to the suitability of shaded substrates for germination.

**Trees.** One hundred twenty-five of the 140 plots (82%) centered around each treated firetree contained at least one ʻōhiʻa tree. The mean number of ʻōhiʻa trees per plot was 1.3. Most of the trees in monitored plots were greater than 3 m in height, but plants from 1 to 3 m tall were also common. No ʻōhiʻa seedlings (<0.1 m high) were noted during this study. The number of ʻōhiʻa observed in treatment and control plots increased or remained the same throughout the year of monitoring. No significant difference in ʻōhiʻa was found among treatments (Table 3).

Table 3. Results of an analysis of variance among seven treatments (including controls) for change in number of individuals of six native plant species at Kīpuka Kahaliʻi. (N = sample size, F = variance ratio, p = probability.)

| Species (Common Name) | Lifeform | N | F | p* |
|---|---|---|---|---|
| *Carex wahuensis* | sedge | 21 | 1.29 | 0.3230 |
| *Dodonaea viscosa* (ʻAʻaliʻi) | shrub | 77 | 1.02 | 0.4188 |
| *Gahnia gahniiformis* | sedge | 29 | 0.11 | 0.9937 |
| *Metrosideros polymorpha* (ʻŌhiʻa) | tree | 125 | 0.79 | 0.5768 |
| *Styphelia tameiameiae* (Pukiawe) | shrub | 40 | 0.82 | 0.5619 |
| *Vaccinium reticulatum* (ʻŌhelo) | shrub | 46 | 1.11 | 0.3738 |

*No comparisons were significant at the 95% level of confidence.

**Shrubs.** Three native shrub species occurred frequently in the study area. ʻAʻaliʻi (*Dodonaea viscosa* Jacq.) was the most widespread of these, growing in more than half of all plots. Most (85%) of the ʻaʻaliʻi shrubs in treatment plots were in the 0.1 to 1 m size categories. Throughout the year of monitoring, increases in ʻaʻaliʻi numbers were observed in all treatments, and no significant differences were detected (Table 3). Only two ʻaʻaliʻi shrubs disappeared during the study, one in a metsulfuron plot and one in the imazapyr/oil treatment (Appendix, Table II).

ʻŌhelo (*Vaccinium reticulatum* Sm.) was found in approximately one-fourth of all treatment plots and was particularly abundant in those of the imazapyr/water treatment. Almost all the ʻōhelo shrubs in the study area were between 0.1 and 1 m in height, although a few scattered seedlings were also observed. Losses of a few ʻōhelo plants were recorded in the glyphosate, imazapyr/water, triclopyr, metsulfuron, and citrus oil plots.

No significant differences in ‘ōhelo numbers over time were found among the seven treatments.

Numbers of pūkiawe (*Styphelia tameiameiae* (Cham. & Schlechtend.) F. v. Muell.), the third-most common shrub in Kīpuka Kahali‘i, increased for every treatment except imazapyr/water, and no significant differences among treatments were found. Even though two shrubs 0.5-1 m in height disappeared from plots of the metsulfuron treatment, recruitment from the seedling class resulted in an increase over the year. Other native shrubs occurred far too sporadically in the study plots for any analysis of trends over time. One ‘ākia (*Wikstroemia phillyreifolia* A. Gray) disappeared from a metsulfuron plot, and a single ‘ulei (*Osteomeles anthyllidifolia* (Sm.) Lindl.) was lost from the citrus oil treatment.

**Sedges and Herbs.** Two species of native sedge (*Carex wahuensis* C.A. Mey. and *Gahnia gahniiformis* (Gaud.) A. Heller) were found in nearly one-fourth of all study plots within all seven treatments, and the mean number of sedges per plot was quite small (0.1 to 2.4). In most treatments, the number of sedges increased over the year of monitoring. However, *Carex* decreased slightly in the glyphosate and citrus oil treatments, and *Gahnia* showed a loss in citrus oil, metsulfuron, and triclopyr plots. These decreases were not significant (Table 3). Other less-common native sedges (*Machaerina angustifolia* (Gaud.) T. Koyama, *Mariscus hillebrandii* (Boeck.) T. Koyama) and an herb (*Dianella sandwicensis* Hook & Arnott) had no extreme losses.

## Thurston Forest Cut Stump Treatments

### Treatment Efficacy

At the wet closed forest site 24 months after treatment, four herbicides (imazapyr/water, imazapyr/oil, triclopyr/water, and metsulfuron/water) inhibited the inititation of resprouts from cut stumps of firetree. A significant difference in the number of resprouts was found among the seven treatments ($F = 5.69$, $p < 0.01$). All treatments except glyphosate were significantly better ($p = 0.05$) at inhibiting resprouts than were controls (Table 4).

Among the treatments in which firetree did resprout, no significant difference was found in resprout height ($F = 2.04$, $p = 0.12$). However, paired t-tests did indicate a difference ($p = 0.05$) between resprout heights of the glyphosate treatment and both the citrus oil and water controls. Although not effective in reducing the number of resprouts, glyphosate apparently inhibited their growth rate.

**Imazapyr/Water.** In the imazapyr/water treatment, all 20 firetree stumps died by 18 months post treatment. This treatment also had the lowest mean resprout height (1 cm) and the fewest resprouting stumps (1) of all the treatments (Appendix, Table III). By 6 months a few chlorotic, deformed, and stunted resprouts 1 cm in height were seen on one stump. From 18 to 24 months, no resprouts were detected on any stumps in this treatment.

Table 4. Mean number of resprouts in firetree (*Myrica faya*) cut-stump treatment groups at Thurston Forest site, Hawaii Volcanoes National Park, compared with Duncan's multiple range test.

| Cut-stump Treatment | Mean No. Resprouts | Duncan Group* | |
|---|---|---|---|
| Water | 15.25 | A | |
| Citrus Oil | 12.50 | A | |
| Glyphosate | 8.25 | A | B |
| Metsulfuron/Water | 0.25 | | B |
| Triclopyr/Water | 0.25 | | B |
| Imazapyr/Water | 0 | | B |
| Imazapyr/Oil | 0 | | B |

*Treatments with different letters are significantly different at the 95% confidence level.

All firetree stumps had live cambium at 3 months, although it was yellow rather than green, indicating a loss of vigor. The number of stumps with live cambium decreased with each monitoring until 18 months, when only dead cambium was noted. The number of imazapyr-treated stumps with dead cambium at 24 months was significantly greater ($p < 0.001$) than the number of dead stumps in the water control (Table 2).

**Imazapyr/Oil.** The imazapyr/citrus oil treatment resulted in the death of all 20 firetree stumps by 24 months post treatment. As in the imazapyr/water treatment, the mean number of resprouts and resprout height were very low. No resprouting was observed until 6 months after treatment, when a few healthy, 1 cm-tall resprouts had developed on one firetree stump. By 12 months, resprouts exhibited moderate chlorosis, and they had disappeared by 18 months.

As with the imazapyr/water treatment, most stumps showed live but yellow cambium at 3 and 6 months. By 12 months, the number of stumps with live cambium had declined, and by 24 months all stumps appeared to be dead. The number of stumps with dead cambium was significantly greater ($p = 0.006$) than in the citrus oil control (Table 2).

**Metsulfuron/Water.** With the metsulfuron treatment, 19 of 20 treated firetree stumps died by 12 months post treatment. A few apparently healthy resprouts, 1 cm in height, appeared on one stump by 6 months and remained alive and free of herbicide-induced abnormalities at the end of the study. The growth rate of these resprouts was very slow at first but increased to 7.5 cm/mo by the end of the study at 24 months. Growth was slower than that of shoots on control stumps (16.7 cm/mo).

At the 3-month monitoring period, most of the firetree stumps retained live, albeit yellow, cambium. Subsequently, the number of stumps with live cambium declined until only one stump appeared to be alive from 12 to 24 months post treatment. At 24 months, the number of metsulfuron- treated stumps with dead cambium was significantly higher ($p < 0.001$) than in the water control (Table 2).

**Triclopyr/Water.** By the end of the study, the death of 19 of 20 firetree stumps was achieved with the triclopyr/water treatment. At 3 months post treatment a few healthy resprouts 1 cm tall were growing from a single stump, and by 12 months, a few chlorotic, deformed, and stunted resprouts were found on a second stump. By the end of the study at 24 months, only the original stump was alive, and some of its resprouts had died. The growth rate of resprouts on the surviving stump was 13 cm/mo at 24 months.

At the first monitoring (3 months), all triclopyr-treated stumps had live (primarily yellow) cambium. This number gradually declined, until only the stump with healthy resprouts retained live cambium at 24 months post treatment. The number of triclopyr-treated stumps with dead cambium was significantly greater ($p < 0.001$) than in the water control (Table 2).

**Glyphosate.** Fifteen of 20 firetree stumps were killed by the glyphosate treatment. No resprouting was seen until six months, when six stumps had a few short (1-2 cm) resprouts with good vigor. The number of resprouting stumps increased to nine over the first year, but during the second year many resprouts died, until only five stumps retained live regrowth at the end of the study.

Vigor of resprouts declined after 6 months, with most stumps bearing stunted, chorotic shoots with deformed leaves. Resprout growth rate was very low at first, but increased to 5.7 cm/mo by 18 months, indicating that resprouting stumps were surviving and recovering from the glyphosate treatment. Growth rate of resprouts rose to 8.6 cm/mo between 18 and 24 months, and the mean height of resprouts was 86 cm at the end of the study.

Cambium was live on almost all stumps during the first 6 months of monitoring, but by 12 months the number with live cambium declined, and at 24 months post treatment green or yellow cambium was observed on only five stumps (those with resprouts). All surviving stumps were in the large-diameter class (>9.5 cm). The number of stumps with dead cambium was significantly greater ($p = 0.011$) in the glyphosate treatment than in the water control (Table 2).

**Citrus Oil.** Citrus oil killed 9 of 20 firetree stumps by 24 months post treatment. Resprouting was rapid; by 3 months post treatment, nine stumps had vigorous resprouts, with only one stump bearing chlorotic regrowth. Although several early-resprouting stumps later died, the overall number of stumps with some regrowth increased over 18 months, then diminished slightly to the final observation of 11 survivors at 24 months.

Resprout vigor was good throughout the 24-month period, with only a few stumps receiving ratings of fair to poor. The growth rate of new shoots was slow at first but steadily increased, until a mean rate of 15.2 cm/mo was achieved at the end of the study. This growth rate nearly equalled that of resprouts in the water control (16.7 cm/mo). The mean height of the tallest resprout also increased throughout the study, until at 24 months these shoots averaged more than 2 m. The stability of the resprout vigor and the increasing growth rate indicated survival of at least 10 of the 11 resprouting stumps.

Live cambium was detected on almost all citrus oil-treated stumps at 3 months, and this number declined only slightly in the first year. By 24 months, the number of stumps exhibiting live green or yellow cambium was 11, corresponding with those bearing resprouts. Apparently citrus oil had some herbicidal activity against firetree, but the numbers of dead stumps in the citrus oil and water treatments did not differ significantly (Table 2).

**Water Control.** Four of the 20 stumps in the water control were dead by 18 months post treatment. Almost half of the control stumps had resprouted by 3 months with normal, vigorous shoots. A peak of 17 resprouting stumps was reached at 12 months post treatment, but the death of one resulted in a count of 16 surviving stumps with new growth at 24 months. Vigor of resprouts remained fair to good throughout the study, with some foliar chlorosis observed. Resprout growth rate was slow at first, but between 18 and 24 months, a mean rate of nearly 16.7 cm/mo was measured. At the last monitoring period, the mean height of the tallest new shoot was 143 cm.

Cambium was alive on all control stumps until 12 months after treatment, when one appeared dead. Three additional stumps exhibited brown cambium at 18 months.

## Effects on Native Plants

The wet forest study site near Thurston Lava Tube is an older, more developed, closed-canopy ʻōhiʻa forest with a greater native plant species diversity than the Kahaliʻi site. Again, the predominant native tree is ʻōhiʻa, but unlike Kīpuka Kahaliʻi, a well-developed layer of secondary tree species and tree ferns is also present. This understory is the stratum in which firetree is most abundant.

**Trees.** At Thurston, the mean number of ʻōhiʻa found in treatment plots was 1.0; most of these were either saplings (0.1-1 m) or larger trees (>3 m). Throughout the study period of one year, the number of ʻōhiʻa increased in all treatments except imazapyr/water and imazapyr/oil, which each showed a net decrease of two individuals. An analysis of variance showed no statistically significant difference among treatments (Table 5). T-tests on the change in number of ʻōhiʻa for paired treatments revealed that both imazapyr treatments and the citrus oil alone were significantly different ($p = 0.05$) from the metsulfuron treatment, which had the largest increase in ʻōhiʻa of all the treatments. Disregarding the increases over the year due to seedling growth, one to three ʻōhiʻa were lost from every treatment except the water control, which showed no loss, and the imazapyr/water treatment, in which eight ʻōhiʻa saplings disappeared (Appendix, Table IV).

Table 5. Results of an analysis of variance among seven cut-stump treatments (including controls) for change in number of individuals of nine native plant species at Thurston. (N = sample size, F = variance ratio, p = probability.)

| Species (Common Name) | Lifeform | N | F | p* |
|---|---|---|---|---|
| *Cibotium glaucum* (Hapuʻu) | fern | 62 | 0.82 | 0.5591 |
| *Coprosma ochracea* (Pilo) | tree | 128 | 0.74 | 0.6218 |
| *Cyrtandra platyphylla* | shrub | 17 | 0.42 | 0.8524 |
| *Ilex anomala* (Kawaʻu) | tree | 111 | 0.71 | 0.6395 |
| *Metrosideros polymorpha* (ʻŌhiʻa) | tree | 95 | 1.81 | 0.1058 |
| *Myrsine lessertiana* (Kolea) | tree | 45 | 0.87 | 0.5236 |
| *Sadleria pallida* (ʻAmaʻu) | fern | 84 | 1.13 | 0.3512 |
| *Uncinia uncinata* | sedge | 58 | 0.56 | 0.7593 |
| *Vaccinium calycinum* (ʻŌhelo-kau-laʻau) | shrub | 91 | 1.49 | 0.1924 |

*No comparisons were significant at the 95% level of confidence.

The most abundant native understory trees in the Thurston study site were pilo (*Coprosma ochracea* W. Oliver), kawaʻu or Hawaiian holly (*Ilex anomala* Hook. & Arnott), and kolea-lau-nui (*Myrsine lessertiana* A. DC). Two other species that occurred less frequently were ʻolapa (*Cheirodendron trigynum* (Gaud.) A. Heller) and manono (*Hedyotis terminalis* (Hook. & Arnott) W.L. Wagner & Herbst).

On the average, each plot had 1.6 pilo (>0.1 m in height) within its boundaries, as well as 5 to 23 seedlings (<0.1 m). During the study period, every treatment except metsulfuron showed a net increase in the number of pilo in the size classes >0.1 m. No significant difference was found among treatments. Disregarding increase due to seedling growth, losses of young pilo <1 m in height occurred in all treatments. Larger trees (>3 m tall) and young trees (1-3 m tall) also disappeared, particularly in the imazapyr/oil treatment. The mean number of pilo seedlings increased fourfold (2.3 to 9.3) in study plots during the year.

Kawaʻu averaged 1.3 trees or saplings per plot at Thurston. The number of kawaʻu increased in all treatments over a year, an increase that was greatest in plants 0.1 to 1 m tall. Despite this overall increase, kawaʻu disappearances were noted, particularly in the 0.1-0.5 m height class, in all treatments except metsulfuron. Kolea trees were far less abundant and occurred in less than half of the 140 treatment plots. Although the sample size was small, kolea did exhibit an increase in numbers for all treatments except glyphosate. One small individual was also lost from both imazapyr treatments, but these were replaced by growing seedlings. Neither kawaʻu nor kolea density changes were significantly different among treatments (Table 5).

**Shrubs.** The shrub layer at Thurston contained approximately six native species, but only one of these, ʻōhelo-kau-laʻau (*Vaccinium calycinum* Sm.), was common enough to occur in plots of all treatments. The mean number of ʻōhelo in treatment plots was 0.6. An increase in ʻōhelo-kau-laʻau numbers occurred in all treatments over the study period and was particularly large in the water control, where every plot gained one or two plants 0.1-1 m tall. Although no significant difference among treatments was detected for the change in ʻōhelo numbers with an analysis of variance (Table 5), paired t-tests did indicate that the increase in ʻōhelo-kau-laʻau numbers in control plots was significantly greater ($p = 0.05$) than the much smaller increases for imazapyr/oil, triclopyr, and citrus oil treatments. A few small ʻōhelo disappeared from all treatments except imazapyr/water.

The succulent endemic shrub *Cyrtandra platyphylla* A. Gray was seen in a few plots of all treatments, where the loss of a few individuals in three treatments and the water control was noted during the monitoring period. These losses were most likely due to mechanical damage of the weak stems of *Cyrtandra* during treatment of firetree. No statistically significant difference was found among treatments for the change in *Cyrtandra* numbers.

**Ferns.** The most important fern at the Thurston site is the tree fern or hapuʻu-pulu (*Cibotium glaucum* (J. Sm.) Hook. & Arnott); this species forms a distinct layer below the mixed native tree understory. On the average, each plot contained 0.5 tree ferns. A moderate increase in tree fern numbers was observed for all treatments except imazapyr/oil during the study period, and no difference among treatments was indicated (Table 5).

The most abundant fern of the ground layer was ʻamaʻu (*Sadleria pallida* Hook. & Arnott). This robust endemic increased in numbers in all treatments except metsulfuron, where no net change was detected. The gain in ʻamaʻu numbers was almost entirely in plants 0.1-1 m tall, most likely representing growth from the <0.1 m category. An analysis of variance revealed no significant difference among seven treatments for change in the number of ʻamaʻu individuals. However, paired t-tests suggested significant differences ($p = 0.05$) between imazapyr/oil and both triclopyr and metsulfuron treatments, which showed no change or a small increase in ʻamaʻu. At least eight other native species of ferns and fern allies were seen in the ground cover at the Thurston site, but none of these were numerous enough to permit comparisons among treatments.

**Sedges and Grasses.** The most common sedge in the Thurston forest was the indigenous *Uncinia uncinata* (L. fil.) Kukenth., which was evenly distributed throughout the study site in low numbers and was found in most of the 140 plots. *Uncinia* numbers decreased in water control plots and in those treated with triclopyr and glyphosate. In both the triclopyr and control plots, the loss amounted to more than half (58-86%) of the *Uncinia* (>0.1 m tall) recorded prior to treatment; the decrease in glyphosate plots was just one individual. These differences among treatments were not significant (Table 5). The second-most common native sedge at Thurston, ʻuki (*Machaerina angustifolia* (Gaud.) T. Koyama), was present in all treatments in very low numbers and increased slightly or remained constant throughout the study period.

The only native grass at the Thurston site, ʻohe (*Isachne distichophylla* Munro), could not be counted accurately because of its growth form, with multiple basally-interconnected shoots. Although ʻohe suffered somewhat from trampling during firetree treatment, after one year the grass had maintained its presence in almost all plots inhabited at the beginning of the study. Other herbaceous plant species occurred too sporadically in Thurston treatment plots for any meaningful analysis of change; most of these were alien species.

## Thurston Forest Frill Treatments

### Treatment Efficacy

After 30 months, both triclopyr/water and glyphosate herbicide treatments inhibited the initiation and development of basal resprouts on firetree. An anlysis of variance showed a significant difference among the seven treatments for both the number of resprouts ($F = 4.09$, $p < 0.01$) and resprout height ($F = 3.05$, $p = 0.02$). Duncan's multiple range test divided the seven treatments into two overlapping groups (Table 6). Triclopyr, glyphosate, and the water control were significantly better at resprout suppression than were metsulfuron or citrus oil ($p = 0.05$). In the water control test, rapid healing of the frill cuts and subsequent reconnection of cambial and phloem tissue reduced resprouting.

Triclopyr was the most effective herbicide at preventing resprouts in the test; none were observed. Among the other treatments, Tukey's studentized range test indicated that glyphosate was better at inhibiting resprout growth than was citrus oil ($p = 0.05$).

Tree death was determined by: 1) absence of live cambium at a minimum of three sites on the trunk below the frill cut; 2) bark peeling away from the trunk cortex; 3) lack of resprouting; and 4) 100% defoliation. To increase the probability of detecting live cambium, at each monitoring interval three different sites on firetree trunks were examined that had no vertical continuity with previously selected sites. When cambium vigor of treated trees at 30 months was compared with that of control trees, all tested treatments showed a significantly larger number with brown cambium than did the water control ($p < 0.0001$). Cambium vigor in the imazapyr/oil treatment did not differ significantly from that in the citrus oil control (Table 2).

Table 6. Mean number of resprouts in firetree (*Myrica faya*) frill treatment groups at Thurston Forest site, Hawaii Volcanoes National Park, compared with Duncan's multiple range test.

| Cut-stump Treatment | Mean No. Resprouts | Duncan Group* | |
|---|---|---|---|
| Citrus Oil | 6.0 | A | |
| Metsulfuron/Water | 5.8 | A | |
| Imazapyr/Water | 3.8 | A | B |
| Imazapyr/Oil | 3.7 | A | B |
| Glyphosate | 0.7 | | B |
| Water | 0.7 | | B |
| Triclopyr/Water | 0 | | B |

*Treatments with different letters are significantly different at the 95% confidence level.

**Triclopyr/Water.** The triclopyr/water herbicide treatment resulted in the death of 18 of 20 trees by 30 months post treatment (Appendix, Table V). No resprouting was detected on any trees in this treatment during the test.

The number of trees with live cambium was high during the first 6 months of the test but declined between 6 and 18 months. At 30 months only two trees had live, dull yellow cambium. These two surviving trees were completely defoliated, with no resprouting in the canopy.

Triclopyr induced heavy (>50%) defoliation on 18 trees by 3 months, increasing to all 20 trees by 18 months. Between 18 and 30 months, defoliation was nearly 100% on all trees.

**Glyphosate.** Glyphosate killed 15 of 20 trees by 30 months post treatment. At 3 months, a low number of resprouts (1-9/tree) were seen on only two firetrees. The overall number of resprouting trees increased to a peak of 10 by 18 months, then declined to four by the end of the study. Only 12 glyphosate-treated trees resprouted at any time during the test. At first, resprout vigor was good, with no apparent abnormalities. Vigor of resprouts diminished by 6 months, and leaves showed chlorosis and stunting. Resprout growth rate was slow at first (1.3 cm/mo), rose to 3.3 cm/mo at the 12-month monitoring, and then decreased to 1.4 by 30 months.

The number of tree trunks on which live cambium was detected fluctuated at a high level for the first 18 months, then declined to only five trees at 30 months. These five survivors had a mean basal diameter of 20 cm; those that succumbed averaged 13 cm. Heavy canopy defoliation (>50%) was observed on 80% of the glyphosate-treated trees by 3 months and on all 20 trees by 12 months.

**Imazapyr/Oil.** In the imazapyr/oil treatment, 14 of 20 firetrees died by 30 months. By 3 months, only one tree had resprouted. This number rose to 14 by 18 months and then declined to six by the end of the study. A total of 17 trees resprouted at some time during the study, and resprout intensity was low, averaging only one to nine shoots per trunk. At 3 months, resprouts were in good vigor, with no abnormalities. Resprout vigor declined by 12 months and was poor at the end of the test. Moderate chlorosis and stunting were noted. The mean growth rate of resprouts was slow throughout the 30 month test, ranging from 1.4 to 3.4 cm/mo.

During the first 18 months, live cambium was observed on most of the imazapyr/oil-treated trees, but by the end of the test at 30 months, only the six resprouting trees showed live, yellow cambium. The six survivors had an initial basal diameter of 17 cm, and the trees that died averaged 11.5 cm.

Canopy defoliation was >50% on more than half (13) of the imazapyr-frilled trees at the first monitoring, and by 18 months, all trees were heavily defoliated. Only one of these trees had partially refoliated by the end of the study.

**Metsulfuron/Water.** The metsulfuron/water treatment resulted in the death of 9 of 20 trees by 30 months. From 3 to 6 months, there were no resprouting trees, but by 12 months, 4 trees were resprouting from below the frill cut. The number of resprouting trees increased to 11 by the end of the test. Resprout vigor ranged from poor, with severe foliar chlorosis and stunting, to good, with no abnormalities. Resprout growth rate was very low (1.3 cm/mo) when new growth first appeared at 12 months, increased to 8 cm/mo by the 18-month monitoring, and then dropped to 3.6 cm/mo at the end of the study.

The number of trees with live cambium fluctuated throughout the test, but by 30 months only the 11 resprouting trees showed live (yellow) cambium. The surviving trees had a mean diameter of 22.6 cm and those that died had a mean of 14.4 cm.

Canopy defoliation was >50% on most of the metsulfuron-treated firetrees at 3 months, and from 6 to 30 months, all trees in this treatment showed heavy defoliation (>50%).

**Imazapyr/Water.** The imazapyr/water herbicide treatment killed 7 of 20 firetrees by 30 months post treatment. At 3 months, only one tree had healthy resprouts growing from the base. The number of resprouting trees gradually rose to 17 at the 18-month monitoring and then fell to 11 at the end of the study. The intensity of resprouting was generally low, with only a few new shoots per trunk. At first, resprouts were of good vigor, but by 12 months post treatment, about half of the resprouting trees exhibited abnormal regrowth (chlorotic, stunted, or with reddish purple veins on leaves). The mean growth rate of new shoots was 1.3 cm/mo at 3 months, increased to 4.5 cm/mo by 18 months, and then declined to 3.7 cm/mo by the end of the test.

The cambium remained alive on most imazapyr-treated trees (13) until 30 months, including all 11 that still had live resprouts. The mean basal diameter of the surviving trees was 18.7 cm, similar to the diameter of those that died, 16.7 cm.

Canopy defoliation was >50% on 70% of imazapyr-treated firetrees at the first monitoring period, and all trees of this treatment showed >50% leaf loss by 18 months. Limited canopy recovery was noted on five of the trees at 30 months, but some of this new foliage was chlorotic.

**Citrus Oil.** One of 20 trees died in the citrus oil control treatment by 18 months post treatment. Resprouting was rapid, with all 20 trees bearing new shoots by 6 months. Subsequently, regrowth died on five of these trees. Resprout vigor was excellent to good from 3 to 12 months and declined to poor by the end of the study. Some chlorosis was noted on resprouts at 12 months; loss of color, epinasty, and flaccidity were more pronounced by 30 months post treatment. Resprout growth rate was only 1.9 cm/mo at 6 months, but increased to 7-8 cm/mo between 12 and 18 months. By 30 months, resprouts were growing at 2.8 cm/mo.

Green cambium was found on all trees until 18 months post treatment. By this time, most trunks exhibited yellow cambium, but only one appeared dead. Healing of the frill cuts was observed on all but the dead tree.

Less than 25% canopy defoliation was seen early in the test, but by 12 months there was a dramatic loss of foliage, with most trees in the 25-50% defoliated category. Between 18 and 30 months, nearly half of the trees were >50% defoliated; the others had become refoliated.

**Water Control.** No trees in the water control were dead at 30 months post treatment. The plant response to frilling was rapid resprouting on most trees by 3 months, continuing through 12 months. Resprout vigor was good for the first 6 months, but by 30 months resprouts had died on most control trees and were of poor vigor on the remainder.

Healthy, green cambium was present below the frill cuts on all 20 trees throughout the study. Severing of the cambium triggered the production of basal resprouts. By 30 months frills were healed on all 20 trees. Less than 25% canopy defoliation occurred in the water controls, peaking at 12 months. After this, refoliation occurred in most of the trees.

## Effects on Native Plants

Firetrees selected for the frill treatments were in the Thurston forest to the northwest but contiguous with the area containing the cut-stump treatments. Vegetation in the two study sites was essentially the same, except for the larger diameter and height of the firetrees in the area used for the frill test.

**Trees.** Over the year of native plant monitoring, increases in the number of ʻōhiʻa were noted in four frill treatments, while slight net decreases were seen in three others: imazapyr/water, metsulfuron, and the water control. ʻŌhiʻa losses in the metsulfuron and control plots were of more ephemeral plants 0.1-1 m tall, but in the imazapyr/water plots the decreases occurred in plants 1-3 m tall. Changes in the numbers of ʻōhiʻa were not significantly different among the seven treatments (Table 7). Several small ʻōhiʻa were also lost from the imazapyr/oil, triclopyr, and citrus oil plots (Appendix, Table VI), but growth of seedlings during the year resulted in a net increase of ʻōhiʻa.

Table 7. Results of an analysis of variance among seven frill treatments (including controls) for change in number of individuals of nine native plant species at the Thurston site. (N = sample size, F = variance ratio, p = probability.)

| Species (Common Name) | Lifeform | N | F | p |
|---|---|---|---|---|
| *Cibotium glaucum* (Hapuʻu) | fern | 52 | 1.20 | 0.3214 |
| *Coprosma ochracea* (Pilo) | tree | 123 | 0.88 | 0.5093 |
| *Ilex anomala* (Kawaʻu) | tree | 105 | 0.31 | 0.9308 |
| *Machaerina angustifolia* (ʻUki) | sedge | 22 | 0.54 | 0.7401 |
| *Metrosideros polymorpha* (Ōhiʻa) | tree | 111 | 0.70 | 0.6486 |
| *Myrsine lessertiana* (Kolea) | tree | 21 | 1.02 | 0.4404 |
| *Sadleria pallida* (ʻAmaʻu) | fern | 111 | 3.60 | 0.0028** |
| *Uncinia uncinata* | sedge | 72 | 1.71 | 0.1331 |
| *Vaccinium calycinum* (ʻŌhelo-kau-laʻau) | shrub | 35 | 0.37 | 0.8920 |

** Significant at the 99% confidence level.

Three common understory tree species were found near the frill treatments: pilo, kawaʻu, and kolea. Net decreases in the number of pilo were observed in three treatments: triclopyr, imazapyr/water, and the water control. Pilo losses were also observed in the other four treatments, particularly metsulfuron, but growth from the seedling class resulted in increases over the year. Most of pilo losses occurred in the size classes <1 m, but four trees >3 m tall died in the imazapyr/water treatment. Three of the four trees were of poor vigor before herbicide treatment of the adjacent firetree. Differences among the seven treatments in change of pilo numbers were not significant.

Small-scale losses in kawaʻu were observed in more than half the treatments during the year of monitoring, including triclopyr, metsulfuron, imazapyr/oil, and the water control. Some kawaʻu also disappeared from imazapyr/water and citrus oil plots, but these treatments gained individuals over the year of monitoring. Kawaʻu that disappeared or died were almost exclusively 0.1 to 1 m tall; only one tree >3 m tall died. Differences among the seven treatments were not significant.

As in the cut-stump plots at Thurston, kolea-lau-nui was the least abundant of the three widespread native understory tree species. Over the year of the study, kolea numbers increased or remained constant in all treatments except metsulfuron, which lost only one individual. Differences in kolea numbers among treatments were not significant.

**Shrubs.** Although six different native shrub species were seen in the study area, only ʻōhelo-kau-laʻau occurred in plots in numbers great enough to warrant analysis. Small net decreases in ʻōhelo numbers were noted in plots of the metsulfuron and imazapyr/water treatments, while ʻōhelo increased or remained constant in all other treatments. ʻŌhelo kau-laʻau losses also occurred in the glyphosate, imazapyr/oil, triclopyr, and water treatments but were compensated by recruitment from the seedling class. The changes in ʻōhelo numbers over time were not significantly different (Table 7).

**Ferns.** Tree ferns occurred in about 40% of all frill plots. Increases in the number of tree ferns were observed in all treatments except triclopyr and metsulfuron, both of which lost one or two individuals over the year. Differences among treatments for change in number of tree ferns over time were not significant (Table 7). However, in t-tests on treatment pairs, metsulfuron plots were significantly different ($p = 0.05$) from controls in change of tree fern numbers.

ʻAmaʻu ferns were even more abundant than tree ferns in the study area, with an average of 1.4 individuals per plot. Over the year, increases in the number of ʻamaʻu individuals >0.1 m in height were observed in all treatments, with a particularly large increase noted in water control plots. The loss of one to four ʻamaʻu was noted in imazapyr/water, triclopyr, metsulfuron, and citrus oil treatments, but growth of young ferns resulted in net increases. A highly significant difference among treatments was indicated with an analysis of variance ($p = 0.0028$). The mean change in ʻamaʻu in control plots was significantly different ($p = 0.05$) from those of the other treatments.

**Sedges.** The most abundant sedge of the study area was *Uncinia uncinata*. During the year of monitoring, the net number of *Uncinia* decreased in metsulfuron and citrus oil treatments. The loss of *Uncinia* was relatively large in metsulfuron plots, where more than 50% died or disappeared over a year's time. An analysis of variance indicated no significant differences among treatments for change in *Uncinia* numbers (Table 7). The t-test on pairs of treatments revealed a significant difference ($p = 0.05$) between the metsulfuron treatment and the water control, as well as between metsulfuron and the glyphosate, imazapyr/water, imazapyr/oil, and triclopyr treatments.

Another sedge, ʻuki, was far less common in the Thurston site, occurring in less than 20% of all plots. Throughout the study, the number of ʻuki increased, and no significant difference was observed among treatments. Approximately seven other herbaceous plant species and nine types of ferns were found in the Thurston forest, but none of these were important components of the ground cover.

# DISCUSSION AND CONCLUSIONS

Cut-stump treatments with imazapyr/water provided 100% kill of firetree at both Kīpuka Kahali'i, the open woodland site, and Thurston, the wet closed forest, site. This treatment also produced the lowest mean number of resprouts and the fewest resprouting stumps of all cut-stump treatments. No significant effects of this treatment on native plants were determined at either site, although at the Thurston site, greater numbers of 'ōhi'a saplings were lost from imazapyr/water plots than from any other treatment (Appendix, Table IV). Cut-stump treatment with imazapyr/oil on the Thurston site also gave 100% kill without resprouts; this treatment was associated with the greatest loss of 'ōhelo and kawa'u observed during the year of monitoring. However, imazapyr/oil applied to cut stumps was far less effective at Kīpuka Kahali'i (only 80% kill) than at Thurston. The number of firetree killed by imazapyr/oil was significantly greater at the Thurston site than at Kīpuka Kahali'i (chi square = 4.44, $p < 0.05$).

The second-most efficacious treatment on cut stumps was triclopyr/water, which produced 90% control at Kīpuka Kahali'i and 95% control at Thurston. Triclopyr had no apparent effect on native plants when applied to cut stumps at Kīpuka Kahali'i, and losses of native tree saplings with this treatment at Thurston were similar to or less than those for other herbicides tested. Cut-stump treatments with metsulfuron/water also gave 95% control at Thurston, but resprout survival was greater than with imazapyr/water and imazapyr/oil; this treatment was much less effective at Kīpuka Kahali'i (75% kill). Although glyphosate was not completely adequate for firetree control in this study, herbicide availability and lack of restrictions may make it a useful tool for the homeowner.

Three of the five herbicide solutions tested were more effective at killing firetree in cut-stump treatments at the Thurston site than at the more open and drier Kīpuka Kahali'i site, although these comparisons were statistically significant only for imazapyr/oil (triclopyr/water chi square = 0.36, $p > 0.50$; metsulfuron chi square = 3.14, $p > 0.05$). Glyphosate was the only herbicide tested that exhibited slightly better control at Kīpuka Kahali'i than at the Thurston site, and this difference was not significant (chi square = 0.62, $p > 0.50$). Even the water control produced a death rate of 20% at Thurston, while all water control stumps resprouted and survived at Kīpuka Kahali'i. The Thurston site is in a closed 'ōhi'a forest with an understory of native trees and tree ferns (Jacobi 1980); the forest was probably more open when firetree invaded during an episode of 'ōhi'a dieback. Vitousek and Walker (1989) found that firetree growth was "strongly dependent on the availability of light" and that growth was zero at a level of shade similar to that under a closed canopy of 'ōhi'a. It appears that firetrees growing in closed forest are relatively easy to kill by cutting and treating and are susceptible to several of the tested herbicides. Because of slow growth under shaded conditions, retreatment intervals resulting in control may be greater in closed forest than in open woodland.

Frill treatments at Thurston with either triclopyr/water or glyphosate suppressed resprouts better than metsulfuron or citrus oil. Triclopyr was the most effective in suppressing resprouts; none were observed. Triclopyr was also the most effective frill treatment at killing the cambium of firetree. Even though canopy defoliation was >50%, metsulfuron and imazapyr/water were ineffective as frill treatments on firetree; more than half the treated firetrees survived. The response of firetree to frill tests was often size dependent, with larger trees less effectively controlled. Several native plant species in frill tests, including ‘ōhi‘a, pilo, tree ferns, ‘ama‘u, and kawa‘u, appeared to show effects related to metsulfuron or imazapyr/water.

In tests at Pa‘auilo, north of Hilo, undiluted glyphosate was effective on firetree when applied to continuous notches (or frills) and to notches spaced 4 in. apart (Motooka and Nagai 1988). Glyphosate controlled firetree, with more than 90% defoliation. In this same study, concentrated triclopyr was inadequate for firetree control, with no defoliation observed with spaced-notch application and less than 70% defoliation when the herbicide was applied to continuous notches. The lack of effectiveness of triclopyr in the Pa‘auilo study may have been due to use of concentrated herbicide (compared with the 50% solution used in the present study), or to an inadequate monitoring period of only 16 months. Concentrated herbicide may be less useful for plant control because tissue at the site of application is killed rapidly and uptake of the herbicide is thus hampered. In the present study, almost all triclopyr-treated trees were heavily defoliated within 3 months, but cambium death progressed more slowly through 30 months. No information is available on the size or pretreatment vigor of firetrees in the Pa‘auilo test; the disparity in results of the two tests might result from differences in these factors.

Picloram was the most effective herbicide tested against firetree by Motooka and Nagai (1988), with nearly complete control achieved with the herbicide applied to either spaced or continuous notches. Picloram (as Tordon 22K) was successfully used on firetree in other tests (Walters and Null 1970) and is the herbicide currently used on cut firetree stumps in Hawaii Volcanoes National Park. Picloram mixed with 2,4-D (as Tordon RTU) was efficacious when applied to frill cuts in large trees (J.T. Tunison, unpub. data). While effective against firetree, picloram is soluble in water, persistent, and relatively mobile in soils (Humburg *et al.* 1989). Other herbicide studies in the Park have indicated that native species rooted near target alien species treated with picloram may be adversely affected (Hawaii Volcanoes National Park, Resources Management Division, unpub. data; Santos *et al.*, in press).

Other application techniques have also been used on firetree. Both glyphosate and picloram killed firetree when applied to rubber tubing reservoirs on cut stems (Gardner and Kageler 1982). While effective, this application method was very time consuming, and the large quantities of rubber tubing required were expensive (J.T. Tunison, pers. comm.).

Selection of a control technique depends on efficacy, safety, cost, and ecological effects. Frill cuts are more rapidly accomplished than cut-stump treatments, equipment is cheaper, and the process is safer, especially with large trees. The continued presence of standing trees may also be beneficial ecologically. In closed forest vegetation, felling trees to apply herbicide to cut stumps mechanically damages surrounding native vegetation. Thus, despite the 30 months it takes trees to die, frill treatments with triclopyr have a number of advantages, especially where most of the trees are large. The technique should be tried in those dry to mesic areas where larger trees exist. Imazapyr/water, which gave best results in cut-stump treatments in both areas, is more expensive than triclopyr, but less expensive than other chemicals tested.

Although felling large firetrees to apply herbicide to cut stumps does open the forest and admit more light to the forest floor, very few firetree seedlings were observed in cut-stump treatment plots during this study (mean of 0.41/plot). Far more seedlings were observed over the year of monitoring in plots surrounding frilled trees (mean of 6.98/plot), including the water control treatment where canopy defoliation did not occur. Seed availability was probably higher around frilled trees, as large firetrees are more prolific producers of fruit. Almost no firetree seedlings appeared in plots at Kīpuka Kahali'i, a sunny, open woodland site (mean of 0.02/plot). Walker (1990) found the greatest rates of firetree seed germination occurred at 63% shade; completely exposed seeds and heavily shaded ones had lower germination rates.

In addition to testing frill-cut treatments on mesic sites, more information on the economics of treatments should be obtained. Worker-hour requirements for frill- versus cut-stump treatments should be determined. Long-term monitoring (24-30 months) to determine efficacy, and studies of succession after control by these two techniques on different sites would also be worthwhile. As new chemicals are developed, additional testing with adequate sampling design and time for monitoring may also be desirable. Studies of the timing of treatment to enhance efficacy, protect native species, and encourage succession of native species also deserve consideration.

Based on the results of these tests, more than one herbicide treatment can be recommended. Both imazapyr/water and triclopyr were highly effective at killing firetree when applied to cut stumps at both wet and dry to moist sites. Triclopyr (Garlon 3A, 50% in water) was the best frill treatment. In areas with both large single-trunked trees and smaller shrubby ones, or where other alien species susceptible to triclopyr are also targeted for control (*e.g.*, strawberry guava, *Psidium cattleianum* Sabine), triclopyr would be the best choice of an effective herbicide.

## ACKNOWLEDGMENTS

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APPENDIX, TABLE I. Results of herbicide treatments on cut stumps of firetree (*Myrica faya*) at the Kīpuka Kahali'i site.

| Treatment | Time Since Treatment (mos) | No. Killed (n = 20) | Mean Resprout Category* (n = 20) | Mean Live Resprout Height in cm | (n) | Resprout Vigor | (n) | Cambium Color (n = 20) | Live Resprout Growth Rate in cm/mo | (n) |
|---|---|---|---|---|---|---|---|---|---|---|
| Imazapyr/ Water | 3 | 3 | 0[a] | 1 | ( 1) | Good | ( 1) | Yellow | -- | |
| | 6 | 10 | 0[a] | 1.3 | ( 3) | Fair | ( 4) | Yellow | 0.4 | ( 3) |
| | 12 | 18 | 0[a] | 7 | ( 2) | Poor | ( 4) | Brown[b] | 0.9 | ( 2) |
| | 18 | 20 | 0 | n/a | ( 0) | Dead | ( 4) | Brown | n/a | ( 0) |
| | 24 | 20 | 0 | n/a | ( 0) | Dead | ( 4) | Brown | n/a | ( 0) |
| Triclopyr/ Water | 3 | 0 | 0[a] | 11.3 | ( 4) | Good | ( 4) | Yellow | -- | |
| | 6 | 8 | 0[a] | 24 | ( 5) | Good | ( 5) | Yellow | 5.1 | ( 5) |
| | 12 | 16 | 0[a] | 57 | ( 3) | Fair | ( 5) | Brown[b] | 4.5 | ( 3) |
| | 18 | 18 | 0[a] | 70 | ( 3) | Poor | ( 6) | Brown[b] | 3.6 | ( 3) |
| | 24 | 18 | 0[a] | 115 | ( 6) | Poor | ( 6) | Brown[b] | 9.2 | ( 2) |
| Glyphosate | 3 | 0 | 10-50 | 6.8 | (14) | Good | (14) | Green | -- | |
| | 6 | 6 | 1-9 | 17 | (10 | Fair | (14) | Yellow | 2.8 | (10) |
| | 12 | 12 | 1-9 | 46.9 | ( 8) | Fair | (15) | Yellow | 4.8 | ( 8) |
| | 18 | 17 | 0[a] | 128.3 | ( 3) | Poor | (15) | Brown[b] | 11.4 | ( 3) |
| | 24 | 17 | 0[a] | 200 | ( 3) | Poor | (15) | Brown[b] | 11.9 | ( 3) |
| Imazapyr/ Oil | 3 | 1 | 1-9 | 10.7 | (11) | Good | (11) | Green | -- | |
| | 6 | 7 | 1-9 | 19.7 | (11) | Fair | (13) | Yellow | 3.5 | (11) |
| | 12 | 14 | 1-9 | 53.7 | ( 6) | Poor | (14) | Brown[b] | 4.7 | ( 6) |
| | 18 | 16 | 1-9 | 155 | ( 4) | Poor | (14) | Brown[b] | 11.7 | ( 4) |
| | 24 | 16 | 1-9 | 232.5 | ( 4) | Poor | (14) | Brown[b] | 12.9 | ( 4) |

APPENDIX, TABLE I, continued.

| Treatment | Time Since Treatment (mos) | No. Killed (n = 20) | Mean Resprout Category* (n = 20) | Mean Live Resprout Height in cm | (n) | Resprout Vigor | (n) | Cambium Color (n = 20) | Live Resprout Growth Rate in cm/mo | (n) |
|---|---|---|---|---|---|---|---|---|---|---|
| Metsulfuron /Water | 3 | 3 | 0[a] | 6.8 | ( 4) | Good | ( 4) | Yellow | -- | |
| | 6 | 13 | 0[a] | 18.5 | ( 4) | Fair | ( 5) | Brown[b] | 3.3 | ( 4) |
| | 12 | 15 | 1-9 | 54 | ( 5) | Fair | ( 7) | Brown[b] | 6.6 | ( 5) |
| | 18 | 16 | 0[a] | 152.5 | ( 4) | Fair | ( 7) | Brown[b] | 14.2 | ( 4) |
| | 24 | 15 | 1-9 | 242 | ( 5) | Fair | ( 8) | Brown[b] | 20 | ( 5) |
| Citrus Oil | 3 | 0 | 10-50 | 34 | (20) | Excellent | (20) | Green | -- | |
| | 6 | 1 | 10-50 | 77.9 | (19) | Good | (20) | Green | 14.2 | (19) |
| | 12 | 2 | 10-50 | 117.2 | (19) | Excellent | (20) | Green | 6.6 | (19) |
| | 18 | 1 | 10-50 | 181.1 | (18) | Good | (20) | Green | 9.8 | (18) |
| | 24 | 2 | 10-50 | 252.8 | (18) | Good | (20) | Green | 11.9 | (18) |
| Water | 3 | 0 | 10-50 | 31.8 | (20) | Excellent | (20) | Green | -- | (20) |
| | 6 | 0 | 10-50 | 69.5 | (20) | Good | (20) | Green | 12.6 | (20) |
| | 12 | 0 | >50 | 124.5 | (20) | Excellent | (20) | Green | 9.2 | (20) |
| | 18 | 0 | 10-50 | 176.5 | (20) | Excellent | (20) | Green | 7.9 | (20) |
| | 24 | 0 | 10-50 | 236.5 | (20) | Excellent | (20) | Green | 10.0 | (20) |

*Categories: 0, 1-9, 10-50, >50 resprouts. Number of resprouts estimated and category assigned at each of 20 stumps. Mean category is given in table.

[a] = <0.5, so rounded to 0.

[b] = some live cambium detected in sample of 20 trees, but insufficient to alter overall rating.

APPENDIX, TABLE II. Observed death or disappearance of native plant species (>0.1 m in height) in 2-m diameter plots surrounding treated firetrees (*Myrica faya*) at Kīpuka Kahali'i.

| Treatment | Species (Common Name) | Height Class (m) | No. Dead | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| Glyphosate | *Carex wahuensis* | 0.1-0.5 | | 2 | 3 |
| | *Vaccinium reticulatum* ('Ōhelo) | 0.1-0.5 | | 1 | 12 |
| | *Vaccinium reticulatum* | 0.5-1 | | 2 | 12 |
| Imazapyr/Water | *Vaccinium reticulatum* | 0.1-0.5 | 1 | | 25 |
| Imazapyr/ Citrus Oil | *Dodonaea viscosa* ('A'ali'i) | 1-2 | | 1 | 7 |
| | *Vaccinium reticulatum* ('Ōhelo) | 1-2 | | 1 | 9 |
| Metsulfuron/ Water | *Dodonaea viscosa* ('A'ali'i) | 0.5-1 | | 1 | 12 |
| | *Dubautia ciliolata* (Na'ena'e) | 0.1-0.5 | 1 | | 1 |
| | *Gahnia gahniiformis* | 0.1-0.5 | | 9 | 34 |
| | *Styphelia tameiameiae* (Pukiawe) | 0.5-1 | | 2 | 25 |
| | *Vaccinium reticulatum* ('Ōhelo) | 0.1-0.5 | | 2 | 17 |
| | *Wikstroemia phillyreifolia* ('Akia) | 0.1-0.5 | | 1 | 5 |
| Triclopyr/ Water | *Gahnia gahniiformis* | 0.1-0.5 | | 1 | 4 |
| | *Vaccinium reticulatum* ('Ōhelo) | 0.1-0.5 | 1 | | 12 |
| Water | *Carex wahuensis* | 0.1-0.5 | | 1 | 2 |

APPENDIX, TABLE II, continued.

| Treatment | Species (Common Name) | Size Class (m) | No. Died | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| Citrus Oil | *Carex wahuensis* | 0.1-0.5 | | 3 | 7 |
| | *Gahnia gahniiformis* | 0.1-0.5 | | 13 | 49 |
| | *Machaerina angustifolia* (ʻUki) | 0.1-0.5 | | 2 | 4 |
| | *Osteomeles anthyllidifolia* (ʻŪlei) | 0.1-0.5 | | 1 | 4 |
| | *Vaccinium reticulatum* (ʻŌhelo) | 0.1-0.5 | | 3 | 7 |

*Total number of individuals >0.1 m tall in 20 plots of treatment at beginning of study (prior to herbicide application).

APPENDIX, TABLE III. Results of herbicide treatments on cut stumps of firetree (*Myrica faya*) at the Thurston Forest site.

| Treatment | Time Since Treatment (mos) | No. Killed (n = 20) | Mean Resprout Category* (n = 20) | Mean Resprout Height in cm | (n) | Resprout Vigor | (n) | Cambium Color (n = 20) | Live Resprout Growth Rate in cm/mo | (n) |
|---|---|---|---|---|---|---|---|---|---|---|
| Imazapyr/ Water | 3 | 0 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | -- | ( 0) |
| | 6 | 7 | 0[a] | 1 | ( 1) | Poor | ( 1) | Yellow | 0.3 | ( 1) |
| | 12 | 14 | 0[a] | 1 | ( 1) | Poor | ( 1) | Brown[b] | 0 | ( 1) |
| | 18 | 20 | 0 | 0 | ( 0) | Dead | ( 1) | Brown | 0 | ( 0) |
| | 24 | 20 | 0 | 0 | ( 0) | Dead | ( 1) | Brown | 0 | ( 0) |
| Triclopyr/ Water | 3 | 0 | 0[a] | 1 | ( 1) | Good | ( 1) | Yellow | -- | ( 1) |
| | 6 | 2 | 0[a] | 16 | ( 1) | Fair | ( 1) | Yellow | 5 | ( 1) |
| | 12 | 8 | 0[a] | 17 | ( 2) | Fair | ( 2) | Yellow | 1.5 | ( 2) |
| | 18 | 15 | 0[a] | 82 | ( 1) | Poor | ( 2) | Brown[b] | 8.3 | ( 1) |
| | 24 | 19 | 0[a] | 160 | ( 1) | Fair | ( 2) | Brown[b] | 13 | ( 1) |
| Glyphosate | 3 | 1 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | -- | ( 0) |
| | 6 | 1 | 0[a] | 1.3 | ( 6) | Good | ( 6) | Yellow | 0.4 | ( 6) |
| | 12 | 8 | 1-9 | 3.1 | ( 9) | Poor | (11) | Yellow | 0.4 | ( 9) |
| | 18 | 12 | 1-9 | 38 | ( 6) | Poor | (11) | Brown[b] | 5.7 | ( 6) |
| | 24 | 15 | 0[a] | 86 | ( 5) | Poor | (11) | Brown[b] | 8.6 | ( 5) |
| Imazapyr/ Oil | 3 | 3 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | -- | ( 0) |
| | 6 | 3 | 0[a] | 1 | ( 1) | Good | ( 1) | Yellow | 0.3 | ( 1) |
| | 12 | 15 | 0[a] | 3 | ( 1) | Fair | ( 1) | Brown[b] | 0.3 | ( 1) |
| | 18 | 19 | 0 | 0 | ( 0) | Dead | ( 1) | Brown[b] | 0 | ( 0) |
| | 24 | 20 | 0 | 0 | ( 0) | Dead | ( 1) | Brown | 0 | ( 0) |

APPENDIX, TABLE III, continued.

| Treatment | Time Since Treatment (mos) | No. Killed (n = 20) | Mean Resprout Category* (n = 20) | Mean Resprout Height in cm | (n) | Resprout Vigor | (n) | Cambium Color (n = 20) | Live Resprout Growth Rate in cm/mo | (n) |
|---|---|---|---|---|---|---|---|---|---|---|
| Metsulfuron /Water | 3 | 7 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | -- | ( 0) |
| | 6 | 16 | 0[a] | 1 | ( 1) | Good | ( 1) | Brown[b] | 0.3 | ( 1) |
| | 12 | 19 | 0[a] | 17 | ( 1) | Good | ( 1) | Brown[b] | 2.7 | ( 1) |
| | 18 | 19 | 0[a] | 40 | ( 1) | Good | ( 1) | Brown[b] | 3.8 | ( 1) |
| | 24 | 19 | 0[a] | 85 | ( 1) | Good | ( 1) | Brown[b] | 7.5 | ( 1) |
| Citrus Oil | 3 | 1 | 1-9 | 7.6 | ( 9) | Good | ( 9) | Green | -- | ( 9) |
| | 6 | 1 | 1-9 | 12 | (11) | Fair | (12) | Yellow | 2 | (11) |
| | 12 | 2 | 1-9 | 49.8 | (12) | Good | (14) | Green | 6.6 | (12) |
| | 18 | 6 | 1-9 | 107.4 | (12) | Good | (15) | Yellow | 9.6 | (12) |
| | 24 | 9 | 1-9 | 206.8 | (11) | Fair | (15) | Yellow | 15.2 | (11) |
| Water | 3 | 0 | 1-9 | 7.6 | ( 9) | Good | ( 9) | Green | -- | ( 9) |
| | 6 | 0 | 1-9 | 12.9 | (11) | Good | (12) | Green | 2.3 | (11) |
| | 12 | 1 | 1-9 | 37.1 | (17) | Good | (17) | Yellow | 4.8 | (17) |
| | 18 | 4 | 1-9 | 78.6 | (16) | Fair | (18) | Yellow | 6.9 | (16) |
| | 24 | 4 | 1-9 | 179.2 | (16) | Good | (18) | Yellow | 16.7 | (16) |

*Categories: 0, 1-9, 10-50, >50.
[a]= <0.5, so rounded to 0.
[b]= some viability detected in sample of 20 trees, but insufficient to alter overall rating.

APPENDIX, TABLE IV. Observed death or disappearance of native plant species (>0.1 m in height) in plots surrounding firetree (*Myrica faya*) cut stumps at the Thurston Forest site.

| Treatment | Species (Common Name) | Height Class (m) | No. Dead | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| Glyphosate | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 8 | 47 |
| | *Coprosma ochracea* | 1-2 | | 1 | 47 |
| | *Cyrtandra platyphylla* | 0.5-1 | | 1 | 2 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 1 | 16 |
| | *Lycopodium cernuum* (Wawae 'iole) | 0.1-0.5 | | 1 | 2 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | | 1 | 19 |
| | *Myrsine lessertiana* (Kolea) | 0.1-0.5 | | 2 | 3 |
| | *Uncinia uncinata* | 0.1-0.5 | | 1 | 8 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.1-0.5 | | 1 | 16 |
| Imazapyr/Water | *Cheirodendron trigynum* ('Ōlapa) | 0.1-0.5 | | 1 | 2 |
| | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 6 | 36 |
| | *Coprosma ochracea* | 0.5-1 | | 2 | 36 |
| | *Coprosma ochracea* | 1-2 | | 1 | 36 |
| | *Cyrtandra platyphylla* | 0.1-0.5 | | 1 | 2 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 2 | 29 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | | 5 | 23 |
| | *Metrosideros polymorpha* | 0.5-1 | | 3 | 23 |
| | *Myrsine lessertiana* (Kolea) | 0.1-0.5 | | 1 | 6 |
| | *Sadleria pallida* ('Ama'u) | 0.1-0.5 | | 2 | 17 |
| | *Uncinia uncinata* | 0.1-0.5 | | 4 | 8 |

APPENDIX, TABLE IV, continued.

| Treatment | Species (Common Name) | Size Class (m) | No. Dead | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| Imazapyr/ Citrus Oil | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 2 | 71 |
| | *Coprosma ochracea* | 0.5-1 | 1 | | 71 |
| | *Coprosma ochracea* | 1-2 | 1 | | 71 |
| | *Coprosma ochracea* | 2-3 | | 3 | 71 |
| | *Coprosma ochracea* | 3-5 | | 1 | 71 |
| | *Cyrtandra platyphylla* | 0.1-0.5 | | 3 | 18 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 6 | 112 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | | 2 | 35 |
| | *Metrosideros polymorpha* | 0.5-1 | | 1 | 35 |
| | *Myrsine lessertiana* (Kolea) | 0.1-0.5 | | 1 | 9 |
| | *Sadleria pallida* ('Ama'u) | 0.1-0.5 | 1 | 1 | 62 |
| | *Uncinia uncinata* | 0.1-0.5 | 1 | 7 | 36 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.1-0.5 | | 6 | 35 |
| | *Vaccinium calycinum* | 1-2 | | 1 | 35 |
| Triclopyr/ Water | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 1 | 19 |
| | *Coprosma ochracea* | 0.5-1 | | 1 | 19 |
| | *Coprosma ochracea* | 1-2 | 2 | | 19 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 1 | 31 |
| | *Ilex anomala* | 0.5-1 | 1 | 2 | 31 |
| | *Ilex anomala* | 1-2 | | 1 | 31 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | | 1 | 8 |
| | *Sadleria pallida* ('Ama'u) | 0.1-0.5 | | 2 | 22 |
| | *Sadleria pallida* | 0.5-1 | | 2 | 22 |
| | *Uncinia uncinata* | 0.1-0.5 | 3 | 4 | 12 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.1-0.5 | | 2 | 6 |

APPENDIX, TABLE IV, continued.

| Treatment | Species (Common Name) | Size Class (m) | No. Dead | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| Metsulfuron/ Water | *Cibotium chamissoi* (Hapu'u 'i'i) | 0.1-0.5 | | 1 | 1 |
| | *Coprosma ochracea* (Pilo) | 0.1-0.5 | 1 | 4 | 30 |
| | *Coprosma ochracea* | 0.5-1 | 1 | 1 | 30 |
| | *Coprosma ochracea* | 3-5 | 1 | | 30 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 3-5 | 1 | | 40 |
| | *Sadleria pallida* ('Ama'u) | 0.1-0.5 | | 1 | 10 |
| | *Sadleria pallida* | 1-2 | 1 | | 10 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.1-0.5 | | 2 | 5 |
| Water | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 2 | 30 |
| | *Cyrtandra platyphylla* | 0.5-1 | 1 | | 1 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 1 | 17 |
| | *Ilex anomala* | 0.5-1 | | 1 | 17 |
| | *Sadleria pallida* ('Ama'u) | 0.1-0.5 | | 1 | 8 |
| | *Uncinia uncinata* | 0.1-0.5 | | 12 | 14 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.1-0.5 | | 1 | 17 |
| Citrus Oil | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 4 | 29 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 3 | 31 |
| | *Lycopodium cernuum* (Wawae 'iole) | 0.1-0.5 | | 2 | 2 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | | 3 | 28 |
| | *Uncinia uncinata* | 0.1-0.5 | | 6 | 13 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.1-0.5 | | 3 | 19 |

*Total number of individuals >0.1 m tall in 20 plots of treatment at beginning of study (prior to herbicide application).

APPENDIX, TABLE V. Results of herbicide treatments on frilled firetree (*Myrica faya*) at the Thurston Forest site.

| Treatment | Time Since Treatment (mos) | No. Killed (n = 20) | No. Live Resprouts* | Mean Resprout Height in cm | (n) | Resprout Vigor | (n) | Cambium Color | Canopy Defoliation % | Live Resprout Growth Rate in cm/mo | (n) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Imazapyr/ Water | 3 | 3 | 0[a] | 5 | ( 1) | Good | ( 1) | Yellow | >50 | -- | ( 1) |
| | 6 | 0 | 0[a] | 4.7 | ( 6) | Good | ( 6) | Green | >50 | 1.3 | ( 6) |
| | 12 | 2 | 1-9 | 29.1 | (10) | Fair | (10) | Yellow | >50 | 4.4 | (10) |
| | 18 | 1 | 1-9 | 44.4 | (17) | Fair | (17) | Yellow | >50 | 4.5 | (17) |
| | 30 | 7 | 3.8[c] | 97 | (11) | Fair | (17) | Yellow | >50 | 3.7 | (11) |
| Triclopyr/ Water | 3 | 7 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | >50 | -- | |
| | 6 | 1 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | >50 | 0 | (20) |
| | 12 | 6 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | >50 | 0 | (20) |
| | 18 | 9 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | >50 | 0 | (20) |
| | 30 | 18 | 0[c] | 0 | ( 0) | n/a | ( 0) | Brown[b] | >50 | 0 | |
| Glyphosate | 3 | 5 | 0[a] | 9 | ( 2) | Good | ( 2) | Yellow | >50 | -- | ( 2) |
| | 6 | 0 | 0[a] | 5.5 | ( 2) | Fair | ( 3) | Green | >50 | 1.3 | ( 2) |
| | 12 | 4 | 0[a] | 22.5 | ( 4) | Poor | ( 5) | Yellow | >50 | 3.3 | ( 4) |
| | 18 | 6 | 1-9 | 22.5 | (10) | Poor | (11) | Yellow | >50 | 2.3 | (10) |
| | 30 | 15 | 0.7[c] | 34.8 | ( 4) | Poor | (11) | Brown[b] | >50 | 1.4 | ( 4) |
| Imazapyr/ Oil | 3 | 2 | 0[a] | 5 | ( 1) | Good | ( 1) | Yellow | >50 | -- | ( 1) |
| | 6 | 0 | 0[a] | 6 | ( 3) | Good | ( 3) | Green | >50 | 1.4 | ( 3) |
| | 12 | 2 | 1-9 | 20.4 | (13) | Fair | (13) | Yellow | >50 | 3.2 | (13) |
| | 18 | 6 | 1-9 | 38.1 | (14) | Fair | (17) | Yellow | >50 | 3.4 | (14) |
| | 30 | 14 | 3.7[c] | 73 | ( 6) | Poor | (17) | Brown[b] | >50 | 2.2 | ( 6) |

APPENDIX, TABLE V, continued.

| Treatment | Time Since Treatment (mos) | No. Killed (n = 20) | No. Live Resprouts* | Mean Resprout Height in cm | (n) | Resprout Vigor | (n) | Cambium Color | Canopy Defoliation % | Live Resprout Growth Rate in cm/mo | (n) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Metsulfuron /Water | 3 | 9 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | >50 | -- | ( 0) |
| | 6 | 4 | 0 | 0 | ( 0) | n/a | ( 0) | Yellow | >50 | 0 | ( 0) |
| | 12 | 9 | 0[a] | 7.5 | ( 4) | Fair | ( 4) | Yellow | >50 | 1.3 | ( 4) |
| | 18 | 7 | 1-9 | 51.4 | (10) | Fair | (10) | Yellow | >50 | 8.1 | (10) |
| | 30 | 9 | 5.8[c] | 88.3 | (11) | Fair | (12) | Yellow | >50 | 3.6 | (11) |
| Citrus Oil | 3 | 0 | 1-9 | 20.3 | (17) | Excellent | (17) | Green | 0[a] | -- | (17) |
| | 6 | 0 | 10-50 | 23 | (20) | Good | (20) | Green | 0[a] | 1.9 | (20) |
| | 12 | 0 | 10-50 | 69.4 | (20) | Good | (20) | Green | 25-50 | 7.7 | (20) |
| | 18 | 1 | 10-50 | 115.5 | (19) | Fair | (20) | Yellow | 25-50 | 7.2 | (19) |
| | 30 | 1 | 6[c] | 145.7 | (15) | Poor | (20) | Yellow | 25-50 | 2.8 | (15) |
| Water | 3 | 0 | 1-9 | 12.5 | (14) | Good | (14) | Green | 1-25 | -- | (14) |
| | 6 | 0 | 1-9 | 13.1 | (14) | Fair | (16) | Green | 1-25 | 0.4 | (14) |
| | 12 | 0 | 1-9 | 30.6 | (14) | Fair | (16) | Green | 1-25 | 3 | (14) |
| | 18 | 0 | 1-9 | 53.9 | (12) | Poor | (16) | Yellow | 1-25 | 3.4 | (12) |
| | 30 | 0 | 0.7[c] | 80.3 | ( 3) | Dead[b] | (16) | Green | 0[a] | 1.9 | ( 3) |

*Mean resprout categories were used for readings through 18 months; at 30 months, resprouts were counted (c).
Resprout categories: 0, 1-9, 10-50, >50.

a = <0.5, so rounded to 0.

b = some live tissue detected, but insufficient to alter overall rating.

c = mean number of resprouts counted.

APPENDIX, TABLE VI. Observed death or disappearance of native plant species (>0.1 m in height) in plots surrounding frilled firetree (*Myrica faya*) at the Thurston Forest site.

| Treatment | Species (Common Name) | Height Class (m) | No. Dead | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| Glyphosate | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 7 | 60 |
| | *Coprosma ochracea* | 1-2 | | 1 | 60 |
| | *Hedyotis terminalis* (Manono) | 0.1-0.5 | | 7 | 1 |
| | *Machaerina angustifolia* ('Uki) | 0.5-1 | | 1** | 1 |
| | *Sadleria pallida* ('Ama'u) | 0.1-0.5 | 1 | 2 | 38 |
| | *Sadleria pallida* | 1-2 | | 2 | 38 |
| | *Uncinia uncinata* | | 2 | 3 | 21 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 1-2 | | 2 | 5 |
| Imazapyr/Water | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 15 | 62 |
| | *Coprosma ochracea* | 0.5-1 | | 3 | 62 |
| | *Coprosma ochracea* | 1-2 | 1 | | 62 |
| | *Coprosma ochracea* | >3 | 2** | 1** | 62 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 4 | 23 |
| | *Ilex anomala* | 0.5-1 | | 1 | 23 |
| | *Ilex anomala* | 1-2 | 1 | | 23 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | | 3 | 47 |
| | *Metrosideros polymorpha* | 1-2 | | 3 | 47 |
| | *Sadleria pallida* ('Ama'u) | 0.1-0.5 | | 1 | 28 |
| | *Sadleria pallida* | 0.5-1 | 1 | | 28 |
| | *Sadleria pallida* | 1-2 | | 2 | 28 |
| | *Uncinia uncinata* | 0.1-0.5 | | 1 | 5 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.5-1 | | 2 | 3 |
| | *Vaccinium calycinum* | 1-2 | | 1 | 3 |

APPENDIX, TABLE VI, continued.

| Treatment | Species (Common Name) | Height Class (m) | No. Dead | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| Imazapyr/ Citrus Oil | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 3 | 27 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 1 | 25 |
| | *Ilex anomala* | 0.5-1 | | 1 | 25 |
| | *Metrosideros polymorpha* (‘Ōhi‘a) | 0.1-0.5 | | 2 | 33 |
| | *Metrosideros polymorpha* | 2-3 | | 1 | 33 |
| | *Uncinia uncinata* | 0.1-0.5 | 2 | 4 | 15 |
| | *Vaccinium calycinum* (‘Ōhelo-kau-la‘au) | 0.1-0.5 | | 2 | 8 |
| | *Vaccinium calycinum* | 0.5-1 | | 1 | 8 |
| Triclopyr/ Water | *Cibotium glaucum* (Hapu‘u pulu) | 1-2 | | 1 | 5 |
| | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 10 | 34 |
| | *Coprosma ochracea* | 0.5-1 | 1** | | 34 |
| | *Coprosma ochracea* | >3 | 2** | | 34 |
| | *Ilex anomala* (Kawa‘u) | 0.1-0.5 | | 1 | 26 |
| | *Metrosideros polymorpha* (‘Ōhi‘a) | 0.1-0.5 | | 2 | 46 |
| | *Metrosideros polymorpha* | 0.5-1 | | 1 | 46 |
| | *Sadleria pallida* ('Ama‘u) | 0.5-1 | 1 | | 19 |
| | *Sphenomeris chinensis* (Pala‘a) | 0.1-0.5 | 1 | | 1 |
| | *Vaccinium calycinum* (‘Ōhelo-kau-la‘au) | 0.1-0.5 | | 1 | 6 |
| Metsulfuron/ Water | *Cibotium glaucum* (Hapu‘u pulu) | >3 | 2 | | 15 |
| | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 17 | 48 |
| | *Coprosma ochracea* | 0.5-1 | | 1 | 48 |
| | *Coprosma ochracea* | >3 | 3** | | 48 |
| | *Ilex anomala* (Kawa‘u) | 0.1-0.5 | 1 | 8 | 31 |

APPENDIX, TABLE VI, continued.

| Treatment | Species (Common Name) | Height Class (m) | No. Dead | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | 2 | 1 | 10 |
| | *Metrosideros polymorpha* | 0.5-1 | 1 | | 10 |
| | *Myrsine lessertiana* (Kolea) | 0.5-1 | | 1 | 2 |
| | *Sadleria pallida* ('Ama'u) | 0.1-0.5 | 1 | | 33 |
| | *Uncinia uncinata* | 0.1-0.5 | 3 | 10 | 25 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.1-0.5 | | 2 | 4 |
| | *Vaccinium calycinum* | 1-2 | 1 | | 4 |
| Water | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 10 | 51 |
| | *Coprosma ochracea* | 0.5-1 | | 2 | 51 |
| | *Coprosma ochracea* | 1-2 | 1 | | 51 |
| | *Coprosma ochracea* | >3 | 1 | | 51 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 5 | 38 |
| | *Machaerina angustifolia* ('Uki) | 0.5-1 | | 1** | 2 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | 1 | 3 | 28 |
| | *Myrsine lessertiana* (Kolea) | 0.1-0.5 | | 1 | 6 |
| | *Uncinia uncinata* | 0.1-0.5 | | 4 | 23 |
| | *Vaccinium calycinum* ('Ōhelo-kau-la'au) | 0.1-0.5 | | 1 | 5 |
| Citrus Oil | *Coprosma ochracea* (Pilo) | 0.1-0.5 | | 1 | 18 |
| | *Coprosma ochracea* | 1-2 | 3 | | 18 |
| | *Coprosma ochracea* | >3 | 1** | | 18 |
| | *Ilex anomala* (Kawa'u) | 0.1-0.5 | | 2 | 31 |
| | *Ilex anomala* | 0.5-1 | 1 | 1** | 31 |
| | *Metrosideros polymorpha* ('Ōhi'a) | 0.1-0.5 | 1** | 1 | 46 |
| | *Metrosideros polymorpha* | 1-2 | 4** | | 46 |

APPENDIX, TABLE VI, continued.

| Treatment | Species (Common Name) | Height Class (m) | No. Dead | No. Disappeared | Original No. in Treatment >0.1 m* |
|---|---|---|---|---|---|
| | *Sadleria pallida* ('Ama'u) | 0.5-1 | | 1 | 23 |
| | *Sadleria pallida* | 1-2 | 1 | | 23 |
| | *Uncinia uncinata* | 0.1-0.5 | | 1 | 5 |

*Total number of individuals >0.1 m tall present in 20 plots of treatment at beginning of study (prior to herbicide application).
**Poor vigor prior to herbicide treatment.

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