THESIS

CONTROL OF *PENNISETUM SETACEUM* (Forssk.) Chiov.

IN NATIVE HAWAIIAN DRY UPLAND ECOSYSTEMS

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY J. MICHAEL CASTILLO ENTITLED CONTROL OF *PENNISETUM SETACEUM* (FORSK.) CHIOV. IN HAWAIIAN DRY UPLAND ECOSYSTEMS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

CONTROL OF *PENNISETUM SETACEUM* (Forssk.) Chiov. IN HAWAIIAN DRY UPLAND ECOSYSTEMS

Alien plant invasions have become a large problem for land managers throughout the world. In many tropical island ecosystems, introduced plant species have displaced native taxa. Mechanisms of displacement are complex and poorly understood. *Pennisetum setaceum* (Forssk.) Chiov. (fountain grass), a grass native to northern Africa, is currently invading extensive dryland habitats on the island of Hawaii. By altering species composition and community structure, this grass interferes with major ecosystem processes such as native plant regeneration, succession, and fire frequency. The survival of many T&E plant species and their habitat are directly threatened by this species. An experiment was conducted to assess the relative effectiveness of various herbicides and a mechanical technique to control *P. setaceum.* Three levels of primary treatment were combined with four levels of secondary treatment to yield 12 factor-level treatment combinations. Effects of a singular application were monitored for two years. Herbicides tested were hexazinone, glyphosate, and triclopyr.

Hexazinone was very effective as a primary treatment in decreasing live *P. setaceum* cover, both when applied alone and in combination with secondary treatments, 1 and 2 years following application (yfa). Triclopyr was more effective in reducing percent *P. setaceum* cover 1 and 2 yfa, when combined with the secondary treatment manual than it was when combined with the lower rate of glyphosate. When applied alone, triclopyr was ineffective in reducing frequency of hits of *P. setaceum*. Plots treated secondarily by manual removal had the most pronounced

effects the first year. Hexazinone combined with manual removal proved to be the most effective overall treatment. Hexazinone combined with either of the two rates of glyphosate also were effective.

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INTRODUCTION

Had Charles Darwin studied the Hawaiian archipelago rather than the Galapagos islands, his efforts might very well have brought as much evolutionary awe and attention to Hawaii as the Galapagos have received. It is unfortunate that he did not, for conservation efforts may have been directed there sooner. Although ecologists now have identified the Hawaiian Islands as “perhaps the most extraordinary living museum of evolution on the planet” (Vitousek, et al. 1987), this acclaim came too late to afford them the international conservation efforts that may have prevented the loss of a diverse range of habitats and the extinction of many native species. The isolation of the Hawaiian Islands has provided for the development of a flora and fauna so unique that 95 % of native taxa occur nowhere else in the world (Carlquist 1980). Only a small fraction of the ecosystems which harbored this unique diversity of life remain intact.

Among the many ecosystems present in Hawaii are tropical dry forests which, according to Janzen (1988), “are the most endangered major tropical ecosystem”. Hawaii’s dry forests are known to contain a great number of threatened and endangered (T&E) species. Unfortunately, 90% of them have already been lost to land conversion and habitat degradation (Bruegmann 1996). Major threats to Hawaiian dry ecosystems include the invasion by alien species, fire, and urban development (Cuddihy and Stone 1990, Bruegmann 1996).

Much of the loss of native Hawaiian biota has been caused by the displacement or replacement of native components by introduced species (Egler 1942, Jacobi and Scott 1985). Not only do biological invasions alter community composition and structure, they also cause large scale ecosystem changes (Smith 1985, Ramakrishnan and Vitousek 1989, and Vitousek 1990 and 1992). Alien plant invasions and their ecological effects are most severe on oceanic islands

(Loope 1992). In fact, alien plant invasions into Hawaii are considered to be worse than in any other place in the world (Taylor 1982).

There has been much speculation as to why Hawaiian ecosystems, and island ecosystems in general, are so adversely affected by alien invasions. The reasons for success of alien invaders on oceanic islands are not completely understood (Loope and Mueller-Dombois 1989, Simberloff 1995a). Island biotas traditionally have been viewed as fragile and as having been subjected to less rigorous natural selection pressures. This quality is attributed to island biotas having fewer species and hence, a lower level of competitiveness. Lack of data on failed introductions, however , make this view hard to assess (Simberloff 1995a). While there are more surviving introductions on islands than continents, this does not necessarily indicate that island biotas are competitively inferior. In fact, research has shown that island species are as competitively resilient as aliens (Mueller-Dombois et al. 1981, Kitayama and Mueller-Dombois 1995). This may be a result of the isolation of islands and the difficulties of long-distance seed migration. Low numbers of species occupying a diverse range of habitats may have enabled surviving taxa to develop wider ecological amplitudes than mainland species. As for competitiveness, resource competition is notoriously hard to document in field situations (Simberloff 1995a). Relatively high success rates of invaders on isolated islands are more likely the result of a predisposition of native biotas to be affected by invaders introducing selective forces that were previously absent (ie. predation, grazing and disease) than a result of competitive inferiority.

Evolutionarily, isolated oceanic islands have not possessed all of the selective forces that are present on continents. For example, mechanisms necessary to cope with fire have not developed. Until relatively recently, the incredible isolation of Hawaii has limited the arrival of large groups of species such as humans, other mammals, reptiles and amphibians and the associated ecological relationships with them. Absence of particular groups of species that might cause ‘disturbance’ like fire, trampling or digging, or otherwise interact with other species (ie. browsing, preying, dispersing, or pollinating) are factors that predispose island ecosystems in island environments to be so drastically affected. Evidently, the pronounced ecological impacts resulting from biological invasions in Hawaii are a result of the absence of certain groups of species and the predisposition of particular introduced organisms to survive in that environment and produce pronounced effects (Loope and Mueller-Dombois 1989, Simberloff 1995b).

In Hawaii over 800 species of alien plants are reproducing without direct human assistance (Wester 1992). Among these is *Pennisetum setaceum* (Forssk.) Chiov. (fountain grass), a C-4 grass native to the Sahara Desert and arid coasts in northern Africa and the Middle East (Wagner, et al. 1990). This species of *Pennisetum* has proved to be particularly invasive in dry regions of the island of Hawaii. Although it is not officially on the U. S. Department of Agriculture noxious weed list, it is considered a noxious weed by the Hawaii Department of Agriculture and the National Park Service (Jacobi and Warshauer 1992). It was first collected on the island of Lanai in 1914 (Jacobi and Warshauer 1992) and introduced as an ornamental to the leeward side of the island of Hawaii in 1917 (Heather Cole, pers. comm.). It since has aggressively invaded extensive dryland areas [< 1250 mm (50 in) precipitation annually] on the western side of the island including ranch land and native habitats up to approximately 2900 m (9512 ft) elevation (Cuddihy and Stone 1990, Jacobi and Warshauer 1992, Wester 1992). On Hawaii, *P. setaceum* is invading highly pristine communities as well as disturbed sites. It also is present on Lanai, Maui, Oahu and Kauai although it is not yet considered a pest on those islands (Smith 1985).

Ecosystem Effects

The rapid spread of this grass alters community structure, thereby disrupting and altering ecosystem processes including native plant population dynamics, natural succession, hydrological transport and disturbance regime (Smith 1985, Cuddihy and Stone 1990, Tunison 1992a, USFWS 1994, Vitousek 1992). The survival of many T&E plant species and their habitat are directly threatened by this species (Cuddihy and Stone 1990, USFWS 1994).

Regeneration of woody and herbaceous plants may be stifled by canopy closure associated with *P. setaceum* invasion. Shaw, et al. (in press.) found that several native species of shrubs in the Kipuka Kalawamauna did not respond favorably to a 1994 wildfire. Only one of several dominant shrub species vigorously sprouted following the burn and after 1 year, several other shrub species did not respond. The native shrub which did sprout, however, was anticipated to take several years to attain cover values similar to those of preburn conditions. *P. setaceum*, however, was able to restore canopy dominance in a much shorter amount of time. In a monotypic stand of *P. setaceum* near the same site, total *Pennisetum* cover only 3 months following the same wildfire was over half (48%) of its maximum, which occurred 21 months following the burn (92%) (Castillo, unpublished data). Dense stands such as these may inhibit or preclude the establishment of plants that evolved with a much more open plant canopy.

Typical patterns of plant community development are altered by *P. setaceum* invasion. The generalized progression of primary succession in these dry upland regions of Hawaii is as follows: sparsely-vegetated woody-dominated landscapes become densely-vegetated woody-dominated communities, that in turn become communities dominated by mixes of grass and woody species, or in some cases, grasslands. It is supposed that this development occurs on a time scale of about 10,000 years. *P. setaceum,* however, forms monotypic stands on young sparsely vegetated or barren lavas (Cuddihy and Stone 1990, Tunison 1992a). The formation of these exotic grasslands catapult the structure of these plant communities from that of a very early successional sere to that of a much later one, thereby preventing the normal progression of woody plant development.

Fire has not been a major evolutionary element in the development of native Hawaiian vegetation (Mueller-Dombois 1981, Smith 1985, Cuddihy and Stone 1990). *P. setaceum*, appears to tolerate fire well, as evidenced by the monotypic stands that dominate many of the montane and lowland areas of Hawaii island that have frequently burned over the last two decades. The low number of ignition sources before human arrival and the discontinuity of fine fuels in these habitats are reasons for the infrequence of fires before *P. setaceum* invasion. With both the widespread distribution and continuity of *Pennisetum* and the availability of frequent ignition sources, fires have become a major frequent disturbance factor on dry midland regions. Alien grasses like *P. setaceum* have invaded dry habitats throughout the islands and appear to promote larger, more frequent wildfires because of increased fuel loadings that occur (Tunison 1992a, D'Antonio and Tunison 1993). *Pennisetum* rapidly recolonizes burned sites; in contrast, most native woody plants take longer to recover, if they do at all (Shaw, et al., in press). This creation of a frequent fire regime is favoring *Pennisetum* spread over perpetuation of native plant assemblages (Smith 1985, Cuddihy and Stone 1990, USFWS 1994). Furthermore, wildland fires are having a direct negative impact on several native plant communities and some of the T&E plant species they contain (Shaw, et al. in press).

P. setaceum is considered by the U.S. Fish & Wildlife Service (USFWS) to be the single largest threat to Hawaiian dry ecosystems (Loyal Mehrhoff, USFWS, pers. comm., 1994). This paper addresses the question of which methods of control are most effective in controlling this problematic taxon.

Biocontrol of *P. setaceum* in Hawaii is impractical for 3 primary reasons (Markin 1989): (1) the process required for the identification, development and experimental testing of a biocontrol agent is long and costly with the chances of a successful agent being found anytime in the near future small (Markin, et al. 1992); (2) *Pennisetum* is related to important agricultural species like sugar cane [*Saccharum robustum* (Brandes & Jesw.) Grassl] and kikuyu grass [*Pennisetum clandestinum* (Hochst.) Chiov.] and therefore, biocontrol of *Pennisetum* would meet with much opposition from associated agricultural industries (Smith 1985); and (3) once introduced, agents are uncontrollable, may be unpredictable and have an impressive list of failures (Howarth & Medeiros 1989). Other control options to be investigated are mechanical control, including tillage or hand-pulling, hot water treatment, and chemical control.

Classical mechanical control is impractical in areas where *Pennisetum* dominates and is spreading. Most of these areas are rocky, young landscapes without much soil development. Furthermore, machinery could not be used in these areas without costly damage to the machinery and disturbance of the site (further favoring alien invasion).

Control strategies within Hawaii Volcanoes National Park (HVNP) have included both manual and chemical techniques. Park Service employees decreased numbers of plants in targeted populations from 8000 to 3000 over a 3-year period by physically uprooting them (Tunison 1992a). More recently, herbicides have been used with success. Tunison (pers. comm.) found that glyphosate (Roundup) was effective on actively growing plants and hexazinone (Velpar) was effective on both actively growing and dormant plants.

Although manual eradication efforts within HVNP have succeeded in confining the grass to highly infested lowland areas, HVNP officials fear that all dry and mesic habitats within HVNP could be invaded if lands are left unmanaged (Cuddihy and Stone 1990, Tunison, et al. 1993). An approach used within the Park has been to confine the single largest infestation while focusing eradication efforts within Special Ecological Areas (SEA) (Tunison 1992a and 1992b, Tunison and Stone 1992, Tunison and Zimmer 1992, and Taylor 1992). SEAs are intensive management and research units where plant communities are intact, diverse, and representative, and population sizes are relatively small making eradication practical.

There also have been efforts to control *P. setaceum* on State lands. The State of Hawaii has implemented an aggressive weed control program, part of which targets *Pennisetum*, within their Natural Areas Reserve System. However, there is little information on which control methods are most effective against *Pennisetum* (J. LeAloha, 1994, pers. comm.). A dry forest restoration project currently underway in Kaupulehu, North Kona, has utilized glyphosate (Roundup) to control *Pennisetum*; however, frequent reapplication is necessary which makes control labor intensive and expensive (Heather Cole, 1994, pers. comm.) While both hexazinone and glyphosate are known to be effective herbicides to control *Pennisetum*, data showing the effectiveness of various rates, combinations of herbicides, or combinations of herbicides with other treatments such as manual removal are lacking.

A quantitative assessment of the effectiveness of various control techniques on *Pennisetum* is warranted.

Objective

1. Assess the relative effectiveness of various chemical and non-chemical treatments, both alone and in combination, to control *P. setaceum*.

Hypothesis Statements

The following hypotheses will be tested:

1. There will be no difference in mean percent foliar cover of live *P. setaceum* between various treatments either 1 or 2 years following application of treatments.

   H_o: $c_1 = c_2 = c_3 = c_4 = c_6 = c_7 = c_8 = c_9 = c_{10} = c_{11} = c_{12}$,

   where c = mean % foliar cover.

2. There will be no difference in mean frequency of hits per point of *P. setaceum* between various treatments 1 and 2 years following application of treatments.

   H_o: $f_1 = f_2 = f_3 = f_4 = f_6 = f_7 = f_8 = f_9 = f_{10} = f_{11} = f_{12}$,

   where f = mean frequency of hits.

STUDY SITE AND METHODS

Study Site

This study was conducted on the U.S. Army's Pohakuloa Training Area on the leeward side of the Pacific island of Hawaii at approximately 1,280 m elevation (Figure 1). This site was chosen because a monotypic *Pennisetum* stand was well established, topography in the area is relatively uniform, the site was easy to access, and the relatively pristine adjacent rare plant habitat was threatened by *Pennisetum* invasion.

The experiment was located in a homogeneous stand of *Pennisetum*, on relatively young (>10,000 years old) Mauna Kea lava (Wolfe and Morris 1996). The stand was recovering from a wildfire that swept through the area in late July 1994; therefore, all plants at the site were members of the same cohort. These conditions provided an optimal setting for an experiment of this nature as the relatively even-aged stand contained actively photosynthesizing plants that favored herbicide absorption and translocation. Application of herbicide to mature *Pennisetum* plants elsewhere on the island has been partially ineffective due to the high amount of herbicide that is invariably intercepted by dead leaves (Heather Cole, pers. comm., 1994). At the time of treatment, grasses in the stand were up to 3 decimeters tall and actively growing.

Sampling

In late September, 1994, six blocks were established on gently sloping (6%) to nearly flat fields of aa lava with similar vegetative cover and topography (Figure 2). Within each block, 12 plots were located along permanent 50-m transects that were marked with a 1-m metal base stake. Plot locations in relation to the block baseline were recorded. Plots were individually marked with painted metal rods driven into two of the four corners of each plot. All plots were spaced at least 5 meters apart to insure that there was no overlap in treatment effects. Each of the 12 treatments were randomly assigned to a plot within each block.

Live and dead foliar cover of *Pennisetum* were measured using the point-intercept method in a 1-m^2 point grid having 121 points (Bonham 1989 and pers. comm. 1994).   Using a small diameter rod (2.38 mm) lowered perpendicularly to the ground, aerial foliar hits were recorded as a height measurement rounded to the nearest cm.

Block transects and plots along those transects were established in October 1994. Plots were sampled and then treated at that time. The first post-treatment sampling occurred in November 1994, and plots subsequently were sampled every four months for the first year following treatment (February, June, and October, 1995). During the second year, plots were sampled twice at six-month intervals (April and October 1996).

Treatments

Twelve chemical and non-chemical treatments were applied in each of 6 blocks (replicates). Treatment codes, treatments, and rates (in brackets) are as follows:

<u>Code</u> <u>Treatment [rate]</u>

a_1b_1 = Hexazinone (Velpar L) x Glyphosate (Roundup) 1

[16.1 kg/ha of a.i. + 5.9 kg/ha a.e. (14.4 lbs/A + 5.3 lbs/A)]

a_1b_2 = Hexazinone x Glyphosate 2

[16.1 kg/ha of a.i. + 11.8 kg/ha a.e. (14.4 lbs/A + 10.5 lbs/A)]

a_1b_3 = Hexazinone x Manual

[16.1 kg/ha of a.i. (14.4 lbs/A) + pick and hand grubbing tools]

a_1b_4 = Hexazinone

[16.1 kg/ha of a.i. (14.4 lbs/A)]

a_2b_1 = Triclopyr (Garlon 3A) x Glyphosate 1

[4.5 kg/ha a.e. + 5.9 kg/ha a.e. (4.0 lbs/A + 5.3 lbs/A)]

a_2b_2 = Triclopyr x Glyphosate 2

[4.5 kg/ha a.e. +11.8 kg/ha a.e. (4.0 lbs/A + 10.5 lbs/A)]

a_2b_3 = Triclopyr x Manual

[4.5 kg/ha a.e. + pick and hand grubbing tools]

a_2b_4 = Triclopyr

[4.5 kg/ha of a.e. (4.0 lbs/A)]

a_3b_1 = Glyphosate 1

[1.5% of the commercial solution (1.3 lb a.e./gal) or 5.9 kg/ha of a.e. (5.3 lbs/A)]

a_3b_2 = Glyphosate 2

[3.0% of the commercial solution (1.3 lb a.e./gal) or 11.8 kg/ha of a.e. (10.5 lbs/A)]

a_3b_3 = Manual removal (pick and hand-grubbing)

a_3b_4 = Control (no treatment)

Herbicides were applied to plots using a pressurized herbicide sprayer equipped with a cone-spray nozzle (orifice size T-jet #1). All chemical treatments were applied as a half-liter of solution over a 50-second period to each 1 m^2 at a pressure of 210 KPa. A buffer zone of approximately 0.23 m surrounding plots was also sprayed to reduce experimental error associated with the plot edge. This equates to 2,500 l of solution per hectare. All herbicidal treatments were single treatments applied by the same person to minimize application error. Manual treatments consisted of removing all above- and below-ground live plant material using a pick and hand-grubbing tool.

Application of treatments occurred one block at a time. Every plot on each block received Factor B and Factor A treatments before the next block was treated. Factor B (secondary) treatments were applied to plots first, followed by factor A (primary) treatments. Treatments were applied in this order because the manual treatments (Factor B_3) needed to occur before Factor A herbicides were applied.

A photographic record of each of the 72 plots showing pre-treatment condition and each of the post-treatment stages were taken to document visually apparent changes.

Data Analysis

Experimental design was a randomized, complete block design with a 3 x 4 factorial arrangement of treatments combining primary treatments (factor A) and secondary treatments (factor B) (Table 1). This arrangement provided 12 factor-level combinations of treatments. This experimental design allowed comparison between factor-level combinations of the independent variables while blocking out extraneous sources of variability (Ott 1993).

A 2-way analysis of variance (ANOVA) procedure for a randomized complete block was performed on several variables: Total (live and dead attached) percent foliar cover, live percent foliar cover, frequency of hits per point, and on square root-transformed data for each of these three variables. The square root-transformation was performed on these data to stabilize error variance. These analyses were conducted to identify statistical differences ($p < 0.05$) in total and live *P. setaceum* cover between treatments at 1 and 2 years, and differences in total and live cover for each treatment on 7 sample dates over the 2-year period. Although real cover values are reported, significance was derived from transformed data. Multiple comparisons identifying differences among least squares means of treatments were corrected for using a Least Significant Difference (LSD) test protected by a significant ($p < 0.05$) F-test.

RESULTS AND DISCUSSION

Cover

Hexazinone (factor a_1) was very effective as a primary treatment in decreasing live *P. setaceum* cover, both when applied alone and in combination with secondary treatments, 1 and 2 years following application (yfa). All primary hexazinone plus secondary treatments decreased *P. setaceum* cover to 2% of control or less 1 yfa and 7% or less 2 yfa (Tables 2a and 2b, Figures 3a and 3b). Triclopyr was more effective in reducing percent *P. setaceum* cover 1 and 2 yfa, when combined with the secondary treatment manual (factor-level a_1 b_3) (2% and 12%, respectively) than it was when combined with the lower rate of glyphosate (13% and 32%, respectively) (Table 2a and 2b, Figures 3a and 3b). In the absence of a secondary treatment, triclopyr was demonstrated to be far less effective (68% 1 yfa) than when combined with any of the secondary treatments (Table 2a and 2b, Figures 3a and 3b). When no primary treatment was applied (factor a_3), glyphosate treatments decreased cover of *P. setaceum* to 6% of control 1 yfa and 17% 2 yfa. In contrast, manual techniques decreased *P. setaceum* cover to 1% and 10% 1 and 2 yfa, respectively (Tables 2a and 2b, Figures 3a and 3b).

One-year analysis of secondary treatments (factor B) across each primary treatment showed no differences in live *P. setaceum* cover within any of the secondary treatments (Table 2a, Figure 3a). After 2 years, however; the lower rate of glyphosate (factor b_1), when applied with hexazinone (7%), was more effective than when applied with triclopyr (32%) (Table 2b, Figure 3b). There were no differences in effectiveness within the higher rate of glyphosate (factor b_2) across primary treatments when it was applied alone or in combination with hexazinone or triclopyr 1 and 2 yfa (Tables 2a and 2b, Figures 3a and 3b). Likewise, there were no differences in effectiveness of manual treatments (factor b_3). Secondary control (factor b_4), which displays effectiveness of primary treatments applied alone, showed no difference between triclopyr and control either 1 or 2 yfa (Tables 2a and 2b, Figures 3a and 3b). Both 1 and 2 yfa, triclopyr alone (68% and 102%, respectively) was far less effective than hexazinone alone (0% and 2%, respectively) to control *P. setaceum* (Tables 2a and 2b, Figures 3a and 3b).

Frequency of hits

Results of the frequency of hits analysis, used here as a descriptor of quantity of foliage, provided data on effectiveness of treatments in decreasing the density of the *P. setaceum* canopy. Plots treated secondarily by manual removal had the most pronounced effects the first year. Manual plots had a lower frequency of hits (3% of control) across all primary treatments 1 yfa than did plots treated secondarily with glyphosate (27%) (factors b_1 and b_2) (Table 3a, Figure 4a).

After two years, plots treated primarily with hexazinone (4%) had decreased frequency of hits of *P. setaceum* as much as manually treated plots (5%) and those treated with the higher rate of glyphosate (10 %) (Table 3b, Figure 4b). The lower rate of glyphosate, however; had a higher frequency (28%) when combined with the primary treatment triclopyr than when it was combined with hexazinone as a primary treatment (6%) or manual plots treated primarily with triclopyr (7%) (Table 3b, Figure 4b). Furthermore, triclopyr, when applied alone, was ineffective in reducing frequency of hits of *P. setaceum* 1 (87%) and 2 (122%) yfa (Tables 3a and 3b, Figures 4a and 4b).

Repeated measures

Repeated measures analysis provided evidence that the treatments varied in effectiveness in reducing *P. setaceum* cover and frequency of hits over the 2-year sampling period following application of treatments (alpha = 0.05).

Cover

Results were consistent for secondary treatments across all primary treatments. Glyphosate as secondary treatments were consistently effective across all primary treatments by maintaining less than 25% cover 2-years after application (Figures 5a, 5b, and 5c). Manual treatments also effectively decreased cover of *P. setaceum* to < 2% for up to 1 year across all primary treatments (Figures 5a, 5b, and 5c). After two-years, however, cover values for manual treatments approached 10% for plots treated primarily with triclopyr or not at all (Figures 5b and

5c). Hexazinone combined with manual removal proved to be the most effective overall treatment as cover was maintained at less than 1.5% for the entire 2-year period (Figure 5a). Hexazinone alone (control) also decreased *P. setaceum* cover to less than 1.5% through the second year, however it took 1 to 4 months for cover to decrease to that level (Figure 5a). Hexazinone combined with either of the two rates of glyphosate also were effective; this combination of treatments maintained a *P. setaceum* cover of less than 6% from 4-months to 2-years following application (Figure 5a). Triclopyr applied alone did not yield lower cover values over the 2-year period than non treated controls (Figure 5b and 5c, respectively).

Frequency of hits

All three primary treatments, when coupled with manual as a secondary treatment, immediately decreased and maintained the frequency of hits of *P. setaceum* at less than 0.1 hits per point over the entire two year period (Figure 6a, 6b, and 6c). All hexazinone treatments, except hexazinone x manual, which displayed a decline in 1 month, showed a steady decline in frequency of hits over time. Hexazinone combined with glyphosate as a secondary treatment resulted in a steady decline over the 2-year period reaching 0.5 hits per point 8-months following application (Figure 6a). Glyphosate, when combined with triclopyr or applied alone, also steadily decreased *P. setaceum* foliage, although these treatments took longer (12 to 18 months) to decrease frequency to 0.5 hits per point (Figures 6b and 6c). Triclopyr alone did not show a decline in frequency of hits over the 2 years; frequency on plots treated solely with triclopyr was not different than control plots, both having a peak of approximately 3 hits per point at 18 months following application (Figures 6b and 6c).

Discussion

Triclopyr was ineffective in decreasing cover or frequency of hits both 1 and 2 years following application. Percent cover on plots treated solely with triclopyr was not different from plots that received no treatment. This result is not surprising given that triclopyr was developed as a broad leaf herbaceous weed and brush herbicide (Weed Science Society of America 1974).

Control, as a primary treatment, measured the effectiveness of each of the individual secondary treatments. All three secondary treatments effectively decreased cover of live *P. setaceum* and maintained it at less than 15% of control through the first year. When any of these three were combined with hexazinone as a primary treatment, however, cover was decreased to less than 7% over the entire 2-year period. Hexazinone, when applied alone, decreased cover to 2% or less for the time-period lasting from 4-months to 2-years following application.

Use of hexazinone, however, has come under scrutiny in recent years. Concern has resulted from findings of hexazinone contamination of ground water on the windward side of the Island. This contamination is a result of the use of large quantities of the product Velpar by sugarcane growers along the wet environment of the Hamakua coast. Infiltration of water and associated leaching of nutrients from the upper soil profile into the uppermost layer of the basal water is common in this region (Armstrong 1983). Use of this product in dry environments, such as those where *P. setaceum* invasion is occurring, should not pose the same threat. Regions of Hawaii where *P. setaceum* is established and spreading are generally dry, receiving on the average 1270 mm or less per year (Jacobi and Warshauer 1992). In contrast, parts of the island where sugarcane is grown receive between 1905 and 7620 mm per year (Armstrong 1983). Hexazinone is known, however, to remain active in the soil (Rhodes 1980). This property may hamper any potential restoration efforts. In contrast, glyphosate has been shown to rapidly bind with soil particles, thereby becoming inactive (Sprankle, et al. 1975).

Primary control treatments demonstrated that after 2 years, differences in frequency of hits were less apparent than after 1 year. On manually treated plots, frequency of hits was 11% of plots treated secondarily with glyphosate after 1 year. This result is not surprising as manually treated plots remove all plant material from the site.

Although the manual treatment was very effective, it has drawbacks. This form of treatment is labor intensive and likely would cause total control costs to be higher than where herbicides were used alone.   Furthermore, manual removal of *P. setaceum* requires the physical uprooting of individual plants, thereby disturbing the site where the plants existed. This disturbance could create an environment that favors the germination and establishment of other exotic species. In addition, manual removal on young lava flows requires the use of a pick or similar instrument which inevitably pulverizes the lava, thereby causing the creation of soil to occur faster than it would normally occur.

An advantage of the manual treatment is that all of the *P. setaceum* is immediately removed from the site. In cases where creation of an immediate fuel break is desired and the manager cannot afford the time required for dead plant material to break down and dissipate, a combination of manual removal followed by herbicide (ie. glyphosate or hexazinone) application at an early stage of regrowth may be desired. Other situations where this method may be desirable include the unplanned eradication of small satellite populations by field personnel, removal of small satellite populations in sensitive areas such as endangered species habitats, or when removal of *P. setaceum* biomass and / or seed stock from the site is desired.

CONCLUSIONS

P. setaceum has aggressively invaded extensive dryland habitats on the island of Hawaii and has the potential to behave similarly if unabated on other islands. The rapid spread of this exotic species alters plant community composition, interferes with natural succession, and alters the natural fire regime by carrying fires more frequently than they would otherwise occur. This combination of factors is forever changing the structure and function of Hawaiian dryland vegetation, thereby threatening the survival of many T&E plant species and their habitat.

Effective means to control *P. setaceum* at the U.S. Army's Pohakuloa Training Area on the island of Hawaii were assessed using a factorial experiment. Of the herbicide treatments applied, those involving hexazinone were the most effective: *P. setaceum* cover of less than 7% was maintained across all secondary treatments involving hexazinone. Hexazinone remains active in the soil, however, which could hamper short-term reclamation efforts. Treatments involving glyphosate also effectively controlled *P. setaceum* for up to 2 years. Glyphosate is known to rapidly become inactive in the soil. Treatments that included the manual removal of *P. setaceum* plants were very effective in killing the grass and removing biomass, particularly viable seed. Although this treatment is the most labor-intensive and creates a disturbed site favorable for recolonization by exotics, fine fuels are immediately removed from the site, thereby immediately creating a fuel break. If plant material is bagged and removed from the site, the threat of wildfire is reduced and potential for future seed maturation and dispersal is eliminated. Triclopyr treatments were ineffective in controlling *P. setaceum*.

The rapid deterioration of the quality and sustainability of native plant communities and their ability to support unique and rare organisms demands immediate efforts to control exotics.

Control of *P. setaceum* along four-wheel drive roads would decrease the dispersal of *P. setaceum* seed, particularly over long distances between regions. *P. setaceum*'s relationship with fire necessitates that fire suppression be an integral part of *P. setaceum* control efforts. Maintenance of fuel breaks and roads, including control of *P. setaceum* and other vegetation is of primary importance. Furthermore, control strategies such as those outlined by Tunison (1992a and 1992b) and Moody and Mack (1988) should be followed to arrest spread.

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Table 1. Factorial arrangement of treatments used in *P. setaceum* control experiment at Pohakuloa Training Area, Hawaii, Hawaii

Factor B	Factor A: Hexaxinone	Triclopyr	Control
Glyphosate 1	a_1b_1	a_2b_1	a_3b_1
Glyphosate 2	a_1b_2	a_2b_2	a_3b_2
Manual	a_1b_3	a_2b_3	a_3b_3
Control	a_1b_4	a_2b_4	a_3b_4

Table 2. Mean % cover and relative percent cover (as a percentage of control [in brackets]) of live *P. setaceum* for treatments 1 (a) and 2 (b) years following application.

a. 1-year

FACTOR	A = Primary Treatment			
	Level	Hexazinone (a1)	Triclopyr (a2)	Control (a3)
B = Secondary treatment	Glyphosate 1 (b1)	1.10 a A* [2]	6.61 a A [13]	3.72 a A [7]
	Glyphosate 2 (b2)	1.24 a A [2]	3.17 ab A [6]	2.48 a A [5]
	Manual (b3)	0.28 a A [1]	1.24 b A [2]	0.55 a A [1]
	Control (b4)	0.14 a A [0]	35.40 c B [68]	52.34 b B [100]

b. 2-year

FACTOR	A = Primary Treatment			
	Level	Hexazinone (a1)	Triclopyr (a2)	Control (a3)
B = Secondary treatment	Glyphosate 1 (b1)	5.37 a A [7]	24.52 a B [32]	18.60 a AB [25]
	Glyphosate 2 (b2)	5.37 a A [7]	17.22 ab A [23]	6.47 a A [9]
	Manual (b3)	1.24 a A [2]	9.09 b A [12]	7.58 a A [10]
	Control (b4)	1.52 a A [2]	77.13 c B [102]	75.62 b B [100]

* Values followed by the same letter in columns (lower case) or in rows (upper case) are not significantly different from one another ($p \leq 0.05$). Significance levels taken from transformed data.

Table 3. Mean frequency of hits and relative frequency of hits (as a percentage of control [in brackets]) of *P. setaceum* for treatments 1 (a) and 2 (b) years following application of treatments.

a. 1-year

FACTOR	A = Primary treatment			
	Level	Hexazinone (a1)	Triclopyr (a2)	Control (a3)
B = Secondary treatment	Glyphosate 1 (b1)	0.52 a A* [23]	0.76 a A [34]	0.68 a A [30]
	Glyphosate 2 (b2)	0.48 a A [21]	0.59 a A [26]	0.59 a A [26]
	Manual (b3)	0.06 b A [3]	0.07 b A [3]	0.07 b A [3]
	Control (b4)	0.52 a A [23]	1.95 c B [87]	2.25 c B [100]

b. 2-year

FACTOR	A = Primary treatment			
	Level	Hexazinone (a1)	Triclopyr (a2)	Control (a3)
B = Secondary treatment	Glyphosate 1 (b1)	0.09 a A [6]	0.45 a B [28]	0.33 a AB [20]
	Glyphosate 2 (b2)	0.08 a A [5]	0.28 ab A [17]	0.12 a A [7]
	Manual (b3)	0.03 a A [2]	0.12 b A [7]	0.10 a A [6]
	Control (b4)	0.05 a A [3]	1.99 c B [122]	1.63 b B [100]

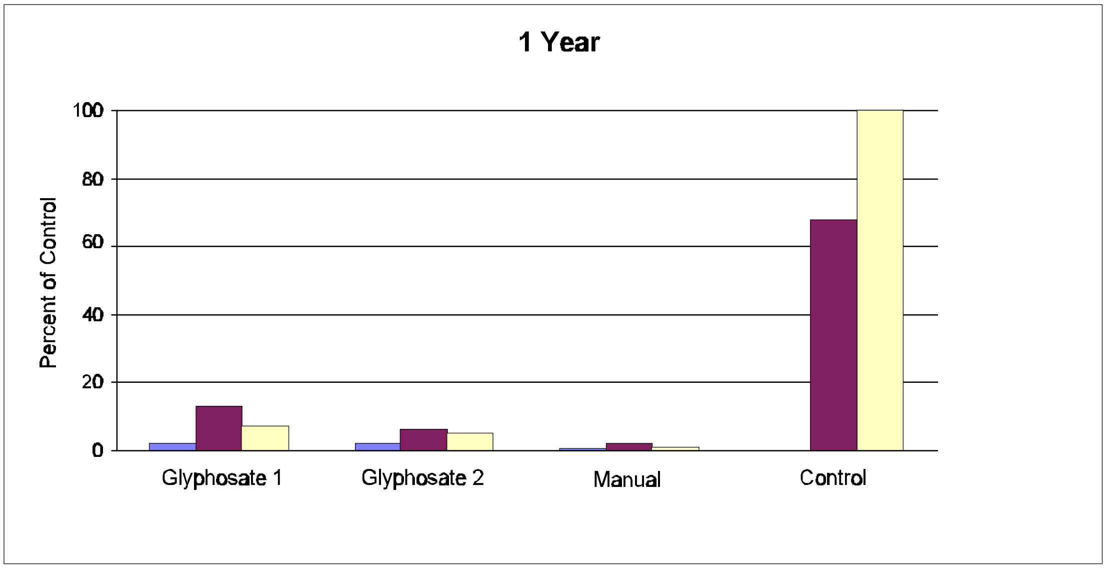
* Values followed by the same letter in columns (lower case) or in rows (upper case) are not significantly different from one another ($p \leq 0.05$). Significance levels taken from transformed data.

Figure 1. Location of study site at Pohakuloa Training Area (PTA), on the island of Hawaii.

Figure 2. Location of block transects at Pohakuloa Training Area, island of Hawaii.

Figure 3. Mean relative percent live *P. setaceum* cover 1 and 2 years following application.

a. 1 year



b. 2 year

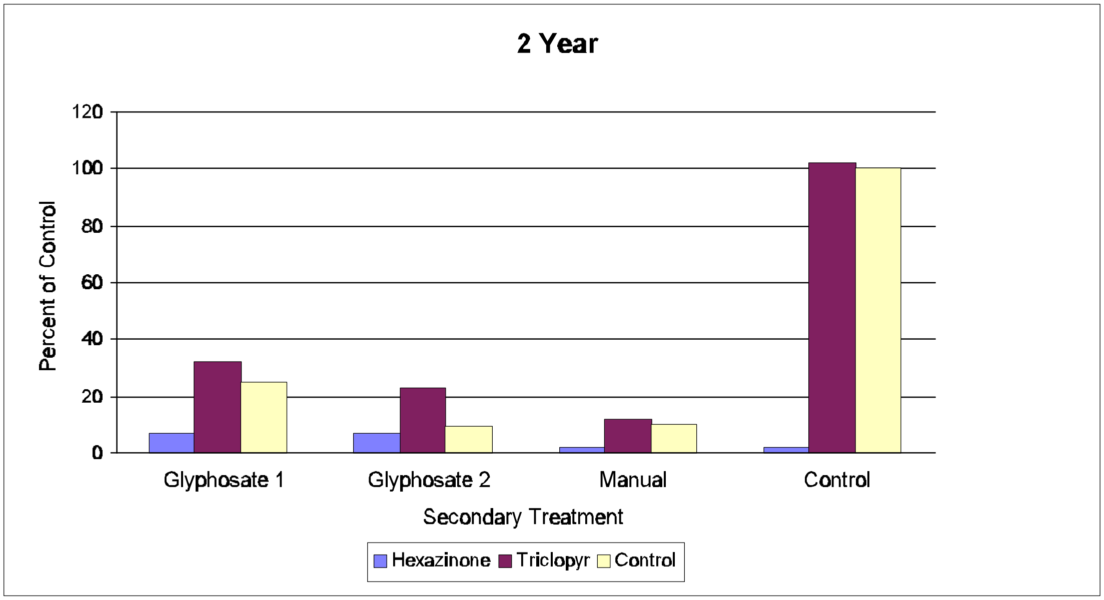
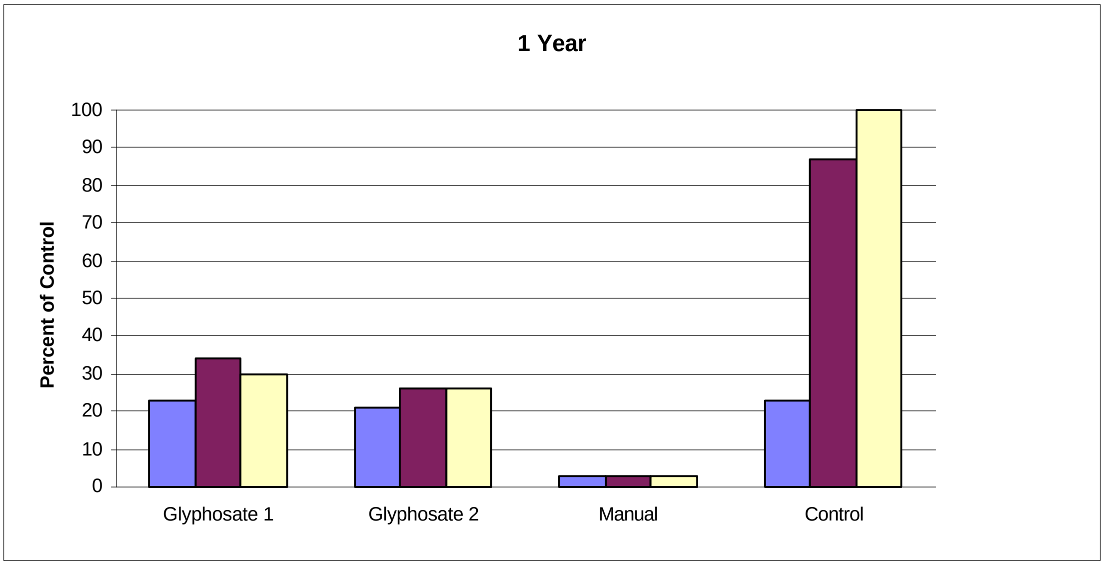


Figure 4. Mean relative frequency of *P. setaceum* hits per point 1 and 2 years following application.

a. 1 year



b. 2 year

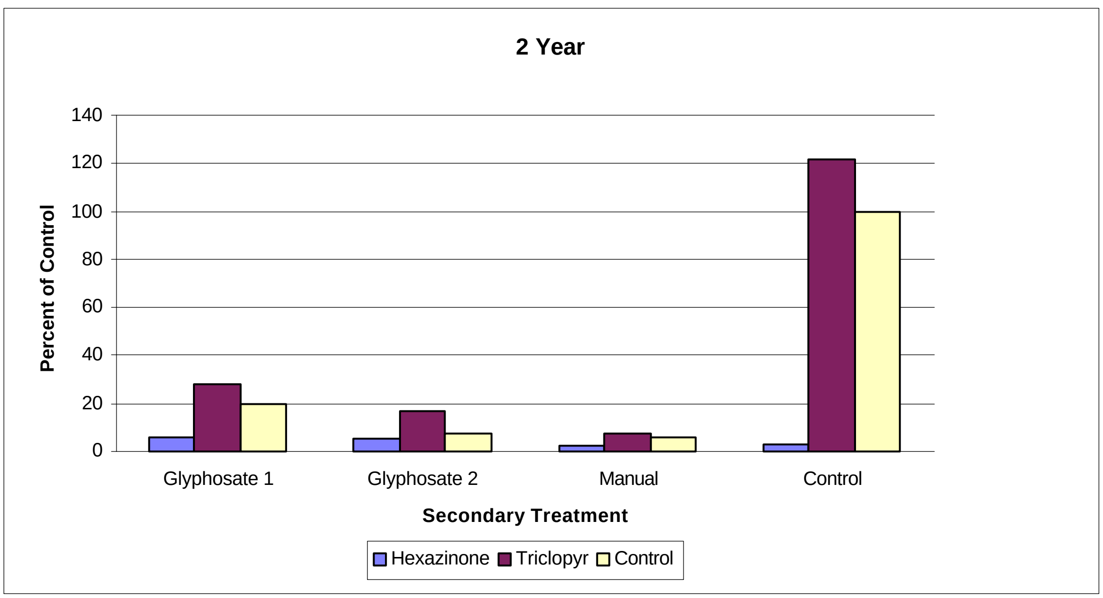


Figure 5. Mean absolute percent cover of live *P. setaceum* for secondary treatments over a 2-year period (arranged by primary treatment).

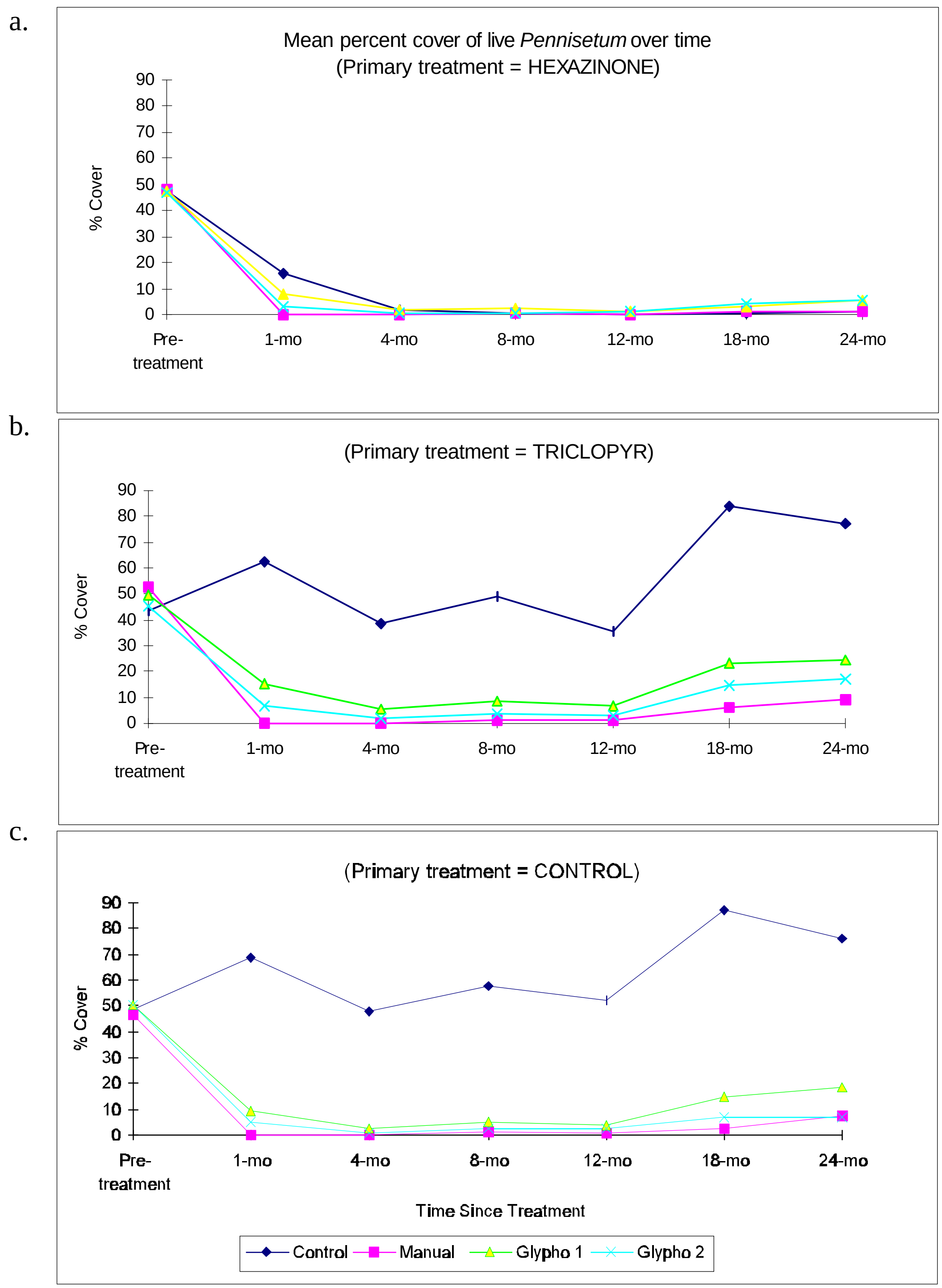
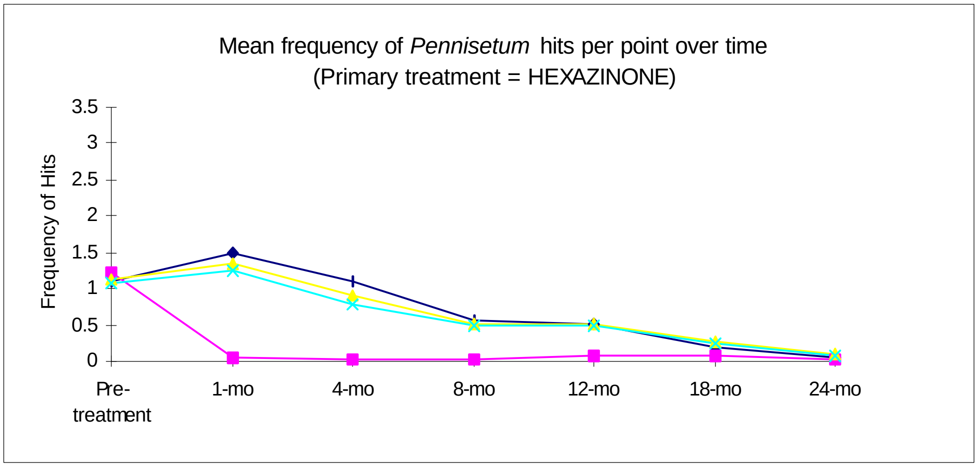
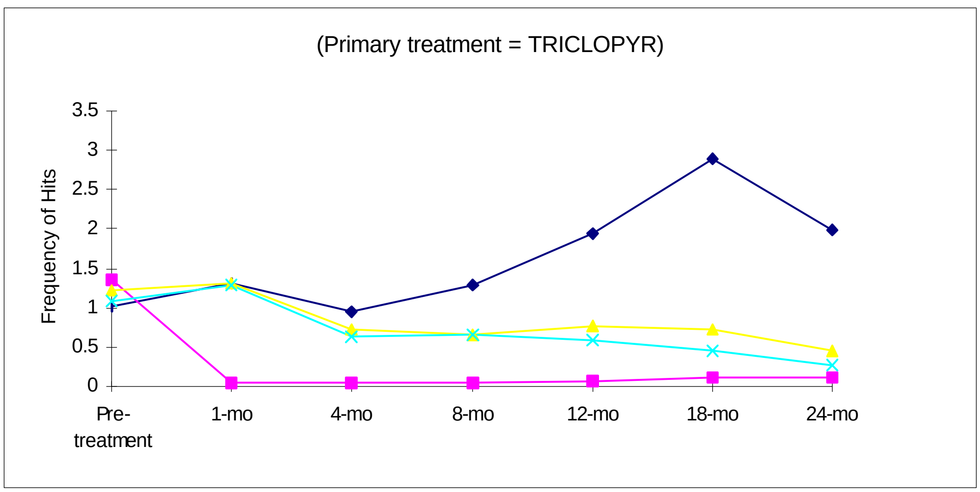


Figure 6. Mean absolute frequency of *P. setaceum* hits per point for secondary treatments over a two year period (arranged by primary treatment).

a.



b.



c.