

Test Effectiveness of Different Control Methods on Invasive Buffelgrass

**Phase 1: Herbicide effects on mortality of invasive buffelgrass (*Cenchrus ciliaris*)
and**

Phase 2: Herbicide impacts on native plants and pre-emergent herbicide effects on *C. ciliaris* and native plant seed emergence

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Peniocereus greggii (nightblooming cereus) at the BLM Headquarters study site.

Executive Summary

Buffelgrass (*Cenchrus ciliaris* syn. *Pennisetum ciliare*), a perennial bunchgrass native to Africa, is rapidly spreading across subtropical regions worldwide, including the Sonoran Desert of southern Arizona and its signature saguaro (*Carnegiea gigantea*) forests and associated wildlife habitat within Saguaro National Park (SNP). *C. ciliaris* competes with native plants for resources, creates dense stands which inhibit native plant growth and establishment, and fuels fire in a community dominated by plants and animals (such as *C. gigantea* and desert tortoises) that are not adapted to fire. SNP's existing *C. ciliaris* management program has been successful on a small scale but cannot keep pace with the rapidly expanding population of the grass, which may double in infested acreage every 3-5 years. Because *C. ciliaris* threatens to irreversibly impair the park's native plant communities and the Sonoran Desert ecosystem, it is essential to expand the knowledge base and available management strategies for *C. ciliaris* control.

The objectives of this study were to evaluate alternative *C. ciliaris* control measures, including the efficacy of different herbicide treatments, and timing of treatment efforts. We selected individuals from four native plant species plus *C. ciliaris* in SNP and applied four different herbicide treatments in order to determine the most effective herbicide for *C. ciliaris* control while minimizing the impact of application on native species. The four herbicides were also tested on the Santa Rita Experimental Range to broaden the scope of inference for the study. Further, the specific impact of one of the four herbicides (imazapic) was evaluated in a greenhouse to determine its pre-emergent properties on a suite of native species and *C. ciliaris*. We collected plant response data including percent green biomass, number of live tillers per plant, and plant size for the field studies and made counts of emergent seedlings and measured seedling biomass for the greenhouse study.

Results of the studies indicate that glyphosate and glyphosate plus imazapic treatments show the most promise for effective control of *C. ciliaris*, though observed mortality was low at rates applied. Arizona cottontop (*Digitaria californica*) and brittlebush (*Encelia farinosa*) are susceptible to glyphosate and imazapic, though only a single rate was tested and a dose response is unknown. *C. gigantea* and *Parkinsonia microphylla* appear to be resistant to glyphosate and imazapic at the rates applied; if rates are increased, their susceptibility should be re-evaluated. No evidence was found for graminicide control of mature *C. ciliaris*. Pre emergence effects of imazapic were documented in the greenhouse for *C. ciliaris* and some native plant seedlings. Field studies investigating appropriate rates for *C. ciliaris* control are warranted.

Introduction

C. ciliaris is a perennial, African bunchgrass that is rapidly spreading across subtropical environments worldwide, including southern Arizona, where it threatens the region's signature *C. gigantea* forests, associated wildlife habitat, and the Sonoran Desert ecosystem

at large. *C. ciliaris* competes with native plants for resources, creates dense stands which inhibit native plant growth, and fuel fires in a community dominated by plants and animals (like *C. gigantea* and desert tortoises) that are not adapted to fire, and may be the greatest non-native species threat Saguaro National Park (SNP) has ever faced. *C. ciliaris* threatens to irreversibly impoverish the Sonoran Desert ecosystem and SNP's native plant and animal communities

The existing *C. ciliaris* management program within SNP has been successful in small areas but cannot keep pace with the rapidly expanding population of the grass. Glyphosate is effective in treating *C. ciliaris* at appropriate application rates, but as a non selective herbicide, it potentially impacts a wide range of herbaceous and woody plant species. Therefore it is essential to expand the knowledge base of *C. ciliaris* control and collateral effects of herbicides.

This is the final report for a multi phased project that began in 2009 to study herbicide effectiveness on controlling invasive *C. ciliaris* and also to document impacts of direct herbicide application on selected non target native species. A map showing locations of the various study sites can be seen in Figure 1. The goal of Phase 1 was to test a selection of various herbicides for use in selective post emergence control of *C. ciliaris* when compared with glyphosate, as well to test the potential of imazapic for enhancing the post emergence effects of glyphosate. Glyphosate is known to act synergistically with many different herbicides, including imazapic. Imazapic has both pre and post emergence activity.

Phase 1 took place at the Santa Rita Experimental Range (SRER) in an area with vegetation characteristic of shrub-invaded semidesert grassland (Figure 2). In this report we present the one-year post treatment *C. ciliaris* response data for the herbicides tested in Phase 1.

The goal of Phase 2 of this study was twofold: (1) to document the impacts of pre emergence herbicide application on emergence and other seedling characteristics of non target native and *C. ciliaris* seeds planted in a greenhouse; and (2) to document the impacts of direct post emergence application of herbicides tested in Phase 1 on non target native vegetation *in situ*. Phase 2 took place on sites with characteristic Arizona Upland vegetation within and adjacent to the SNP northeastern boundary and within SNP near an interpretive pullout known as Javelina Rocks. Cumulative results are presented for the last monitoring date greenhouse study and of the one-year post treatment plant response data for the *in situ* portion of the study.

Phase 1

Methods - Phase 1

We identified an experimental area near the northwestern boundary of the SRER (Figure 2) and established experimental plots in a single factor (herbicide) randomized block design with individual *C. ciliaris* plants considered plots. The design included 39 replicates of 5

levels of the factor (a single rate for each of 4 different herbicides and one control). The original design was repeated for irrigated and ambient plants. However, no differences were observed between irrigated and non-irrigated plants, so irrigated plants were not used for the subsequent experiment.

Also, preliminary trials performed on several *C. ciliaris* patches (separate from those mentioned above) in September 2009 evaluated four herbicides, each sprayed at an average rate of 140 gal A⁻¹ with a single nozzle CO₂ backpack sprayer at 40 psi of pressure using a TeeJet 8002vs nozzle and 50 mesh screen. The four herbicides were Clove Leaf Oil (“Matran EC”) (44.75 lb ai A⁻¹), Glyphosate (“RazorPro”) (12.875 lb ae A⁻¹ + 1% Choice)¹, Clethodim (“Section 2EC”) (0.25 lb ai A⁻¹ + 1% Herbimax), and Fluazifop (“Fusion”) (0.375 lb ai A⁻¹ + 1% Herbimax). These sites were evaluated in August of 2010 to determine the impact of the herbicides tested on the patches selected near the experimental plants. There was no visible effect on any of the test patches except for the glyphosate treatment, in which ~ 90% of plants treated were dead.

The formal experiment was to be initiated in 2009 so the results could influence the selection of herbicides to be used in Phase 2. Due to timing of the monsoon rains, the experiment at SRER was postponed until 2010. Treatments were applied on August 20, 2010 and included the following herbicides and adjuvants in the concentrations listed below (ai = active ingredient; ae = acid equivalent; A = Acre)²:

- Clethodim (trade name “Section 2EC”): 0.25 lb ai A⁻¹ + 1% v/v Herbimax
- Fluazifop (trade name “Fusilade DX”): 0.375 lb ai A⁻¹ + 1% v/v Herbimax
- Glyphosate (trade name “RazorPro”): 3.0 lb ae A⁻¹ + 0.2% v/v Choice
- Glyphosate + Imazapic (trade name “Plateau”): 3.0 lb A⁻¹ Razor Pro + 0.1875 lb ae A⁻¹ Plateau + 1% v/v Methylated Seed Oil + 0.2% v/v Choice

Herbicides were applied with two CO₂ sprayers, each with a single nozzle wand calibrated to a reduced carrier rate of 50 gal A⁻¹ and applied using a TeeJet 8001EVS nozzle with a 100 mesh screen at 20 psi. The volume of mixture applied was determined by applying mixture for a set number of seconds per area to be treated. The smallest area treated was 0.25 m², and was treated for 3 seconds. Herbicide was applied evenly across the area from above rather than concentrating on the target plant, in order to ensure a uniform rate. We developed a table for use in the field to determine the number of seconds to apply for areas described by the canopy of plants with area greater than 0.25 m² in order to maintain the

¹ Rates for Matran EC and Razor Pro are very high. This is most likely because they were formulated as spot-spray (percent-solution) rates and then applied at 140 gal A⁻¹.

² **Active ingredient** indicates the amount of non-acid herbicide in a formulation. **Acid equivalent** indicates the amount of an acid herbicide in a formulation: that portion of a formulation that could theoretically be converted back to the parent acid. The parent acid is the herbicidally active portion of the formulation. Acid equivalent is therefore a more precise measure of herbicidal activity and is the preferred measure for herbicides formulated as a derivative (ester, salt, amine, etc.).

50 gal A⁻¹ rate (Appendix A), which was the standard carrier rate for all herbicides in Phase 1 during 2010.

To determine herbicide effectiveness, greenness class was visually estimated for each plant immediately prior to herbicide application using a six class system according to percent greenness. 0% = 0; 1-20% = 1; 21-40% = 2; 41 – 60% = 3; 61 – 80% = 4; 81 – 100% = 5. Greenness was assessed again on September 14, 2010, April 6, 2011, and September 5, 2011. Results from the last monitoring date are reported here. Counts of living tillers per plant were made on the last sampling date (no counts were made on prior monitoring dates or prior to treatment). Tillers were considered to be living if they had green leaves or internodes. No *C. ciliaris* seedlings were observed within 1 m of the sprayed plant. A few plants were either not located or had been misidentified in the initial set-up. For these, all five treatments in the block containing the missing plant were removed from analysis, resulting in 33 replicates for the final analysis.

Results - Phase 1

Soil temperature and moisture data

Appendix B shows that volumetric water content (volume of water per volume of soil) for soil at the SRER study site from Phase 1 indicates that temperatures appear to be cooler for this site than the Phase 2 sites during the same time period (see Phase 2 results below). The SRER site appears to have experienced a precipitation event on the evening of August 15, 2010, and after a jump in soil moisture (0.10 to 0.25 m³ m⁻³), the soil dries out quickly by the spraying date of August 20, 2010.

C. ciliaris response

Data were analyzed using an analysis of variance (ANOVA) procedure, with a Duncan's multiple range test to assess differences among treatments for greenness and live tiller counts per plant. Significance was set at $P \leq 0.05$. Greenness class midpoint values (percentage) were arcsine-transformed and live tiller counts were log-transformed prior to analysis to meet assumptions of normality. Back-transformed values are presented in the Table 1. A coefficient of variation (CV) value is presented as a measure of the level of variation in the data. This is a unitless value that is calculated from transformed values (where applicable) as the ratio of the root mean square error to the mean.

Percent green tissue was lower for the glyphosate plus imazapic treatment than for the control, clethodim, or fluazifop treatments (Figure 3), but there was no difference with the glyphosate treatment. Percent green tissue was lower for the glyphosate treatment than the clethodim treatment, but there was no difference with the control and fluazifop treatments. Green tiller abundance was lower for the glyphosate plus imazapic and glyphosate treatments than for the control, clethodim, or fluazifop treatments. None of the treatments proved effective at killing *C. ciliaris* in a single application for the majority of

plants sprayed (Table 2), with glyphosate being the most effective but only killing 18.2% of the plants treated.

Discussion - Phase 1

Greenup at the SRER site for *C. ciliaris* was poor during most of the 2011 monsoon season, as evidenced in the control plants at less than 40% green. Water stress at the time of monitoring could have masked some of the herbicide effects and impaired the ability to detect differences among treatments.

A likely explanation for the low mortality may be the size of the plants at the site, which were located in a gravelly sandy loam soil next to a major drainage that was observed to experience ponding during large rainfall events. These plants were much larger (thigh and hip-high) in terms aboveground biomass than their counterparts found on rocky slopes (typically shin-high) and thus require a larger dose (higher rate) of herbicide to account for the difference in biomass. *C. ciliaris* basal diameter, which is a proxy of aboveground biomass for perennial bunchgrasses³, was found to have a significant effect on plant response to glyphosate and imazapic applications in a related study by Bean, McCloskey, and Casady. Nevertheless, for Phase 1 both of the glyphosate treatments proved superior to the clethodim and fluazifop treatments, which did not differ from the control for either plant response variable.

Based solely on data collected and analyzed in Phase 1 of this study, best recommendations for chemical control of *C. ciliaris* would be glyphosate or glyphosate plus imazapic, but applied at higher rates than were used in this study. Based on the findings here, next steps for research would be to assess the interaction of plant size and treatment effectiveness, potential pre emergence effects of imazapic in the field, and combinations of monocot-specific and glyphosate herbicides. These topics are beginning to be addressed by Dr. William McCloskey and Travis Bean in other projects, though the studies are in the early stages and many questions remain unaddressed. Additionally, replication of these studies in multiple years across multiple sites is necessary for acceptance of results into a peer-reviewed publication.

Phase 2 – Greenhouse Experiment

Methods - Greenhouse Trial Run

Initial greenhouse trials were carried out in April through June of 2010 at the University of Arizona's Office of Arid Land Studies greenhouses. Soil for the study was collected near the helipad south of SNP Headquarters. The soil consisted of a gravelly sandy loam, and was collected at this location to be representative of Sonoran Desert upland soils at SNP. A total of 0.5 m³ of soil was taken by shovel from the surface (<10cm depth) in the area

³Nafus, AM, MP McClaran, SR Archer, and HL Throop. 2009. Multispecies Allometric Models Predict Grass Biomass in Semidesert Rangeland. *Rangeland Ecology and Management* 62:68–72.

immediately surrounding the helipad to minimize the impacts of digging in more natural areas. The soil was sifted at the greenhouse using a 0.6 cm sieve to remove any large debris, and placed in individual pots. Pots measured 15.24 cm (6 in) in diameter by 10.8 cm (4.25 in) deep. An amount of 725 cm³ was placed into pots and watered daily for two weeks beginning on April 7, 2010. Watering was done prior to planting of experimental seeds to allow germination of any active seeds existing within the soil prior to planting. Plants found in the pots were removed and the soil was allowed to dry.

In order to apply herbicide, 175 cm³ of soil per pot from all pots was measured and placed on a tarp where herbicide was added using a spray bottle and mixed evenly. Soil was then re-added to the surface of the pots immediately prior to planting experimental seeds. 125 cm³ was added first to each pot, and then seeds were added, followed by the remainder of the soil (50 cm³) to cover seeds and provide good seed-soil contact. Three treatments were conducted on 40 pots each, including a control, soil treated with 0.125 lb ae A⁻¹ imazapic, and soil treated with 0.1875 lb ae A⁻¹ of imazapic.

On April 29, 2010 three cool season species including *Vulpia octoflora* (an annual grass), *Phacelia crenulata* (an annual forb) and *Aristida purpurea* (a perennial grass) were planted in pots with herbicide applied as above according to a randomized split block design. Ten pots were planted for each species with an additional ten pots left unplanted as a control for a total of 40 pots per treatment. An initial germination trial was done to verify that the seeds would germinate. *V. octoflora* and *P. crenulata* were obtained from Granite Seed (collected in California and Mexico, respectively). *A. purpurea* seed was gathered by Park Service personnel from SNP.

All pots were watered for two minutes daily allowing water to accumulate evenly on the surface of the soil (~2mm). Watering never exceeded two minutes to prevent oversaturation and leaching of the herbicide from the soil. A mist nozzle was selected to minimize soil surface disturbance. Pots were monitored daily to check for germination. Following initial germination, plant height and plant number were recorded approximately every other day. Observation continued through June 3, 2010 whereupon plants were measured, clipped and sorted into individual envelopes by pot to be weighed. Plant material was dried at 60° C for 72 hours and weighed to determine dry weight.

Results - Greenhouse Trial Run

The first emergence of *A. purpurea* occurred May 8, 2010 in the control treatment with new emergence occurring continually in all three treatment methods throughout the test period. There was no emergence of either *V. octoflora* or *P. crenulata* recorded throughout the observation period. Emergence of *A. purpurea* was observed at a higher rate in the control over both the 0.125 lb and 0.1875 lb treatment. At the conclusion of the observation period the control exhibited a total emergence of 73 plants out of a potential

total of 100 seeds planted, as compared to 22 plants in the 0.125 lb treatment and 16 plants in the 0.1875 lb treatment. This result suggests that emergence may be suppressed by 0.125 lb ae/A, with a slight increase in this suppression at the 0.1875 lb ae/A treatment level. These results were used to inform the more rigorous 2011 experiment.

Methods - 2011 Greenhouse Experiment

A second greenhouse experiment was initiated in December/January of 2011 and again in March/April of 2011. These experiments were performed at the University of Arizona Campus Agricultural Center greenhouses (Figure 1) using a different irrigation system than the trial run. It was suspected that the January run was over-irrigated, resulting in the dilution and leaching of the herbicide, which has high soil mobility. The experiment was performed again in March/April 2011 using a new irrigation setup with a lower rate which led to measurable results. The irrigation system included misters at a rate of 5.3 GPH for 6 seconds every 16 minutes. Soil and pots were set up and herbicide applied as in 2010, except that an additional treatment of 0.0625 lb ae A⁻¹ was included such that the experiment tested the effects of 0.0625, 0.125, and 0.1875 lb ae A⁻¹ of imazapic as well as an untreated control. A larger suite of species was also included for the March/April 2011 run (Table 3).

Prior to these experiments, emergence rates needed to be tested to determine appropriate planting densities: 100 seeds per species were planted in a single pot and emergent seedlings were counted 26 days later. From these counts a number of seeds to plant per pot were calculated such that we could reasonably expect five to ten plants to germinate per pot. The number of seeds planted per pot for the species evaluated is recorded in Table 3.

To initiate the March/April 2011 herbicide experiment, all species were planted on March 28, 2011. Ten pots per species per treatment were planted, as well as ten pots left unplanted, resulting in a total of 90 pots per treatment, or a total of 360 pots. Pots were monitored three times a week, and the number of plants and height of the median plant was recorded for each plot. This was done starting on April 4, 2011 and monitoring was completed on May 5. Plants were harvested on May 6, dried in a drying oven and dry weight and number of plants per pot was recorded.

Data were analyzed using ANOVA, with a Duncan's multiple range test to assess differences among treatments for plant response variables. Significance was set at $P \leq 0.05$. Seedling counts were log-transformed prior to analysis to meet assumptions of normality. Back-transformed values are presented in Tables 4-6. A CV value is presented as a measure of the level of variation in the data.

Results - 2011 Greenhouse Experiment

Number of emerged seedlings

Number of emerged seedlings did not differ among rates of imazapic for any species except *D. californica*, for which less seedlings were observed at the 0.1875 lb ae A⁻¹ rate than for other rates (Table 4).

Mean seedling weight

Mean seedling weight did not differ among rates of imazapic for *B. barbinodis*, *D. californica*, *E. farinosa*, *P. crenulata*, or *V. octoflora*. Mean seedling weight of *A. purpurea* was lower for the 0.0625 lb ae A⁻¹ imazapic rate than the control, though neither differed from the 0.125 and 0.1875 lb rates (Table 5). Mean seedling weight of *C. ciliaris* was lower for all treatments over the control, though the treatments did not differ among each other. Mean seedling weight of *S. ambigua* was higher for the control and 0.0625 lb ae A⁻¹ rates than for the 0.125 and 0.1875 lb rates.

Mean seedling height

Mean seedling height did not differ among rates of imazapic for *D. californica*, *E. farinosa*, and *V. octoflora* (Table 6). Mean seedling height of *A. purpurea*, *P. crenulata*, and *S. ambigua* was lower for all treatments over the control, though there were no differences among the treatment rates. Mean seedling height of *B. barbinodis* was higher for the 0.1875 lb ae A⁻¹ rate of imazapic than for the 0.125 lb rate, while there were no differences with the control and 0.125 lb rates. Mean seedling height of *C. ciliaris* was lower for the 0.1875 lb rate than the control or 0.125 lb rate, but not the 0.0625 lb rate. Similarly, the 0.125 lb rate was lower than the control but not the 0.0625 lb rate.

Discussion - 2011 Greenhouse Experiment

None of the rates of imazapic applied prevented emergence completely for any species (Figure 4), suggesting imperfect control even at the highest rate, which is also the maximum annual rate per the Plateau® label. In fact, several species showed little or no effects at any level of treatment for the response variables measured. *C. ciliaris* was only affected in terms of seedling height and weight, but not emergence. Although most species showed no effect for seedling emergence in the greenhouse, a reduction in seedling height or weight could lead to a reduction in vigor and overall recruitment (survival to maturity) in the field.

The least vulnerable species include *E. farinosa*, and *V. octoflora*, neither of which were affected in terms of number of emerged seedlings, mean seedling weight, or mean seedling height. These species may be tolerant to imazapic. *D. californica* was only slightly more vulnerable as it did experience less emergence at the highest rate of imazapic. The next least vulnerable species include *B. barbinodis* and *P. crenulata*, which were only affected in terms of reduced seedling height for the treatments over the controls. The *B. barbinodis* results are somewhat anomalous given that no effect was seen at the highest rate. The

most vulnerable species include *A. purpurea*, *C. ciliaris*, and *S. ambigua*. Although these are all ruderal species, there is a limited sample of plant life history strategies in the study, so speculation about patterns of susceptibility should be cautious.

It is possible that herbicide was leached from the surface layer to a depth at which its effectiveness was muted. Imazapic can have high soil mobility depending on soil adsorptive properties and pH. In future investigations it may be possible to utilize shallower pots or flats in order to prevent this kind of leaching. Also, the amount of water might be incorporated into the experiment such that water is varied across treatments in order to achieve a balance whereby water is sufficient to provide for plant growth but not carry the herbicide below the zone of germination and emergence.

It is unclear how well these results will translate to results in a field setting, especially given high variation in soil parent material, texture and organic matter in native soils, which are major determinants of imazapic mobility and longevity of plant activity. However, these results do show a range of pre emergence tolerances to imazapic, with some native species being more tolerant. Fortunately, *C. ciliaris* appears to be one of the most sensitive species of those tested, suggesting that further research into the pre emergence effects is warranted. Now that a pre emergence effect on *C. ciliaris* has been documented in the greenhouse, a research priority for this herbicide should be to develop a dose response curve for *C. ciliaris* response across a gradation of rates of imazapic in the field. Once this information is determined, effects on non targets at those rates determined to be effective for *C. ciliaris* can be evaluated. *In situ* applications should consider tests across a gradient of soil textures and organic matter levels. In practice, this may be extremely difficult to accomplish given the spatial and temporal variability and availability of water, seedling emergence, number of seeds available for germination, and thus may require some serendipity on the part of the researcher in site selection.

Along those lines, a preliminary, unreplicated study in SNP experimented with pre emergence applied imazapic at a single rate and found evidence for reduced *C. ciliaris* and native species emergence in the months following the onset of monsoon precipitation. Results of the SNP study have informed this and other studies on imazapic effects on *C. ciliaris* and native plants. Similar to results from this report, a University of Arizona/Forest Service UA/FS study⁴ (Bean, McCloskey and Casady) observed that only 16 of 192 plots experienced seedling emergence, thus data was insufficient to test hypotheses about effects of treatments on pre emergence control in the field.

⁴ Pesticide Impact Assessment Program Project R3-0110

Phase 2 - *In Situ* Experiment

Methods - *In Situ* Experiment

The second portion of Phase 2 of the project involved locating *in situ* plants selected for herbicide treatment. Two sites were used to select representative non-target plants based on species distribution, access, and SNP priorities. Fifty plants were selected for each of five species. All species were marked and labeled with aluminum tags along with a nail and blue flagging placed in the ground on the north side of the plant. In addition, the location of each specimen was recorded using a GPS receiver. All GPS waypoints were then uploaded and mapped, providing spatial data necessary for specimen relocation.

The first site is located ~500m northwest of the Javelina Rocks trailhead in SNP East (Figure 5). Three target species were located at this site, including *E. farinosa*, *Heteropogon contortus* (tanglehead) and *C. ciliaris*. The second site was located at the former Bureau of Land Management (BLM) Headquarters and adjoining Park Service land to the east (Figure 6). Referred to henceforth as the BLM Headquarters study site, it is located at the extreme east end of Broadway Boulevard in Tucson. The remaining two non target species, *C. gigantea* and *Parkinsonia microphylla* (yellow paloverde) were selected so that 25 plants of each species were selected from both the BLM and SNP properties. Controls were randomly assigned to the selected plants at each site along with the 4 treatments.

All *in situ* specimens were <2 m in height so spraying could be conducted efficiently and evenly from ground level. All specimens were located >2 m from all other plants to minimize impacts of overspray. All specimens are located >25 m from the nearest road and >10 m from trails to avoid public visibility and disturbance during spraying. Specimens appearing necrotic or in direct contact with plants not incorporated by this study were selectively avoided.

During the pre-treatment assessment of plants scheduled for treatment it was discovered that a large proportion of the *H. contortus* plants had died. The decision was made to replace *H. contortus* with *D. californica*, another native perennial bunch grass. *D. californica* was located at the Javelina Rocks site.

The herbicide products selected for Phase 2 were intended to be based on results of Phase 1. Due to the delayed timing of Phase 1, it was determined to use the same herbicides, mixtures, carrier rates and concentrations as were used in Phase 1. All treatments were conducted between 5:30 am and 11:00 am according to the following schedule (wind speed, temperature, and relative humidity, respectively, are in parentheses):

- 8/11/2010 (start: 0.0 mph, 78°, 61%; end: 1.1 mph, 93°, 44%)
 - glyphosate – *C. gigantea*, *P. microphylla*, *C. ciliaris*
- 8/17/2010 (start: 0.8 mph, 88°, 50%; end: 1.6 mph, 90°, 62%)
 - glyphosate – *E. farinosa*

- glyphosate + imazapic – *C. gigantea*, *P. microphylla*, *C. ciliaris*, *E. farinosa*
- 8/18/2010 (start: 0.0 mph, 74°, 72%; end: 1.1 mph, 100°, 30%)
 - glyphosate – *D. californica*
 - fluazifop – *C. gigantea*, *P. microphylla*, *C. ciliaris*, *E. farinosa*, *D. californica*
- 8/19/2010 (start: 0.6 mph, 73°, 68%; end: 1.0 mph, 101°, 48%)
 - glyphosate + imazapic – *D. californica*
 - clethodim – *C. gigantea*, *P. microphylla*, *C. ciliaris*, *E. farinosa*, *D. californica*

Greenness was assessed for each treated plant immediately prior to treatment, but was not assessed for the control plants. Greenness was assessed for all plants again on September 8-9, 2010, April 4-5, 2011, and August 27 and 29, 2011. *C. gigantea* individuals were measured by assessing the percentage of the tissue that showed evidence of chlorosis and other tissue damage pre- and post-treatment. *P. microphylla*, *C. ciliaris*, *E. farinosa*, and *D. californica* were assessed by measuring the percent of live material according to the scale used in Phase 1. Additionally, *P. microphylla* were assessed qualitatively by noting the number of leaves according to three ordinal categories: 0 = no leaves, 1 = few leaves, 2 = some leaves, 3 = many leaves.

Data were analyzed using ANOVA, with a Duncan's multiple range tests to assess differences among treatments for greenness and live tiller counts per plant for the two perennial grasses. Significance was set at $P \leq 0.05$. Greenness values were arcsine-transformed and live tiller counts were log-transformed prior to analysis to meet assumptions of normality. Back-transformed values are presented in the Tables 6-10. *P. microphylla* leaf abundance data were ordinal data and were analyzed using ordered logistic regression with leaf abundance as the explanatory variable for treatments. As with the Phase 1 study and the UA/FS study, insufficient seedling emergence was observed at the study sites to allow for statistical analyses. A CV value is presented as a measure of the level of variation in the data.

Results - *In situ* Experiment

Soil temperature and moisture data

Appendix B shows that volumetric water content for soil at the Javelina Rocks was 0.12-0.15 m³ m⁻³ and for 0.06-0.08 m³ m⁻³ the BLM Headquarters study site. Soil temperature was similar for both sites.

C. gigantea response

No differences in percent green tissue on north or south sides of *C. gigantea* were observed among treatments (Table 7, Figure 7).

P. microphylla response

No differences in percent green tissue for *P. microphylla* were observed among treatments (Table 8, Figure 7). The results of the ordered logistic regression for the leaf abundance data indicate that the overall model is not significant ($P \leq 0.1489$).

E. farinosa response

Percent green tissue was lower for the glyphosate plus imazapic treatment than for the fluazifop treatment, but not for the control, clethodim, or glyphosate treatments (Table 9, Figure 8).

D. californica response

Percent green tissue was lower for the glyphosate treatment than for control, but not for the clethodim, fluazifop, or glyphosate plus imazapic treatment. No differences in abundance of green tillers were observed among treatments (Table 10, Figure 9).

C. ciliaris response

Percent green tissue was lower for both the glyphosate and glyphosate plus imazapic treatments than for the control, clethodim, or fluazifop treatments. Similarly, green tiller abundance was lower for both the glyphosate and glyphosate plus imazapic treatments than for the control, clethodim, or fluazifop treatments (Table 11, Figure 10).

Discussion - *In situ* Experiment

The data loggers experienced numerous problems during the course of the study, including batteries leaking, water damage from flooding, packrats chewing through cables, etc., and presents at best, an incomplete picture of soil temperature and moisture conditions at the study sites during the experiment. However, the data collected during the time frame when the herbicide was applied was preserved and is presented in Appendix B. Caution should be used in interpreting these measurements, as relevant values for plant water stress such as permanent wilting point under field conditions are not constant for any given soil but are determined by the integrated effects of plant, soil, and atmospheric conditions. Comparisons between values from different soils should not be made without additional information.

At one-year post treatment, neither *C. gigantea* nor *P. microphylla* showed any signs of damage in terms of plant tissue greenness from the herbicide treatments applied. This is not surprising, as glyphosate is known to be largely ineffective for controlling woody species and the other herbicides evaluated, with the exception of imazapic, were monocot selective. The resistance of cacti and woody species to glyphosate has been further demonstrated in an ongoing study on the effects of aerially applied glyphosate on *C. ciliaris* and non-target vegetation in the Sonoran Desert (unpublished data, interagency aerial application test project, August 2011). This experiment offers evidence that imazapic has no effect in terms of greenness at one year post treatment on adult *C. gigantea* or *P. microphylla* plants when applied at the maximum label rate (0.1875 lb ae A⁻¹).

In the analyses performed for *P. microphylla*, no differences in treatments were detected. Future studies should include a more quantitative metric be selected, such as abundance classes corresponding to percent of the stems with leaves, leaf area index measurements, or photographic image analysis. Ordinal categories are limiting in terms of options for analyses. The use of a grid overlay was initially discussed by the PI and the sponsor but was rejected by both in subsequent discussions. The use of photographic image analysis to detect phenological changes and herbicide damage for *C. ciliaris* is currently being investigated by Travis Bean, and software script could potentially be modified for woody species like *P. microphylla*.

The only detectable difference among treatments for *E. farinosa* was that the glyphosate plus imazapic treatment was more damaging than the fluazifop treatment, though neither was different from the control. These data had a high CV and one potential issue confounding these results is the prolonged freeze during the early spring of 2011, which killed several of the plants and severely damaged the others (Table 12). The freeze effects might have masked differences that could have otherwise been attributed to the treatments. Although difficult to interpret, these results do suggest that *E. farinosa* will likely be susceptible to post emergence damage from glyphosate plus imazapic.

Similarly, with *D. californica* there were no differences in tiller counts, although glyphosate was more damaging compared to the control (though not different from the other treatments) in reducing plant greenness. The freeze may have played a part in obscuring differences. *D. californica* will likely be susceptible to damage from glyphosate.

Also, because replicates were not divided into blocks for the *in situ* experiment, with limited replicates (n=10) and some of these perishing in the freeze, the power of the statistical analyses to detect differences (should they exist) was hindered. In other words, even though there may be a seemingly large gap in the reported means, there is too much variation to allow for a statistically significant difference to be detected. Future studies should include blocking to account for environmental variation and more replication to minimize experimental error. Repeating studies across sites and years will also make results more publishable in peer-reviewed literature.

Individuals of *C. ciliaris* showed a more consistent response in that both glyphosate treatments were superior to other treatments and the control in terms of both response variables measured. Both Phase 1 and 2 studies were complimentary in this regard, indicating that glyphosate shows promise for more complete control, while graminicides do not, at least not by themselves at the rates applied in this study. However, actual mortality was low with glyphosate treatments in both phases. This is in conflict with the findings of the UA/FS study which found complete mortality for a lower rate of glyphosate applied here (1.5 lb vs 3 lb ae A⁻¹) plus 0.0625-0.125 lb ae A⁻¹ imazapic (less than was used

here) at less than half the carrier rate used in this study (20 vs 50 gal A⁻¹). Otherwise, plant sizes for *C. ciliaris* were similar at both the Javelina Rocks site and the UA/FS study site, so it may be that factors specific to the Javelina Rocks site affected vegetation response to treatments.

The objectives of the previously mentioned the UA/FS study at multiple sites are twofold: to determine if imazapic can reduce the need to repeat herbicide treatments by providing pre emergence control of *C. ciliaris*, and if imazapic-glyphosate mixtures can improve the post emergence control of *C. ciliaris*. Results from the one-year monitoring of the 2010 treatments at the first site indicate that imazapic does have a significant interaction with glyphosate when tested on plant response variables, indicating enhanced post emergence control. Best results for post emergence control were obtained by using a 20 gal A⁻¹ carrier rate and 1.5 lb ae/A glyphosate and 0.0625-0.125 lb A⁻¹ or greater concentration of imazapic, or with 2.25 lb ae/A glyphosate regardless of imazapic concentration. Monitoring is ongoing for the 2011 treatments at all sites and a final report will be made to the sponsor (US Forest Service) in Fall/Winter 2012.

Higher carrier rates are known to inhibit effectiveness for symplastically (transported predominantly in phloem as opposed to xylem tissue) translocated herbicides like glyphosate and the other herbicides in this study⁵, which may explain some of the difference in results. Adding the same amount of herbicide to a reduced volume of carrier increased the concentration of herbicide per droplet. Herbicides penetrate the leaf tissue by diffusion, so a greater concentration in the droplets should increase the concentration gradient against the cuticle, thus increasing the herbicide molecule diffusion rate into the plant leaf.

Another possible explanation is that the vegetation response to the herbicide treatments was delayed due to drought, which can be extremely spatially variable during the summer monsoon season the UA/FS study, *C. ciliaris* plants sprayed with glyphosate and imazapic mixtures in August 2010 and assessed one year after herbicide application in August 2011 showed very low mortality compared to an assessment done in October 2011. Herbicide translocation depends on source-sink relationships of photosynthate within the plant, and assumes active photosynthesis and adequate moisture for metabolism. Timing of the summer rains was late, and it may be that at the time of monitoring, apparently living tissue observed in August 2011 could have been functionally dead, with vascular connections to the rest of the plant having been destroyed. Green growth has been observed at the ends of otherwise dead stems on herbicide-sprayed *C. ciliaris* in the field (Bean, personal observation). This “relict” green tissue would be due to the extreme

⁵ Ross, MA, and CA Lembi. 2009. Chapter 9: Plant herbicide interactions *in*: Applied weed science: including the ecology and management of invasive species. Upper Saddle River, NJ: Pearson Education, Inc.

drought tolerance of *C. ciliaris*, and the fact that all meristematic tissue on the plant is unlikely to be active at any one time, even during peak vegetative growth, thus preventing complete herbicide translocation. Unfortunately, individual plant markers were required to be removed for this study and so additional monitoring to confirm this would be very difficult.

As mentioned above for the SRER study, and given results of the UA/FS study, best recommendations for chemical control of *C. ciliaris* at sites similar to Javelina Rocks and the SRER would be glyphosate or glyphosate plus imazapic, but (assuming that mortality was not delayed) at higher herbicide rates and/or lower carrier rates than those used in this study. Current data show an effect on *E. farinosa* and *D. californica* for at least one of these herbicides, so future research is warranted if overspray onto these species is a concern. Based on the collective findings of these studies, priority next steps for research would be to assess the interaction of plant size and treatment effectiveness, carrier rate, and combinations of monocot-specific and glyphosate herbicides. The latter suggestion could reduce the rate of glyphosate and thereby reduce potential for non target damage to native forbs without reducing treatment effectiveness. This research is currently underway (McCloskey) with funding from Saguaro National Park because the Park is interested in using a monocot-specific herbicide or in combination with glyphosate for aerial application of herbicides in remote locations. However, this may be a moot point as recent research by Olsson *et al* (2012)⁶ indicates that forbs, grasses and smaller shrubs are the first natives to be displaced by *C. ciliaris*, usually disappearing in 5-10 years since colonization of the invader.

To increase research efficiency and economy, it is recommended that research into non target effects be delayed until specific herbicides and rates are determined for the control of *C. ciliaris*. Findings of these studies indicate that glyphosate and glyphosate plus imazapic mixtures show promise for post emergence control of *C. ciliaris*, and that the graminicides clethodim and fluazifop do not, at least when used alone (not in mixture with glyphosate) or at the rates tested in these studies. However, work being done at Lower Rio Grande Valley Wildlife Refuge (USFWS) has found clethodim used alone at rate of 0.25 lb ai A⁻¹ is effective on *C. ciliaris* yearlings (Kim Wahl, personal communications). In other words, we recommend an approach that first determines if an herbicide has an effect on *C. ciliaris*, then determines the rate needed for the desired effect, then determines if that herbicide at that rate has an effect on non target vegetation. This stepwise process for herbicide evaluation will take more time, but would serve to focus research objectives,

⁶ Olsson, AD, JL Betancourt, MP McClaran, and SE Marsh. 2012. Sonoran Desert Ecosystem transformation by a C₄ grass without the grass/fire cycle. *Diversity and Distributions* 18:10-21.

allowing for more replication and a more robust experimental design in individual studies saving money in the long run.

Finally, consider that the results of these experiments are all expressed in broadcast spray application measurements of amount of product per area, not percent solution as in a spot spray application. There is no direct translation from one method of measurement to the other, but with proper calibration of backpack spraying applications, broadcast rate can be calculated. This will greatly facilitate the manager's ability to take advantage of herbicide research findings from this study and others, and should improve herbicide efficacy by reducing carrier rates. See Appendix C for a brief description of the steps involved in calibrating backpack sprayers.

Summary findings and future research needs

- Of the herbicides tested, glyphosate or glyphosate plus imazapic offers the most promise for control of *C. ciliaris*
- Further research into the use of graminicides used alone at different rates or on different size plants, or in combination with other herbicides is warranted
- Plant size may play a role in herbicide response, and appropriate glyphosate and imazapic rates need to be determined for plants across a range of size classes
- Pre emergence effects of imazapic were seen for *C. ciliaris* and some native species in the greenhouse; field research is needed to determine appropriate rates for *C. ciliaris* control
- *C. gigantea* and *P. microphylla* appear to be resistant to glyphosate and imazapic at the rates applied; if rates are increased, their susceptibility should be re-evaluated
- *D. californica* and *E. farinosa* are partially susceptible to glyphosate and imazapic, though only a single rate was tested and a dose response is unknown
- Results from this and other herbicide studies are difficult to apply to spot spray applications without calibration (see Appendix C)
- Future herbicide studies should include more replication, blocking, and pursue research objectives in a stepwise hierarchy (1st determine an effect on the target, then determine the target rate-response, then determine non target effects at those rates)

Acknowledgements:

We would like to thank the National Park Service for funding the study and Saguaro National Park, the Tucson BLM Field Office, and the University of Arizona Santa Rita Experimental Range for allowing us to place study sites on their properties. We would like to thank Dana Backer and Perry Grissom of Saguaro National Park, who helped obtain permits for conducting research in the Park, secured the funding, located potential study sites, collaborated on the study design, and for helpful comments on earlier drafts of this

report. We would also like to thank Denise Garcia, Anahi Ocampo Melgar, Taryn Kong, Brett Blum, and Ashley Shepherd for their assistance in plot installation and monitoring.

Table 1: Response of green tissue and green tiller abundance of individuals of *C. ciliaris* subjected to various herbicide treatments at the Santa Rita Experimental Range study site. Values within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

Treatment	Green Tissue (%)	Tiller Abundance
Control	37.88 ^{AB}	39.95 ^A
Clethodim	46.36 ^A	41.84 ^A
Fluazifop	37.88 ^{AB}	43.37 ^A
Glyphosate	31.82 ^{BC}	25.32 ^B
Glyphosate + Imazapic	22.12 ^C	23.21 ^B
Model CV (%)	51.77	37.01

Table 2: Mortality of *C. ciliaris* for Phase 1 plants on the Santa Rita Experimental Range (# dead plants/# total plants in treatment) in September 2011 by treatment.

Treatment	Mortality (%)
Control	0
Clethodim	6.1
Fluazifop	6.1
Glyphosate	12.1
Glyphosate + Imazapic	18.2

Table 3: Species tested in the December/January and March/April 2011 greenhouse trials, including the growth form of the plant, the number of seeds planted per pot, and the source of the seed.

Species	Growth form	Number of seeds	Source
<i>Aristida purpurea</i>	Perennial grass	10	SAGU
<i>Bothriochloa barbinodis</i>	Perennial grass	15	USDA NRCS Plant
<i>Digitaria californica</i>	Perennial grass	10	USDA NRCS Plant
<i>Encelia farinosa</i>	Perennial	125	USDA NRCS Plant
<i>Cenchrus ciliaris</i>	Perennial grass	10	SAGU
<i>Phacelia crenulata</i>	Annual forb	25	Granite Seed
<i>Sphaeralcea ambigua</i>	Perennial forb	100	USDA NRCS Plant
<i>Vulpia octiflora</i>	Annual grass	10	Granite Seed

Table 4: Number of emerged seedlings per pot of species sown from seed in the greenhouse in response to increasing rates of imazapic. Values within the same row that are followed by the same letter are not significantly different ($P \leq 0.05$).

Species	Control	0.0625 lb ae A ⁻¹	0.125 lb ae A ⁻¹	0.1875 lb ae A ⁻¹	CV (%)
<i>Aristida purpurea</i>	7.60 ^A	7.40 ^A	7.40 ^A	6.60 ^A	9.38
<i>Bothriochloa barbinodis</i>	6.10 ^A	5.80 ^A	5.22 ^A	6.22 ^A	22.89
<i>Digitaria californica</i>	6.11 ^A	6.40 ^A	5.00 ^A	3.40 ^B	16.44

<i>Encelia farinosa</i>	13.80 ^A	14.30 ^A	9.40 ^A	13.50 ^A	21.07
<i>Cenchrus ciliaris</i>	4.80 ^A	5.50 ^A	6.30 ^A	6.60 ^A	14.37
<i>Phaecelia crenulata</i>	6.90 ^A	7.20 ^A	9.10 ^A	7.22 ^A	29.67
<i>Sphaeralcea ambigua</i>	8.40 ^A	7.50 ^A	7.20 ^A	8.10 ^A	18.57
<i>Vulpia octoflora</i>	8.80 ^A	8.50 ^A	8.70 ^A	7.60 ^A	11.55

Table 5: Mean seedling weight (mg plant⁻¹) of species sown from seed in the greenhouse in response to increasing rates of imazapic. Values within the same row that are followed by the same letter are not significantly different ($P \leq 0.05$).

Species	Control	0.0625 lb ae A ⁻¹	0.125 lb ae A ⁻¹	0.1875 lb ae A ⁻¹	CV (%)
<i>Aristida purpurea</i>	2.77 ^A	0.41 ^B	1.99 ^{AB}	0.62 ^{AB}	178.30
<i>Bothriochloa barbinodis</i>	7.71 ^A	2.19 ^A	3.67 ^A	6.78 ^A	125.28
<i>Digitaria californica</i>	7.08 ^A	6.62 ^A	8.95 ^A	5.52 ^A	134.04
<i>Encelia farinosa</i>	10.49 ^A	11.11 ^A	9.42 ^A	6.56 ^A	56.45
<i>Cenchrus ciliaris</i>	44.99 ^A	10.53 ^B	12.46 ^B	13.35 ^B	84.48
<i>Phaecelia crenulata</i>	3.79 ^A	2.74 ^A	2.16 ^A	0.89 ^A	139.41
<i>Sphaeralcea ambigua</i>	19.57 ^A	13.35 ^A	6.11 ^B	5.06 ^B	63.84
<i>Vulpia octoflora</i>	1.03 ^A	1.30 ^A	2.93 ^A	1.13 ^A	174.50

Table 6: Mean seedling height (cm) of species sown from seed in the greenhouse in response to increasing rates of imazapic. Values within the same row that are followed by the same letter are not significantly different ($P \leq 0.05$).

Species	Control	0.0625 lb ae A ⁻¹	0.125 lb ae A ⁻¹	0.1875 lb ae A ⁻¹	CV (%)
<i>Aristida purpurea</i>	5.50 ^A	2.35 ^B	2.20 ^B	2.45 ^B	63.86
<i>Bothriochloa barbinodis</i>	5.90 ^{AB}	5.35 ^{AB}	4.06 ^B	6.61 ^A	40.82
<i>Digitaria californica</i>	6.67 ^A	3.65 ^A	4.50 ^A	3.60 ^A	73.24
<i>Encelia farinosa</i>	1.60 ^A	1.55 ^A	1.45 ^A	1.20 ^A	35.33
<i>Cenchrus ciliaris</i>	10.80 ^A	3.95 ^{BC}	6.10 ^B	3.20 ^C	49.77
<i>Phaecelia crenulata</i>	1.65 ^A	1.15 ^B	1.10 ^B	1.22 ^B	30.94
<i>Sphaeralcea ambigua</i>	2.35 ^A	1.35 ^B	1.00 ^B	0.85 ^B	39.97
<i>Vulpia octoflora</i>	4.40 ^A	4.60 ^A	3.75 ^A	3.70 ^A	27.79

Table 7: Response of green tissue on north and south side of individuals of *Carnegia gigantea* subjected to various herbicide treatments at the BLM Headquarters study site. Values within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

Treatment	Green Tissue (%) on N side of plant	Green Tissue (%) on S side of plant
Control	90.00 ^A	90.00 ^A
Clethodim	90.00 ^A	90.00 ^A
Fluazifop	90.00 ^A	90.00 ^A

Glyphosate	90.00 ^A	90.00 ^A
Glyphosate + Imazapic	90.00 ^A	90.00 ^A
CV (%)	0	0

Table 8: Response of green tissue and leaf abundance of individuals of *Parkinsonia microphylla* subjected to various herbicide treatments at the BLM Headquarters study site. Values within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

Treatment	Green Tissue (%)
Control	90.00 ^A
Clethodim	90.00 ^A
Fluazifop	85.56 ^A
Glyphosate	90.00 ^A
Glyphosate + Imazapic	84.00 ^A
CV (%)	11.60

Table 9: Response of green tissue of individuals of *Encelia farinosa* subjected to various herbicide treatments at the Javelina Rocks study site. Values within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

Treatment	Green Tissue (%)
Control	10.91 ^{AB}
Clethodim	33.00 ^{AB}
Fluazifop	41.00 ^A
Glyphosate	23.33 ^{AB}
Glyphosate + Imazapic	5.00 ^B
CV (%)	162.39

Table 10: Response of green tissue and green tiller abundance of individuals of *Digitaria californica* subjected to various herbicide treatments at the Javelina Rocks study site. Values within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

Treatment	Green Tissue (%)	Tiller Abundance
Control	62.00 ^A	20.20 ^A
Clethodim	54.00 ^{AB}	20.20 ^A
Fluazifop	45.56 ^{AB}	15.89 ^A
Glyphosate	27.00 ^B	9.10 ^A
Glyphosate + Imazapic	38.00 ^{AB}	11.10 ^A
CV (%)	77.71	53.20

Table 11: Response of green tissue and green tiller abundance of individuals of *Cenchrus ciliaris* subjected to various herbicide treatments at the Javelina Rocks study site. Values within the same column that are followed by the same letter are not significantly different ($P \leq 0.05$).

Treatment	Green Tissue (%)	Tiller Abundance ¹
Control	40.91 ^A	19.82 ^A

Clethodim	37.00 ^A	20.90 ^A
Fluazifop	46.00 ^A	22.90 ^A
Glyphosate	15.00 ^B	7.75 ^B
Glyphosate + Imazapic	3.00 ^B	2.50 ^B
CV (%)	66.61	38.20

Table 12: Mortality of *E. farinosa*, *D. californica*, and *C. ciliaris* (# dead plants/# total plants in treatment) at the Javelina Rocks study site in August 2011 by treatment.

Treatment	<i>E. farinosa</i> mortality (%)	<i>D. californica</i> mortality (%)	<i>C. ciliaris</i> mortality (%)
Control	17.6	4.1	0
Clethodim	9.8	0	2.0
Fluazifop	9.8	2.0	0
Glyphosate	17.6	0	14.3
Glyphosate + Imazapic	11.8	6.1	4.1

Figure 1: Locations of the study sites used in all phases of the study.

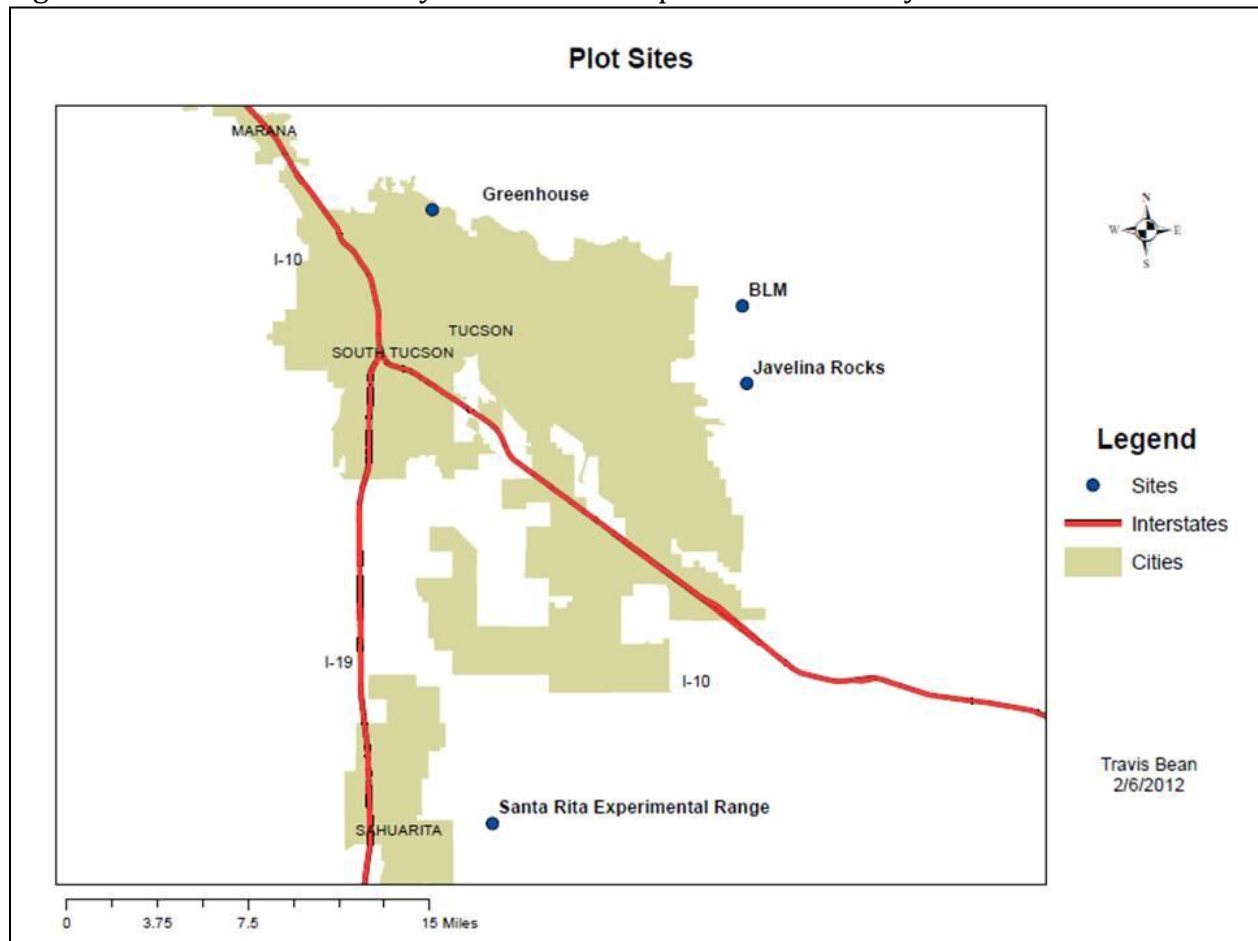


Figure 2: Location of the treatment plots at the Santa Rita Experimental Range used in Phase 1 of the study.

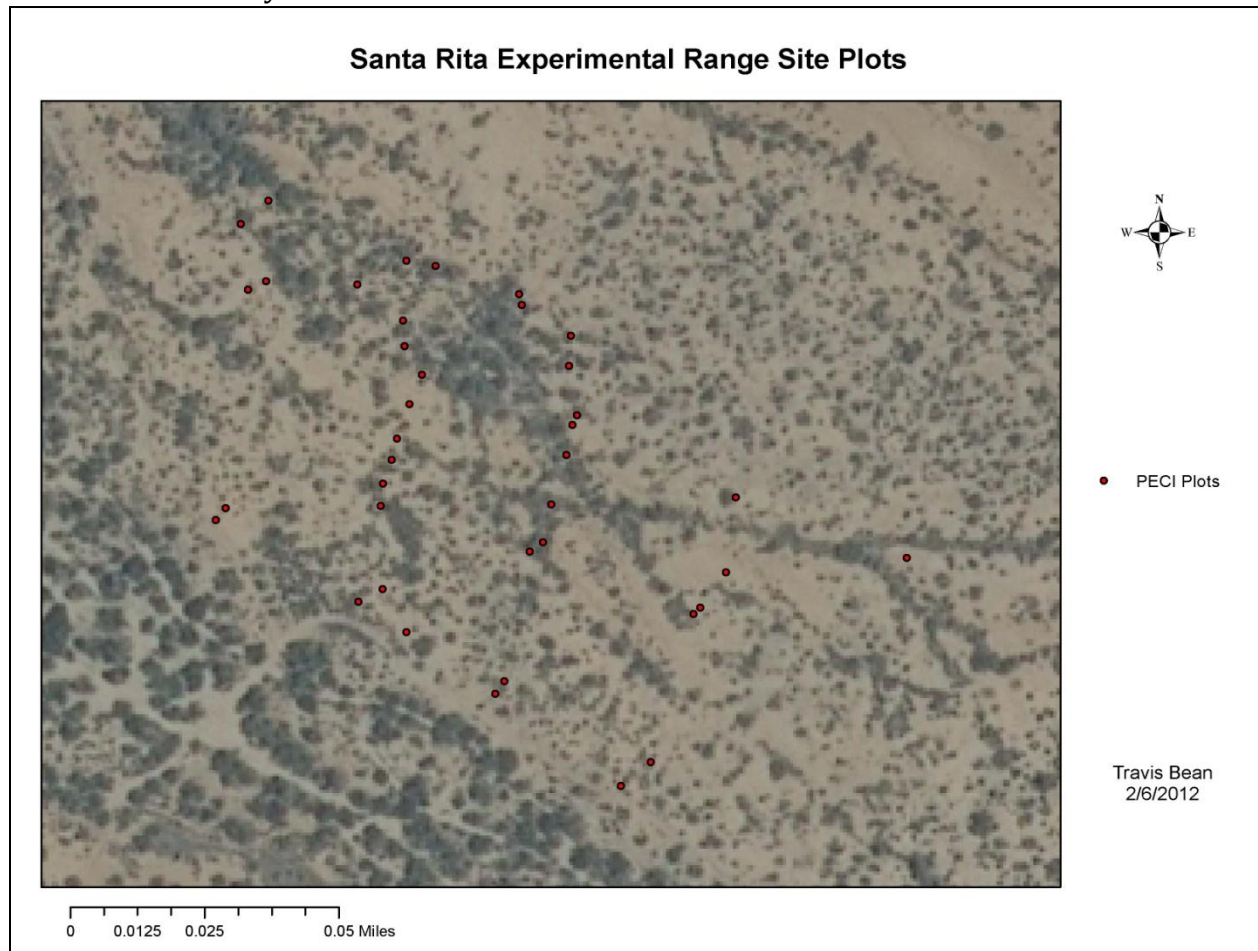


Figure 3: A plant treated with clethodim (left) and glyphosate plus imazapic (right) at the SREER study site. Photos taken August 5, 2011.

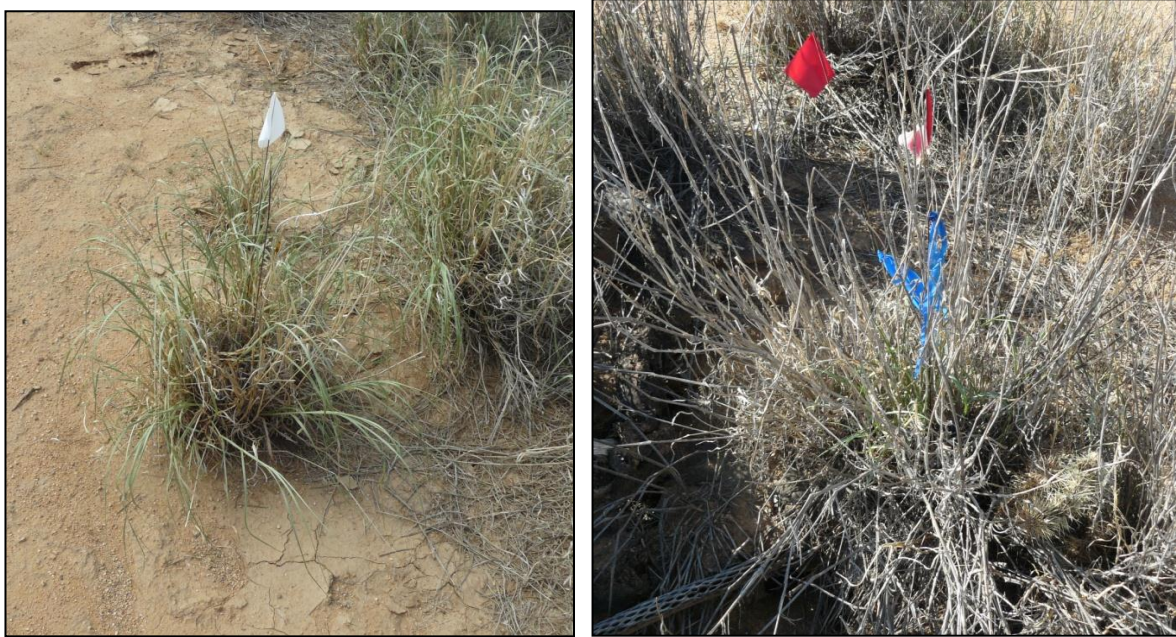


Figure 4: Control (left) and 0.1875 lb ae/A imazapic treatment (right) in the greenhouse study. Photo taken February 8, 2011.

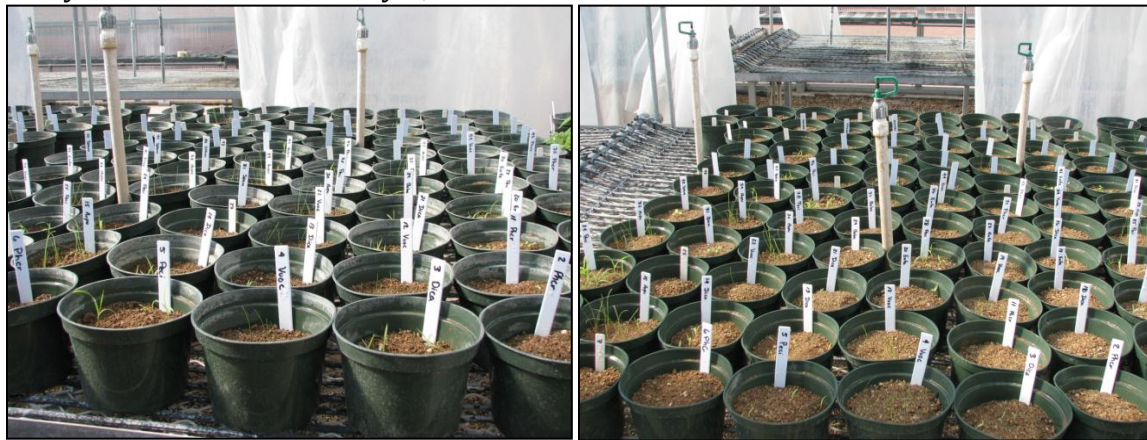


Figure 5: Location of the Javelina Rocks site used in the *in situ* portion of the study.

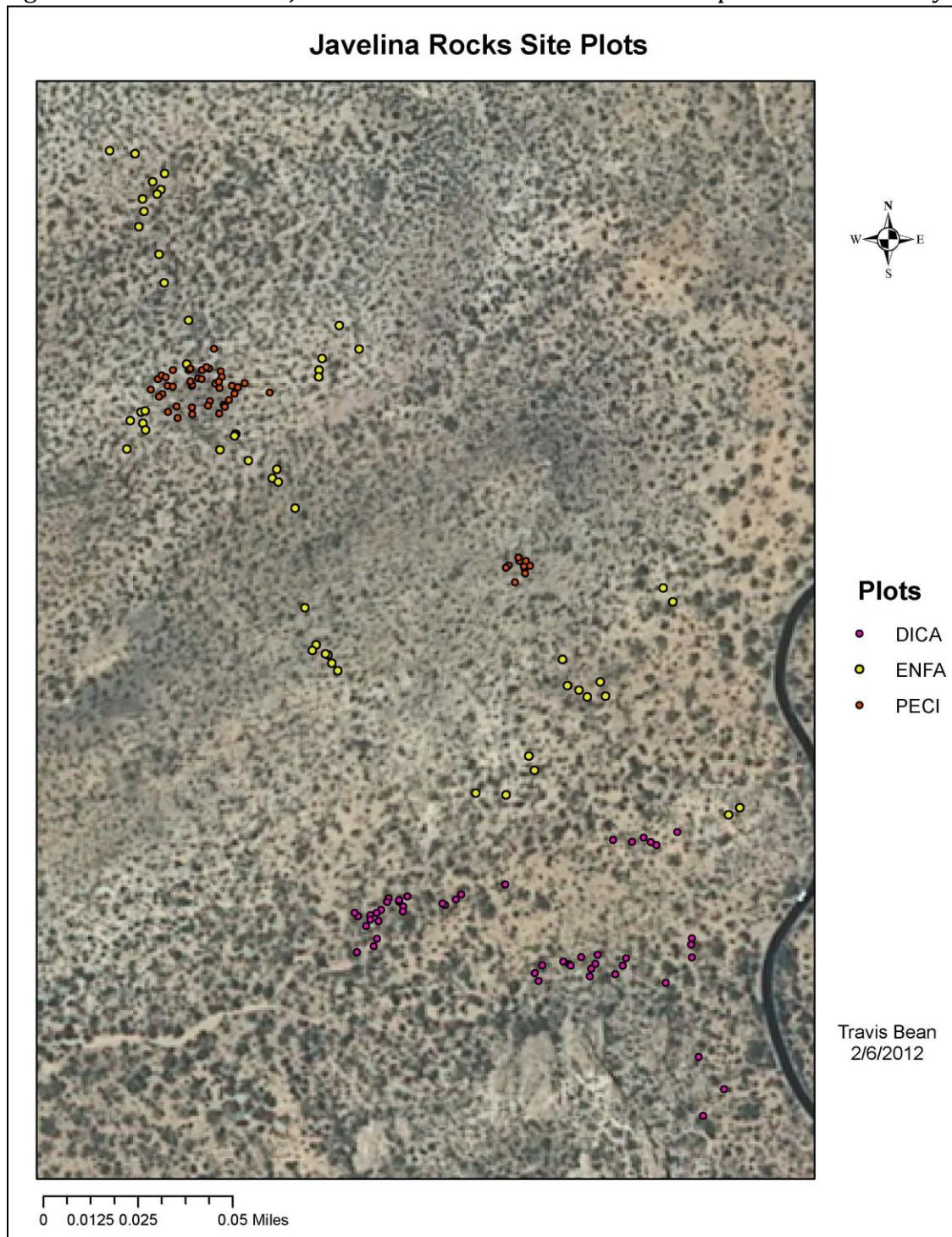


Figure 6: Location of the BLM headquarters site used in the *in situ* portion of the study.

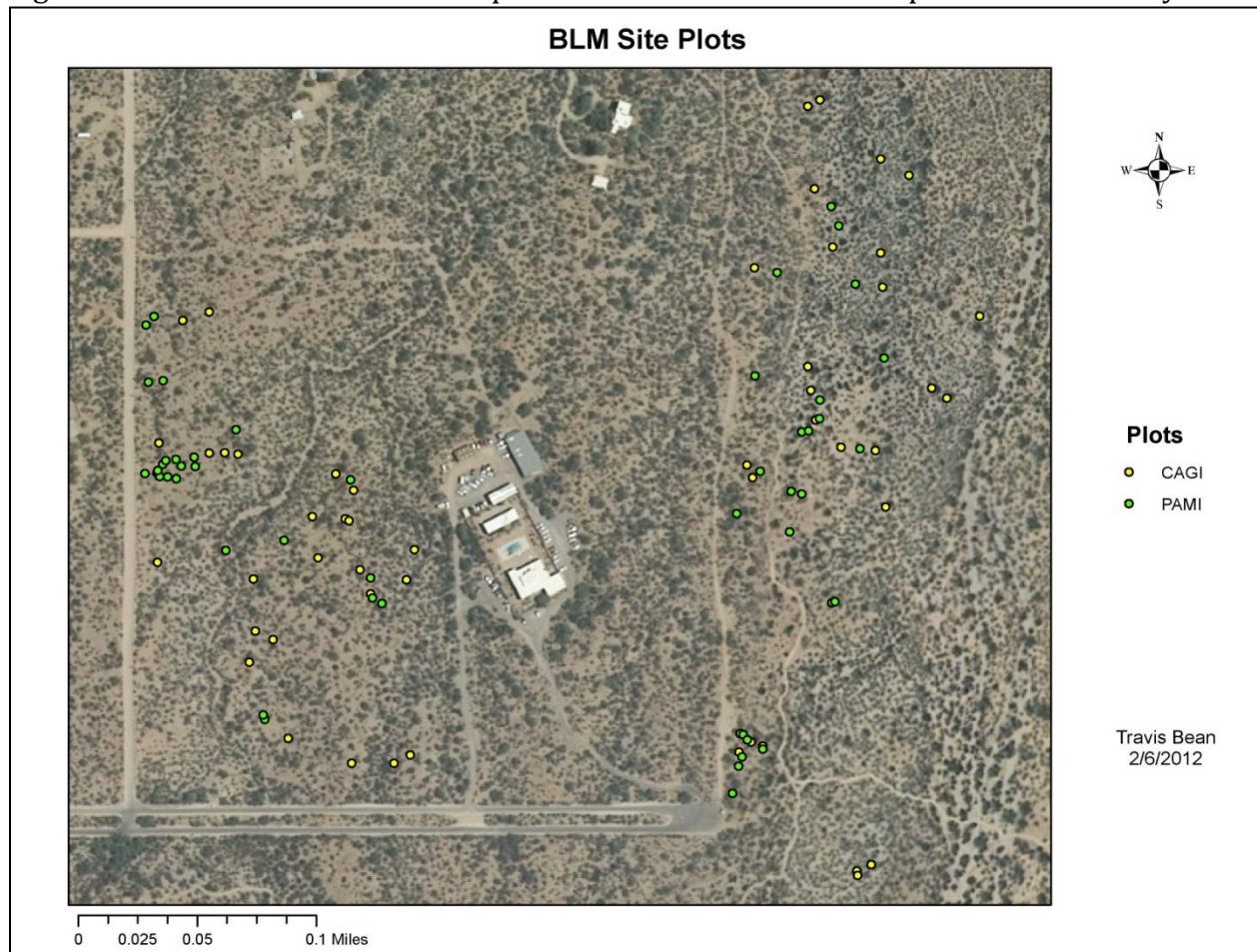


Figure 7: A *C. gigantea* treated with glyphosate and imazapic (left) and a *P. microphylla* treated with glyphosate (right) at the BLM headquarters study site. Photo taken July 27, 2011.



Figure 8: *E. farinosa* treated with fluazifop (left) and glyphosate (right) at the Javelina Rocks study site. Photos taken July 29, 2011.



Figure 9: *D. californica* control plant (left) and plant treated with glyphosate (right) at the Javelina Rocks study site. Photo taken July 29, 2011.



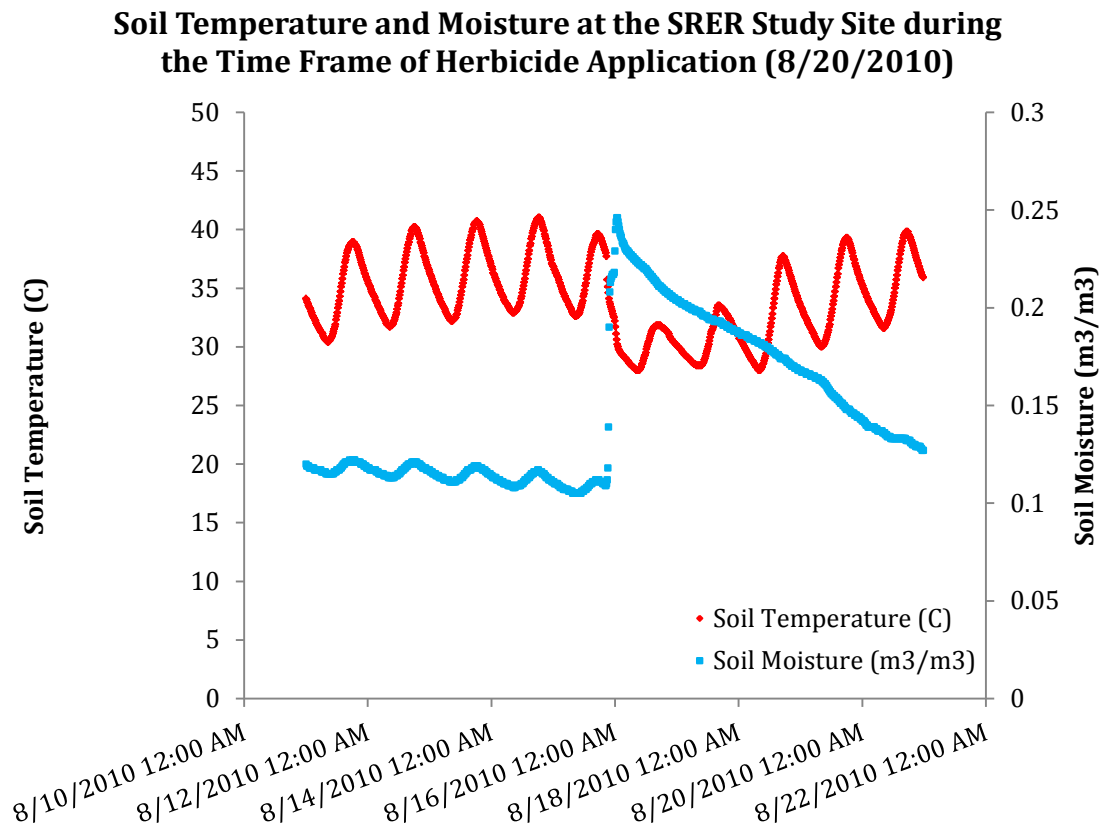
Figure 10: *C. ciliaris* control (left), clethodim treatment (middle), and glyphosate plus imazapic treatment (right) at the Javelina Rocks study site. Photo taken July 29, 2011.



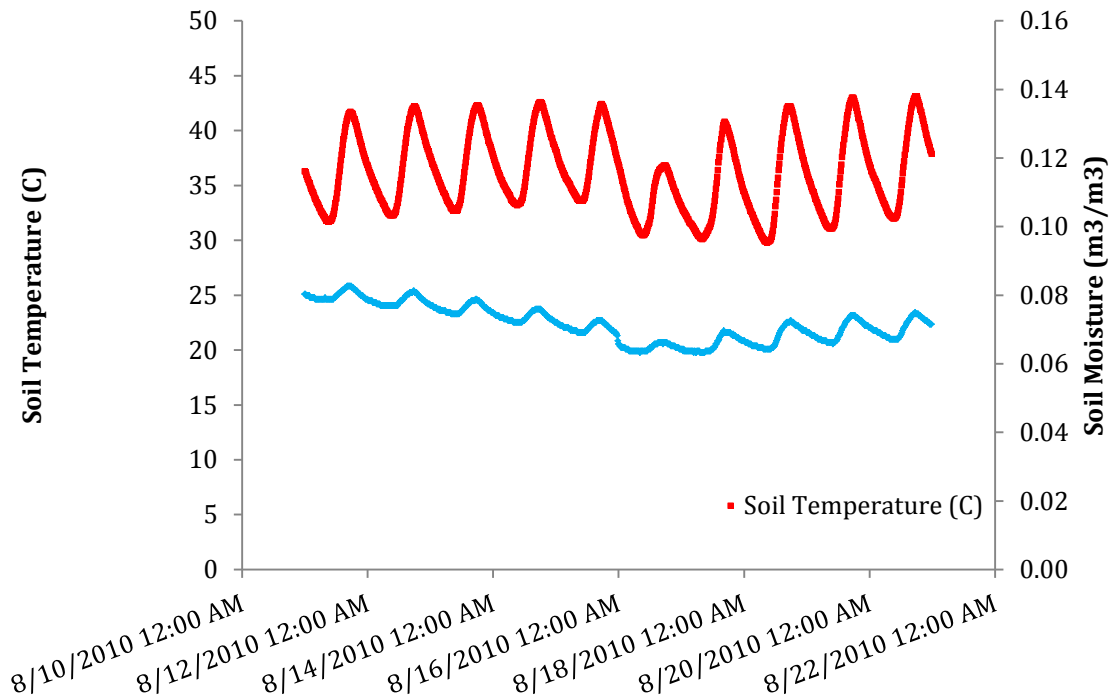
Appendix A: Table for use in the field to determine the number of seconds to apply for areas described by the canopy of plants with area greater than 0.25m² in order to maintain the 50 gal A⁻¹ rate assuming the use of a 8001EVS nozzle with a 100 mesh filter at 20 psi. Timing for canopies with diameter over 1.57 m were calculated in the field.

Canopy Diameter	seconds
< 0.61	3
0.61 - 0.68	4
0.69 - 0.75	5
0.76 - 0.82	6
0.83 - 0.88	7
0.89 - 0.94	8
0.95 - 0.99	9
1.00 - 1.05	10
1.06 - 1.09	11
1.10 - 1.14	12
1.15 - 1.19	13
1.20 - 1.23	14
1.24 - 1.27	15
1.28 - 1.31	16
1.32 - 1.35	17
1.36 - 1.39	18
1.40 - 1.43	19
1.44 - 1.46	20
1.47 - 1.5	21
1.51 - 1.54	22
1.55 - 1.57	23

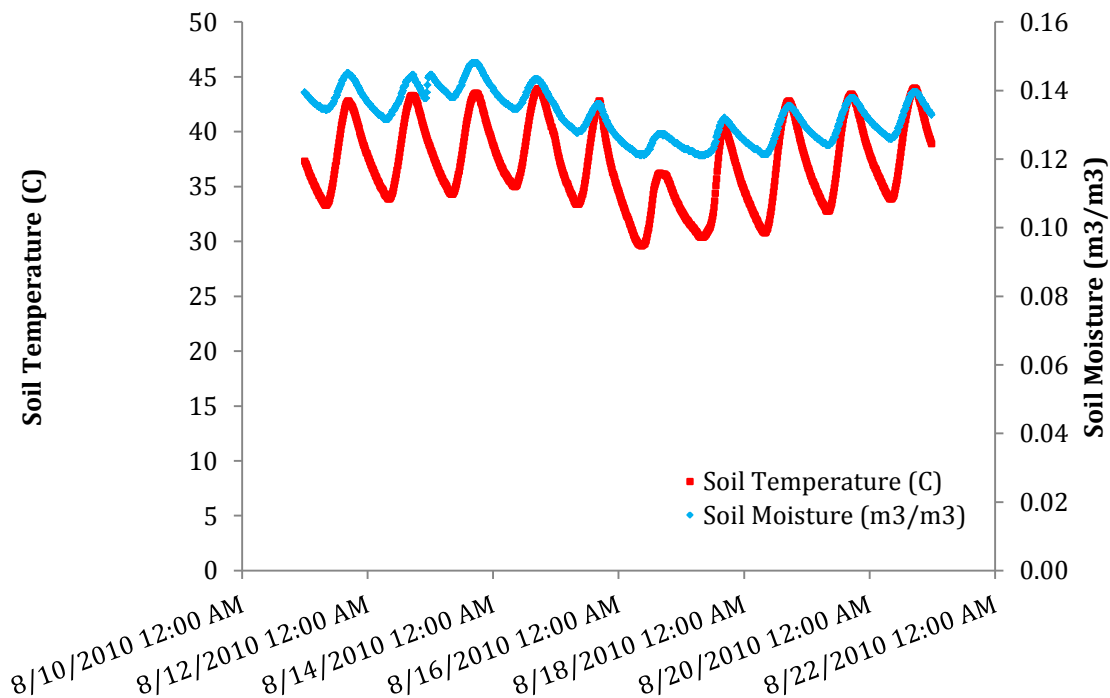
Appendix B: Soil moisture and temperature information at the SRER, University of Arizona Campus Ag. Center Greenhouses, BLM Headquarters, and Javelina Rocks over varying time periods. Note that scales are different on all graphs.



**Soil Temperature and Moisture at the BLM HQ Study Site
During the Time Frame of Herbicide Application (8/11/2010,
8/17-19/2010)**



**Soil Temperature and Moisture at the Javelina Rocks Study
Site During the Time Frame of Herbicide Application
(8/11/2010, 8/17-19/2010)**



Appendix C: An overview of how to calibrate a backpack sprayer for *C. ciliaris* spraying
Calibration of backpack sprayers is easily achieved in 6 simple steps:

1. Fill clean spray tank with water
2. Measure a known area in the location you will be spraying, or at least on similar slope and terrain, and having a similar density of *C. ciliaris*. A 18.5 ft by 18.5 ft square area is often used as this equates to 1/128 of an acre.
3. Time the number of seconds required to spray *C. ciliaris* plants in the measured area uniformly. Repeat this step at least twice and use the average measurement for improved accuracy of calibration.
4. Spray water from the sprayer into a container for the same number of seconds recorded in #3. Measure the ounces of water collected. Because the number of ounces per gallon is 128, and the area sprayed was 1/128 of an acre, the number of ounces collected is equal to the number of gallons of water per acre the sprayer is delivering (carrier rate).
5. With a carrier rate calculated, you can now add the appropriate amount of herbicide to the mixing vessel to match the recommended rates from experimental results.