THESIS

VEGETATION MANAGEMENT AND RESTORATION SPECIES SAFETY WITH AMINOCYCLOPYRACHLOR

Submitted by

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ABSTRACT

VEGETATION MANAGEMENT AND RESTORATION SPECIES SAFETY WITH AMINOCYCLOPYRACHLOR

Aminocyclopyrachlor is a synthetic auxin herbicide in the pyrimidine carboxylic acid family, and is the only herbicide within the family. Aminocyclopyrachlor exhibits excellent herbicide activity offering multiple year control of many broadleaf noxious weeds and many non-desirable tree species (DuPont 2009). A non-native tree, Russian olive is the fourth most common woody species in the western United States and has been shown to cause many detrimental ecological impacts. Removing Russian olive allows native species to reestablish within certain areas. Where the soil seed bank is depleted and there is not a native seed source nearby, planting restoration species can be desirable after invasive species removal. Biodiversity of native plant species can help support larger suites of desirable species within an ecosystem. Restoration is not just important after invasive species removal, but after disturbances such as mining, fire, and floods

Two studies were conducted to investigate potential restoration uses of aminocyclopyrachlor within the Northern Front Range of Colorado. The objective of the first research project was to assess restoration species herbicide tolerance. Two types of tolerance were of interest; species soil residual herbicide tolerance, and species tolerance to foliar herbicide applications. The objective of the second research project was to determine the effectiveness of cut stump applications of aminocyclopyrachlor for the control large Russian olive trees.

The first study evaluated the tolerance of eight monocot species and eight broadleaf species to thirteen soil residual herbicide treatments at two pre plant application timings and two post emergence application timings of sixteen herbicides. The study was located at the Colorado State University Horticultural Research Farm from 2010 to 2012. Initial percent frequency, relative change in percent

frequency, and biomass were used to evaluate the tolerance of species tested. Variables were analyzed for each species, at each application timing, looking for differences among herbicide treatments. No difference in initial establishment percent frequency was detected for any species*herbicide combination compared to the untreated check (p>05). Relative percent frequency change from 2011 to 2012 was not significant compared to the untreated for any monocot species*herbicide combination (p>.05). However, differences were detected for dicot species* herbicide combinations (p<.05). No differences in biomass occurred for any species*herbicide combination compared to the untreated check (p>.05). Generally there were numerical trends in the data, suggesting monocot species were relatively tolerant to the herbicides tested at all four application timings. Numerically, percent frequency and biomass values indicated certain dicot species establishment was inhibited by certain soil residual herbicide treatments, and were completely removed by certain foliar herbicide applications. In general monocot species tested were more tolerant than dicot species tested, especially in the foliar treatments. However, many instances of monocot and dicot species tolerances to herbicide applications tested were found. This implies that when an herbicide is used to control an invasive species, many restoration species tolerant to the soil residual herbicide could be safely planted the following year. Additionally many restoration species were tolerant to foliar herbicide applications, indicating certain applications could be made to control non-planted weedy species during restoration species establishment.

The second study assessed the effectiveness of Aminocyclopyrachlor, imazapyr, triclopyr and glyphosate for cut stump application control of Russian olive. Thirty nine replications of herbicide treatments were tested at three field sites in the Northern Urban Front Range of Colorado. Treatment mortality and off-target impact were assessed every six months for thirty months. Thirty months after treatment, glyphosate, aminocyclopyrachlor, imazapyr, triclopyr, and the untreated check had 95, 92, 74, 71, and 18 percent mortality of Russian olive trees. All herbicide treatments had higher mortality compared to the untreated check (p<.05), but no herbicides were different from one another (p>.05). Herbicide applications have the potential to cause injury to non-target vegetation. The bare soil around each stump was measured (Radius of Inhibition) to capture the off target impact of herbicide applications.

Thirty months after treatment there was a radius of inhibition of 4 cm, 8 cm, 13 cm, and 26 cm *for* glyphosate, triclopyr, imazapyr, and aminocyclopyrachlor respectively. Aminocyclopyrachlor had a larger radius of inhibition than other herbicide treatments tested thirty months after application ($p<.05$). In order to treat an average size Russian olive within our study, the cost of herbicide products were $1.47, $1.98, $1.16, and $5.95 for glyphosate, triclopyr, imazapyr, and aminocyclopyrachlor respectively. Overall we found aminocyclopyrachlor offered Russian olive control comparable to other herbicides tested. However, it had the largest off target impact, and was three times the cost of the second most expensive treatment.

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CHAPTER 1: RESTORATION SPECIES HERBICIDE TOLERANCE

Introduction

Multiple reasons and opportunities for re-vegetation efforts exist in Colorado. Restoration species are often planted after anthropogenic disturbances (ex. natural resource extraction, or invasive species removal). Establishing diverse perennial plant communities with ecological value, is a common goal of restoration plantings. However successful establishment can be hindered by competition with non-planted species growing from the seedbank. Selective herbicides can be used as a tool to improve species establishment in restoration plantings (Bahm and Barnes 2011).

Resource extraction, which is widely practiced in Colorado can create large scale disturbances. Colorado produces minerals including molybdenum, gold, gypsum, limestone, sodium bicarbonate, and uranium (CMA 2014). Colorado leads the nation in molybdenum production and is the fourth largest gold producing state (CMA 2014). Colorado also produces many resources for energy production. In 2013, 28,642,452 tons of coal were produced in Colorado (CDRMS 2013). In 2014 Colorado had 52,938 active oil and natural gas wells that produced 4 billion cubic feet of natural gas, and 177,800 barrels of oil per day (Colorado Oil and Gas Conservation Commission 2014). Laws such as the Surface Mining Reclamation Act require mining companies to restore land and water resources (US Congress 1977). One of the first steps in restoration is often establishing plant species within these disturbed areas.

Techniques used to control invasive plant species often create another type of disturbance. Colorado passed a noxious weed act mandating that certain plant species be controlled (CDA 2003). These plants are classified into three lists (A, B, C) designating the level of priority for their control (CDA 2003). Many control methods are available to land managers, such as mechanical, cultural, biocontrol, and chemical control (Motooka et al. 2002). Depending on the weed species, different approaches will be selected under a variety of different circumstances. Mechanical or chemical techniques are often chosen for control when eradication is desired. However, on large acreages chemical control is often more economical and effective than physical control methods such as mowing or hand pulling (Beck 2013).

When noxious weeds are controlled with herbicides, and the remnant soil seedbank contains non-desirable species, restoration species need to be planted to establish desirable species. Sometimes it is not known if the planted restoration species have tolerance to the herbicide residue still contained in the soil and litter (Renz et al. 2011). Known tolerance is important so resources are not wasted on seeds that can't establish through the herbicide residue. When the foliar tolerance of the planted species is known to an herbicide, that herbicide can be used directly to control non-desirable plant species that may outcompete the planted species (Harrington 2007).

Herbicides can be used to control non planted species both before and after planting restoration species. Knowing the tolerance of these species to certain herbicides could be a valuable tool for land managers. Researchers have examined the response of some common restoration grass and forb species to select herbicides in areas outside of Colorado. (Boutin et al. 2004; Haufman and Jacoby 1984; Bahm and Barnes 2011; Renz et al. 2012). Likewise the foliar herbicide tolerance of some common restoration species has been investigated for select herbicides (Harrington and Schmitt 2007; Derr 1993; Norcini 2003 & Wies 2011). Thousands of different species may be chosen for restoration plantings, and many herbicides are available on the market to control non-desirable vegetation. The tolerance of the majority of native species is not known to the majority of these herbicides. This is because only a few select species and herbicides have been tested, in relatively few locations. Research assessing the herbicide tolerance of more restoration species in more locations needs to be done.

The objective of our study was to determine the tolerance of common restoration species to common herbicides used in the Northern Colorado area. We collaborated with local county land managers to select typical restoration species and herbicides commonly used within the area. We were interested in investigating soil residual and foliar herbicide tolerance at two application timings. Our research aimed to answer the following questions: 1) If herbicide is applied in July or September, would a species planted the following year be tolerant to the soil residual herbicide left behind? It was hypothesized that species would be more tolerant to applications made in July compared to September because there would be more time for the herbicide to be degraded. 2) If a restoration planting was done in the spring, would species planted that year be tolerant to foliar herbicide applications in July and/or September? Species tolerance was expected to vary based on the herbicide and application timing. It was hypothesized species tested would be more tolerant to soil residual herbicide exposure than direct foliar applications.

To demonstrate the potential implications and practicality of this work, Table 1.1 shows herbicides tested commonly used by county managers, and the numbers of Colorado noxious weeds label for control broken down by priority. Table 1.2 shows many weed species of concern to Larimer County, and the number of herbicides in Table 1.1 that are labeled to control them. Many widespread and agricultural weeds are not included on the noxious weed list as to avoid placing undue burden on land owners (CDA 2003). Table 1.3 lists the common herbicides used in Larimer County and the common undesirable plant species they are labeled to control.

Materials and Methods

Location

Our study site was located at the Colorado State University Horticultural Field Research Center (Hort farm) near Fort Collins within Larimer County Colorado (Decimal degree latitude and longitude of 40.6128, -104.9930). Available space, field machinery, proximity to campus, and a willing farm manager helped us select the Hort farm as our study location. The soil at the research farm has a USGS classification of a Nunn fine clay loam. In an adjacent field (~200 ft. from the research site) the soil consisted of 34% sand, 25.2% silt, 40.8% clay, 1.46% organic matter, and a pH of 8.0 (Westra 2012).

Implementation

Implementation of our study began in July of 2010. The study area preparation included tilling with a disk following a burn-down treatment of 2.3liters/ha of Roundup Weathermax® to remove all surface vegetation. Three replications of thirteen herbicide treatments were laid out in a randomized complete block design. Table 1.4 lists the rate of the 13 herbicides applied to investigate the soil residual tolerance. Plot dimensions were 3 x 14 meters. Treatments were sprayed using a C02 pressurized backpack sprayer at rate of 200 l/ha. July applications were made midday on 7-2-10. The second set of soil applied herbicide treatments were made on a separate, untreated portion of the field on 9-24-10, using the same plot size and application equipment.

In 10-25-10 Roundup Weathermax® was applied at 2.3liters/ha to control winter annual weeds across the entire study. In particular *Descurainia sophia* (L.) Webb ex Prantl was readily establishing on the freshly tilled soil. Additionally, on 4-5-11 Roundup Weathermax® was applied at the same rate to control escaped winter annuals before planting.

Two rows of each of the sixteen species were planted on 4-29-11. Species names and taxonomic authorities can be found in Table 1.6. Species were planted in a randomized strip plot design. Grasses were planted by functional group with a 25.4 cm row spacing using a Truax® seed drill (New Hope, MN), and broadleaf species were planted with a 30.5 cm row spacing using a cone seeder. Species were planted perpendicular to the soil applied herbicide treatments, and into an untreated portion of the field where foliar applications would occur. This created a checkerboard pattern of herbicide treatments and planted species.

Sixteen foliar herbicide treatments were applied after species emerged. Application rates can be found in Table 1.5. Treatment implementation and plot layout were the same as the soil applied herbicide applications. The July foliar applications was made on 7-25-11, where the September applications were made on 9-19-11. Foliar applications were made onto the portion of the field that had not previously been treated.

Because our study site was located within a former agricultural field, there were some indigenous weeds. The weed species present were *Sisymbrium Sophia* (L.) Webb ex Prantl, *Cirsium arvense* (L.) Scop, *Convolvulus arvensis* L., *Kochia scoparia* (L.) A.J. Scott, *Chenopodium album* L., *Amaranthus retroflexus* L., *Sonchus oleraceus* L., *Setaria pumila* (Poir.) Roem. & Schult., *Echinochloa crus-galli* (L.) P. Beauv., *Distichlis spicata* L. Greene, and *Hordeum jubatum* L. . All taxonomic authorities were found using the USDA PLANTS Database.

Study maintenance

Hand weeding was used throughout the duration of the study to reduce effects of indigenous plant competition on the planted restoration species.

In the arid west restoration species establishment can be affected by precipitation (Chambers et al. 2014). Dr. George Beck and Jim Sebastian at Colorado State University have conducted similar studies along the Front Range, and in certain cases were unable to assess the tolerance of seeded species because of a lack of establishment (personal communication). The goal of our study was to assess the tolerance of these species to herbicide applications so precipitation was supplemented with irrigation to ensure establishment. Irrigation and precipitation amounts are graphically displayed for 2011 and 2012 in Figure 1.1 and Figure 1.2 respectively. We recorded 63 cm of rainfall/irrigation in 2011 and 51 cm in 2012.

After the 2011 growing season the study was mowed with a tractor-mounted rotary mower after all species senesced. This was done to prepare the site for an herbicide application aimed at inhibiting weed seed germination. On 3-15-12, 1.75 liters/hectare Prowl H2O® and 1.55 liters/ hectare Dual II Magnum® were applied to the entire study using a tractor-mounted sprayer. These products were applied to reduce the germination of both weeds and the seeds set by planted species in the fall of 2011, and reduce the amount of hand weeding needed in 2012.

Measurements

Percent frequency (stand counts)

Restoration species initial establishment was assessed using the percent frequency of species within plots. A meter stick was divided up into 10,10cm segments and placed between the two rows of a species in the middle of each plot. Binomial presence/absence data were collected for each of the ten cells for both rows of each species, for a maximum value of 20. Species were considered present if a plant was rooted in either of the planted rows to the side of each cell. Frequency counts were conducted in late June of both 2011 and 2012. 2011 frequency counts were used to determine initial establishment of all species. *Sphaeralcea coccinea, Schizachyrium scoparium, Bouteloua curtipendula* were excluded from all analysis because of poor/inconsistent establishment. Percent frequency = (number of cells with plants present/total number of cells)*100

Differences in percent frequency for pre-emergent herbicide applications were analyzed for individual species at each application timing. ANOVA was used to determine the effects of the herbicides to the species percent frequency. Data were transformed to attempt to meet assumptions of ANOVA. If assumptions could not be met, population medians were analyzed with the Wilcoxon rank sum test. If either the ANOVA or Wilcoxon test indicated differences ($p<.05$), Tukey pair wise comparisons or Wilcoxon pair wise comparisons were used to separate mean or median differences (alpha=0.05). JMP Pro 11 was used to conduct all statistical analysis.

The change in relative percent frequency from 2011 to 2012 was calculated and analyzed for the 2011 foliar herbicide applications. Change in relative percent frequency= ((2012 frequency-2011 frequency)/2011 frequency)*100. Statistical analysis was conducted using the same methodology described above, in order to determine which foliar applications reduced the planted species stands. *Rudbeckia hirta* was excluded from analysis because the annual variety had accidentally been planted instead of the perennial variety. *Rudbeckia hirta* plants were not consistent enough throughout the study to measure during the 2012 growing season.

Biomass

Biomass was collected in the middle of August 2012. A sickle bar mower with an 81 cm cutting bar was used to cut above ground biomass of each species in both rows. Total area harvested for monocot species biomass was 0.2 m^2, and 0.25 m^2 for dicot species. Wet biomass was taken for all species. Eight subsamples of each species wet biomass were dried in an oven at 49 degrees Celsius degrees for 2 weeks. Samples were reweighed and average percent moisture was calculated for each species. Wet biomass weights were converted to kg of dry biomass/m^2 for analysis.

Differences in dry biomass for all herbicide applications were analyzed for individual species at each application timing. ANOVA was used to determine the effects of the herbicides to the dry biomass of each species. Data were transformed to attempt to meet assumptions of ANOVA. If assumptions could not be met, population medians were analyzed with the Wilcoxon rank sum test. If either the ANOVA or Wilcoxon test indicated differences, ($p<.05$) Tukey pair wise comparisons or Wilcoxon pair wise comparisons were used to separate mean or median differences (alpha=0.05).

Results and Discussion

Our study was designed to assess tolerance of multiple restoration species to multiple herbicides applied at 4 different times. Our field site was large, just under 1 hectare, where each combination of species*herbicide* timing was replicated three times. If more space and resources would have been available more replications would have been used. When a species was completely killed within an herbicide treatment, there was little variability in the data, but when a species was not completely killed there was variability in either the biomass or frequency data. This in combination with the limited number of replications limited the power of the statistical analyses that could be conducted to identify true differences among treatments. Often non-parametric analysis was preformed, because the assumptions for ANOVA could not be met. Unfortunately because of the small number of replications, Wilcoxon pair wise comparisons showed no differences between treatments at the 95% confidence level. Below statistical differences are discussed, and general numerical trends in the data sets are highlighted.

Percent frequency

Percent frequency 2011 (establishment year 1)

Initial establishment was quantified by estimating the frequency of seeded species in 2011 to determine the response of seeded species to the soil applied herbicide treatments. Primarily, initial percent frequency of species, quantified where the soil applied herbicide residues inhibited species establishment. The 2011 frequency counts, also provided a baseline to determine how species frequency increased or decreased after the 2012 foliar herbicide applications were made.

We achieved relatively successful initial species establishment across the entire field study (23 - 86% frequency in 2011). Initial establishment values varied by species and can be found in Tables 7 and 8 for monocots and dicots respectively.

To assess where species initial establishment was inhibited, Percent frequency was analyzed for each species individually across herbicide treatments. Only frequency counts from the 2010 application timings were analyzed, because at the time frequency counts were conducted, none of the 2011 foliar application had been made.

Initial 2011 percent frequency did not differ between herbicide treatments for any cool season or warm season grass for either the July or September 2010 application timing (Table 1.9). Dicot percent frequency did not differ by herbicide treatment for the July and September herbicide application timings, except for *Atriplex canescens* at the September application timing (Table 1.10). The percent frequency of *Atriplex canescens* in the September chlorsulfuron plot was statistically lower ($p<.05$) than the 0.07 kg ai/ha application of aminocyclopyrachlor. However, both the chlorsulfuron and 0.07 kg ai/ha aminocyclopyrachlor treatments were statistically similar to the untreated check, and all other herbicide treatments (Table 1.10).

Generally, there were some numerical trends in frequency from the soil residual herbicide applications. There were four instances where monocot frequency was numerically was less than 60% of the untreated checks. Conversely there were 40 instances where dicot species frequency numerically was less than 60% of the untreated checks. This numerical trend indicates dicot species establishment generally was impacted more than monocot species by from the soil residual herbicide applications. Color coded Appendix Tables A.1.9 and A.1.10 display frequency for each species as a percentage of the untreated check.

Relative percent frequency changes from 2011 to 2012

2011 frequency counts were used to create a baseline establishment level for the foliar herbicide application plots. The change in frequency from 2011 to 2012 was used to assess if a species was removed by a foliar herbicide application. Change in absolute frequency from 2011 to 2012 is discussed as a relative percent increase or decrease. If a number is positive, there was an increase in the absolute frequency, from 2011 to 2012. However this change in abundance is relative to the initial frequency of that plot. Species had variable initial establishment ranging from 23% to 86%. It does not necessarily matter how much the absolute frequency increased from 2011 to 2012 because the increase is relative to the starting point. However it is important to note when the change in absolute frequency was negative, because this indicates that the relative frequency decreased after the foliar herbicide applications.

The relative percent frequency change was analyzed separately for each species between each herbicide for both foliar application timings (Table 1.11). Table 1.7 presents the relative percent frequency increase for the monocot species from the 2011 stand counts. There was variability from 23% to 85% initial frequency between monocot species for 2011. Species with a lower initial frequency had more potential for a relative increase from 2011 to 2012 than species that had high initial frequencies. For example if a species established well, there was not space for the frequency to increase dramatically.

Generally monocot species frequencies were not reduced by the foliar applications; relative percent change can be viewed in (Table 1.11 and Appendix Table A.1.11). No statistical differences were observed between herbicide treatments for individual species except the July foliar application to *Elymus canadensis*. *Elymus canadensis* had a relative percent frequency increase for every herbicide treatment, and none of the herbicide treatments were statically different than the untreated check.

Monocots relative percent change only decreased numerically for an individual species*herbicide combination four times. *Elymus trachycaulus* had a 4% relative decrease in the July 2011 foliar application of 0.22 kg ai/ha of imazapic. *Nassella viridula* decreased 7%, 45% and 19% from the July 2011 foliar application of chlorsulfuron, 0.22 kg ai/ha imazapic, and 0.11 kg ai/ha imazapic respectively. No other monocot species*foliar herbicide combinations resulted in a numerical relative percent frequency decrease. This indicates than monocot species were generally tolerant to the foliar herbicide applications tested at both application time points.

Dicot species relative percent frequency change from 2011 to 2012 and statistical differences between herbicide treatments were variable (Table 1.12 and Appendix Table A.1.12). Dicot species' responses to both foliar herbicide application timings were more variable than the monocot species.

No statistical differences p<.05, were observed for *Achillea lanulosa* at either the July or September foliar application timing. However, there were many stark numerical difference in relative percent frequency change. *Achillea lanulosa* had a relative percent increase of 41% and 50% for the July and September untreated checks respectively. Where *Achillea lanulosa* was removed by foliar herbicide applications, there was a numerical relative percent frequency decrease of 100% for metsulfuron and clopyralid in July, and in September for metsulfuron, clopyralid, aminopyrlid, picloram and aminocyclopyrachlor 0.07 ai/ha. A numerical relative percent frequency decrease of *Achillea lanulosa* occurred for five of the fifteen July foliar herbicide applications. Where there was a numerical relative percent decrease for 9 out of the 15 foliar herbicide applications in September. This indicates that the September applications generally may have been more injurious than the July applications for *Achillea lanulosa*.

Atriplex canescens did not experience a decrease in relative percent frequency for any of the July or September foliar applications indicating relatively good herbicide tolerance. However, *Atriplex canescens* had a larger relative percent frequency increase for the foliar July rimsulfuron application compared to foliar July metsulfuron application. All other treatments had a statistically similar relative percent change to each other and the untreated check. No statistical differences were detected between September foliar herbicide applications for *Atriplex canescens*, and all relative percent frequency changes were positive. Generally *Atriplex canescens* was tolerant to most foliar herbicide applications.

No statistical differences in relative percent frequency change occurred for *Gaillardia* spp., for either the July or September foliar herbicide applications. Numerically, there was a relative percent frequency decrease for 10 of the July herbicide applications and 9 of the September herbicide applications. Generally *Gaillardia* spp. was relatively susceptible to the foliar herbicide applications at both timings. Numerically *Gaillardia* spp. had a relative percent frequency increase for quinclorac, rimsulfuron, and tebuthiuron at both foliar application time points. Indicating that *Gaillardia* Spp. was not susceptible to all foliar herbicide applications, and tolerance may occur to specific herbicides.

No statistical differences in relative percent frequency change of *Linum perenne* were detected between herbicide treatments for either foliar application timing (Table 1.12). Numerically in July, 7 out of the 15 herbicides caused a slight relative percent decrease of *Linum perenne*. In September numerically 11 out of the 15 herbicide treatments caused a relative percent frequency decrease of *Linum perenne*. With a relative percent decrease of 89%, 72% and 50% from picloram, aminocyclopyrachlor .07 kg ai/ha and dicamba respectively. In general the July foliar applications were safer than the September foliar applications for *Linum perenne*.

Quinclorac, tebuthiuron and both rates of imazapic caused a numerical relative percent frequency decrease of *Penstemon palmeri* from the July foliar herbicide applications. Of these four treatments, all except the lower rate of imazapic had a statistically lower relative percent frequency change than the untreated check. For the September foliar applications no statistical differences of relative percent change between herbicides were detected for *Penstemon palmeri*, but quinclorac, picloram and dicamba did cause a numerical relative percent frequency decrease.

Statistical differences of relative percent change occurred among herbicide treatments for *Ratibida columnifera* at both the July and September foliar applications. For the July application timing picloram, clopyralid, metsulfuron, and chlorsulfuron all had a relative percent frequency decrease compared to the untreated check. *Ratibida columnifera* also numerically had a relative percent decrease in frequency within the July aminopyralid plot, but was statistically similar to the untreated check. None of the other July foliar herbicide applications caused a numerical relative percent frequency decrease for *Ratibida columnifera*, and were statically similar to the untreated check. September foliar applications of metsulfuron, dicamba, and aminocyclopyrachlor 0.07 kg ai/ha, statistically had a lower relative percent frequency change for *Ratibida columnifera.* Ten of the September foliar herbicide application caused a numerical relative percent frequency decrease for *Ratibida columnifera. Ratibida columnifera* in September applications of tebuthiuron, imazapic 0.11 kg ai/ha, rimsulfuron, fluroxypyr, and 24-d amine, had a relative percent frequency decrease, all of which were similar to the untreated check. This indicates that many, but not all foliar herbicide treatments were injurious to *Ratibida columnifera.*

Many of the herbicides tested were injurious to certain species at specific application timings. In general dicot species were more susceptible to September foliar applications compared to the July foliar applications. One dicot, *Atriplex canescens,* did not experience any numerical relative percent frequency decreases in stand from any foliar application at either timing. Generally, 2011 initial stand count frequencies were useful in determining when a species establishment was inhibited from residual herbicide effects. Where the 2011 to 2012 relative percent frequency change was a good indicator of when foliar herbicide applications injured a species.

Biomass

Biomass was collected in the fall of 2012. At the time of biomass collection, herbicide treatments had not been sprayed for a minimum of 12 months, and a maximum 26 months. The passing of time allowed biomass to be used as a measure to assess how plants rebounded after the initial herbicide exposure. Many plants that were initially injured by an herbicide but not killed, outgrew the injury with time. Barnes (2007) conducted a similar study showing that biomass was often reduced in the season of herbicide application. However, in the following growing season no detectable differences in biomass were present (Barnes 2007). Initial injury was best captured by the percent frequency data discussed above. Dry biomass in kg/m^2 can be viewed in Tables 1.13-1.16. (Appendix Tables A.1.13-A.1.16 display biomass as a percentage of the untreated check and are color coded).

Monocot species biomass: soil herbicide applications

Numerically, monocot biomass from soil applied herbicide applications varied greatly within species and between species. Average monocot biomass values for each species for all soil residual tolerance applications and statistical differences can be viewed in Table 1.13 (Appendix Table A.1.13 displays a color coded version).

Only one instance occurred where there was a statistical difference in biomass between soil residual herbicide treatments for a monocot species. It was in July for *Elymus canadensis* where rimsulfuron and aminocyclopyrachlor 0.03 kg ai/ha plots had lower biomass than in the aminocyclopyrachlor 0.07 kg ai/ha plot. Biomass from *Elymus canadensis* in all three of these herbicide treatments was statistically similar to the untreated check.

There were some general numerical trends in the data. One numerical trend observed was that many of the monocot species, had below average biomass for the September applications of imazapyr and imazapic at 0.22 kg a.i/ha. Numerically biomass from the cool season grasses was below average in the July applications of rimsulfuron. Overall, biomass indicated monocot species were relatively tolerant to the soil applied herbicides tested and only four instances occurred where monocot biomass was less than 60% of the untreated check.

Dicot species biomass: soil herbicide applications

Biomass for dicot species in soil residual herbicide tolerance treatments can be viewed in Table 1.14 (Appendix Table A.1.14 is color coded). Few statistical differences in biomass were detected between herbicide treatments for individual species.

Linum perenne biomass in the July chlorsulfuron plots were statistically similar ($p>.05$) to imazapyr, imazapic at 0.22 kg ai/ha, and rimsulfuron. *Linum perenne* biomass in the July chlorsulfuron plots were statistically lower than biomass from all other herbicide treatments and the untreated check. Biomass from all other herbicide treatments were similar to one another, and similar to the untreated check. *Linum perenne* numerically accumulated no measurable biomass in the September chlorsulfuron treatment, and very low biomass in the metsulfuron treatment, however, these biomass values were not statistically different from the untreated check due to high variation within treatments.

For the July applications, no statistical differences in biomass between herbicide treatments existed for *Ratibida columnifera.* Within the September application timing, *Ratibida columnifera* treated with quinclorac had a greater biomass than when treated with chlorsulfuron or metsulfuron. All other September herbicide treatments had statistically similar biomass for *Ratibida columnifera.*

Generally, there were some numerical trends in dicot species biomass within the soil applied herbicide applications. Biomass for all dicot species in chlorsulfuron applications, except *Gaillardia* spp. in September, had numerically lower biomass than the untreated checks. Numerically, *Atriplex canescens*, and *Ratibida columnifera* had above average biomass for both quinclorac application timings. There were 24 instances where dicot species biomass was numerically less than 60% of the untreated check and there were 120 instances where dicot species biomass numerically was greater than 60% of the untreated check. This indicates that dicot species generally were relatively tolerant to soil applied herbicide applications. However, certain species*herbicide combinations resulted in numerically lower biomass compared to the untreated check, where in two instances dicot species accumulated no biomass. These numerical reductions are presented in Table 1.14 (Appendix Table A.1.14).

Monocot species biomass: foliar herbicide applications

From the foliar herbicide applications, monocot species biomass and statistical differences are presented in Table 1.15 (Appendix Table A.1.15). There were very few statistical differences between foliar herbicide treatments for the majority of monocot species tested.

A few statistical differences in biomass were detected for *Elymus canadensis* in the July foliar herbicide applications. *Elymus canadensis* treated with imazapic at the 0.22 kg ai/ha rate had lower biomass than fluroxypyr, aminocyclopyrachlor 0.03 kg ai/ha and 2-4,D amine. *Elymus canadensis* treated with fluroxypyr had higher biomass than plants treated with tebuthiuron. Biomass of *Elymus canadensis* for all other herbicide treatments were statistically similar to each other, additionally no treatments had biomass different than the untreated check.

Over all monocot species and herbicides, all biomass values were statistically similar with the untreated check. This indicates relatively good tolerance for the monocot restoration species tested to the foliar herbicide applications tested. In instances of planting monocot restoration species, many products could be available to help reduce completion from non-planted species.

There were some general numerical trends apparent in the monocot species foliar applications biomass. All monocot species, except *Bouteloua gracilis,* numerically had less biomass than the untreated check for imazapic applications at both rates in July. This was especially apparent for the cool season species at the higher rate of imazapic. Conversely, this trend was not apparent for the September application timing of imazapic. Cool season grasses treated with fluroxypyr, and chlorsulfuron in July, numerically had above average biomass. This trend was not apparent for fluroxypyr and chlorsulfuron in the September application timing. Across all monocot species and herbicides there were only 15 numerical instances where biomass was less than 60% of the untreated check. Generally monocot species were tolerant to both timings of foliar herbicide applications, as was indicated by no monocot species being completely killed by any foliar herbicide application.

Dicot species biomass: foliar herbicide applications

Dicot species biomass and statistical differences from foliar herbicide treatments are presented in Table 1.16 (Appendix Table A.1.16 is a color coded version). Certain foliar herbicide applications to dicot species resulted in drastic reductions in biomass compared to the untreated checks. However ANOVA could not be used for any of the analysis, because none of the data sets met model assumptions. Zero variance in biomass occurred for herbicide treatments that killed dicot species in all three replications. Zero variance for specific treatments resulted in unequal variance between treatments (even with transformation), which is a major assumption of ANOVA. Instead non-parametric Wilcoxon rank sum tests were conducted. These tests often showed statistical differences at the whole model level ($p<.05$); however, when non-parametric Wilcoxon multiple comparisons were conducted no statistical differences in herbicide treatment medians were observed ($p>.05$).

General numerical trends in dicot species biomass from foliar herbicide applications did occur. All dicot species numerically had less biomass that the untreated checks when chlorsulfuron was applied as a foliar application in July. This was not the case in September chlorsulfuron applications, where *Linum perenne* and *Penstemon palmeri* numerically had above average biomass. *Linum perenne* and *Penstemon palmeri* numerically had above average biomass in all of the September sulfonylurea herbicide applications. All other dicot species had below average biomass numerically in the September sulfonylurea herbicide applications. This demonstrates that tolerance to specific herbicides can be variable for species within the same functional group. There were a total of 81 instances where dicot biomass was numerically was less than 60% of the untreated check. In 32 instances dicot biomass was numerically was less than 10% of the untreated check. Generally, many of our foliar herbicide applications were injurious to many of our dicot species. However there were 57 instances where numerically dicot biomass was 90% of the untreated check or greater. This indicates that while some foliar herbicide applications tested were injurious, others were not.

Conclusions

Generally we found that most species were tolerant to multiple herbicides at all four application timings. However no application timing offered complete safety for all species, or all herbicides. As a general rule July applications timings were less injurious than the September application timings, for either the foliar or soil applications. Also, in general, more injury and biomass reduction was observed from the direct foliar applications compared to the soil residual herbicide exposure. All herbicides offered some safety for at least some of the restoration species tested at both soil application timings. This indicates that if any herbicide we tested needs to be selected for control of an undesirable plant species, there would be options for replanting some tolerant restoration species through the soil residue. Likewise, all foliar herbicide applications we tested did not adversely affect all species. This suggests that if a restoration planting had been made, there would be potential herbicides that could be safely used to help release planted restoration species from competition with non-planted weedy species.

Importantly, some instances of low to no tolerance of restoration species to products tested were found. Finding the lack of tolerance of a particular species, to a particular product is beneficial. Knowing what species are susceptible to specific herbicide residues can help prevent loss of resources purchasing and planting of seeds that will not establish through that herbicide residue. Likewise, knowing the lack of a species tolerance to a specific herbicide, can prevent that application from being made.

Choosing what herbicide to use, and what species to plant is dependent on many factors such as site, cost, and management objectives. More information about the tolerance of restoration species to herbicides may give land managers additional tools to aid in successful restoration plantings. This study is a good start in developing local information about restoration species herbicide tolerance for Larimer County. This study is by no means a comprehensive test of these restoration species tolerance within our local area. It would be beneficial for similar research to be conducted both locally and in other areas.

One of the additional measures that could have been taken to help improve this study would be to measure herbicide control of non-planted species. Weed control can be one of the major challenges facing restoration plantings. Quantifying weed control by both types of herbicide applications tested, could help land mangers make decisions about which products controlled non planted species, while not injuring planted species. This is important because hand weeding or other weed control methods are not often part of large restoration plantings. If steps are not taken to control weeds in restoration plantings, plantings could fail.

Overall, restoration and reclamation plantings will continue to be conducted in Colorado and elsewhere. The need for plantings is present wherever resource extraction is occurring, and in some instances where invasive weeds are controlled. Herbicides can be used as a tool to help improve the chances of planted species success, but only when tolerance of that species to the application is known. The variation in species tolerance to herbicides can be quite dramatic even within a functional group, which is why more studies are needed on a regional scale. More information about restoration species herbicide tolerance has the potential to assist with successful species establishment from restoration plantings.

TABLES AND FIGURES

Table 1.1: Number of Colorado noxious weed species labeled for control by herbicide tested. Table separated by noxious species lists.

Herbicide	List A	List B	List C	Total
aminopyrlid	3	12	3	18
quinclorac	0	2	4	6
picloram	1	11	4	16
clopyralid	2	8	2	12
2,4-D amine	1	2	4	7
fluroxypyr	0	0	0	0
dicamba	1	12	4	17
metsulfuron	0	9	4	13
rimsulfuron	0	2	3	5
chlorsulfuron	1	8	2	11
imazapic	0	6	5	11
tebuthiuron	3	3	4	10
imazapyr	1	4	7	12
Total	13	79	46	138

Table 1.2: Important weeds of Larimer county, and the number of herbicides tested that are labeled for control.		
Latin Name	Common Name	Number of Herbicides
Hieracium aurantiacum L.	orange hawkweed	2
Centaurea solstitialis L.	yellow starthistle	7
Linaria dalmatica (L.) Mill.	broad-leaved Dalmatian toadflax	3
Cirsium vulgare (Savi) Ten.	bull thistle	9
Cirsium arvense (L.) Scop.	Canada thistle	9
Cynoglossum officinale L.	houndstongue	3
Euphorbia esula L.	leafy spurge	4
Carduus nutans L.	musk thistle	8
Centaurea diffusa Lam.	diffuse knapweed	4
Acroptilon repens (L.) DC.	Russian knapweed	6
Centaurea maculosa auct. non Lam.	spotted knapweed	4
linaria vulgaris	yellow toadflax	3
Arctium minus Bernh.	common burdock	7
Verbascum thapsus L.	common mullein	5
Bromus tectorum L.	downy brome	3
Convolvulus arvensis L.	field bindweed	6
Tribulus terrestris L.	puncturevine	3
Abutilon theophrasti Medik.	velvetleaf	6

Table 1.3: Plant species of potential concern in Larimer county labeled for control, regardless of noxious status.				
Trade Name	Active Ingredient	kg a.i./ha	Product rate/acre	Species Controlled
MAT 28	aminocyclopyrachlor	0.03	2 fl oz	No label
MAT 28	aminocyclopyrachlor	0.07	4 fl oz	No label
Milestone	aminopyralid	0.13	7 fl oz	*Centaurea diffusa, Acroptilon repens, Centaurea maculosa, Verbascum thapsus, Dipsacus spp., Cirsium arvense, Cirsium vulgare, Onopordum acanthium, Achillea millefolium, Robinia pseudoacacia, Chondrilla juncea L., Sonchus spp., Centaurea solstitialis, Carduus nutans*
Paramount	quinclorac	0.84	16 oz	*Convolvulus arvensis, Cirsium arvense, Euphorbia esula, Kochia scoparia*
Tordon	picloram	0.58	32 fl oz	*Convolvulus arvensis, Opuntia polyacantha, Centaurea x moncktonii, Centaurea diffusa, Centaurea maculosa, Acroptilon repens, Centaurea virgata, Delphinium spp., Lupinus argenteus, Iva annua, Asclepias syriaca L. , Verbascum thapsus, Amaranthus retroflexus, Salvia aethiopis L., thistle, bull musk, scotch, Canada, wavy leaf, Dalmatian, and yellow toadflax, Cirsium vulgare, Onopordum acanthium, Cirsium undulatum, Linaria dalmatica, Linaria vulgaris*
Transline	clopyralid	0.56	20.8 fl oz	*Cirsium arvense, Carduus nutans, Dipsacus spp., Astragalus spp., Oxytropis spp., Centaurea diffusa, Centaurea maculosa, Acroptilon repens, Xanthium strumarium, Arctium minus*
2,4-D Amine	2,4-D amine	1.09	32 fl oz	*Kochia scoparia, Cirsium vulgare, Carduus nutans, and many other broadleaf weeds*
Vista	fluroxypyr	0.16	12 fl oz	*Galium aparine, Portulaca oleracea, Ranunculus sardous, Apocynum cannabinum, Kochia scoparia, Iva annua, Stellaria spp., Xanthium strumarium, Ambrosia artemisiifolia, Rumex crispus, Taraxacum officinale, Conyza spp. Ipomoea purpurea, Lactuca serriola, Helianthus spp., Vicia spp., Abutilon theophrasti, Ambrosia psilostachya*

Banvel	dicamba	1.15	32 fl oz	*Cardus nutans, Cirsium vulgare, Centaurea diffusa, Centaurea maculosa, Arctium minus, Convolvulus arvensis, Centaurea nigra, Acroptilon repens, Asclepias syriaca, Urtica dioica, Euphorbia esula, Cirsium arvense, Linaria dalmatica, Achillea millefolium*
Habitat	imazapyr	0.58	32 fl oz	*Poa annua, Bromus tectorum, Festuca spp., Setaria spp., Lolium multiflorum, Sorghum halepense, Poa pratensis, Agropyron repens, Cenchrus spp., Sporobulus cryptandrus, Bromus inermis, Avena fatua,, Panicum capillare, Arctium spp., Trifolium spp., Stellaria media, Ambrosia artemisiifolia, Taraxacum officinale, Erodium spp., Erigeron spp., Kochia scoparia, Chenopodium album, Verbascum spp., Chrysanthemum leucanthemum, Lepidium spp., Amaranthus spp., Tribulus terrestris, Salsola kali, Helianthus spp., Melilotus spp., Ambrosia psilostachya, Daucus carota, Lactuca spp.*
Escort	metsulfuron	0.04	1 oz	*Cirsium vulgare, Carduus nutans, Sisymbrium altissimum L., Verbascum thapsus, Convolvulus arvensis, Cynoglossum officinale, Lupinus argenteus, Lythrum salicaria, Onopordum acanthium*
Matrix	rimsulfuron	0.07	4 oz	*Echinochloa crus-galli, Bromus tectorum, Digitaria sanguinalis, Setaria faberi, Seteria glauca, Erodium cicutarium, Conyza bonariensis, Malva neglecta, Conyyza canadensis, Taeniatherum caput-medusae, Brassica nigra, Amaranthus retroflexus, Amaranthus hybridus, Tribulus terrestris*
Telar	chlorsulfuron	0.05	1 oz	*Verbascum thapsus, Onopordum acanthium, Cirsium arvense, Carduus nutans, Carduus nutans, Cynoglossum officinale, Achillea millefolium, Salsola tragus*
Plateau	imazapic	0.22	12 fl oz	*Galium aparine, Xanthium strumarium, Chenopodium album, Halogeton glomeratus, Amaranthus retroflexus, Daucus carota, Abutilon theophrasti, Bromus tectorum L., Digitaria spp. , Setaria viridis, Aegilops cylindrica, Sorghum halepense, Taeniatherum crinitum, Cenchrus, Sorghum bicolor ,*

				Gypsophila spp., Convolvulus arvensis, Xanthium strumarium, Stellaria spp., Taraxacum officinale, Rumex crispus, Cynoglossum officinale, Datura stramonium, Acroptilon repens, Polygonum aviculare, Kochia scoparia, Ipomoea purpurea, Lepidium latifolium, Tribulus terrestris, Euphorbia esula, Euphorbia dentata , Dipsacus spp., Cirsium vulgare, Cardus nutans, Lepidium draba, Elymus elymoides, Echinochloa spp., Phalaris canariensis, Avena fatua
Plateau	imazapic	0.11	6 fl oz	*Galium aparine, Xanthium strumarium, Chenopodium album, Halogeton glomeratus, Amaranthus retroflexus, Daucus carota, Abutilon theophrasti, Bromus tectorum L., Digitaria spp. , Setaria viridis, Aegilops cylindrica, Sorghum halepense, Taeniatherum crinitum, Cenchrus, Sorghum bicolor*
Spike	tebuthiuron	0.34	6 oz	*Bromus spp., Brassica spp., Ranunculus testiculatus*

Table 1.4: Herbicides and applications rates applied to test species tolerance to soil residual herbicide residues.			
Trade Name	Active Ingredient	kg ai/ha	Product rate/acre
MAT 28	aminocyclopyrachlor	0.07	2 fl oz
MAT 28	aminocyclopyrachlor	0.14	4 fl oz
Milestone	aminopyrlid	0.13	7 fl oz
Paramount	quinclorac	0.84	16 oz
Tordon	picloram	0.58	32 fl oz
Transline	clopyralid	0.56	20.8 fl oz
Escort	metsulfuron	0.04	1 oz
Matrix	rimsulfuron	0.07	4 oz
Telar	chlorsulfuron	0.05	1 oz
Habitat	imazapyr	0.58	32 fl oz
Plateau	imazapic	0.22	12 fl oz
Plateau	imazapic	0.11	6 fl oz
Untreated check	NA	NA	NA
All treatments applied with 0.5 % v/v NIS except Paramount – MSO @ 32 fl oz/acre			

Table 1.5: Herbicides and applications rates applied to test species tolerance to direct foliar applications.			
Trade Name	Active Ingredient	kg ai/ha	Product rate/acre
MAT 28	aminocyclopyrachlor	0.07	2 fl oz
MAT 28	aminocyclopyrachlor	0.14	4 fl oz
Milestone	aminopyrlid	0.13	7 fl oz
Paramount	quinclorac	0.84	16 oz
Tordon	picloram	0.58	32 fl oz
Transline	clopyralid	0.56	20.8 fl oz
2,4-D Amine	2,4-D amine	1.09	32 fl oz
Vista	fluroxypyr	0.16	12 fl oz
Banvel	dicamba	1.15	32 fl oz
Escort	metsulfuron	0.04	1 oz
Matrix	rimsulfuron	0.07	4 oz
Telar	chlorsulfuron	0.05	1 oz
Plateau	imazapic	0.22	12 fl oz
Plateau	imazapic	0.11	6 fl oz
Spike	tebuthiuron	0.34	6 oz
Untreated check	NA	NA	NA
All treatments applied with 0.5 % v/v NIS except Paramount – MSO @ 1 qt/acre			

Table 1.6: Restoration species planted common name, Latin name and seeding rate in kg seed/ha.		
Dicot Species	Latin Name	kg seed/ha
blue flax	*Linum perenne* L.	6.3
blackeye susan	*Rudbeckia hirta* L.	5.4
blanket flower	*Gallardia* spp.	3.2
prairie coneflower	*Ratibida columnifera* (Nutt.) Woot. & Standl.	6.4
Palmer's penstemon	*Penstemon palmeri* A. Gray	4.5
scarlet globemallow	*Sphaeralcea coccinea* (Nutt.) Rydb.	3.2
western yarrow	*Achillea lanulosa* Nutt.	4.3
four winged saltbush	*Atriplex canescens* (Pursh) Nutt.	12.1
Monocot Species	Latin Name	kg seed/ha
western wheatgrass	*Pascopyrum smithii* (Rydb.) Á. Löve	1.8
slender wheatgrass	*Elymus trachycaulus* (Link) Gould ex Shinners	1.8
Canada wildrye	*Elymus canadensis* L.	1.8
green needlegrass	*Nassella viridula* (Trin.) Barkworth	2
little bluestem	*Schizachyrium scoparium* (Michx.) Nash	3.5
sideoats grama	*Bouteloua curtipendula* (Michx.) Torr.	2.4
switchgrass	*Panicum virgatum* L.	1.5
blue grama	*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths	3.5

Table 1.7: 2011 monocot species stand counts initial percent frequency averaged across entire study site		
Monocot Species	Mean	Std Dev
Elymus Canadensis	40	20
Elymus trachycaulus	85	14
Nassella viridula	38	21
Pascopyrum smithii	23	18
Bouteloua gracilis	57	24
Panicum virgatum l.	34	22

Table 1.8: 2011 dicot species stand initial percent frequency averaged across entire study site		
Dicot Species	Mean	Std Dev
Rudbeckia hirta	86	23
Gallardia spp.	28	18
Linum perenne	73	28
Atriplex canescens	38	21
Penstemon palmeri	24	18
Ratibida columnifera	34	21
Achillea lanulosa	74	26

Table 1.9: Monocot species soil residual herbicide tolerance, 2011 initial percent frequency. Statistics were ran for each species and application timing comparing percent frequency between herbicide treatments. Statistical differences are denoted with letters by column (p<.05), N/S indicated no detectable differences. ANOVA or WILCOX, indicate which statistical analysis was used for the respective column.

	Elymus Canadensis		*Elymus trachycaulus*		*Nassella viridula*		*Pascopyrum smithii*		*Bouteloua gracilis*		*Panicum virgatum l.*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	40	45	85	93	60	22	28	30	68	50	35	18
aminocyclopyrachlor .03	28	45	88	67	65	45	33	23	80	53	33	32
aminopyralid	57	43	90	88	53	35	45	20	42	72	27	45
quinclorac	33	42	88	70	48	35	28	15	65	58	27	28
picloram	42	50	98	80	60	15	55	38	73	57	60	57
clopyralid	63	45	88	83	33	48	42	30	57	62	32	53
metsulfuron	53	43	90	80	42	27	53	33	65	67	42	22
rimsulfuron	77	40	98	70	62	13	20	10	77	60	47	17
chlorsulfuron	62	68	100	70	52	35	48	25	75	45	35	12
imazapyr	50	35	97	80	65	33	37	8	80	27	38	30
imazapic .22	58	50	100	67	57	27	60	12	72	55	67	20
imazapic .11	37	28	93	78	28	25	33	12	78	75	63	23
untreated	45	55	95	60	42	18	22	15	70	57	28	23
	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S
	ANOVA	WILCOX	WILCOX	WILCOX	ANOVA	ANOVA	ANOVA	ANOVA	WILCOX	WILCOX	ANOVA	ANOVA

Table 1.10: Dicot species soil residual herbicide tolerance, 2011 initial percent frequency. Statistics were ran for each species and application timing comparing percent frequency between herbicide treatments. Statistical differences are denoted with letters by column (p<.05), N/S indicated no detectable differences. ANOVA or WILCOX, indicate which statistical analysis was used for the respective column.

	Achillea lanulosa		*Atriplex canescens*		*Gaillardia spp.*		*Linum perenne*		*Penstemon palmeri*		*Ratibida columnifera*		*Rudbeckia hirta*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	83	90	63	50 a	23	30	77	70	47	33	48	28	92	78
aminocyclopyrachlor .03	70	85	30	30 ab	27	22	93	85	7	22	38	25	95	93
aminopyralid	63	80	57	53 ab	17	28	92	88	23	25	10	13	100	40
quinclorac	88	90	63	61 ab	10	30	90	23	18	17	30	35	97	83
picloram	72	68	38	25 ab	20	15	58	63	22	33	28	15	75	23
clopyralid	63	90	32	38 ab	32	25	90	88	23	27	27	32	87	77
metsulfuron	90	28	63	38 ab	25	8	53	0	63	3	38	2	82	5
rimsulfuron	90	37	67	56 ab	27	5	82	13	67	13	62	3	97	53
chlorsulfuron	78	7	13	0 b	32	12	0	0	12	0	17	0	88	65
imazapyr	65	78	58	15 ab	25	8	57	47	30	10	28	28	93	15
imazapic .22	93	85	48	15 ab	17	20	55	18	27	0	55	33	95	78
imazapic .11	85	72	63	43 ab	30	23	82	37	37	12	52	27	97	88
untreated	73	97	28	50 ab	17	35	80	85	17	27	28	52	92	73
	N/S	N/S	N/S		N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S
	WILCOX	WILCOX	ANOVA	WILCOX	ANOVA	ANOVA	WILCOX	WILCOX	WILCOX	WILCOX	ANOVA	WILCOX	WILCOX	WILCOX

Table 1.11: Monocot species foliar herbicide tolerance, percent relative frequency change from 2011 to 2012. Statistics were ran for each species and application timing comparing percent relative frequency change between herbicide treatments. Statistical differences are denoted with letters by column (p<.05), N/S indicated no detectable differences. ANOVA or WILCOX, indicate which statistical analysis was used for the respective column.

	Elymus Canadensis		*Elymus trachycaulus*		*Nassella viridula*		*Pascopyrum smithii*		*Bouteloua gracilis*		*Panicum virgatum l.*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	444 ab	422	10	2	58	161	467	647	30	9	111	145
aminocyclopyrachlor .03	316 ab	607	10	44	110	183	440	733	40	35	264	136
aminopyralid	181 ab	205	14	10	58	93	762	733	241	81	133	219
quinclorac	300 ab	752	28	31	86	61	733	733	61	29	444	386
picloram	285 ab	155	5	11	64	57	833	556	15	19	129	198
clopyralid	303 ab	333	29	20	81	23	700	389	17	193	239	144
2,4-D amine	97 b	224	3	5	65	98	193	511	27	25	88	77
fluroxypyr	120 ab	151	18	11	103	76	456	433	83	28	100	71
dicamba	190 ab	262	15	12	40	85	298	429	43	15	137	206
metsulfuron	211 ab	303	15	31	99	20	400	483	14	26	104	122
rimsulfuron	911 a	95	32	18	14	31	326	283	15	78	64	112
chlorsulfuron	96 ab	168	9	23	-7	67	817	922	155	8	119	117
imazapic.22	148 b	245	-4	5	-45	106	133	289	18	15	39	91
imazapic.11	119 ab	550	22	12	-19	0	544	333	63	5	63	121
tebuthiuron	52 b	72	10	17	80	192	125	391	179	34	127	268
untreated	91 ab	238	12	2	326	96	839	311	41	9	301	48
		N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S
	ANOVA	ANOVA	WILCOX	ANOVA	WILCOX	WILCOX	WILCOX	WILCOX	WILCOX	WILCOX	WILCOX	ANOVA

Table 1.12: Dicot species foliar herbicide tolerance, percent relative frequency change from 2011 to 2012. Statistics were ran for each species and application timing comparing percent relative frequency change between herbicide treatments. Statistical differences are denoted with letters by column (p<.05), N/S indicated no detectable differences. ANOVA or WILCOX, indicate which statistical analysis was used for the respective column.												
	Achillea lanulosa		*Atriplex canescens*		*Gallardia spp.*		*Linum perenne*		*Penstemon palmeri*		*Ratibida columnifera*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	68	-100	278 ab	196	-53	-100	2	-72	275 abc	48	128 abc	-100 c
aminocyclopyrachlor .03	81	-33	178 ab	298	-85	-100	2	-36	172 ab	435	84 ab	-71 abc
aminopyralid	16	-100	89 ab	385	-61	-83	2	-27	80 bcdef	94	-44 abc	-100 abc
quinclorac	55	18	113 ab	532	30	13	-5	93	-22 ef	-33	59 abc	-65 abc
picloram	-25	-100	103 ab	25	-53	-87	-14	-89	350 abcdef	-28	-78 c	-100 abc
clopyralid	-100	-100	45 ab	387	-56	-31	8	2	403 a	250	-92 bc	-100 abc
2,4-D amine	33	17	0 ab	46	-39	-63	-2	-11	177 abc	0	52 abc	55 ab
fluroxypyr	112	108	156 ab	189	45	0	-28	-14	244 abcd	238	71 abc	56 ab
dicamba	21	-92	19 ab	192	-60	23	-9	-50	156 abcde	-34	75 abc	-100 bc
metsulfuron	-100	-100	57 b	189	-78	-100	-4	-10	53 cdef	219	-74 bc	-100 c
rimsulfuron	45	20	717 a	114	4	160	0	22	229 abcd	170	201 ab	115 a
chlorsulfuron	-43	-94	180 ab	131	-19	10	-6	-15	23 bcdef	171	-46 abc	-80 abc
imazapic.22	39	50	199 ab	265	-41	-67	6	-4	-50 def	57	83 ab	-39 abc
imazapic.11	42	-7	67 ab	325	18	-41	3	-23	-8 bcdef	58	86 abc	56 ab
tebuthiuron	-11	3	121 ab	148	23	83	2	4	-93 f	52	227 ab	64 a
untreated	41	50	235 ab	248	-7	219	14	42	356 abc	111	209 a	125 a
	N/S	N/S		N/S	N/S	N/S	N/S	N/S		N/S		
	WILCOX	WILCOX	ANOVA	ANOVA	ANOVA	WILCOX	WILCOX	WILCOX	ANOVA	WILCOX	ANOVA	ANOVA

Table 1.13: Monocot species soil residual herbicide tolerance dry biomass kg/m^2. Statistics were ran for each species and application timing comparing biomass between herbicide treatments. Statistical differences are denoted with letters by column (p<.05), N/S indicated no detectable differences. ANOVA or WILCOX, indicate which statistical analysis was used for the respective column.

	Elymus Canadensis		*Elymus trachycaulus*		*Nassella viridula*		*Pascopyrum smithii*		*Bouteloua gracilis*		*Panicum virgatum l.*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	4.4 a	3.9	1.8	2.4	1.8	1.2	4.9	2.3	2.0	2.0	0.6	1.2
aminocyclopyrachlor .03	1.9 b	3.7	2.3	1.9	2.3	1.7	3.2	4.2	1.9	1.7	0.8	2.6
aminopyralid	3.3 ab	3.8	1.8	1.7	1.0	1.5	2.8	3.1	1.5	2.1	0.8	3.2
quinclorac	3.5 ab	3.9	1.9	2.0	1.3	1.1	3.7	3.2	2.2	1.9	1.4	2.3
picloram	3.2 ab	3.5	1.7	2.1	1.5	1.2	1.8	3.9	1.7	2.0	1.5	3.0
clopyralid	3.9 ab	3.6	2.0	2.0	1.7	1.1	3.1	3.0	1.2	1.8	1.0	2.8
metsulfuron	3.1 ab	4.5	1.6	1.8	1.6	1.3	3.9	3.6	1.2	2.1	1.7	1.9
rimsulfuron	2 b	3.7	1.4	2.1	1.1	1.0	2.2	3.6	2.2	1.9	1.6	1.8
chlorsulfuron	3.1 ab	3.9	1.4	1.7	1.1	1.0	3.7	3.2	2.6	2.1	1.2	1.5
imazapyr	3.4 ab	2.6	1.7	1.3	1.4	0.6	3.5	2.1	2.3	1.3	1.5	1.3
imazapic .22	4.1 ab	3.8	1.7	1.3	1.3	0.7	3.8	1.4	1.6	1.2	2.3	1.6
imazapic .11	3.8 ab	4.3	2.5	1.7	1.7	1.1	3.9	3.3	1.5	2.0	2.8	1.8
untreated	3.6 ab	4.2	2.2	2.0	1.4	1.0	3.1	3.4	1.8	1.7	0.7	1.8
		N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S
	ANOVA	ANOVA	ANOVA	ANOVA	WILCOX	WILCOX	ANOVA	ANOVA	ANOVA	ANOVA	ANOVA	WILCOX

Table 1.14: Dicot species soil residual herbicide tolerance dry biomass kg/m^2. Statistics were ran for each species and application timing comparing biomass between herbicide treatments. Statistical differences are denoted with letters by column (p<.05), N/S indicated no detectable differences. ANOVA or WILCOX, indicate which statistical analysis was used for the respective column.

	Achillea lanulosa		*Atriplex canescens*		*Gallardia spp.*		*Linum perenne*		*Penstemon palmeri*		*Ratibida columnifera*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	2.3	2.4	5.8	4.5	1.8	0.6	1.4 a	1.8	1.5	1.1	1.6	2.6 ab
aminocyclopyrachlor .03	1.8	2.1	3.9	3.7	2.1	1.1	1.4 a	1.4	0.4	1.1	1.7	1.9 ab
aminopyralid	2.1	2.2	4.9	4.5	1.8	3.0	1.3 a	1.8	0.6	1.3	1.5	1.9 ab
quinclorac	1.9	2.1	5.8	5.8	1.4	1.4	1.3 a	1.0	0.8	0.8	2.5	3.2 a
picloram	1.4	2.3	5.1	2.9	1.0	2.0	1.2 a	1.3	0.2	1.5	1.1	2.2 ab
clopyralid	2.4	2.1	3.9	4.3	2.6	2.8	1.4 a	1.8	0.5	0.7	1.4	2.3 ab
metsulfuron	2.1	1.6	5.8	4.3	1.4	1.1	1.3 a	0.1	1.5	0.9	2.2	1.1 b
rimsulfuron	1.3	2.3	4.5	5.7	1.6	1.0	1.0 ab	0.8	1.3	1.4	1.4	1.3 ab
chlorsulfuron	1.9	1.0	1.6	2.3	1.9	2.2	0.1 b	0.0	0.6	0.0	1.5	0.7 b
imazapyr	2.0	2.8	6.1	4.4	2.0	0.6	0.9 ab	1.2	1.3	1.3	2.5	2.6 ab
imazapic .22	1.9	2.3	4.1	4.1	1.9	2.6	0.7 ab	0.8	0.9	0.1	2.3	2.6 ab
imazapic .11	2.1	2.2	4.7	4.1	2.0	2.0	1.2 a	1.0	1.1	0.6	1.9	2.4 ab
untreated	2.9	2.5	4.1	4.0	2.4	2.1	1.3 a	1.2	0.7	0.6	2.3	2.1 ab
	N/S	N/S	N/S	N/S	N/S	N/S		N/S	N/S	N/S	N/S	
	ANOVA	ANOVA	WILCOX	ANOVA	ANOVA	WILCOX	ANOVA	WILCOX	WILCOX	WILCOX	ANOVA	ANOVA

Table 1.15: Monocot species foliar herbicide tolerance dry biomass kg/m^2. Statistics were ran for each species and application timing comparing biomass between herbicide treatments. Statistical differences are denoted with letters by column (p<.05), N/S indicated no detectable differences. ANOVA or WILCOX, indicate which statistical analysis was used for the respective column.

	Elymus Canadensis		*Elymus trachycaulus*		*Nassella viridula*		*Pascopyrum smithii*		*Bouteloua gracilis*		*Panicum virgatum l.*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	2.1 abc	3.5	1.8	2.5	1.0	1.7	3.1	2.2	1.8	1.9	1.7	2.6
aminocyclopyrachlor .03	4.3 ab	3.9	2.0	2.7	1.0	1.5	3.3	3.2	1.8	1.9	1.2	3.1
aminopyralid	3.2 abc	5.3	2.2	2.5	1.2	1.8	2.9	4.3	1.7	1.7	2.0	2.9
quinclorac	3.4 abc	5.0	2.4	2.2	1.5	2.1	2.7	2.5	1.6	1.7	1.7	2.1
picloram	3.5 abc	3.5	1.7	2.7	1.4	2.0	3.3	3.6	1.5	1.9	1.2	3.2
clopyralid	3.4 abc	3.8	1.9	1.4	1.0	1.5	2.1	3.7	1.6	1.7	1.6	3.2
2,4-D amine	4.1 ab	4.1	2.2	2.5	1.1	2.2	2.7	4.4	1.4	2.6	1.3	4.0
fluroxypyr	5.2 a	4.8	2.1	2.1	1.5	1.4	4.3	4.0	1.9	1.8	1.7	1.7
dicamba	3.7 abc	4.5	2.1	2.5	1.3	1.7	3.5	3.2	1.6	2.0	1.1	2.5
metsulfuron	2.9 abc	4.3	2.0	2.7	1.2	1.3	3.3	3.6	2.1	2.1	1.8	2.3
rimsulfuron	2.3 abc	5.0	1.4	2.3	1.1	1.2	1.6	2.2	1.7	1.6	0.4	2.1
chlorsulfuron	4.0 abc	5.2	2.0	2.6	1.5	1.3	3.7	3.6	1.6	1.4	1.3	2.2
imazapic.22	1.0 c	2.4	1.0	2.5	0.3	0.9	0.6	2.8	1.5	2.1	0.7	2.1
imazapic.11	2.9 abc	3.3	1.8	2.6	0.4	2.0	1.1	2.0	1.4	2.1	0.7	2.3
tebuthiuron	2.0 bc	3.6	2.0	2.1	1.6	1.5	1.2	1.3	2.2	2.1	2.0	1.6
untreated	3.5 abc	4.2	2.3	2.9	1.1	1.3	1.9	3.6	1.1	1.6	1.6	1.9
		N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S
	ANOVA	ANOVA	ANOVA	WILCOX	ANOVA	WILCOX	WILCOX	ANOVA	WILCOX	ANOVA	ANOVA	ANOVA

Table 1.16: Dicot species foliar herbicide tolerance dry biomass kg/m^2. Statistics were ran for each species and application timing comparing biomass between herbicide treatments. Statistical differences are denoted with letters by column (p<.05), N/S indicated no detectable differences. ANOVA or WILCOX, indicate which statistical analysis was used for the respective column.

	Achillea lanulosa		*Atriplex canescens*		*Gallardia spp.*		*Linum perenne*		*Penstemon palmeri*		*Ratibida columnifera*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	3.1	0.0	4.0	7.5	0.0	2.3	1.9	0.3	0.8	1.6	0.6	0.0
aminocyclopyrachlor .03	4.3	0.8	3.6	5.6	0.4	0.1	2.0	1.0	1.5	3.0	3.1	0.0
aminopyralid	2.0	0.0	6.5	6.2	0.7	0.7	2.1	1.8	1.9	1.8	0.1	0.0
quinclorac	2.7	3.9	7.1	4.5	1.4	2.3	1.7	0.0	0.4	0.2	2.4	0.3
picloram	1.3	0.0	2.7	8.5	0.5	0.6	1.7	0.3	0.5	1.0	0.0	0.0
clopyralid	0.0	0.0	6.2	7.4	0.7	1.7	1.8	2.4	2.1	2.0	0.1	0.0
2,4-D amine	3.6	4.6	2.6	2.9	0.5	0.9	1.7	2.2	0.6	0.0	1.5	1.2
fluroxypyr	3.4	3.1	6.2	8.2	1.3	0.4	1.4	1.7	1.7	1.7	1.4	1.3
dicamba	1.1	0.2	2.7	4.8	0.1	2.3	2.4	0.8	1.5	0.8	0.3	0.0
metsulfuron	0.0	0.0	1.5	4.2	0.0	0.0	2.3	2.1	0.5	2.1	0.4	0.0
rimsulfuron	2.7	2.5	7.3	5.4	2.2	0.8	1.9	2.4	1.7	2.5	1.8	0.7
chlorsulfuron	1.0	0.0	5.2	5.8	0.9	0.4	1.6	2.1	0.3	2.0	0.6	0.2
imazapic.22	2.3	3.6	4.7	5.6	0.8	0.2	1.3	2.1	0.1	0.5	2.3	0.6
imazapic.11	2.7	2.9	7.0	7.6	1.2	1.0	1.3	2.5	0.2	1.0	1.9	2.2
tebuthiuron	1.4	0.4	5.0	7.4	3.7	1.9	1.8	2.6	0.0	0.0	3.6	3.3
untreated	3.2	3.2	5.7	6.5	2.1	3.0	2.2	1.7	1.0	1.0	2.5	4.4
	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S	N/S
	WILCOX	WILCOX	ANOVA	ANOVA	WILCOX	WILCOX	ANOVA	WILCOX	WILCOX	WILCOX	WILCOX	WILCOX

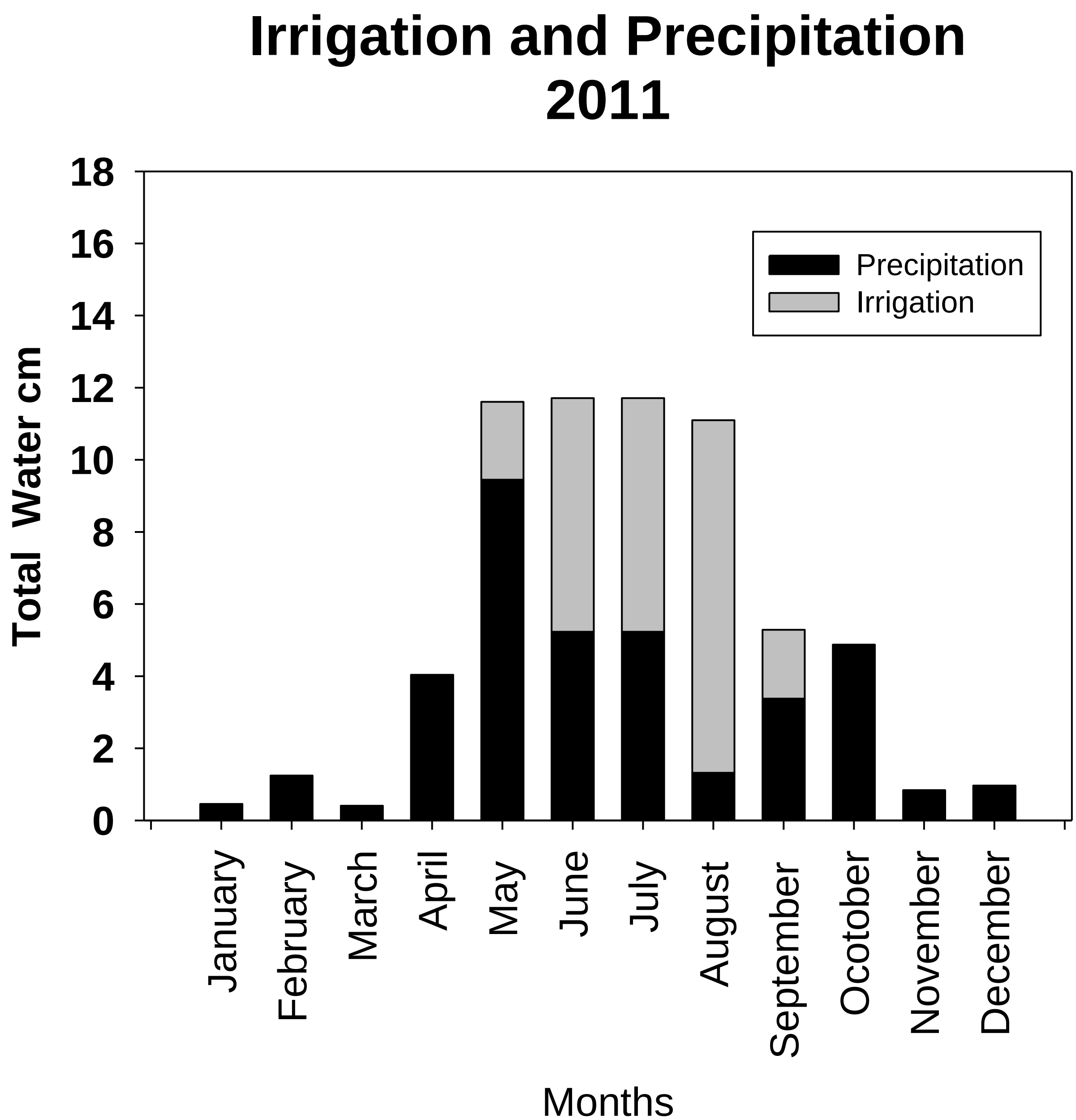

Figure 1.1: 2011 precipitation recorded by a weather station adjacent to the field site, and irrigation applied at the Horticulture Research Farm.

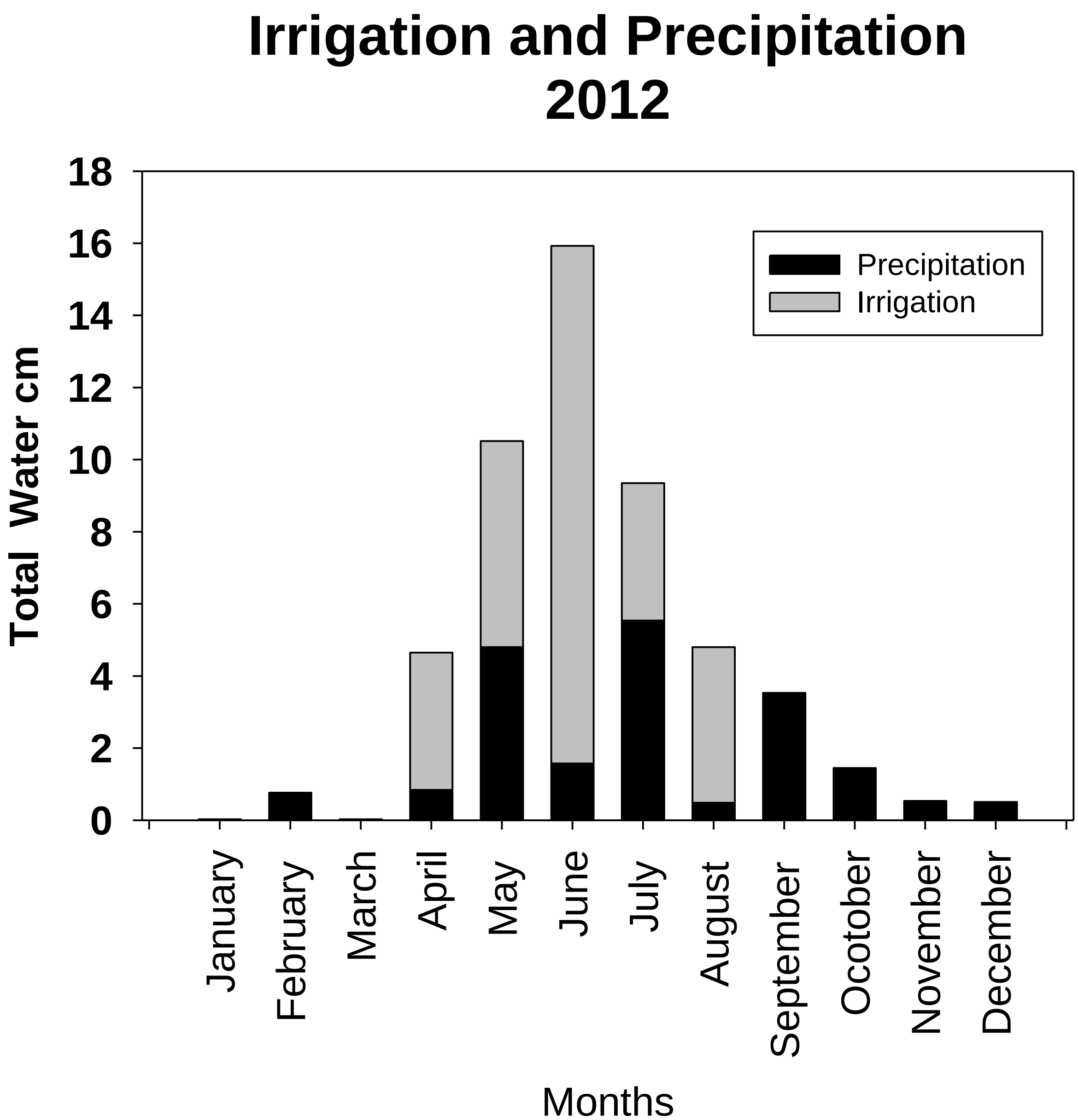

Figure 1.2: 2012 precipitation recorded by a weather station adjacent to the field site, and irrigation applied at the Horticulture Research Farm.

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CHAPTER 2: CUT STUMP RUSSIAN OLIVE CONTROL

Introduction

Many states require management of certain invasive weed species. Russian olive (*Eleaguns angustifolia* L.) is considered noxious in Colorado, Wyoming, New Mexico, Connecticut, and select counties in Utah and Montana (Montana Audubon 2010; NRCS 2014). There are many different methods used to control Russian olive stands, including a combination of mechanical removal and chemical treatment of the stump. Cut stump treatments are chosen when leaving Russian olive biomass on site is not acceptable, and to eliminate new Russian olive biomass production.

Russian olive is an invasive woody species originally from Eurasia, widely planted during the early 1900's in North America to provide windbreaks, soil stabilization, and wildlife habitat (Olsen and Knopf 1986; Katz 2003; Stannard et al. 2002; and others). Currently it is the fourth most common tree within riparian areas of the Western United States (Friedman et al. 2005). A multitude of factors have given Russian olive a competitive advantage in these ecosystems: drought tolerance, salt tolerance, shade tolerance, and regulated flow regimes of rivers in the Western United States (Lessica and Miles 2001; and others). Russian olive has been shown to successfully germinate in conditions that are both favorable, and unfavorable to cottonwoods, giving it an establishment advantage (Shafroth et al. 1995). Russian olive seed dispersal can be facilitated by wildlife, water, and gravity among other vectors (Tu 2003). It has been postulated that Russian olive has slow propagule dispersal, but the range of Russian olive establishment is still expanding (Friedman et al. 2005).

Russian olive is thought to be beneficial to certain wildlife species and detrimental to others. Native vegetation often has higher diversity of arthropods compared to Russian olive stands (Bateman and Paxton 2009). Bird diversity has been shown to be lower in Russian olive stands compared with native vegetation, in particular cavity dwelling and insectivorous bird species (Knopf and Olsen 1984). Beaver preferentially eat native woody phreatophytes when available instead of Russian olive (Lessica and Miles 2001). Large ungulates will eat Russian olive seedlings, but large thorns deter browsing in the sapling growth stage (Pearce and Smith 2001; Creech and Rafferty 2007; Forest Service 2012). Russian olive forms a relationship with *Frankia* spp., a nitrogen fixing bacteria (Zitzer and Dawson 1989). DeCant (2008) found more organic matter and nitrogen under Russian olive stands compared to cottonwood stands.

Currently there are no biological control species for Russian olive. There are 17 species being studied with potential releases coming in 2020 (O'Meara et al. 2009). Physical control methods such as pulling, bulldozing, excavating, chaining and mowing can be used to control Russian olive (Zouhar 2005, and Forest Service 2012). However this tree has the ability to resprout after being cut or broken leading to the need for follow up treatments (O'Meara et al. 2009). Further mechanical treatments often result in increased erosion and water sedimentation (O'Meara et al. 2009). Chemical control can be used alone in broadcast foliar applications, or targeted basal bark applications (O'Meara et al. 2009). High off target impacts often occur from broadcast applications, because both desirable and undesirable species will be sprayed (Zouhar 2005). Hack and squirt applications and cut stump applications, are treatments that combine mechanical and chemical methods. Hack and squirt applications consist of making incisions around the bole of the tree, and applying low volumes of herbicide to the wound. Cut stump treatments consist of cutting the bole of the tree at the ground level and applying herbicides to the cambial layer of the stump. Both can be highly effective for controlling Russian olive (Stannard et al. 2002; and Forest Service 2012). However only cut stump treatments facilitate the removal of aboveground biomass.

Imazapyr, triclopyr and glyphosate are used for Russian olive cut stump applications (Forest Service 2012). Aminocyclopyrachlor is a relatively new compound with unknown effectiveness for controlling large Russian olive trees. A study was designed to investigate the effectiveness of aminocyclopyrachlor compared to commonly used triclopyr, imazapyr, and glyphosate cut stump herbicide applications to Russian olive. This study was conducted in Northern Colorado working in conjunction with Boulder and Larimer Counties where Russian olive is designated a noxious weed.

Material and Methods

Locations

Studies were conducted at three sites along the urban front range of Northern Colorado: two under conservation easements with Boulder County (7 mile ranch and RD. 16.5), and a third at Curtis lake in Larimer County. All sites were in the riparian zone, and close to streams, ditches and lakes or ponds. The USGS soil classifications for the three sites were: Loveland soils, aquells and aquents, gravel substrate, Bankard sandy loam, and Longmont clay. A wide range of soil textures existed ranging from 1-50% clay, 2-32% silt, 22-97% sand, and 0-3% organic matter. Site elevation ranged from 1494 m to 1560 m. Cottonwoods were present at all sites, where Russian olive were established inside and outside the understory canopy. Study sites supported a wide range of obligate wetland, facultative, and upland plant species.

Applications:

Trees were cut, and stumps were left standing 2-4 ft. tall. Stump circumference was measured at ground level. The Russian olive trees at all three sites were relatively large, with an average stump diameter of 33cm, a standard deviation of 13cm, and a range of 11 to 97cm. Trees were placed into four stump diameter size classes 10-20 cm, 20-30cm, 30-40cm and 40cm+ (Table 2.1). Equal numbers of trees in each size class were randomly assigned to each treatment, at each study site, based on availability of trees at each site. Each treatment was replicated based on the number of trees available at each site with 3, 5, and 31 trees at 7mile, Curtis Lake, and Rd. 16.5 respectively.

Stumps were cut with a chainsaw near the ground level. Within 5 minutes, herbicide applications were made using a ZEP® 30oz hand squirt bottle. Five ml of herbicide solution were applied for every 2.5cm of stump circumference. Herbicides were applied to the cambial layer of the stump, as well as the shoulder of the stump down to the ground. Herbicide solutions were comprised of a v/v ratio of herbicide product into a vegetable based JLB basal bark oil (Brewer International, www.brewerint.com). The treatments were 20% Garlon 4 (triclopyr), 8% Habitat (imazapyr), 50% Rodeo (glyphosate), and 10%

MAT128 (aminocyclopyrachlor). For each treatment, Table 2 lists the percent active ingredient of the herbicide solution, the product trade name, percent product of the herbicide solution, and the average g/ai applied to each stump.

Stumps were geo-referenced and marked with cattle tags for easy relocation and identification over the next thirty months. Wood screws and a rechargeable electric drill were used to attach the cattle tags to the stumps.

Data collection

Stumps were relocated every six months for thirty months to collect information on certain parameters. The first measure was to determine stump mortality on a binomial scale of alive or dead. Any green buds or shoots coming off the stump or attached roots signified the stump was alive. If the stump was alive, regrowth was quantified by documenting the average number and height of shoots. The distance from each stump to the nearest stump was measured. Shoots within a radius half the distance to the nearest stump up to maximum radius of 15 ft. were located and measured. On average a 6 ft. radius was evaluated for shoots around each stump.

The radius of inhibition (ROI) was defined as the area of bare soil around the stump and was a measure of off-target impact from the herbicide application. This was quantified by measuring from the edge of the stump to the nearest live non-Russian olive plant life. This measure was taken to quantify the minimum amount of off target impact from our low volume cut stump herbicide applications. Each stump was photographed every six months, to visually capture regrowth, and off target impacts.

Statistics

Mortality

Treated stump survival was measured on a binomial scale 0 or 1. Proc glimmix (generalized linear mixed model) SAS version 9.3 was used to analyze the data. The model assumed data were from a binomial distribution, where it was blocked by study. Differences in herbicide treatments were analyzed at each time point separately, using least squared means and the Tukey pairwise adjustment. One replication of the untreated check was changed to have the value of dead, in order to complete model convergence.

Regrowth

Data for numbers of shoots were analyzed using Wilcoxon/Kruskal Wallis non parametric rank sums test in JMP 11. Only trees that exhibited regrowth were included in the analysis. The non-parametric test was chosen because no data transformation tested corrected the non-normality of the data. All herbicide treatments were averaged together and compared against the untreated check. Non parametric Wilcoxon ranked sum tests were used to compare treated stumps with the untreated check.

Radius of inhibition (ROI)

Untreated trees were excluded from the radius of inhibition analysis, because no herbicide or oil was applied. Radius of inhibition values had a non-normal distribution; however, square root transformation corrected the non-normality. Tukey pair wise comparisons were made using the least square means comparisons, to identify differences among treatments, at each time point. Distribution of square root transformed data appeared normal after looking at studentized residual plots. SAS 9.3 Proc mixed was used to analyze the results. Our mixed linear model examined treatment, size class, time, and the interactions between each pair, as well as the interaction of all three variables. A separate analysis was conducted to analyze radius of inhibition by time averaged across all herbicide treatments.

Cost analysis

Cost analysis was conducted for each of the four herbicides tested. Prices of products were obtained through a local herbicide distributor. Aminocyclopyrachlor is not currently on the market as a solo product. The cost of Streamline (a product that contains aminocyclopyrachlor and metsulfuron) was used to determine the cost of aminocyclopyrachlor while ignoring the minimal cost of metsulfuron.

Results and Discussion

The purpose of this experiment was to determine if aminocyclopyrachlor provided control similar to other herbicides currently used for Russian olive cut stump treatments. Measurements taken 12 months and 24 months after treatment were during the dormant season. In hindsight information collected during the dormant season may have been unreliable because vegetation was not actively growing. Only information collected during the growing season at 6, 18, and 30 MAT will be presented.

Mortality

Size class was not significant at any of the three time points $p>.05$, but treatment was significant, $p<.05$. (More detailed information on mortality and size class can be found in Appendix Figures A.2.6 and A.2.7)

Long term control of invasive perennial species is the management objective when making herbicide applications. Therefore the focus will be on the mortality data 30 months after treatment. Mortality data for 6 months and 18 months can be found in Appendix Figure A.2.1 and Tables A.2.1-A.2.3. Thirty months after treatment 70, 74, 92, 95, and 18 percent of trees were dead for triclopyr, imazapyr, glyphosate, aminocyclopyrachlor, and the untreated check respectively (Figure 2.1). Eighteen percent of the untreated check trees were dead 30 months after treatment. This possibly could be explained by high overbank spring flows in 2011 and 2013 along Boulder Creek, affecting the 7 mile Ranch and RD. 16.5 sites. Some of our trees were flooded and Stannard et al. (2002) states Russian olive does not tolerate prolonged inundation. However because our treatments were randomly distributed, many treated trees also experienced this flooding. Based on the Tukey adjusted p-value, there were no differences among any of the herbicide treatments at alpha .05 (Table 2.3).

All treatments caused higher tree mortality compared to the untreated check $p<.0001$ (Table 2.3 and Figure 2.1). When dealing with a binomial variable and the variability that exists within natural systems, our statistical model was not robust enough to differentiate statistical differences among herbicide treatments. However, from a land manger's perspective, none of our treatments would be ideal, because all had a certain percentage of Russian olive regrowth, necessitating a reapplication to achieve eradication. In terms of a reapplication, treatments with a numerically lower percentage of trees growing would be more desirable, such as aminocyclopyrachlor and glyphosate.

Regrowth

Shoot height analysis was simplified by averaging herbicide treatments together for comparison with the untreated check. This was due partially to the low number of trees that were alive in some herbicide treatments. More detailed information about specific treatment shoot height can be found in the Appendix Figures A.2.2, A.2.3 and Tables A.2.4-A.2.21. Treated trees had statistically shorter shoot height than the untreated check at the 6, 18, and 30 month after treatment time points $p<.05$ (Table 2.4). Untreated Russian olive trees had larger shoot height than treated Russian olive trees at all three time points. Shoot height of treated stumps was approximately 50% of the shoot height of the untreated stumps. This indicates herbicide treatments stunted regrowth, even when mortality was not achieved.

Radius of inhibition (ROI)

Treatment, size class, time, treatment*time, size class*time were significant, p-value$<.05$ (Table 2.5). Treatment*size class and treatment*size class* time did not have significant interactions p-value$>.05$ (Table 2.5). Analysis was conducted for all three study sites, where sites were treated as blocks to account for differences. Tukey pair wise comparisons were used to separate herbicide treatment ROI at each time point.

Six months after treatment, ROI were 21, 21, 35, and 41 cm for glyphosate, triclopyr, imazapyr, and aminocyclopyrachlor respectively. Glyphosate and triclopyr were statistically similar $p>.05$, and imazapyr and aminocyclopyrachlor were statistically similar, $p>.05$. However, the groups were statically different from each other, $p<.05$. ROI means, standard errors and mean separation letters ($p<.05$) can be viewed in Table 2.6 six months after treatment. Averaged across all herbicide treatments ROI six months after treatment was statistically larger than at eighteen and thirty months after treatment, $p<.05$ (Table 7).

It was expected that imazapyr would have a large off-target impact, because it is weakly bound to soil, has a half-life from 25-142 days, and can be absorbed by plant roots (Senseman 2007). It was unknown what off-target impact aminocyclopyrachlor would have. Lindermayer (2012) found a 28 day half-life, where DuPont EI (2009) found a half-life of 72-128 days. Triclopyr is also is not strongly bound to the soil, and has a moderate half-life between 10-46 days (Senseman 2007). It was expected that there would be some off target impact from the triclopyr, but not as much as imazapyr, which is what did occur. Glyphosate binds to soil readily and is not available for plant up take. A ROI was not expected for glyphosate, and it was postulated that the basal bark oil may have had some effect. A pilot study conducted in the greenhouse showed JLB basal bark oil to cause mortality of plants for both pre and post emergence applications (Appendix Figures A.2.8 and A.2.9).

Eighteen months after treatment, average ROI across all herbicide treatments was lower than six months after treatment and higher than thirty months after treatment $p<.05$ (Table 2.7). Tukey pair wise comparisons were made between all treatments. ROI was 10, 15, 23, and 32 cm for glyphosate, triclopyr, imazapyr, and aminocyclopyrachlor respectively (Table 2.8). Glyphosate had a similar ROI to triclopyr, $p>.05$, but a lower ROI than imazapyr and aminocyclopyrachlor, $p<.05$. Triclopyr had a ROI similar to imazapyr $p>.05$. Aminocyclopyrachlor had the largest ROI compared to other herbicide treatments, $p <.05$.

It was unexpected that aminocyclopyrachlor would have a statistically larger ROI than the other treatments. This signifies a larger potential for off-target impact from this molecule. If the maximum half-life estimation by DuPont (2009) is correct, then less than 1/8 of the herbicide that was applied would still be there available for plants, indicating a very active herbicide compound. It was expected that ROI would decrease for all treatments as the herbicides had time to break down in the environment. It was also expected that glyphosate and triclopyr would have low ROI's. This measure signifies that aminocyclopyrachlor has more potential for off-target impact than imazapyr eighteen months after treatment.

Thirty month ROI measurements continued to decline for all treatments, and on average were lower than six and eighteen months after treatment (Table 2.7). Least square means Tukey pair wise comparisons were run to elucidate differences. ROI was 4, 8, 13, and 26 cm for glyphosate, triclopyr, imazapyr, and aminocyclopyrachlor respectively (Table 2.9). Glyphosate had a similar ROI to triclopyr, $p>.05$, but a lower ROI than imazapyr and aminocyclopyrachlor, $p<.05$. Triclopyr had a similar ROI to imazapyr, $p>.05$. Where aminocyclopyrachlor had the largest ROI compared to the other herbicides tested, $p<.05$. A general decline in ROI for all treatments was observed, as well as the same statistical differences between treatments at the previous time point. Our results indicate that glyphosate had the lowest off-target impact, then triclopyr, then imazapyr, and finally aminocyclopyrachlor had the largest off-target impact.

One caveat to our ROI data, was that the type of species growing next to each stump was not recorded. Many of the stumps treated with Imazapyr had kochia, *Bassia scoparia* (L.) (A.J. Scott), growing in a ring directly next to the stump eighteen months after treatment. Colorado is known to have multiple populations of ALS resistant *Bassia scoparia* and it was suspected that the *Bassia scoparia* growing next to the imazapyr treated stumps could have been ALS resistant (Nissen 2014).

ROI was not statically different among size class, averaged across all herbicide treatments six months after treatment. Eighteen months and thirty months after treatments, size class 40 cm+ had statistically larger ROI than size class 10-20 cm. We expected there to be more differences in ROI based on tree size class, because more herbicide was used to treat larger trees. However, these expected differences did not occur. (More detailed information about size class can be found in the Appendix Figures A.2.4 and A.2.5).

Cut stump applications are low volume, high concentration applications. These low volume but high concentration applications can quickly exceed the labeled rate of product per acre, if many spot treatments are planned. The Radius of Inhibition looked at the minimum amount of off-target impact these products may have had. Herbicide injury was observed outside of the ROI for species such as *Asclepias syriaca* L., *Arctium minus* Bernh., *Cirsium arvense* (L.) Scop., *Maianthemum stellatum* (L.) Link, *Chenopodium album* L., *Symphoricarpos albus* (L.) S.F. Blake, and others (all taxonomic authorities from USDA PLANTS). More research is needed to quantify the off-target impact from cut stump herbicide applications on desirable species that may be in the understory.

Aminocyclopyrachlor caused the largest amount of off-target impact compared to the other herbicides tested, indicating that glyphosate or triclopyr might be better options for land managers' trying to minimize off-target impacts. Minimizing off target impacts of cut stump applications can be beneficial when desirable vegetation is present on site.

Cost analysis

The herbicides we tested differed numerically in off-target impact and percent mortality, as well as in cost. Cost of an application can often be the determining factor for a land manger making decisions on a tight budget. We calculated the cost of the herbicide active ingredient in price per kg/ai, and by price to treat one average sized tree in our study (33 cm diameter). The price per kg/ai was $141, $23, $74, and $564 for imazapyr, glyphosate, triclopyr, and aminocyclopyrachlor respectively. The cost to treat one average sized stump was $1.16, $1.47, $1.98, and $5.95 respectively (Table 2.10). There is a large cost discrepancy between aminocyclopyrachlor and the other herbicides tested on an individual tree basis. Additionally the cost difference between imazapyr and triclopyr could be considered significant if large numbers of trees need to be controlled. Cost of herbicide applications is also an important factor when choosing what herbicide to apply.

Conclusions

Russian olive control can be achieved through multiple management techniques. When aboveground biomass removal is part of the management objective, cut stump applications may be chosen as the desired management technique. When choosing which herbicide to apply, considerations such as mortality effectiveness, off-target impact to desirable vegetation, and cost can all be taken into consideration. After reviewing these three factors, glyphosate would be the recommended herbicide option for large cut stump Russian olive control in Northern Colorado. Glyphosate provided a high mortality rate, a low-off target impact, and was the second most cost effective product tested. Aminocyclopyrachlor offered similar mortality to other herbicides tested, but had significantly higher off-target impact, and cost of product per application.

TABLES AND FIGURES

Table 2.1: The total number of Russian olive trees within each size class across all sites. Size class was determined by measuring stump diameter in cm at the ground level.

Sample number	Stump diameter cm
47	10 to 20
60	20 to 30
41	30 to 40
47	40+

Table 2.2: Herbicide treatments, listed by common name, trade name, percent a.i. percent product, and average g of a.i. applied per Russian olive tree. Herbicides were mixed as a percent product into JLB basal bark oil.

Common Name	Percent a.i.	Trade Name	Percent Product	Average g a.i./tree
Glyphosate	27%	Rodeo	50%	64.5
Triclopyr	12%	Garlon 4	20%	19.5
Aminocyclopyrachlor	5%	MAT28112	10%	9.5
Imazapyr	2%	Habitat	8%	4.0
Untreated	n/a	Untreated	n/a	n/a

Table 2.3: Mortality Least square means across all sites and adjusted p-values from Tukey pair wise comparisons 30 months after treatment. (AMCP= aminocyclopyrachlor)

Mortality 30 Months After treatment
Differences of treat Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

treat	Treat	Estimate	Std Error	DF	t Value	Pr > |t|	Adj P
triclopyr 12%	imazapyr 2%	0.2028	0.5454	178	0.37	0.7105	0.9959
triclopyr 12%	AMCP 5%	1.6575	0.7350	178	2.26	0.0253	0.1647
triclopyr 12%	glyphosate 27%	2.1896	0.8440	178	2.59	0.0103	0.0757
triclopyr 12%	Untreated	-2.6560	0.5931	178	-4.48	<.0001	0.0001
imazapyr 2%	AMCP 5%	1.4547	0.7362	178	1.98	0.0497	0.2820
imazapyr 2%	glyphosate 27%	1.9869	0.8434	178	2.36	0.0196	0.1326
imazapyr 2%	Untreated	-2.8588	0.5951	178	-4.80	<.0001	<.0001
AMCP 5%	glyphosate 27%	0.5322	0.9689	178	0.55	0.5835	0.9819
AMCP 5%	Untreated	-4.3135	0.7827	178	-5.51	<.0001	<.0001
glyphosate 27%	Untreated	-4.8456	0.8908	178	-5.44	<.0001	<.0001

Table 2.4: Average shoot height in cm for Russian olive trees alive 6, 18, and 30 months after treatment. Treated Russian olive stumps had statistically lower shoot regrowth than untreated Russian olive stumps at all three time points p<.05. P-values are based off the Wilcoxon rank sum analysis.

Months after Treatment	Treated	Untreated	p-value
6	4	7	0.0014
18	61	145	<.0001
30	112	255	<.0002

Table 2.5: Interactions of treatment (treat), size class, and time (months after treatment) for the radius of inhibition.

Radius of Inhibition Interactions
Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
treat	3	140	34.04	<.0001
size class	3	141	3.25	0.0237
treat*size class	9	140	0.97	0.4707
time	2	271	148.25	<.0001
treat*Time	6	271	8.36	<.0001
size class*Time	6	271	2.82	0.0111
treat*size class*Time	18	271	0.56	0.9229

Table 2.6: Radius of inhibition, means, standard error, and mean separation letters for each herbicide six months after treatment. Mean separation letters signify differences from Tukey pair wise comparisons ($p<.05$).

Treatment	Time	Mean cm	Std Error cm	Mean Separation Letters
triclopyr 12%	6	21	2	A
imazapyr 2%	6	41	3	B
aminocyclopyrachlor 5%	6	35	2	B
glyphosate 27%	6	21	1	A

Table 2.7: Radius of inhibition averaged across all herbicide treatments excluding the untreated check by months after treatment. Mean separation letters signify differences from Tukey pair wise comparisons p<.05.

Time	Mean cm	Std Error cm	Mean Separation Letters
6	24	1	A
18	16	1	B
30	10	1	C

Table 2.8: Radius of inhibition, means, standard error, and mean separation letters for each herbicide eighteen months after treatment. Mean separation letters signify differences from Tukey pair wise comparisons (p<.05).

Treatment	Time	Mean cm	Std Error cm	Mean Separation Letters
triclopyr 12%	18	15	2	AB
imazapyr 2%	18	23	3	B
aminocyclopyrachlor 5%	18	32	3	C
glyphosate 27%	18	10	1	A

Table 2.9: Radius of inhibition, means, standard error, and mean separation letters for each herbicide thirty months after treatment. Mean separation letters signify differences from Tukey pair wise comparisons (p<.05).

Treatment	Time	Mean cm	Std Error cm	Mean Separation Letters
triclopyr 12%	30	8	1	AB
imazapyr 2%	30	13	2	B
aminocyclopyrachlor 5%	30	26	3	C
glyphosate 27%	30	4	1	A

Table 2.10: Cost analysis of herbicide and JLB Basal Bark oil. The table is broken into cost per kg/a.i., cost per one 33 cm stump (average size in study) and cost per 100 33 cm stumps. The cost per stump can be used to compare relative price among treatments.

Measure	Imazapyr 2%	Glyphosate 27%	Triclopyr 12%	Streamline (Aminocyclopyrachlor 5%)
Price kg/ai	$141.08	$23.34	$74.38	$546.10
One-33 cm Dia stump	$1.16	$1.47	$1.98	$5.95
100-33 cm Dia stumps	$116	$147	$198	$595

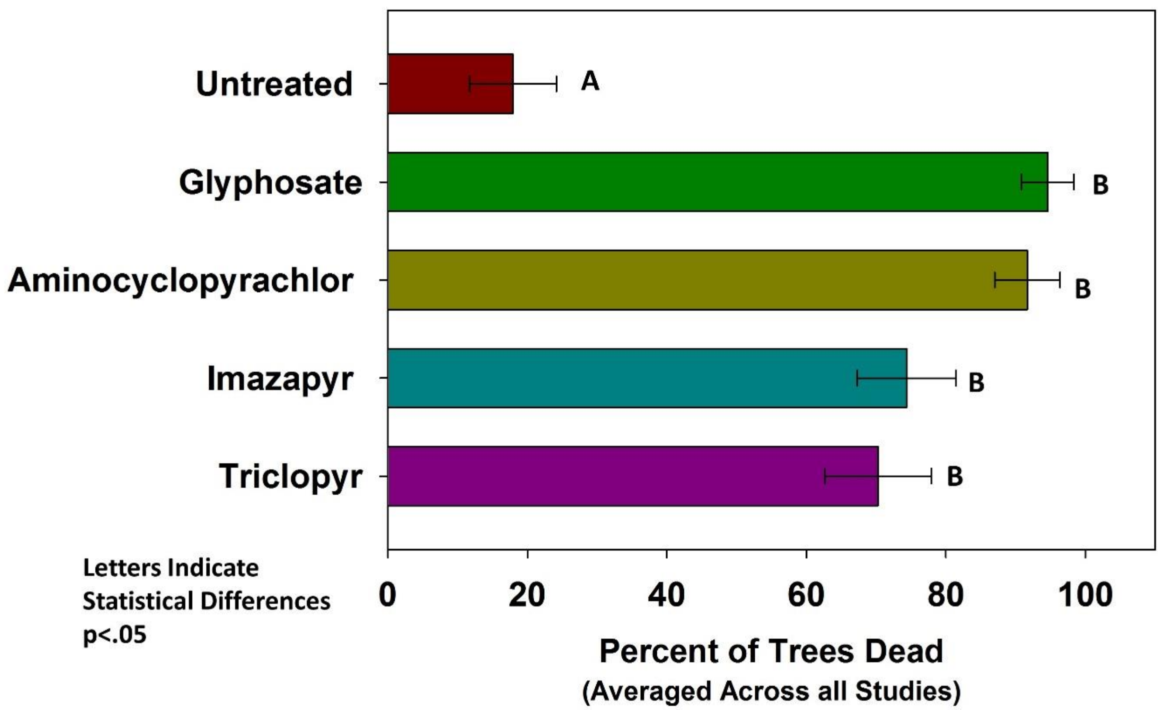

Figure 2.1: Percent of Russian olive trees dead by treatment, averaged across all three study sites. Letters indicate statistical differences $p<.05$. Bars indicate standard errors. Herbicide solutions consisted of Glyphosate 27%, Aminocyclopyrachlor 5%, Imazapyr 2%, and Triclopyr 12% mixed in JLB basal bark oil.

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CHAPTER 3: RUSSIAN OLIVE HISTORY AND CONTROL METHODS

Introduction

Globalization throughout the past 500 years has expedited the movement of plant species outside of their evolved range. In many cases the introduction of species has not led to major ecosystem changes. Meanwhile other introduced species have shifted community compositions, and in turn altered ecosystem function. In certain instances native species have a competitive disadvantage due to anthropogenic actions directly or indirectly aiding introduced species (Stromberg 2001). Within the Western United States Russian olive (*elaeagnus angustifolia*) has arguably been favored by anthropogenic actions, and in turn has altered certain riparian ecosystems dynamics.

Russian olive is native to western/central Asia and southern Europe (Stannard et al. 2002; Little 1961). In its native range, Russian olive can be found in moist ecotypes such as riparian or coastal areas (Shiskin 1949; Katz 2003). In Western North America Russian olive is often found growing within intermixed forests of cottonwoods or *tamarix*, but can also be found growing in monotypic stands (Stannard et al. 2002; Katz 2003; and others).

Russian olive is reputed to have been introduced to North America by Mennonite settlers in the late 1800's (Hanson 1901; Katz 2003). Russian olive escaped domestication and consequently many naturalized populations were established between 1930 and 1960 (Christenson 1963; Knopf and Olsen 1984). In 1954 Harrington noted naturalized Russian olive populations located along streamsides and valleys within Colorado's urban Front Range (Christenson 1963). Russian olive studies included in chapter two, were within Colorado's urban Front Range.

Promotion of Russian olive plantings was conducted both by individuals and governments (Katz 2003; Stannard et al. 2002). They were planted for windbreaks, erosion control, wildlife plantings and highway beatification (Olsen and Knopf 1986; Katz 2003; Stannard et al. 2002; and others). Russian olive has also been planted in the Eastern United States as a mine reclamation species (Cote et al. 1988, Katz 2003), and in coastal areas due to its salt tolerance (Morehart et al. 1980; Katz 2003). Plantings were recommended by the US Soil Conservation Service up until the 1980's (Tu et al. 2003; Stannard et al. 2002), but because of Russian olive's invasive properties, plantings are no longer recommended. Russian olive has also been utilized in the understory of black walnut production to provide a nitrogen source (Zitzer and Dawson 1989). Drought tolerance, salt tolerance, rapid growth, and large fruits are some of the characteristics that drove widespread planting of Russian olive throughout the last century (Creech and Rafferty 2007). Recently, studies have estimated that Russian olive is the fourth most abundant tree within the Western United States riparian ecosystems (Friedman et al. 2005).

Russian Olive Biology/Ecology

Russian olive trees can grow in a wide range of environments, which has resulted in the establishment of Russian olive across the majority of the continental United States (NRCS 2014). The maximum height of Russian olive trees has been listed as 9.1, 12.2, and 13.7 meters by Tu et al. (2003), Lessica and Miles (2001), and Stannard et al. (2002), respectively. In our Russian olive studies from chapter two, we observed Russian olive trees as tall as 12.1 meters. The diameter of Russian olive has been reported to range from 10-50 cm's (Stannard et al. 2002). We observed larger specimens at our field sites in chapter two, with the largest specimen having a diameter of 119 cm at the ground level.

Leaves of Russian olive are deciduous, lanceolate, silvery grey, and range from 2-10 cm long and 1-4 cm wide (Stannard et al. 2002; Forest Service 2012). Perfect yellow colored flowers start to bloom in early May or June, are pollinated by insects, and borne on umbel like inflorescences (Tu et al. 2003). Russian olive will often grow in dense thickets with new growth having thorns that will deter livestock from grazing (Pearce and Smith 2001; Creech and Rafferty 2007; Forest Service 2012). Tu et al. (2003) states that within three years Russian olive may produce viable offspring, where Lessica and Miles (2001) observed reproduction occurring at an average age of ten years. Russian olive fruits are oval, 1-1.5cm long, and consist of a relatively large seed enclosed within a mealy casing (Tu et al. 2003; Katz 2003; Zouhar 2005).

Russian olive seeds/fruits have been shown to be eaten by over 50 species of mammals and birds, and are considered an important source of food for wildlife (Borell 1976; Knopf and Olsen 1984). Seeds often stay attached to the tree during winter, providing a source of food for wildlife in deep snow conditions (Borell 1951, and personal observation). Borell (1951) also noted that Russian olive seeds are preferentially eaten over other food sources by certain birds. Bateman and Paxton (2009) state some birds preferentially eat Russian olive seeds, where other bird species may avoid eating the seed. Some studies have found Russian olive is beneficial to wildlife, where other studies have found native vegetation offers more ecological benefit (Katz 2003; and others). Russian olive seed dispersal can be facilitated by gravity, water, and biological organisms (Zohar 2005). Many species of birds have been observed ingesting seeds and defecating them at other locations, which has contributed to the spread of Russian olive (Zohar 2005). Kindschy (1998) and Edwards (2011) both tested the viability of Russian olive seeds after being ingested by European Starlings, and found that seed viability was not reduced. Friedman et al. (2005) states Russian olive may still be expanding its range based on the relatively slow dispersal of propagules.

Russian olive has been shown to form actinorhizal relationships with the nitrogen fixing bacteria *Frankia* spp. (Stannard et al. 2002; Zitzer and Dawson 1989). The fixed nitrogen can become available to other plants by root nodule exudation, as well as from Russia olive litter (Zitzer and Dawson 1989). Native woody phreatophyte species such as cottonwoods and willows do not have the ability to fix nitrogen. Therefore, Russian olive stands have the potential to alter nutrient cycling and nutrient availability in western riparian systems. In one study, fifty percent more nitrogen, and seventy three percent more organic matter was found under Russian olive stands compared to cottonwood stands alone (DeCant 2008).

Ecological Impacts

Biological factors such as drought, shade, and salt tolerance along with large seed size has allowed Russian olive trees to establish and succeed within the Western United States (Lessica and Miles

2001 and others). Willows and cottonwoods require specific moisture conditions to allow for successful establishment (Shafroth et al. 1995). Sharfroth et al. (1995) showed that Russian olive seedlings can establish both within and outside conditions that are favorable for cottonwood seedling establishment. This suggests there is a wide range of environmental conditions suitable for Russian olive establishment, which could help contribute to its invasiveness (Shafroth et al. 1995). Russian olive can establish directly within the understory of established cottonwood trees (Lessica and Miles 2001), while the understory of Russian olive is considered unfavorable for establishment of many plant species (Shafroth et al. 1995). A management pamphlet form the USFS (2012) states Russian olive presence can impede the establishment of native cottonwood and willow stands. It has also been shown that dams resulting in altered flow regimes can result in increased soil salinity levels, which favors nonnative tamarisk and Russian olive trees over native woody species (Stromberg 2001).

Few studies have focused on the impacts of Russian olive on wildlife (Montana Audubon 2010). However, Knopf and Olsen (1984) found fewer occurrences of cavity nesting and insectivorous birds in Russian olive stands compared to native woody vegetation. It was shown Russian olive trees had lower avian biodiversity than native riparian vegetation, but higher avian biodiversity compared to upland vegetation (Knopf and Olsen 1984). Authors also observed more mammals present in Russian olive stands when compared to native woody riparian vegetation (Knopf and Olsen 1984). The US Fish and Wildlife Service proposes that Russian olive trees provide habitat for skunks, raccoons and hawks that may feed on duck and goose offspring (Montana Audubon 2010). Beavers will preferentially eat cottonwood and willows, only eating Russian olive when it is the sole woody species present (Lessica and Miles 2001). During the sapling stage, Russian olive thorns may deter browsing by large ungulates, where cottonwood and willow saplings are more palatable (Pearce and Smith 2001, Creech and Rafferty 2007, Forest Service 2012).

Native vegetation and Russian olive can support different communities of arthropods within their stands (Bateman and Paxton 2009). Diversity of these arthropods often is higher in native vegetation, although the biomass of arthropods is typically similar between the vegetation types (Bateman and Paxton

2009). Little information is known about impacts of Russian olive on amphibian and reptile populations, but certain lizard species seem to respond beneficially to Russian olive removal (Bateman and Paxton, 2009). It has been postulated that fish populations could be negatively affected by Russian olive because of differences in arthropod population compositions; however studies have not been conducted to validate this hypothesis (Bateman and Paxton 2009).

Overall, there is still debate over whether Russian olive is beneficial or detrimental to wildlife, and more studies are needed to quantify its impact on wildlife. However, impact on wildlife is hard to measure when Russian olive is the only vegetation present in an ecosystem. Wildlife species that have adapted to native vegetation, may utilize exotic vegetation when native vegetation is not present (Sogge et al. 2005). The extent of ecological impacts from Russian olive growth on such a large scale in the Western United Sates is still unknown at this point.

Noxious status

Currently Russian olive is listed as a noxious species within New Mexico, Colorado, Wyoming, Connecticut, seven Utah counties, and one county in Montana (Montana Audubon 2010; NRCS 2014). Since September 2010, the sale of Russian olive has been made illegal within the entire state of Montana (Montana Audubon 2010). Russian olive is a C list species in New Mexico, and B list species in Colorado. (CDA 2014; Ashigh et al. 2010). Russian olive is considered naturalized within 17 Western States of the continental United States (Tu et al. 2003; Olson and Knopf 1986; and Katz 2003). In total, Russian olive has escaped domestication within 34 US states and 4 of the Southern Canadian provinces (Katz 2003; and others). Many of these states have not listed Russian olive as noxious species because it is still considered beneficial for windbreaks, and as an ornamental (O'Meara et al. 2009). Additionally because Russian olive is so wide spread in some areas, many states feel that it may put an unnecessary or unrealistic burden on landowners if listed as a noxious species. (O'Meara et al. 2009).

Control methods

Russian olive is legally required to be controlled where it is listed as a noxious species, and in other areas control methods may be implemented by land owners that consider the species undesirable on their land. Russian olive control can be implemented using several strategies which include cultural, physical, biological and chemical control options.

Cultural Control

Preventing Russian olive establishment may be the most effective type of cultural control available (Zouhar 2005). This can be accomplished by preventing Russian olive sales, monitoring livestock and machinery for offsite propagule movement, and regulating flow regimes in to favor native species establishment (Zouhar 2005). Changing the mindset of how the general public perceives Russian olive may also help aid in successful control of this species. Throughout the years governmental organizations have promoted the use of Russian olive for many purposes discussed above. However, educating the public that Russian olive and other noxious weeds can have detrimental ecological and economic consequences is important for successful control efforts. Cultural control will do little to eliminate an established Russian olive stand, which is why prevention of establishment is emphasized for cultural control options.

Physical Control

Physical control methods can also be utilized to control Russian olive stands. Small trees can be hand pulled, or uprooted, using a weed wrench (Zouhar 2005; Forest Service 2012). Fire will suppress Russian olive by removing the above ground portion of the plant, but Russian olive can readily re-sprout from roots (Zouhar 2005; Forest Service 2012). Mowing operations can also be used to suppress smaller Russian olive trees (Zouhar 2005). Other physical control methods such as tillage, bulldozing, chaining, excavation and girdling can be used to effectively control Russian olive stands (Zouhar 2005; Forest Service 2012). Russian olive can sustain flooding, but is fairly susceptible to continual ponding or standing water (Stannard 2002). However, with any management action there are side effects. For some of the available physical control methods, soil disturbance and lack of species selectivity may not achieve desirable results (Zouhar 2005; Stannard 2002). Using heavy machinery can result in massive soil disturbance, often contributing to soil erosion, and consequent sedimentation in nearby water sources (O'Meara et al. 2009). Mechanical control can often provide a quick and effective control option, where other available control methods may have longer time frames for desired levels of control (O'Meara et al. 2009).

Biological control

Biological control can be used for species when suppression is the goal, but it does not provide species eradication. When species suppression is the goal, biological control is often a more economical alternative to other control methods (O'Meara et al. 2009). However, time and financial investments are needed to research potential pitfalls and off-target impacts of releasing a new biological control species (O'Meara et al. 2009). One simple biocontrol method for Russian olive seedlings is grazing livestock before the thorns grow during the sapling stage (Forest Service 2012). There is a canker that currently utilizes Russian olive as a host species, however mass mortality has not been observed (Stannard 2002).

Russian olive is a good candidate for biocontrol agents, but currently there are no biological control options approved for use (O'Meara et al. 2009). At present seventeen species of biocontrol agents that target Russian olive seed production are being researched, however, release of any as biocontrol agents is not expected until 2020 (O'Meara et al. 2009). Only biocontrol species that target the reproductive systems of Russian olive are being investigated, because Russian olive can still be considered a desirable species in windbreaks, and for soil stabilization (Shafroth 2009; O'Meara et al. 2009).

Chemical Control

Two exclusively chemical control options exist for Russian olive control. These options include foliar applications and basal bark applications. There are also combinations of chemical and physical methods available for Russian olive control that will be discussed below.

Foliar chemical applications can be made either as broadcast or spot treatments. Broadcast applications can be made by equipment on the ground, or aerially by helicopters and airplanes (O'Meara et al. 2009). Helicopters can fly at slower speeds than airplanes, and often can deliver more directed herbicide applications (O'Meara et al. 2009). However, regardless of the method used to make broadcast applications, high probability of off-target impacts exist, since all of the vegetation in the vicinity is sprayed with the herbicide (Zouhar 2005). Foliar spot applications can be made using a sprayer mounted on an ATV or backpack. Normally, these applications can be made to Russian olive less than 2 meters tall (Forest Service, 2012). Initial control methods often result in some sprouting from roots after treatment, which can be controlled by using spot foliar applications (Forest Service 2012). Large stands of Russian olive may be more economically treated by broadcast applications, whereas smaller, less dense infestations, maybe more effectively treated by spot applications (O'Meara et al. 2009)

Basal bark applications consist of herbicide mixed in either diesel or oil, which is then applied to the lower 30-40 cm of a Russian olive bole (Forest Service 2012). This method is most effective on trees with a diameter of 13 cm or less (Forest Service 2012). The oil or diesel helps penetrate and saturate the bark of the tree, in order to increase herbicide penetration (Stannard 2002). Larger trees with corky bark are often not successfully controlled by basal bark applications, possibly due to the lack of herbicide penetration. Triclopyr and imazapyr are often recommended herbicides for Russian olive basal bark treatments (O'Meara et al. 2002; Forest Service 2012). While basal bark treatments can result in off-target impacts to desirable species, off-target impacts are less likely when compared to foliar applications (Wilson and Bernards 2005; Nowak and Ballard 2005). As mentioned before, there are a few methods that combine physical and chemical control methods: these include hack and squirt treatments, cut stump treatments, and mowing with a wet rotary blade.

Hack and squirt treatments involve cutting through the Russian olive bark, exposing the cambial layer on the main trunk, and applying a small amount of herbicide into the cut (Forest Service 2012; Zouhar 2005). Two inches of bark can be left between each cut, however, overlapping the cuts will essentially girdle the tree (Forest Service 2012). Applying herbicides to the cuts, results in a direct application of herbicide to the cambial layer of the tree. Hack and squirt applications of undiluted imazapyr, and glyphosate have been shown to effectively kill Russian olive. (Stannard et al. 2002). One difficult aspect of both hack and squirt or basal bark treatments is gaining physical access to the bole of the tree. Oftentimes, many shoots from the base of the tree, and/or low growing branches, make it impossible to physically reach the main stump. These branches need to be cut, in order to make a successful basal bark, or hack and squirt applications, which can increase the labor associated with these treatment methods.

Control of small saplings can be achieved by mowing with a wet rotary blade covered with glyphosate (Forest Service 2012). While mowing alone can provide small Russian olive suppression, but the addition of a systemic herbicide such as glyphosate to the blade will help increase Russian olive control (Forest Service 2012).

Cut stump applications involve removing the above ground Russian olive biomass, typically with a chainsaw (Forest Service 2012). Within 5-15 minutes of cutting the tree, an application of a low volume herbicide is applied to the cambial layer of the stump for subsequent herbicide uptake and control (Forest Service 2012; Tu et al. 2003; O'Meara et al. 2009). The biomass can then be disposed of by chipping, slash plies, or hauled away for beneficial purposes (Forest Service, 2012). Cut stump treatments can have varying levels of control on Russian olive trees. Wilson (2008) achieved 95% control using a variety of herbicides for cut stump treatment of Russian olive averaging 23 cm in diameter. Edwards (2011) achieved 83-100% control of Russian olive using triclopyr and aminocyclopyrachlor at varying rates for Russian olive cut stump treatments. Edwards (2011) focused on two Russian olive size classes: 8-22 cm diameter, and 22-38 cm diameter. Generally, the Russian olive in the smaller size class were controlled by the cut stump treatments, where trees in the larger size class were not completely controlled by any herbicide evaluated (Edwards 2011). Edwards (2011) also noted that Russian olive on dry sites were more easily controlled than trees located on sites with more moisture. Wilson (2008) noted perennial grass injury surrounding certain cut stump applications of imazapyr and hexazinone. Leaving Russian olive biomass on site may not be desirable. Cut stump applications, or mowing with a wet rotary blade may be the control method chosen when biomass removal is a priority.

Common Herbicides Used

In the literature many herbicides are cited to give good control of Russian olive for the various chemical application methods. A few herbicides labeled for Russian olive control are described in detail below. Based on results from chapter two, aminocyclopyrachlor is also described below, as research indicated good activity when used as a cut stump application.

Imazapyr, a relatively nonselective branched chain amino acid inhibitor within the imidazolinone family of herbicides, was discovered by American Cyanamid in the 1970's (Senseman 2007). Imazapyr has low toxicity to mammals, fish, and invertebrates (Senseman 2007). It has a long soil half-life between 25-141 days, and is degraded by both microbes and light (WSDA 2003). Imazapyr is water soluble and has a Log KOW of 1.3 (Senseman 2007). It is formulated as a salt or an acid, were the salt formulation can be used around riparian areas, or applied directly to water bodies for control of aquatic plant species (WSDA 2003). Many authors have stated imazapyr offers effective Russian olive control and recommend it for chemical control of Russian olive (Stannard 2002; Nowak and Ballard 2005; O'Meara et al. 2009; Creech and Rafferty 2007; Katz 2003; Tu et al. 2003). Imazapyr can be applied as a basal bark, foliar, or cut stump application treatment (Creech and Rafferty 2007; Wilson 2008; Edwards 2011).

Glyphosate is a nonselective amino acid inhibitor of ESPS synthase, which in turn inhibits essential aromatic amino acid production which leads to subsequent plant death (Senseman 2007). Glyphosate has a relatively high water solubility and a Log KOW of 0.0006-0.0017 (Senseman 2007). Glyphosate has a 47 day half-life in the soil and is degraded by microbes (Senseman 2007). Because glyphosate binds tightly to soil particles, plants can be seeded directly into soil with glyphosate residual levels, as the residues will not be available for plant uptake (Senseman 2007). Glyphosate has relatively low mammalian toxicity, but is toxic to bacteria (Senseman 2007). Glyphosate has been shown to be an effective herbicide for Russian olive control (Stananrd et. al. 2002, O'Meara et al 2009, Creech and Rafferty 2007, Forest Service 2012). In terms of application methods, foliar, cut stump, basal bark, or hack and squirt treatments of glyphosate have been shown to offer effective Russian olive control (Wilson 2008; Stannard et al. 2002; Creech and Rafferty 2007; Forest Service 2012). Since glyphosate is a non-selective herbicide, the majority of vegetation that receives a foliar application of glyphosate will eventually die. This characteristic can increase off target effects from foliar applications. However, low soil residual activity can reduce off-target impacts compared to herbicides that have high soil residual activity. Like imazapyr, an aquatic use formulation of glyphosate exists that can be used around riparian areas, or directly applied to water bodies to control aquatic plant species (O'Meara et al. 2009).

Triclopyr is an herbicide within the pyridine carboxylic acid family, and has a synthetic auxin mode of action (Senseman 2007). Triclopyr has a Log KOW of 2.64, and the water solubility is dependent on the chemical formulation (Senseman 2007). Triclopyr is not strongly absorbed to the soil, but is rapidly degraded by both light and microbial activity (Senseman 2007). It has a half-life of 10-46 days based on soil characteristics and climate (Senseman 2007). Triclopyr has slight oral and dermal human toxicity, and is listed under the toxicology 3 category (EPA 2003). Russian olive is commonly treated with triclopyr applications as a chemical control method (Stannard 2002; O'Meara et al. 2009; Creech and Rafferty 2007; Forest Service 2012). Triclopyr can be used in multiple application methods such as cut stump, basal bark, foliar, and hack and squirt applications (Stannard 2002; O'Meara et al. 2009; Creech and Rafferty 2007; Forest Service 2012).

Aminocyclopyrachlor is a compound that is not currently labeled for Russian olive control. However, the chemistry of the molecule, and results from chapter two, suggest aminocyclopyrachlor can provide effective Russian olive control. Aminocyclopyrachlor is the first synthetic auxin herbicide in the pyrimidine carboxylic acid family (DuPont 2009). The chemical name is 6-amino-5-chloro-2-cyclopropyl-4-pyrimidinecarboxylic acid, and the molecular formula is $C_8H_8ClN_3O_2$ (DuPont 2009).

Aminocyclopyrachlor has a PKA of 4.65 and a Log KOW of -2.48 and -1.12 at pH 7 and 4, respectively (Bukun et al. 2010; Edwards 2011; DuPont 2009). Bukun et al. (2010) stated that aminocyclopyrachlor has an optimum PKA for phloem transport. Aminocyclopyrachlor was shown to have similar percent of herbicide translocated to the root of Canada thistle as aminopyrlid, an herbicide in the pyridine carboxylic acid family (Bukun et al. 2010). Many difficult to control broadleaf species, such as leafy spurge, Canada thistle, knapweed species, and field bindweed are effectively controlled by aminocyclopyrachlor (DuPont 2009; Bukun et al. 2010). Generally, aminocyclopyrachlor can be used as a selective herbicide application over the top of grasses to control broadleaf weed species (DuPont 2009). The main market for aminocyclopyrachlor is broadleaf weed and brush control in non-crop areas, right of ways, industrial areas, and natural areas (DuPont 2009). Currently no aquatic formulations of aminocyclopyrachlor are available on the market.

Conclusions

Russian olive is not a native species in North America, but it has become widespread within the Western United States. The biological characteristics of Russian olive, specifically tolerance to abiotic factors, help it establish over a large range of conditions more favorable to Russian olive than native woody phreatophytes. The exact ecological impacts of Russian olive are currently unknown, however, long term impacts on nutrient cycling are suspected due to its ability to fix nitrogen. Russian olive also has been shown to have adverse effects on certain bird, insect, and mammal species. Russian olive is considered noxious in some states, which legally mandate control of the species. Physical, cultural, and chemical control methods can currently be used, where biological control options will not be available until the next decade. Because the range of Russian olive is thought to still be expanding (Friedman et al. 2005), more research on ecological impacts, and control methods would be beneficial to minimize negative ecological impacts and maximize the effectiveness of available control options.

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APPENDIX

CHAPTER 1: DESCRIPTION AND TABLES

Color coded tables of stand counts and biomass. Color coding was done by using condition formatting in excel. Yellow signifies average, a light shade of green to dark green indicates above average, orange to a gradient of dark red signifies below average. Conditional color formatting was conducted over all cells per table. These color coded charts are to help visualize the data.

Initial 2011 stand count frequencies are displayed as a percent frequency of the untreated check (Tables 1.9a and 1.10a). Change in frequency form 2011to 2012 is displayed as a relative percent frequency change (Tables 1.11a and 1.12a). Species biomass from soil residual herbicide application, are displayed as a percentage of the untreated check biomass by species (Tables 1.13a and 1.14a). Species biomass from foliar herbicide applications, are displayed as a percentage of the untreated check biomass by species (Tables 1.15a and 1.16a).

CHAPTER 2: NO DESCRIPTION NEEDED

Table A.1.9: Monocot Species 2011 initial frequency stand counts for soil residual tolerance treatments. Initial frequency is displayed as a percent of the untreated check for each species. Table is color coded (red=low number, green= high number).

	Elymus Canadensis		*Elymus trachycaulus*		*Nassella viridula*		*Pascopyrum smithii*		*Bouteloua gracilis*		*Panicum virgatum l.*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	89	82	89	155	143	122	127	200	97	88	125	78
aminocyclopyrachlor .03	62	82	93	112	155	250	150	153	114	93	118	139
aminopyralid	127	78	95	147	126	194	205	133	60	126	96	196
quinclorac	74	76	93	117	114	194	127	100	93	102	96	122
picloram	93	91	103	133	143	83	250	253	104	100	214	248
clopyralid	140	82	93	138	79	267	191	200	81	109	114	230
metsulfuron	118	78	95	133	100	150	241	220	93	118	150	96
rimsulfuron	171	73	103	117	148	72	91	67	110	105	168	74
chlorsulfuron	138	124	105	117	124	194	218	167	107	79	125	52
imazapyr	111	64	102	133	155	183	168	53	114	47	136	130
imazapic .22	129	91	105	112	136	150	273	80	103	96	239	87
imazapic .11	82	51	98	130	67	139	150	80	111	132	225	100
untreated	100	100	100	100	100	100	100	100	100	100	100	100

Table A.1.10: Dicot Species 2011 initial frequency stand counts for soil residual tolerance treatments. Initial frequency is displayed as a percent of the untreated check for each species. Table is color coded (red=low number, green= high number).

	Achillea lanulosa		*Atriplex canescens*		*Gaillardia spp.*		*Linum perenne*		*Penstemon palmeri*		*Ratibida columnifera*		*Rudbeckia hirta*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	114	93	224	100	140	86	96	82	280	171	171	55	100	107
aminocyclopyrachlor .03	95	88	106	60	160	62	117	100	40	135	135	48	104	127
aminopyralid	86	83	200	106	100	81	115	104	140	35	35	26	109	55
quinclorac	120	93	224	122	60	86	113	27	110	106	106	68	105	114
picloram	98	71	135	50	120	43	73	75	130	100	100	29	82	32
clopyralid	86	93	112	76	190	71	113	104	140	94	94	61	95	105
metsulfuron	123	29	224	76	150	24	67	0	380	135	135	3	89	7
rimsulfuron	123	38	235	112	160	14	102	16	400	218	218	6	105	73
chlorsulfuron	107	7	47	0	190	33	0	0	70	59	59	0	96	89
imazapyr	89	81	206	30	150	24	71	55	180	100	100	55	102	20
imazapic .22	127	88	171	30	100	57	69	22	160	194	194	65	104	107
imazapic .11	116	74	224	86	180	67	102	43	220	182	182	52	105	120
untreated	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table A.1.11: Monocot species 2011 to 2012 relative percent frequency change from foliar herbicide applications. Table is color coded (red=low number, green= high number).

	Elymus Canadensis		*Elymus trachycaulus*		*Nassella viridula*		*Pascopyrum smithii*		*Bouteloua gracilis*		*Panicum virgatum l.*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	444	422	10	2	58	161	467	647	30	9	111	145
aminocyclopyrachlor .03	316	607	10	44	110	183	440	733	40	35	264	136
aminopyralid	181	205	14	10	58	93	762	733	241	81	133	219
quinclorac	300	752	28	31	86	61	733	733	61	29	444	386
picloram	285	155	5	11	64	57	833	556	15	19	129	198
clopyralid	303	333	29	20	81	23	700	389	17	193	239	144
2,4-D amine	97	224	3	5	65	98	193	511	27	25	88	77
fluroxypyr	120	151	18	11	103	76	456	433	83	28	100	71
dicamba	190	262	15	12	40	85	298	429	43	15	137	206
metsulfuron	211	303	15	31	99	20	400	483	14	26	104	122
rimsulfuron	911	95	32	18	14	31	326	283	15	78	64	112
chlorsulfuron	96	168	9	23	-7	67	817	922	155	8	119	117
imazapic.22	148	245	-4	5	-45	106	133	289	18	15	39	91
imazapic.11	119	550	22	12	-19	0	544	333	63	5	63	121
tebuthiuron	52	72	10	17	80	192	125	391	179	34	127	268
untreated	91	238	12	2	326	96	839	311	41	9	301	48

Table A.1.12: Dicot species 2011 to 2012 relative percent frequency change from foliar herbicide applications. Table is color coded (red=low number, green= high number).

	Achillea lanulosa		*Atriplex canescens*		*Gallardia spp.*		*Linum perenne*		*Penstemon palmeri*		*Ratibida columnifera*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	68	-100	278	196	-53	-100	2	-72	275	48	128	-100
aminocyclopyrachlor .03	81	-33	178	298	-85	-100	2	-36	172	435	84	-71
aminopyralid	16	-100	89	385	-61	-83	2	-27	80	94	-44	-100
quinclorac	55	18	113	532	30	13	-5	93	-22	-33	59	-65
picloram	-25	-100	103	25	-53	-87	-14	-89	350	-28	-78	-100
clopyralid	-100	-100	45	387	-56	-31	8	2	403	250	-92	-100
2,4-D amine	33	17	0	46	-39	-63	-2	-11	177	0	52	55
fluroxypyr	112	108	156	189	45	0	-28	-14	244	238	71	56
dicamba	21	-92	19	192	-60	23	-9	-50	156	-34	75	-100
metsulfuron	-100	-100	57	189	-78	-100	-4	-10	53	219	-74	-100
rimsulfuron	45	20	717	114	4	160	0	22	229	170	201	115
chlorsulfuron	-43	-94	180	131	-19	10	-6	-15	23	171	-46	-80
imazapic.22	39	50	199	265	-41	-67	6	-4	-50	57	83	-39
imazapic.11	42	-7	67	325	18	-41	3	-23	-8	58	86	56
tebuthiuron	-11	3	121	148	23	83	2	4	-93	52	227	64
untreated	41	50	235	248	-7	219	14	42	356	111	209	125

Table A.1.13: Monocot species soil residual herbicide tolerance dry biomass. Dry biomass is displayed as a percent of the untreated check by species. Table is color coded (red=low number, green= high number).

	Elymus Canadensis		*Elymus trachycaulus*		*Nassella viridula*		*Pascopyrum smithii*		*Bouteloua gracilis*		*Panicum virgatum l.*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07?	121	94	84	122	136	125	158	68	114	121	80	65
aminocyclopyrachlor .03	53	90	107	98	171	175	103	126	108	106	113	143
aminopyralid	89	92	84	85	75	155	91	93	84	126	113	178
quinclorac	95	94	89	100	93	115	120	94	122	115	187	130
picloram	87	84	80	107	107	120	59	116	95	121	200	165
clopyralid	107	87	91	100	125	110	100	90	65	109	140	154
metsulfuron	84	107	71	93	118	135	127	107	68	129	233	108
rimsulfuron	56	90	64	105	82	105	72	109	124	118	213	100
chlorsulfuron	84	94	62	88	82	105	119	94	146	129	167	84
imazapyr	93	63	78	66	100	60	114	62	127	76	207	73
imazapic .22	112	91	78	66	93	70	123	42	89	74	320	86
imazapic .11	105	102	113	85	129	115	127	97	84	121	387	103
untreated	100	100	100	100	100	100	100	100	100	100	100	100

Table A.1.14: Dicot species soil residual herbicide tolerance dry biomass. Dry biomass is displayed as a percent of the untreated check by species. Table is color coded (red=low number, green= high number).

	Achillea lanulosa		*Atriplex canescens*		*Gaillardia spp.*		*Linum perenne*		*Penstemon palmeri*		*Ratibida columnifera*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	79	97	140	111	75	31	106	155	212	193	70	121
aminocyclopyrachlor .03	62	85	94	93	90	52	109	121	65	193	75	92
aminopyralid	72	90	119	112	76	140	103	152	82	221	66	92
quinclorac	68	87	140	145	59	65	97	86	118	143	111	154
picloram	49	93	125	73	42	96	91	107	29	271	50	106
clopyralid	83	85	95	106	107	135	109	155	71	121	63	112
metsulfuron	73	66	141	108	58	52	100	10	212	157	98	54
rimsulfuron	46	92	110	142	66	48	78	69	194	243	61	62
chlorsulfuron	68	39	39	59	78	104	9	0	82	0	64	35
imazapyr	70	111	147	109	85	29	66	103	188	229	111	121
imazapic .22	66	95	100	101	80	121	56	66	135	14	104	121
imazapic .11	73	90	113	102	85	94	91	86	159	107	84	115
untreated	100	100	100	100	100	100	100	100	100	100	100	100

Table A.1.15: Monocot species foliar herbicide tolerance dry biomass. Dry biomass is displayed as a percent of the untreated check by species. Table is color coded (red=low number, green= high number).												
	Elymus Canadensis		*Elymus trachycaulus*		*Nassella viridula*		*Pascopyrum smithii*		*Bouteloua gracilis*		*Panicum virgatum l.*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	62	83	77	86	95	135	164	62	161	121	106	136
aminocyclopyrachlor .03	125	93	88	93	91	115	174	88	165	121	73	164
aminopyralid	92	126	94	86	109	142	151	119	152	109	127	151
quinclorac	99	117	104	76	136	169	141	70	139	106	109	113
picloram	103	84	75	93	127	158	174	101	135	121	76	167
clopyralid	97	91	81	47	95	115	113	104	143	103	97	167
2,4-D amine	120	98	96	88	100	177	144	123	122	164	82	213
fluroxypyr	149	113	90	73	136	112	226	111	170	112	109	87
dicamba	108	107	92	88	118	135	182	89	139	127	67	133
metsulfuron	85	102	85	93	109	100	172	100	191	130	112	121
rimsulfuron	66	118	58	80	100	96	85	61	148	100	24	113
chlorsulfuron	117	123	88	92	141	100	197	100	143	88	82	115
imazapic.22	30	56	44	88	27	73	33	78	135	133	45	110
imazapic.11	83	77	77	90	41	158	59	57	122	133	42	121
tebuthiuron	58	86	88	73	145	115	62	35	200	133	124	85
untreated	100	100	100	100	100	100	100	100	100	100	100	100

Table A.1.16: Dicot species foliar herbicide tolerance dry biomass. Dry biomass is displayed as a percent of the untreated check by species. Table is color coded (red=low number, green= high number).												
	Achillea lanulosa		*Atriplex canescens*		*Gallardia spp.*		*Linum perenne*		*Penstemon palmeri*		*Ratibida columnifera*	
Herbicide Treatment	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.	July	Sept.
aminocyclopyrachlor .07	97	0	70	116	0	76	84	19	83	156	25	0
aminocyclopyrachlor .03	137	24	63	86	17	4	91	60	158	300	126	0
aminopyralid	63	0	114	96	34	24	96	105	192	180	5	0
quinclorac	85	123	124	69	66	76	78	0	38	24	98	7
picloram	40	0	48	131	23	20	75	19	50	100	0	0
clopyralid	0	0	108	114	32	58	82	143	217	200	3	0
2,4-D amine	113	145	45	44	25	28	75	129	58	4	59	28
fluroxypyr	108	99	108	126	62	12	62	98	179	168	56	28
dicamba	35	5	47	74	4	77	109	48	158	76	13	0
metsulfuron	0	0	27	65	0	0	102	121	50	212	16	0
rimsulfuron	85	79	128	84	102	26	85	143	171	244	74	16
chlorsulfuron	31	1	91	89	40	14	71	124	33	200	25	5
imazapic.22	74	113	82	87	36	7	58	124	8	52	92	13
imazapic.11	86	91	122	118	57	32	58	148	25	96	75	50
tebuthiuron	45	13	87	114	174	62	82	152	0	4	144	74
untreated	100	100	100	100	100	100	100	100	100	100	100	100

Table A.2.1: Mortality six months after treatment, least square means and adjusted p-values from Tukey pair wise comparisons. (AMCP=aminocyclopyrachlor)

Mortality 6 Months After treatment
Differences of treat Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

treat	treat	Estimate	Standard Error	DF	t Value	Pr > |t|	Adj P
triclopyr 12%	imazapyr 2%	-0.2227	0.6896	185	-0.32	0.7471	0.9976
triclopyr 12%	AMCP 5%	-0.3025	0.6911	185	-0.44	0.6621	0.9923
triclopyr 12%	glyphosate 27%	1.1030	0.8992	185	1.23	0.2215	0.7358
triclopyr 12%	untreated	-6.5396	1.3496	185	-4.85	<.0001	<.0001
imazapyr 2%	AMCP 5%	-0.07985	0.6676	185	-0.12	0.9049	1.0000
imazapyr 2%	glyphosate 27%	1.3257	0.8813	185	1.50	0.1342	0.5611
imazapyr 2%	untreated	-6.3169	1.3322	185	-4.74	<.0001	<.0001
AMCP 5%	glyphosate 27%	1.4055	0.8851	185	1.59	0.1140	0.5070
AMCP 5%	untreated	-6.2370	1.3269	185	-4.70	<.0001	<.0001
glyphosate 27%	untreated	-7.6426	1.4656	185	-5.21	<.0001	<.0001

Table A.2.2: Mortality eighteen months after treatment, least square means and adjusted p-values from Tukey pair wise comparisons. (AMCP=aminocyclopyrachlor)

Mortality 18 Months After treatment
Differences of treat Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

treat	treat	Estimate	Standard Error	DF	t Value	Pr > |t|	Adj P
triclopyr 12%	imazapyr 2%	0.6970	0.5674	177	1.23	0.2209	0.7348
triclopyr 12%	AMCP 5%	1.3454	0.6532	177	2.06	0.0409	0.2425
triclopyr 12%	glyphosate 27%	0.8581	0.5932	177	1.45	0.1498	0.5985
triclopyr 12%	untreated	-2.6690	0.5918	177	-4.51	<.0001	0.0001
imazapyr 2%	AMCP 5%	0.6483	0.6854	177	0.95	0.3455	0.8784
imazapyr 2%	glyphosate 27%	0.1611	0.6258	177	0.26	0.7972	0.9990
imazapyr 2%	untreated	-3.3660	0.6311	177	-5.33	<.0001	<.0001
AMCP 5%	glyphosate 27%	-0.4873	0.7058	177	-0.69	0.4908	0.9583
AMCP 5%	untreated	-4.0144	0.7103	177	-5.65	<.0001	<.0001
glyphosate 27%	untreated	-3.5271	0.6567	177	-5.37	<.0001	<.0001

Table A.2.3: Mortality thirty months after treatment, least square means and adjusted p-values from Tukey pair wise comparisons. (AMCP=aminocyclopyrachlor)

Mortality 30 Months After treatment
Differences of treat Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

treat	treat	Estimate	Standard Error	DF	t Value	Pr > |t|	Adj P
triclopyr 12%	imazapyr 2%	0.2028	0.5454	178	0.37	0.7105	0.9959
triclopyr 12%	AMCP 5%	1.6575	0.7350	178	2.26	0.0253	0.1647
triclopyr 12%	glyphosate 27%	2.1896	0.8440	178	2.59	0.0103	0.0757
triclopyr 12%	Untreated	-2.6560	0.5931	178	-4.48	<.0001	0.0001
imazapyr 2%	AMCP 5%	1.4547	0.7362	178	1.98	0.0497	0.2820
imazapyr 2%	glyphosate 27%	1.9869	0.8434	178	2.36	0.0196	0.1326
imazapyr 2%	Untreated	-2.8588	0.5951	178	-4.80	<.0001	<.0001
AMCP 5%	glyphosate 27%	0.5322	0.9689	178	0.55	0.5835	0.9819
AMCP 5%	Untreated	-4.3135	0.7827	178	-5.51	<.0001	<.0001
glyphosate 27%	Untreated	-4.8456	0.8908	178	-5.44	<.0001	<.0001

Table A.2.4: Russian olive shoot heights six months after herbicide treatment Wilcoxon Chisquare approximation (all trees).		
1-way Test, ChiSquare Approximation		
ChiSquare	DF	Prob>ChiSq
129.051	4	<.0001

Table A.2.5: Russian olive shoot heights six months after herbicide treatment Wilcoxon pair wise comparisons (all trees). (AMCP=aminocyclopyrachlor)					
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
untreated	glyphosate 27%	38.1538	4.844777	7.87525	<.0001
untreated	imazapyr 2%	37.6154	4.927851	7.63322	<.0001
untreated	triclopyr 12%	37	4.888058	7.56947	<.0001
untreated	AMCP 5%	33.9744	4.926601	6.89611	<.0001
imazapyr 2%	glyphosate 27%	3.8205	2.701673	1.41413	0.1573
triclopyr 12%	glyphosate 27%	1.9744	2.370383	0.83293	0.4049
imazapyr 2%	AMCP 5%	-0.5897	3.221587	-0.18306	0.8548
triclopyr 12%	imazapyr 2%	-1.641	2.980623	-0.55056	0.5819
triclopyr 12%	AMCP 5%	-2.1795	2.980679	-0.7312	0.4647
glyphosate 27%	AMCP 5%	-4.1282	2.701673	-1.52802	0.1265

Table A.2.6: Russian olive shoot heights six months after herbicide treatment, mean separation report (all trees).	
untreated	A
triclopyr 12%	B
glyphosate 27%	B
aminocyclopyrachlor 5%	B
imazapyr 2%	B

Table A.2.7: Russian olive shoot heights eighteen months after herbicide treatment Wilcoxon Chisquare approximation (all trees).		
1-way Test, ChiSquare Approximation		
ChiSquare	DF	Prob>ChiSq
87.2221	4	<.0001

Table A.2.8: Russian olive shoot heights eighteen months after herbicide treatment Wilcoxon pair wise comparison (all trees). (AMCP=aminocyclopyrachlor)					
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
untreated	glyphosate 27%	31.30769	4.795693	6.528294	<.0001
untreated	imazapyr 2%	31	4.821212	6.429918	<.0001
untreated	AMCP 5%	30.58974	4.737815	6.456509	<.0001
untreated	triclopyr 12%	29.46154	4.889794	6.025108	<.0001
triclopyr 12%	AMCP 5%	5.30769	3.433203	1.545989	0.1221
triclopyr 12%	glyphosate 27%	3.94872	3.620528	1.090647	0.2754
triclopyr 12%	imazapyr 2%	3.12821	3.706336	0.844015	0.3987
imazapyr 2%	AMCP 5%	2.38462	3.105483	0.767873	0.4426
glyphosate 27%	AMCP 5%	1.48718	2.980903	0.498902	0.6178
imazapyr 2%	glyphosate 27%	0.94872	3.330852	0.284827	0.7758

Table A.2.9: Russian olive shoot heights eighteen months after herbicide treatment, mean separation report (all trees).	
untreated	A
triclopyr 12%	B
glyphosate 27%	B
aminocyclopyrachlor 5%	B
imazapyr 2%	B

Table A.2.10: Russian olive shoot heights thirty months after herbicide treatment Wilcoxon Chisquare approximation (all trees).		
1-way Test, ChiSquare Approximation		
ChiSquare	DF	Prob>ChiSq
87.865	4	<.0001

Table A.2.11: Russian olive shoot heights thirty months after herbicide treatment Wilcoxon pair wise comparison (all trees). (AMCP=aminocyclopyrachlor)					
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
untreated	glyphosate 27%	30.9231	4.644111	6.65856	<.0001
untreated	AMCP 5%	30.5641	4.676693	6.53541	<.0001
untreated	imazapyr 2%	28.7179	4.867201	5.9003	<.0001
untreated	triclopyr 12%	27.9744	4.867406	5.74728	<.0001
triclopyr 12%	glyphosate 27%	8.0256	3.221432	2.49133	0.0127
imazapyr 2%	glyphosate 27%	7.9231	3.221638	2.45933	0.0139
triclopyr 12%	AMCP 5%	6.7692	3.330402	2.03256	0.0421
imazapyr 2%	AMCP 5%	6.7179	3.330202	2.01728	0.0437
triclopyr 12%	imazapyr 2%	0.3333	3.93601	0.08469	0.9325
glyphosate 27%	AMCP 5%	-0.9744	2.178666	-0.44723	0.6547

Table A.2.12: Russian olive shoot heights eighteen months after herbicide treatment, mean separation report (all trees).	
untreated	A
triclopyr 12%	C
glyphosate 27%	B
aminocyclopyrachlor 5%	B
imazapyr 2%	C

Table A.2.13: Russian olive shoot heights six months after herbicide treatment Wilcoxon Chisquare approximation (only alive trees).		
1-way Test, ChiSquare Approximation		
ChiSquare	DF	Prob>ChiSq
14.127	4	0.0069

Table A.2.14: Russian olive shoot heights six months after herbicide treatment Wilcoxon pair wise comparisons (only alive trees). (AMCP=aminocyclopyrachlor)					
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
untreated	imazapyr 2%	17.3077	5.727075	3.02208	0.0025
untreated	triclopyr 12%	13.2	6.061147	2.17781	0.0294
untreated	glyphosate 27%	11.8269	8.625423	1.37117	0.1703
untreated	AMCP 5%	3.6538	5.720011	0.63878	0.523
triclopyr 12%	imazapyr 2%	1.1	1.980741	0.55535	0.5787
triclopyr 12%	glyphosate 27%	-0.35	1.638088	-0.21366	0.8308
glyphosate 27%	AMCP 5%	-1.6667	1.939563	-0.8593	0.3902
imazapyr 2%	glyphosate 27%	-1.6667	1.939563	-0.8593	0.3902
triclopyr 12%	AMCP 5%	-2.3833	1.985363	-1.20045	0.23
imazapyr 2%	AMCP 5%	-3.8333	2.056033	-1.86443	0.0623

Table A.2.15: Russian olive shoot heights six months after herbicide treatment, mean separation report (only alive trees).	
untreated	A
triclopyr 12%	B
glyphosate 27%	AB
aminocyclopyrachlor 5%	AB
imazapyr 2%	B

Table A.2.16: Russian olive shoot heights eighteen months after herbicide treatment Wilcoxon Chisquare approximation (only alive trees).		
1-way Test, ChiSquare Approximation		
ChiSquare	DF	Prob>ChiSq
29.8829	4	<.0001

Table A.2.17: Russian olive shoot heights eighteen months after herbicide treatment Wilcoxon pair wise comparisons (only alive trees). (AMCP=aminocyclopyrachlor)					
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
untreated	triclopyr 12%	17.3939	4.450495	3.90832	<.0001
untreated	imazapyr 2%	16.8831	4.833101	3.49323	0.0005
untreated	glyphosate 27%	16.5455	5.025811	3.2921	0.001
untreated	AMCP 5%	8.6894	5.665562	1.53372	0.1251
imazapyr 2%	glyphosate 27%	0	2.160706	0	1
triclopyr 12%	imazapyr 2%	-0.1169	2.574483	-0.0454	0.9638
triclopyr 12%	glyphosate 27%	-0.7727	2.556557	-0.30225	0.7625
glyphosate 27%	AMCP 5%	-3.75	1.948409	-1.92465	0.0543
imazapyr 2%	AMCP 5%	-4.3214	2.069334	-2.08832	0.0368
triclopyr 12%	AMCP 5%	-4.9432	2.604161	-1.89819	0.0577

Table A.2.18: Russian olive shoot heights eighteen months after herbicide treatment, mean separation report (only alive trees).	
untreated	A
triclopyr 12%	BC
glyphosate 27%	BC
aminocyclopyrachlor 5%	AB
imazapyr 2%	C

Table A.2.19: Russian olive shoot heights thirty months after herbicide treatment Wilcoxon Chisquare approximation (only alive trees).		
1-way Test, ChiSquare Approximation		
ChiSquare	DF	Prob>ChiSq
24.88	4	<.0001

Table A.2.20: Russian olive shoot heights thirty months after herbicide treatment Wilcoxon pair wise comparisons (only alive trees). (AMCP=aminocyclopyrachlor)					
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value
untreated	imazapyr 2%	17.1938	4.413912	3.89535	<.0001
untreated	triclopyr 12%	16.1861	4.361579	3.71106	0.0002
untreated	AMCP 5%	11.1198	6.119658	1.81706	0.0692
untreated	glyphosate 27%	9.5625	7.190851	1.32981	0.1836
triclopyr 12%	imazapyr 2%	0.2864	2.669397	0.10728	0.9146
glyphosate 27%	AMCP 5%	0	1.406829	0	1
triclopyr 12%	glyphosate 27%	0	2.952272	0	1
imazapyr 2%	glyphosate 27%	-0.3	2.763397	-0.10856	0.9135
imazapyr 2%	AMCP 5%	-1.95	2.510257	-0.77681	0.4373
triclopyr 12%	AMCP 5%	-2.1212	2.691608	-0.78808	0.4306

Table A.2.21: Russian olive shoot heights eighteen months after herbicide treatment, mean separation report (only alive trees).	
untreated	A
triclopyr 12%	B
glyphosate 27%	AB
aminocyclopyrachlor 5%	AB
imazapyr 2%	B

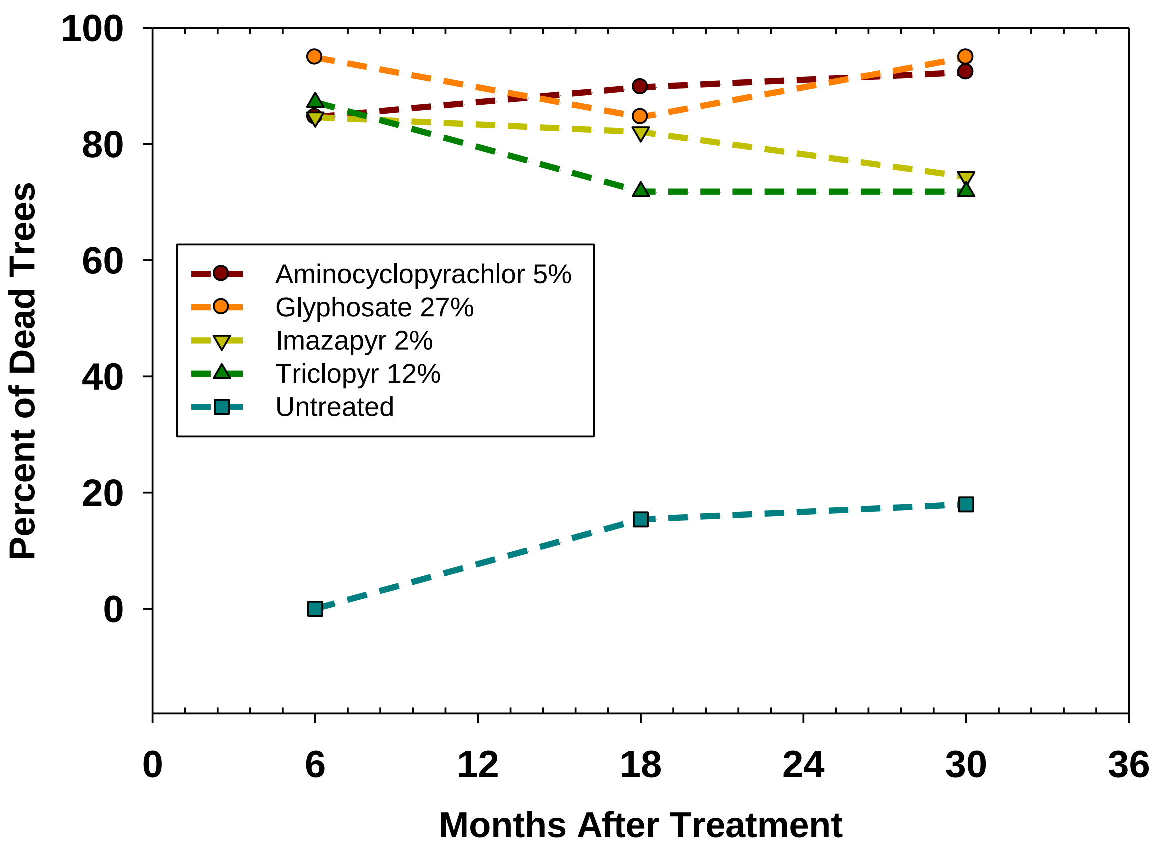

Figure A.2.1: Mortality of Russian olive for all treatments 6, 18, and 30 months after treatments, n=39. Statistical differences are located in Tables A.2.1-A.2.3.

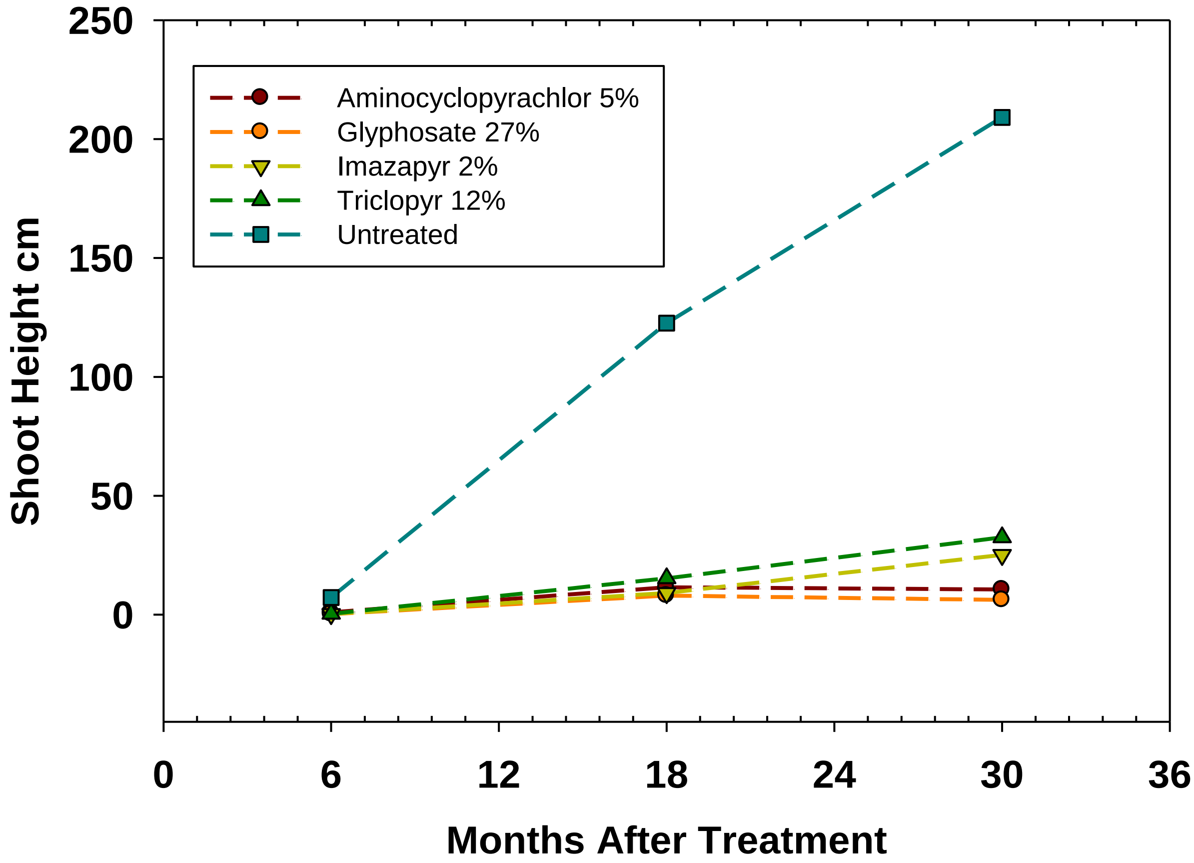

Figure A.2.2: Russian olive shoot height in cm average across all trees (n=39). All treatments had smaller shoot height than the untreated check. Statistical differences located in Tables A.2.4-A.2.12.

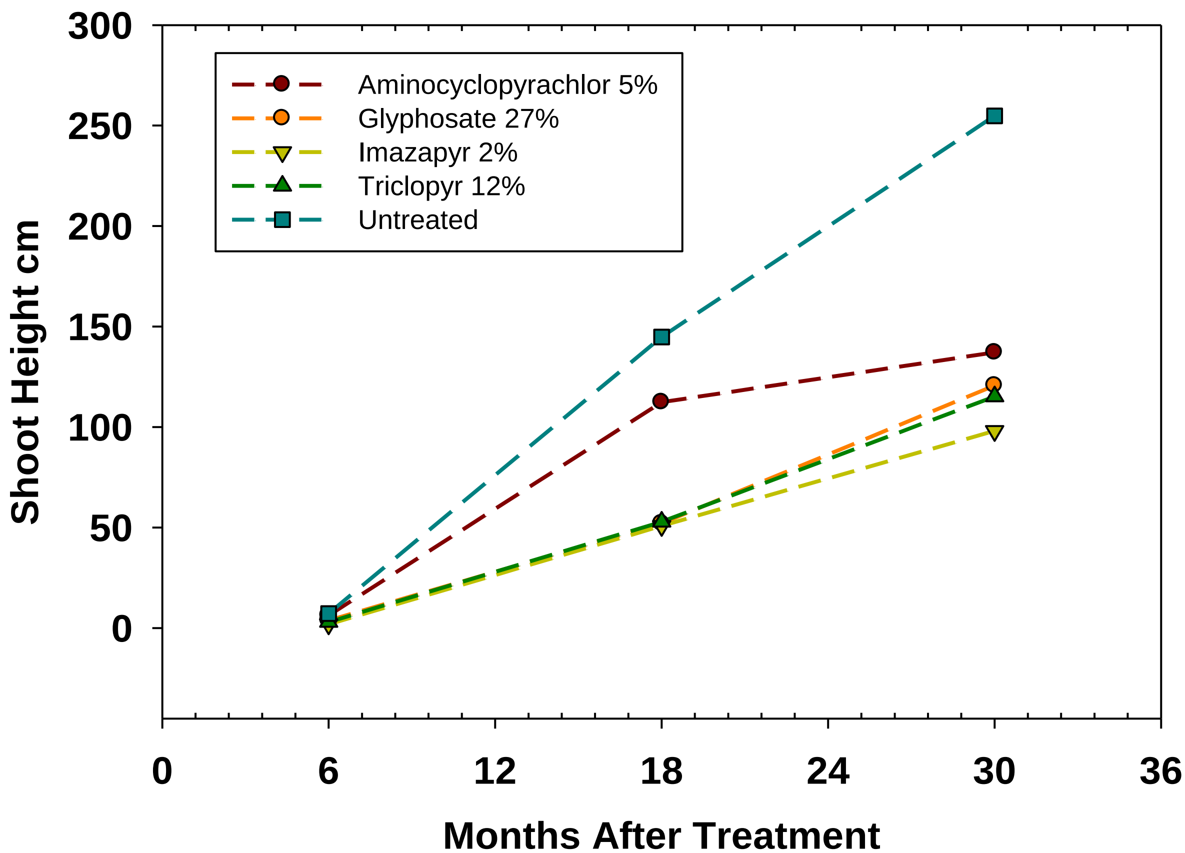

Figure A.2.3: Russian olive shoot height in cm, averaged across all trees that were alive. (Aminocyclopyrachlor (n=4), glyphosate (n=2), imazapyr (n=10), triclopyr (n=11), and the untreated check (n=32)). Statistical differences located in Tables A.2.13-A.2.19.

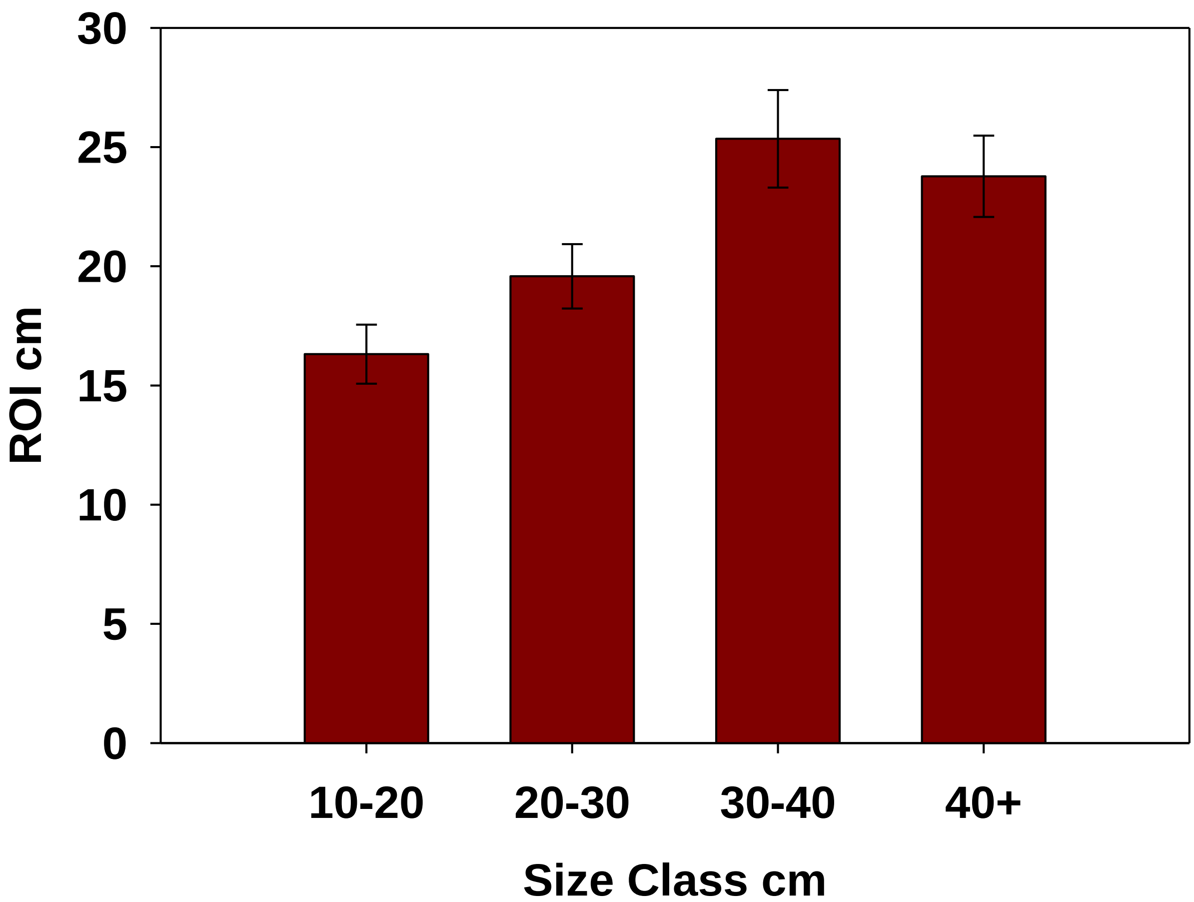

Figure A.2.4: Radius of inhibition separated by Russian olive size class. Averaged across all four herbicide treatments and months after treatment (not including untreated checks or 12 and 24 month after treatment data). Size class 10-20 cm n= 111, 20-30 cm n=144, 30-40 cm n=99, 40+ n=114.

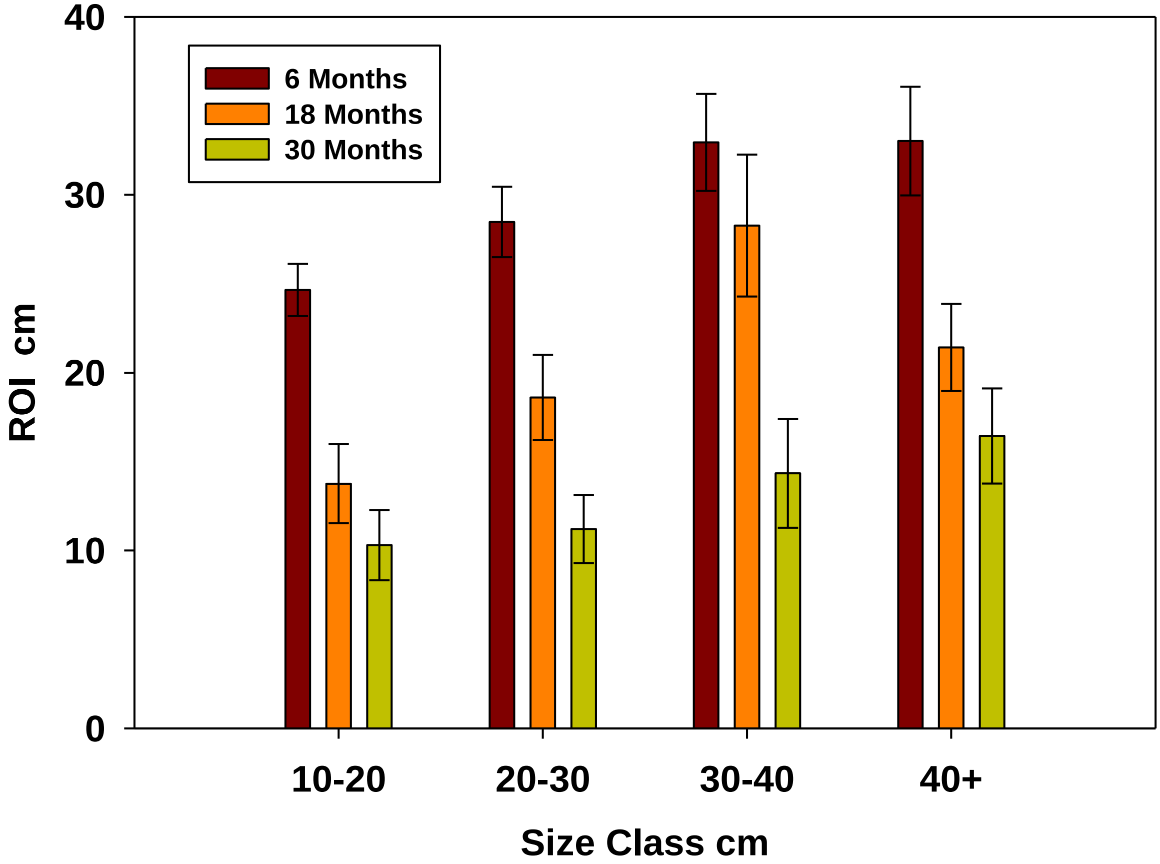

Figure A.2.5: Radius of inhibition by Russian olive size class. Averaged across all four herbicide treatments, separated by months after treatment (not including untreated checks or 12 and 24 month data). Size class 10-20 cm n= 37, 20-30 cm n=48, 30-40 cm n=33, 40+ n=38.

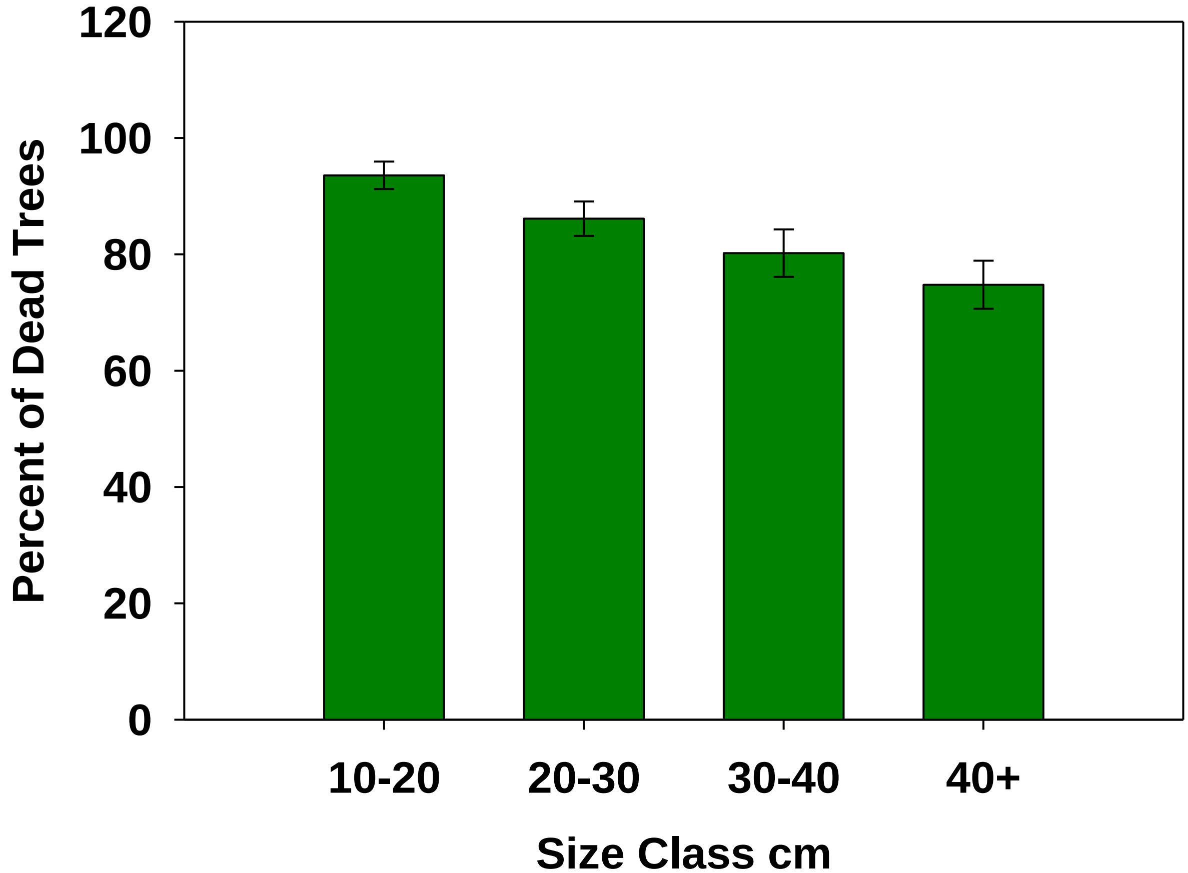

Figure A.2.6: Mortality separated by Russian olive size class. Averaged across all four herbicide treatments and months after treatment (not including untreated checks or 12 and 24 month after treatment data). Size class 10-20 cm n= 111, 20-30 cm n=144, 30-40 cm n=99, 40+ n=114.

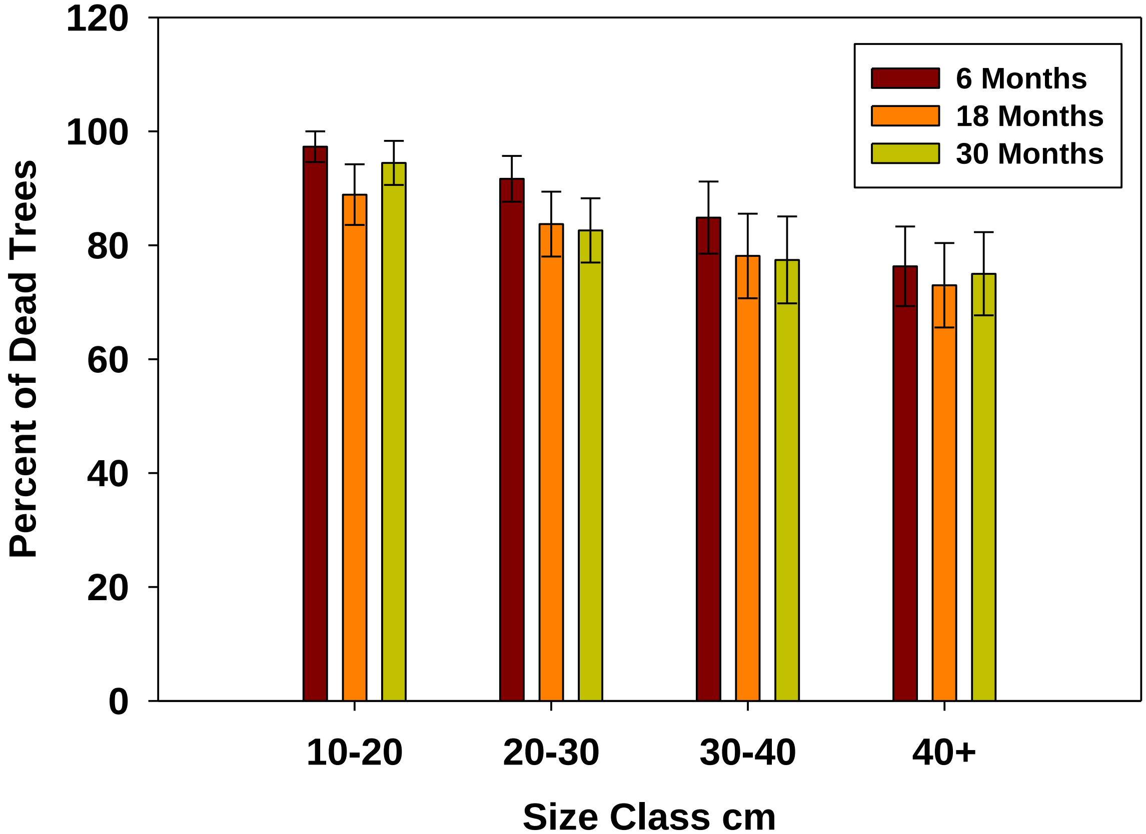

Figure A.2.7: Mortality separated by Russian olive size class. Averaged across all four herbicide treatments, separated by months after treatment (not including untreated checks or 12 and 24 month data). Size class 10-20 cm n= 37, 20-30 cm n=48, 30-40 cm n=33, 40+ n=38.

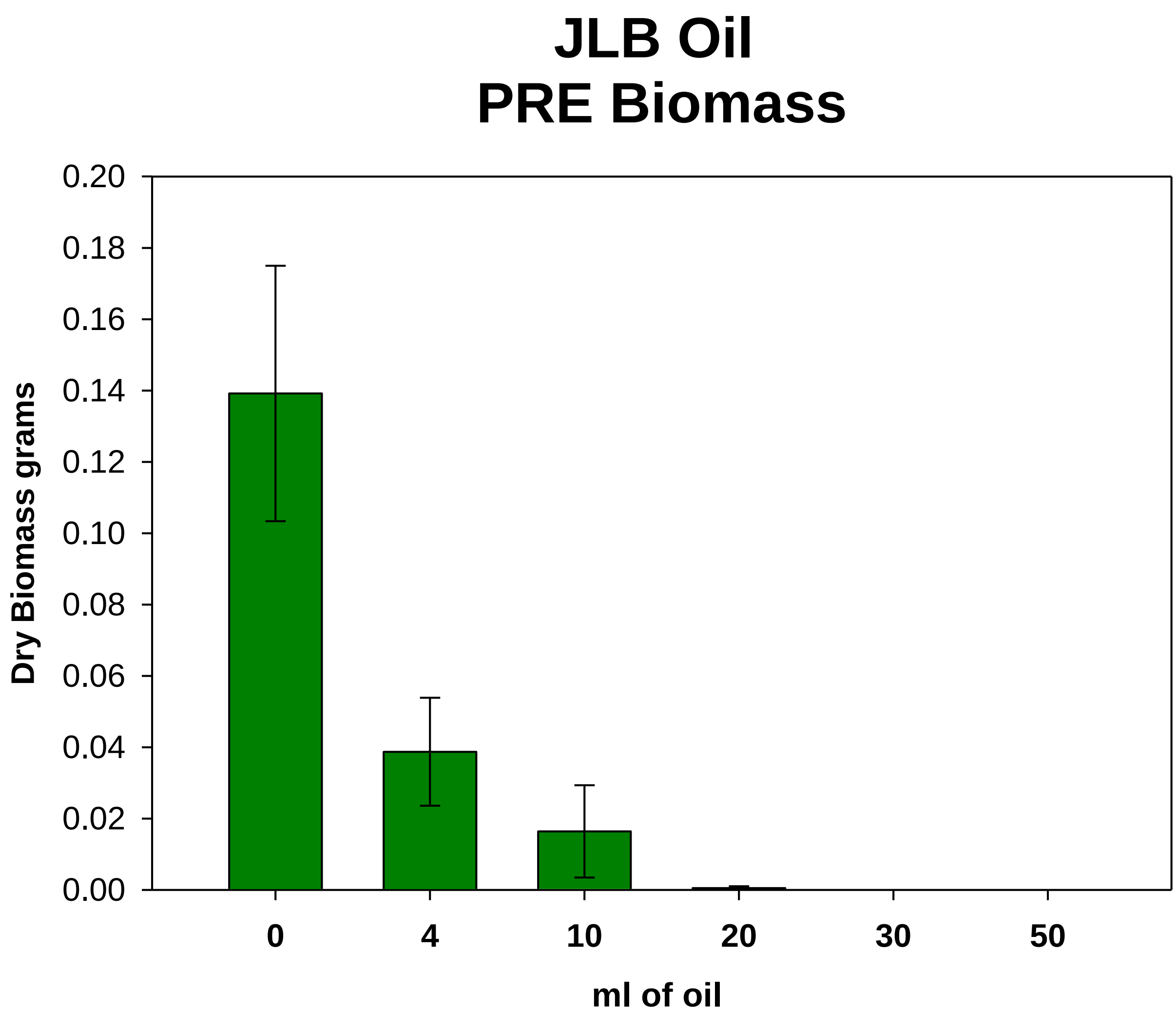

Figure A.2.8: Three replications of kochia, pigweed, velvetleaf, rye, western wheatgrass, and slender wheatgrass were planted in potting soil within 7cm*7cm*7cm inserts. Oil treatments were applied with a hand squirt bottle the day after planting before watering. Six oil rates were tested 0, 4, 10, 20, 30, and 50 ml JLB oil per insert. Above ground biomass was collected 4 weeks after planting, and dried in an oven at 120 degrees Fahrenheit. Biomass was averaged across all species for each oil rate. Plants were injured at even the lowest PRE JLB oil rate. N=21.

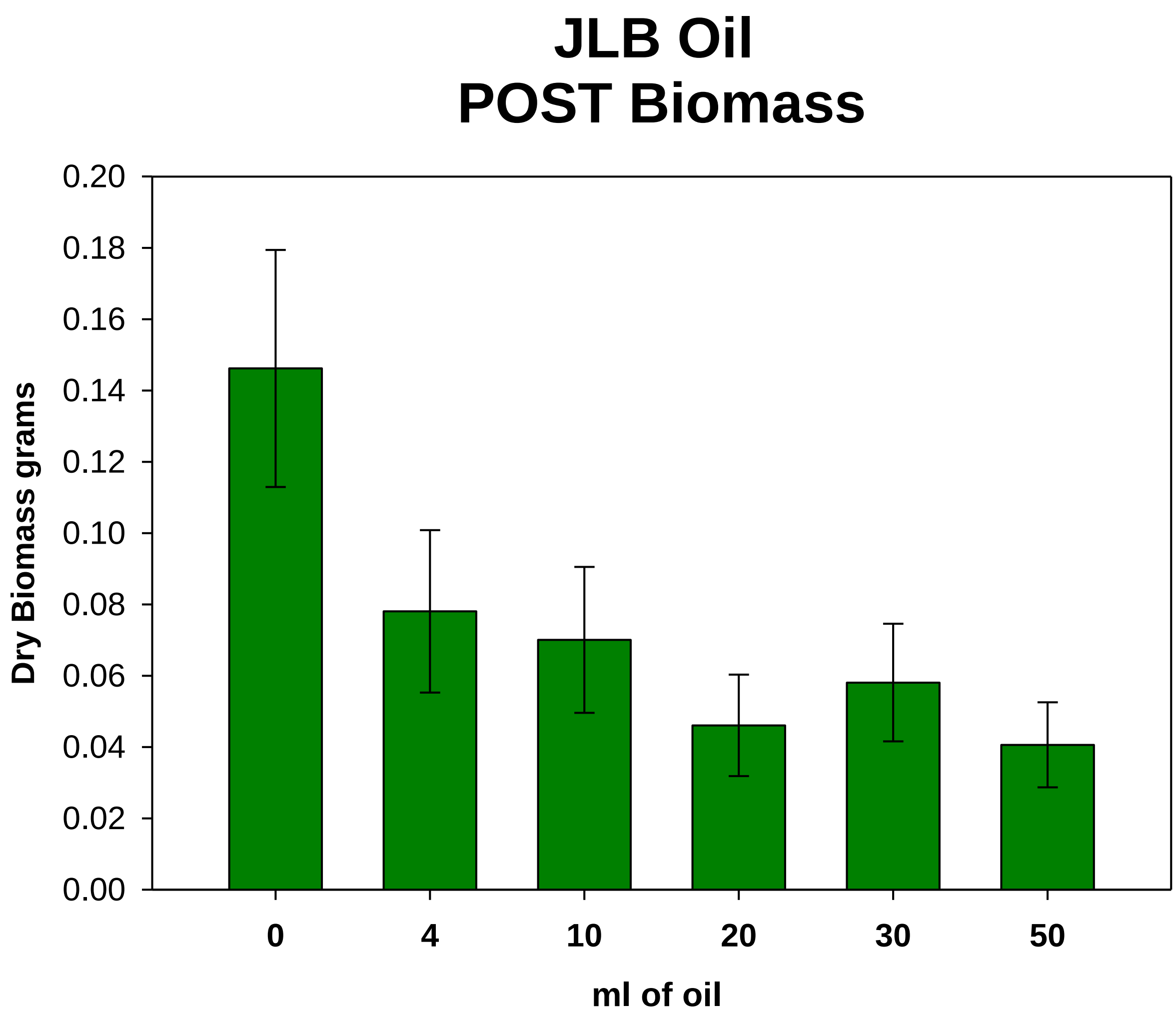

Figure A.2.9: Three replications of kochia, pigweed, velvetleaf, rye, western wheatgrass, and slender wheatgrass were planted in potting soil within 7cm*7cm*7cm inserts. Oil treatments were applied to each insert with a squirt bottle two weeks after planting and after species had emerged. Six rates were tested 0, 4, 10, 20, 30, and 50 ml JLB oil per insert. Above ground biomass was collected 4 weeks after planting, and dried in an oven at 120 degrees Fahrenheit. Biomass was averaged across all species for each oil rate. Plants were injured at even the lowest POST JLB oil rate. N=21.