THESIS

INVESTIGATING THE IMPACT OF SOIL TYPE, SOIL MOISTURE, AND SOIL SURFACE RESIDUE COVER ON THE EFFICACY OF DIFLUFENICAN

Submitted by

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ABSTRACT

INVESTIGATING THE IMPACT OF SOIL TYPE, SOIL MOISTURE, AND SOIL SURFACE RESIDUE COVER ON THE EFFICACY OF DIFLUFENICAN

Diflufenican is a pre-emergent and early post-emergent herbicide that inhibits phytoene desaturase, an essential enzyme in the biosynthesis of carotenoids. It has been used effectively in overseas markets such as Europe and Australia, but it never has been registered for use in the United States. With the herbicide resistance issues in the United States continuing to increase each year, the necessity for developing effective options to combat herbicide-resistant weeds magnifies. Recently, Bayer CropScience has begun research into developing diflufenican as a tool to manage herbicide-resistant weeds, namely Palmer amaranth (*Amaranthus palmeri*), in United States' corn and soybean systems. In this thesis, research is presented on the impacts soil type, soil moisture, and soil surface residue cover have on diflufenican efficacy.

Broad-spectrum weed control with diflufenican was reduced when applied to soils with higher organic matter. This is a consequence of diflufenican having higher sorption coefficients in soils with higher organic matter. Control of Palmer amaranth with diflufenican was not impacted by soil moisture when applied to sandy soils. Under increasing levels of corn residue cover, control of redroot pigweed (*Amaranthus retroflexus*) was not impacted in the field or the greenhouse. In the greenhouse, control of Palmer amaranth with diflufenican was reduced when applied at a lower rate to the highest corn residue coverage in comparison to treatments with no residue cover. Indications are that when robust rates of diflufenican are applied to soil surfaces with high corn residue cover, necessary control can be expected of susceptible species.

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Introduction

Diflufenican is a pre-emergent and early post-emergent herbicide that inhibits phytoene desaturase, an essential enzyme in the biosynthesis of carotenoids (2014). In higher plants, carotenoids are located in thylakoid membranes where they assist in light-harvesting and the chloroplast's defense against photooxidation (Demmig-Adams et al., 1996). Photooxidation occurs when the amount of harvested light exceeds the electron transport chain's capacity, which can excite chlorophyll molecules into a triplet state (Demmig-Adams et al., 1996). The excited chlorophyll needs to give off this energy, that cannot be funneled towards photosynthesis, to revert to its ground state. Oxygen molecules can accept this energy, creating reactive singlet oxygen molecules (Demmig-Adams et al., 1996). Singlet oxygen can react with the unsaturated fatty acids found in cell membranes along with aromatic amino acids and purines (Siefermannharms, 1987) (Krinsky, 1979). These reactions with the cell membrane create unstable lipid radicals, which then react with neighboring unsaturated fatty acids producing a destructive chain reaction (2014). These reactions destroy cells, leading to tissue necrosis, which can ultimately be fatal to the plant (Krinsky, 1979). Thus, compounds that inhibit phytoene desaturase and the eventual biosynthesis of carotenoids can be very effective herbicides.

Carotenoids are classified as terpenoids due to being derived from the five-carbon building blocks isopentenyl diphosphate (IPP) and dimethylallyl diphosphate (DMAPP) (Carretero-Paulet et al., 2006; Rodriguez-Concepcion and Boronat, 2002). These building blocks are both synthesized in independent pathways; the mevalonate (MVA) pathway and the methylerythritol phosphate (MEP) pathway (Rodriguez-Concepcion and Boronat, 2002). The MVA pathway is located in the cytosol, and the MEP pathway is found in the plastid

(Lichtenthaler et al., 1997). The MEP pathway is responsible for the synthesis of the five-carbon building blocks that carotenoids are assembled from. Those 5-carbon building blocks, IPP and/or DMAPP, are added together until the 20-carbon molecule geranylgeranyl pyrophosphate (GGPP) is synthesized (Witschel and Hamprecht, 2019). Then, two GGPP molecules are assembled to create the 40-carbon molecule phytoene, which has to undergo a few desaturation steps to become lycopene (Britton, 1979; Witschel and Hamprecht, 2019). Lycopene is the base molecule unto which cyclization reactions occur to synthesize the various carotenoids (Witschel and Hamprecht, 2019). The first desaturation step in the formation of lycopene from phytoene is carried out by the aforementioned enzyme, phytoene desaturase, which is the target of diflufenican (Sandmann et al., 1991).

Diflufenican was discovered in 1979 by May & Baker (now Bayer CropScience) (Witschel and Hamprecht, 2019). Its primary use is pre-emergent control of broadleaf weed species in winter cereals and leguminous crops, but it also has early post-emergent activity and control of certain annual grasses (2014) (Conte et al., 1998; Witschel and Hamprecht, 2019). It has been utilized, primarily in mixtures (Conte et al., 1998), overseas in Australia and Europe but has never been registered for use in the United States.

The United States currently has 165 documented, unique cases of herbicide resistance (Heap, 2020). Palmer amaranth (*Amaranthus palmeri*) has 68 documented, unique cases of herbicide resistance, with 62 of them occurring in the United States (Heap, 2020). In two of the cases, Palmer amaranth individuals had evolved resistance to five modes of action (Kumar et al., 2019; Schwartz-Lazaro et al., 2017) and, in total, has documented resistance to eight modes of action (Heap, 2020). The issue of herbicide resistance in the United States is dire, especially with

Palmer amaranth, where “zero-tolerance” measures have had to be implemented to save fields and slow the spread of resistance (Barber et al., 2015).

Phytoene Desaturase Inhibitors could be a useful tool in managing herbicide-resistant Palmer amaranth. In 2020, the Herbicide Resistance Action Committee (HRAC) updated its classification of herbicide modes of action. They have seven active ingredients currently listed as phytoene desaturase inhibitors. Of those seven active ingredients, only two are currently registered for use in the United States, fluridone and norflurazon. Fluridone is primarily used to control aquatic species but also has registration for use in cotton and particular fruit and nut crops to control annual weed species (2014). In 2017, the USGS estimated that around 10,000 kilograms was used on agricultural land. Norflurazon was a popular herbicide for use in cotton and orchards in the 1990s, topping out at over an estimated 1.5 million kilograms in 1995 and 1996. The amount of norflurazon applied has fallen dramatically over the years, where estimated use on agricultural land was around 5000 kilograms as recently as 2016. In comparison, popular herbicides that Palmer amaranth has evolved wide-spread resistance to, glyphosate and atrazine, were applied in estimated amounts greater than 100 million and 25 million kilograms in 2017, respectively.

With the lack of continuous, wide-spread use of PDS inhibitor herbicides in the United States, only two weed species have been documented to have evolved resistance to PDS inhibitors in the United States, Hydrilla (*Hydrilla verticillata*) and annual bluegrass (*Poa annua*) (Dayan et al., 2014). Hydrilla is an aquatic species, and annual bluegrass is a turfgrass species. Both species have no impact on row-crop production, meaning resistance to PDS inhibitors have not been documented in cropping systems where Palmer amaranth has its most pronounced impact.

Bayer CropScience has been investigating the potential utility of diflufenican for use in the United States. With the low usage of phytoene desaturase inhibitors in row cropping systems in the United States, diflufenican can be a critical tool to help control herbicide-resistant Palmer amaranth.

With that, there are still some questions that need further investigation so that diflufenican can be implemented in ways that will offer a greater likelihood of success in the United States. Our first objective in our research with diflufenican is evaluate its performance on weeds and soils found in the United States. Our second objective is to determine the impact of soil moisture across multiple soil types on Palmer amaranth control performance. Our third objective is to investigate if increasing corn residue cover can significantly reduce weed control. This research will help guide Bayer CropScience in their development of diflufenican for registration in the United States.

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Chapter 1: Evaluating Broad-Spectrum Weed Control on United States Soils with Diflufenican

Efficacy of diflufenican was tested on U.S. soils against a variety of weeds commonly found in U.S. corn and soybean systems. Since diflufenican has commonly been applied in herbicide mixtures in overseas markets, its efficacy was tested with Balance Flexx®, Warrant®, and Sencor® DF. Although diflufenican had good control of Palmer amaranth, redroot pigweed, and giant foxtail, it is likely best utilized in combination with another herbicide. Results of this study indicate that Balance Flexx® provides the best control in combination with diflufenican followed closely by Sencor® DF.

INTRODUCTION

With diflufenican never receiving registration for use in the United States, investigating its performance on weeds and soils found in the United States was a good place to start. Palmer amaranth (*Amaranthus palmeri)*, giant foxtail (*Setaria faberi*), velvetleaf (*Abutilon theophrasti*), redroot pigweed (*Amaranthus retroflexus*), and Texas panicum (*Panicum texanum*) represent a good variety of weed species that can be found in U.S. corn and soybean systems. Effective control of all species would indicate good broad-spectrum control could be obtained in the field. Soils from California, Iowa, New York, and Washington state were used as the medium in which the weeds were grown in and the herbicide was applied to. They possess a range of properties so that differences in control can be attributed to certain properties of the soil in which the differences occur in.

Oftentimes, diflufenican is applied in mixtures with other herbicides. Balance Flexx®, Warrant®, and Sencor® DF are three soil-applied herbicides included in this study to evaluate their performance applied alone and in combination with diflufenican.

Balance Flexx® is an HPPD-inhibitor (MOA group 27) with the active ingredient isoxaflutole. It is applied pre-plant, pre-emergence, or early post-emergence to control certain grass and broadleaf weeds in field corn. It was estimated that over 250,000 kilograms of isoxaflutole was applied to United States corn fields in 2017.

Warrant® is an inhibitor of very long chain fatty acid synthesis (MOA group 15) with the active ingredient acetochlor. Warrant is a unique acetochlor product as the active ingredient is micro-encapsulated. This allows for a slower release of the herbicide which results in longer residual control of various emerging grasses and broadleaf weeds and increased crop safety. It is labeled for pre-plant, pre-emergence, and post-emergence use in a number of crops including

corn and soybean. In 2017, over 22 million estimated kilograms of acetochlor was applied in the United States, with around 18 million kilograms of acetochlor being applied in corn.

Sencor® DF is an inhibitor of photosynthesis at photosystem II (MOA group 5) with the active ingredient metribuzin. Sencor DF is labeled for use in turf to control certain grass and broadleaf species but metribuzin has many different formulations in the marketplace allowing for pre-emergence and post-emergence application in a variety of crop species (2014). Its primary use is soil- and foliar-applied control of weeds in soybean. In 2017, the estimated total amount of metribuzin applied was around 2.5 million kilograms, with about 2 million kilograms of that being applied in soybean.

MATERIALS AND METHODS

Soils

Four distinct soils were collected and shipped to Colorado State University by employees of Bayer CropScience. These soils were collected from research farms located in California, Iowa, New York, and Washington state after the growing season of 2019 and will be denoted as CA, IA, NY, and WA, respectively. The sampling was made using a clean, spade shovel to a depth of 15 cm. The properties of these soils were analyzed by the Colorado State University Soil Testing Laboratory using the methods from (1996). The results of this analysis are presented in Table 1.1.

Experiment Design and Implementation

This experiment was set up as a two-way factorial, with the factors being herbicide treatment and soil type. There were 21 herbicide treatments consisting of diflufenican, BalanceFlexx®, Warrant®, and Sencor® DF applied alone at three different application rates

(Table 1.2). Diflufenican was also applied in combination with BalanceFlexx®, Warrant®, and Sencor® DF separately at the same rates previously described. These treatments were applied to the four previously described CA, IA, NY, and WA soils, which make 84 herbicide-soil treatments. There were three replications of each herbicide-soil treatment.

Soils were sieved through a 6 mm screen and placed into 17 cm x 12.5 cm x 4 cm trays to a depth of 4 cm. Palmer amaranth, giant foxtail, velvetleaf, redroot pigweed, and Texas panicum were planted in rows to target ten emerged seedlings and then covered with another centimeter of soil.

The following day, herbicide treatments were applied using a Generation 4 Research Track Sprayer (Devries Manufacturing, Hollandale, MN). The sprayer was equipped with a Tee-Jet 8002 EVS spray nozzle and calibrated to deliver 187 L ha^{-1}. After application, each soil tray was incorporated with 10 mm of simulated rainfall in the spray chamber.

Herbicide-soil treatments were completely randomized in the greenhouse maintained at 14-h/10-h photoperiod with temperatures between 22 and 26˚ C. Soil trays were rotated every three days to account for any potential differences in greenhouse conditions and were watered once or twice daily to ensure adequate moisture.

Emergence and stand counts were evaluated at 7 and 14 days after application to verify that weeds completely controlled were because of the herbicide application and not poor emergence. Final visual control rankings were made 35 days. Visual control was assessed on a 0-100% scale following the guidelines described by Jursik et al. (2015).

RESULTS

The results of treatment effect on Texas panicum are omitted due to inconsistent germination. All of the individual visual control data points were plotted with dot charts using the ggplot2 statistical package in R software (Wickham, 2016). The results of treatment performance on all four soils used in this study are presented side by side within each plot. Each weed species has their own figure with Palmer amaranth, redroot pigweed, velvetleaf, and giant foxtail being presented in Figures 1.1, 1.2, 1.3, and 1.4 respectively. The data is presented in Tables 1.4, 1.5, 1.6, and 1.7 as well.

Treatment performance was generally better when applied to the sand-based CA and WA soils. Only three treatments delivered greater than 95% control of all species across all soil types. Those treatments were the medium and high rate combinations of diflufenican and isoxaflutole (treatments 14 and 15) and the highest rate combination of diflufenican and metribuzin (treatment 21). When only looking at the results of the treatments applied to the sand-based CA and WA soils, there were 8 total treatments that obtained at least an average of 95% control of all species.

This impact was more pronounced on giant foxtail and velvetleaf control. For giant foxtail, 7 treatments (treatments 9, 14, 15, 16, 17, 18, 21) averaged greater than 95% control on all 4 soils, meaning, these treatments were effective enough to overcome any impact soil properties have on control. When looking at the results of the other 14 treatments on giant foxtail control, the impact of differing soil types becomes evident. Each soil was ranked 1-4, with a 1 meaning that giant foxtail grown in this soil were controlled most effectively and vice versa for a ranking of 4. The most frequent ranking for the sandy CA and WA soils were 1, with an average ranking of 2 and 1.29, respectively. For the clay-based IA and NY soils, the most frequent

ranking was 4 and 3, with an average ranking of 3.14 and 3.07, respectively. The sandier soils allowed for more effective control of giant foxtail.

For velvetleaf, 9 treatments (treatments 5, 6, 11, 12, 14, 15, 19, 20, 21) were able to overcome any impact of soil properties on herbicide activity by obtaining an average greater than 95% control on all soils. The same rankings applied with giant foxtail control were done on the remaining 12 treatment results on velvetleaf control. The most frequent ranking for the CA and WA soils were 2 and 1 with an average ranking of 1.58 and 1.25, respectively. For the IA and NY soils, the most frequent ranking was 4 and 3 with an average ranking of 3.58 and 3.17, respectively. The same trends with giant foxtail control are seen with velvetleaf control.

Diflufenican is best utilized in combination with other active ingredients. The highest rate of diflufenican (75 g ai/ha) was able to effectively control Palmer amaranth, giant foxtail and redroot pigweed (> 95% average control) but was unable to control velvetleaf at an acceptable level (maximum average control of 77%) . The highest performing herbicide applied alone was Balance Flexx®, with average control evaluations exceeding 93% for all species grown in all soil types at a rate of 52.5 g ai ha^{-1}. Thus, the best performance of active ingredient combinations was the addition of diflufenican with Balance Flexx®. The combination of the second highest rates of each product used in this study (37.5 g ai ha^{-1} of diflufenican, 26.25 g ai ha^{-1} of Balance Flexx®) completely controlled (100%) all species across all soils.

Diflufenican applied with Sencor® DF was also an effective herbicide combination in this study. Each treatment replication of the second highest rate combination (37.5 g ai ha^{-1} of diflufenican, 75 g ai ha^{-1} of Sencor® DF) obtained at least 97% control of all species across all soils, with the exception of one replication of the IA soil only having 65% control of velvetleaf. The highest rate combination of these herbicides had at least 97% control of all species across all

soil types. The application of the highest rate of metribuzin alone (150 g ai ha^{-1}) was an effective treatment, (average control >95%) with the exception of inconsistent giant foxtail control on the IA soil. The addition of diflufenican was able to remedy that issue.

The least effective herbicide combination in this study was diflufenican with Warrant®. Velvetleaf was the species this combination was least effective at controlling, especially in the IA and NY soils which contain higher soil organic matter and clay content. The highest rate combination of these two herbicides (75 g ai ha^{-1} of diflufenican, 630 g ai ha^{-1} of Warrant®) did provide an average control greater than 97% against Palmer amaranth, giant foxtail, and redroot pigweed, while also providing an average control of velvetleaf greater than 95% on the sandier CA and WA soils.

DISCUSSION

This study included many variables to provide insight into how to further develop diflufenican so that it has the best chance of success when it hits the U.S. market. Originally, this study was going to be the first of multiple greenhouse, efficacy studies using these variables to deliver results that signify how impactful soil type and mixtures with other active ingredients are on broad-spectrum weed control with diflufenican. Plans changed with the COVID-19 pandemic which turned this study into a large, screening study to identify trends instead of firm results. These trends would illuminate plans of smaller, specific studies with diflufenican that could be done in the future at Colorado State University, while also providing more information to Bayer CropScience's previously completed research with diflufenican and these parameters.

An important trend that was elucidated with this study is that the performance of these soil-applied herbicides differed when applied to the CA, IA, NY, and WA soils used in this

study. It has long been known that the interaction between the herbicide active ingredient and soil matrix affects the herbicide's impact on emerging plants. The soil properties that have the most pronounced impact on herbicide performance are often soil organic matter, clay content, and soil pH (Corbin et al., 1971; Harrison et al., 1976; Upchurch et al., 1966). Soil organic matter and clay content are often positively correlated with each other; meaning, herbicide soil adsorption studies often find that these two properties are highly correlated with increased herbicide adsorption. Research has elucidated that the main driver of herbicide adsorption is soil organic matter with clay content often being higher in soils with high organic matter content, but not having as much of an impact on herbicide adsorption (Mitra et al., 1999).

Research investigating isoxaflutole, acetochlor, and metribuzin soil adsorption has yielded results that align with the previous information. Isoxaflutole adsorption is higher in soils with more soil organic matter and lower pH (Mitra et al., 1999; Rice et al., 2004) with increased clay content not always being highly correlated with higher adsorption (Mitra et al., 1999). Higher soil organic matter content is also the primary factor influencing acetochlor adsorption (Wang et al., 1999; Weber and Peter, 1982) leading to reduced weed control (Weber and Peter, 1982). Soil organic matter positively correlates with metribuzin adsorption as well (Peter and Weber, 1985; Savage, 1976) with increased adsorption also seen in soils with lower pH (Ladlie et al., 1976).

Researchers at Bayer CropScience investigated diflufenican adsorption to soil and organic matter with six European soils (Table 1.7). Diflufenican had higher K_d (soil adsorption coefficient) and K_{oc} (organic carbon to water partition coefficient) in soils with higher organic matter. Higher K_d and K_{oc} values mean that more herbicide is bound, rendering it unavailable for plant uptake. The soils from California and Washington used in our study had 1.4 and 0.6% soil

organic matter, respectively, while the soils from Iowa and New York had 3.4 and 4.5%, respectively. The results from our study backup previous research unveiling that soils with higher organic matter will have more of the soil-applied herbicide adsorb, resulting in reduced weed control.

The other noteworthy trend identified in this study is that diflufenican is best utilized in combination with other active ingredients. Encouragingly, out of all the species in this study, diflufenican performed best at controlling the *Amaranthaceae* species, notably, Palmer amaranth. This is a critical finding as the mode of action family diflufenican resides in is underutilized in U.S. row cropping systems. Bringing diflufenican to the market would introduce another active ingredient to use judiciously against herbicide-resistant Palmer amaranth. Formulating or mixing diflufenican with active ingredients currently used to control herbicide-resistant Palmer amaranth would help extend their period of effectiveness by reducing the likelihood of weeds it effectively controls evolving resistance mechanisms against it.

Evans et al. (2016), revealed that glyphosate resistance in waterhemp (*Amaranthus tuberculatus*) was 83 times less likely to evolve in 4-6 years when an average of 2.5 herbicide modes of action were used per application in comparison to an average of 1.5 herbicide modes of action used per application. Herbicide mixtures of ethametsulfuron, bromoxynil, and MCPA, applied post-emergence to small plots seeded with field pennycress (*Thlaspi arvense*) seed of which five percent was resistant to ALS-herbicides, did not allow the percent of resistant seed returned to the seedbank to increase after four consecutive years of application (Beckie and Reboud, 2009). In contrast, the same study revealed that applying ethametsulfuron only one time at any point during the four-year experiment increased in the percentage of ALS-resistant field pennycress. Busi et al. (2020), demonstrated with their model how applying mixtures of popular

soil-applied herbicides in Australian cropping systems can delay resistance in annual ryegrass (*Lolium rigidum*) up to six times more than herbicides applied alone or in simple rotation. Although applying multiple active ingredients with different modes of action is more expensive, Livingston et al. (2016) revealed in a 20-year simulation model that managing glyphosate resistance proactively can pay for itself within the first 2-3 years and lead to a 14-17.5% profit increase at the end of the 20-year cycle.

The combination of diflufenican and all three other active ingredients used in this study can provide effective control of important weed species in U.S. corn and soybean production. With the rapid evolution of herbicide resistance in the U.S., it is being stressed that multiple herbicide modes of action, along with other methods of weed control, need to be used to obtain effective broad-spectrum weed control and slow the evolution of herbicide resistance. Busi et al. (2020), presents an interesting template into how diflufenican could be effectively utilized in United States' cropping systems. The annual ryegrass resistance issue in Australia is akin to the Palmer amaranth resistance issue in the United States. High genetic diversity and ability to effectively spread and adapt to new environments has allowed these two species to evolve resistance to many popular foliar-applied herbicides. Bringing diflufenican to the marketplace would provide a unique mode of action to incorporate into soil-applied herbicide mixtures to effectively control or delay the evolution of herbicide-resistant weed species, notably Palmer amaranth, while also providing effective broad-spectrum control of other weeds.

Table 1.1:

Results from soil property analysis conducted by the Colorado State University Soils Laboratory.

Soil	pH	EC (mmhos/cm)	OM %	Sand %	Silt %	Clay %	Taxonomic Class
CA	5.7	3.4	1.4	72	17	11	Nord fine sandy loam
IA	6.3	0.3	3.4	14	53	33	Taintor silty clay loam
NY	5.8	0.1	4.5	23	36	41	Niagara silt loam
WA	8.3	0.2	0.6	82	12	6	Quincy loamy fine sand

Table 1.2:

Herbicide Treatment List.

Treatment #	Active Ingredient	Rate (g ai ha^{-1})
1	Diflufenican	18.75
2	Diflufenican	37.5
3	Diflufenican	75
4	Balance Flexx	13.13
5	Balance Flexx	26.25
6	Balance Flexx	52.5
7	Warrant	157.5
8	Warrant	315
9	Warrant	630
10	Sencor DF	37.5
11	Sencor DF	75
12	Sencor DF	150
13	Diflufenican	18.75
	Balance Flexx	13.13
14	Diflufenican	37.5
	Balance Flexx	26.25
15	Diflufenican	75
	Balance Flexx	52.5
16	Diflufenican	18.75
	Warrant	157.5
17	Diflufenican	37.5
	Warrant	315
18	Diflufenican	75
	Warrant	630
19	Diflufenican	18.75
	Sencor DF	37.5
20	Diflufenican	37.5
	Sencor DF	75
21	Diflufenican	75
	Sencor DF	150

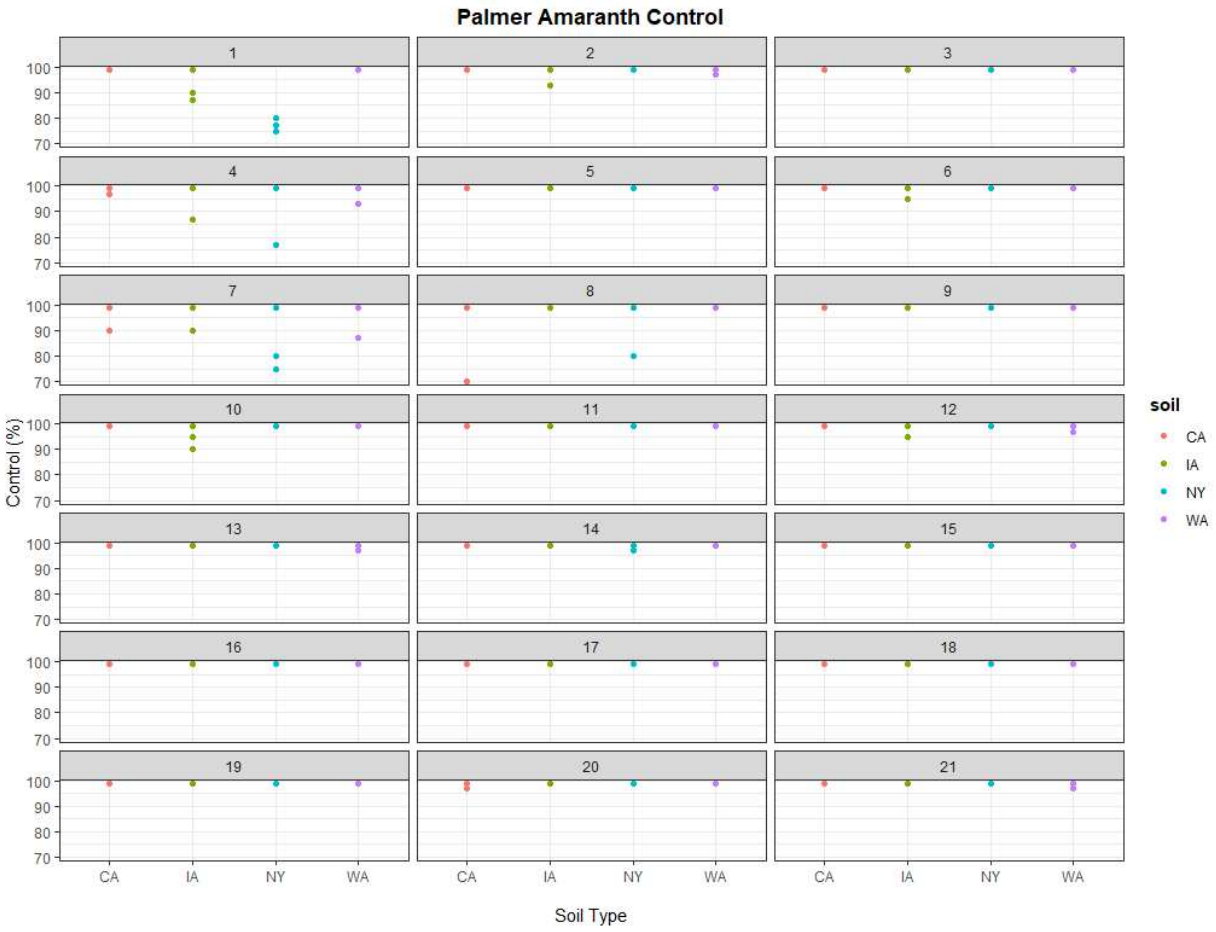

Figure 1.1:

Dot plot of all visual control assessments (0-100%) made for Palmer amaranth. The number above each plot indicates the treatment number.

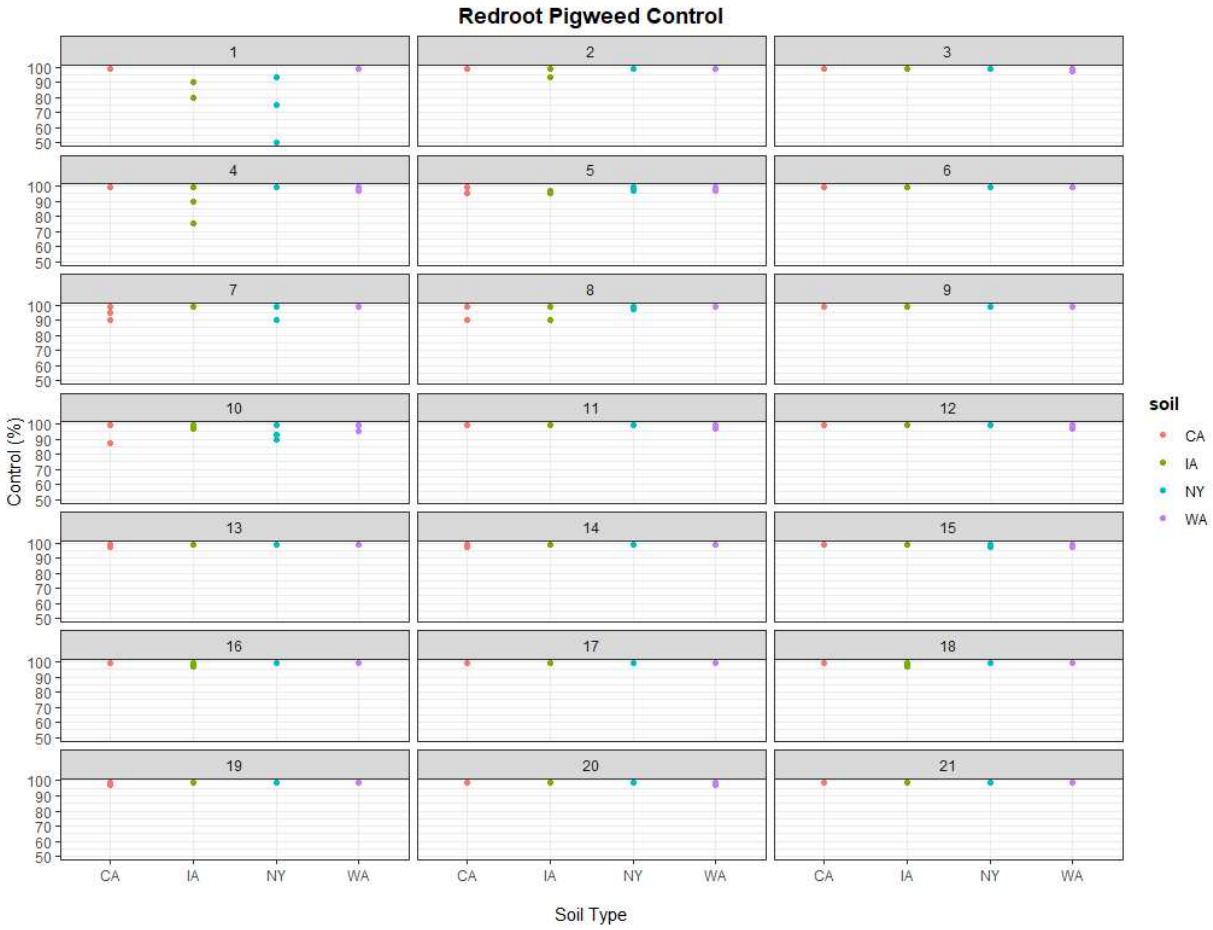

Figure 1.2:

Dot plot of all visual control assessments (0-100%) made for redroot pigweed. The number above each plot indicates the treatment number.

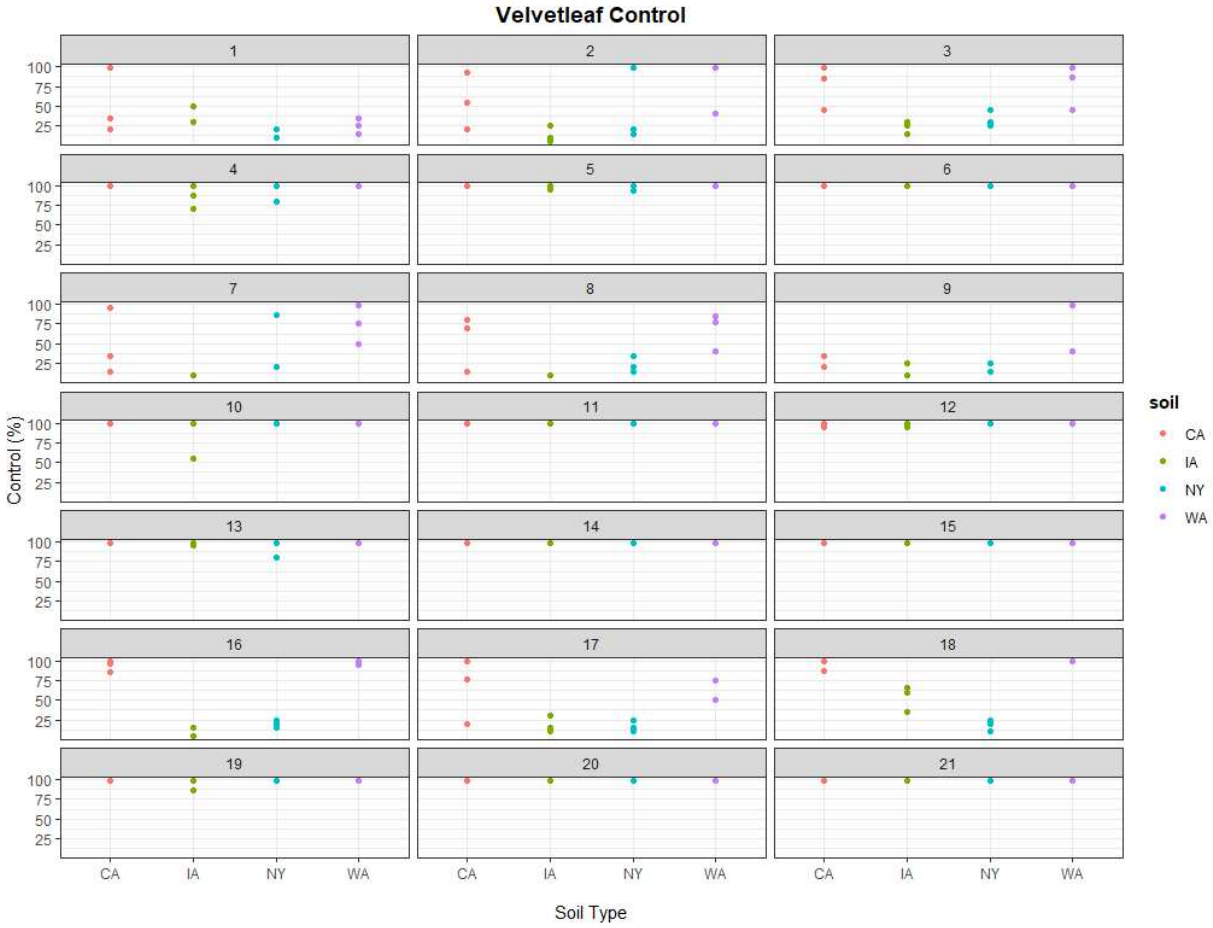

Figure 1.3:

Dot plot of all visual control assessments (0-100%) made for velvetleaf. The number above each plot indicates the treatment number.

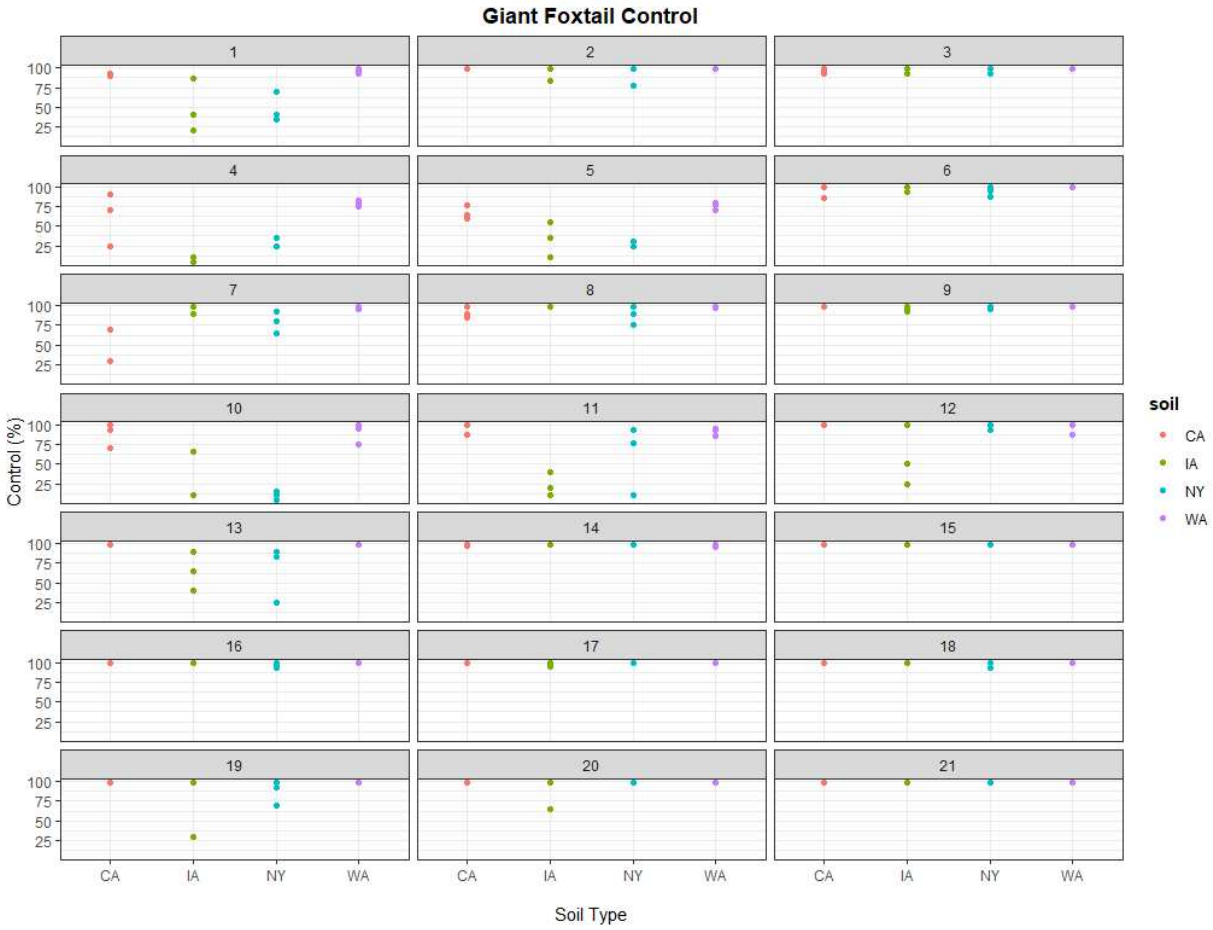

Figure 1.4:

Dot plot of all visual control assessments (0-100%) made for giant foxtail. The number above each plot indicates the treatment number.

Table 1.3:

Means and standard deviations of visual control data (0-100%) of Palmer amaranth.

	Palmer Amaranth			
Treatment	Mean (SD) CA Soil	Mean (SD) IA Soil	Mean (SD) NY Soil	Mean (SD) WA Soil
1	99 (0)	92 (6)	77 (3)	99 (0)
2	99 (0)	97 (3)	99 (0)	98 (1)
3	99 (0)	99 (0)	99 (0)	99 (0)
4	98 (1)	95 (7)	92 (13)	97 (3)
5	99 (0)	99 (0)	99 (0)	99 (0)
6	99 (0)	98 (2)	99 (0)	99 (0)
7	96 (5)	96 (5)	85 (13)	95 (7)
8	89 (17)	99 (0)	86 (11)	99 (0)
9	99 (0)	99 (0)	99 (0)	99 (0)
10	99 (0)	95 (5)	99 (0)	99 (0)
11	99 (0)	99 (0)	99 (0)	99 (0)
12	99 (0)	98 (2)	99 (0)	98 (1)
13	99 (0)	99 (0)	99 (0)	98 (1)
14	99 (0)	99 (0)	98 (1)	99 (0)
15	99 (0)	99 (0)	99 (0)	99 (0)
16	99 (0)	99 (0)	99 (0)	99 (0)
17	99 (0)	99 (0)	99 (0)	99 (0)
18	99 (0)	99 (0)	99 (0)	99 (0)
19	99 (0)	99 (0)	99 (0)	99 (0)
20	98 (1)	99 (0)	99 (0)	99 (0)
21	99 (0)	99 (0)	99 (0)	98 (1)

Table 1.4:

Means and standard deviations of visual control data (0-100%) of redroot pigweed.

	Redroot Pigweed			
Treatment	Mean (SD) CA Soil	Mean (SD) IA Soil	Mean (SD) NY Soil	Mean (SD) WA Soil
1	99 (0)	99 (0)	87 (5)	73 (18)
2	99 (0)	99 (0)	97 (3)	99 (0)
3	99 (0)	98 (1)	99 (0)	99 (0)
4	99 (0)	98 (1)	88 (10)	99 (0)
5	98 (2)	98 (1)	96 (1)	98 (1)
6	99 (0)	99 (0)	99 (0)	99 (0)
7	95 (4)	99 (0)	99 (0)	93 (4)
8	96 (4)	99 (0)	96 (4)	98 (1)
9	99 (0)	99 (0)	99 (0)	99 (0)
10	95 (6)	98 (2)	98 (1)	94 (4)
11	99 (0)	98 (1)	99 (0)	99 (0)
12	99 (0)	98 (1)	99 (0)	99 (0)
13	98 (1)	99 (0)	99 (0)	99 (0)
14	98 (1)	99 (0)	99 (0)	99 (0)
15	99 (0)	98 (1)	99 (0)	98 (1)
16	99 (0)	99 (0)	98 (1)	99 (0)
17	99 (0)	99 (0)	99 (0)	99 (0)
18	99 (0)	99 (0)	98 (1)	99 (0)
19	98 (1)	99 (0)	99 (0)	99 (0)
20	99 (0)	98 (1)	99 (0)	99 (0)
21	99 (0)	99 (0)	99 (0)	99 (0)

Table 1.5:

Means and standard deviations of visual control data (0-100%) of velvetleaf.

	Velvetleaf			
Treatment	Mean (SD) CA Soil	Mean (SD) IA Soil	Mean (SD) NY Soil	Mean (SD) WA Soil
1	51 (34)	37 (9)	17 (5)	25 (8)
2	56 (30)	13 (9)	45 (38)	60 (28)
3	76 (23)	23 (6)	33 (9)	77 (23)
4	99 (0)	85 (12)	93 (9)	99 (0)
5	99 (0)	98 (2)	97 (3)	99 (0)
6	99 (0)	99 (0)	99 (0)	99 (0)
7	48 (34)	10 (0)	42 (32)	75 (20)
8	55 (29)	10 (0)	23 (9)	67 (20)
9	30 (7)	15 (7)	18 (5)	79 (28)
10	99 (0)	84 (21)	99 (0)	99 (0)
11	99 (0)	99 (0)	99 (0)	99 (0)
12	98 (2)	98 (2)	99 (0)	99 (0)
13	99 (0)	98 (2)	93 (9)	99 (0)
14	99 (0)	99 (0)	99 (0)	99 (0)
15	99 (0)	99 (0)	99 (0)	99 (0)
16	94 (6)	8 (5)	20 (4)	98 (2)
17	65 (33)	18 (9)	17 (6)	58 (12)
18	95 (6)	53 (13)	18 (6)	99 (0)
19	99 (0)	95 (6)	99 (0)	99 (0)
20	99 (0)	99 (0)	99 (0)	99 (0)
21	99 (0)	99 (0)	99 (0)	99 (0)

Table 1.6:

Means and standard deviations of visual control data (0-100%) of giant foxtail.

	Giant Foxtail			
Treatment	Mean (SD) CA Soil	Mean (SD) IA Soil	Mean (SD) NY Soil	Mean (SD) WA Soil
1	92 (1)	49 (28)	48 (15)	96 (2)
2	99 (0)	88 (8)	92 (10)	99 (0)
3	96 (2)	97 (3)	97 (3)	99 (0)
4	62 (27)	7 (2)	28 (5)	79 (3)
5	67 (7)	33 (18)	28 (2)	76 (4)
6	94 (7)	97 (3)	94 (5)	99 (0)
7	57 (19)	96 (4)	79 (11)	96 (2)
8	91 (6)	99 (0)	88 (10)	98 (1)
9	99 (0)	96 (2)	98 (2)	99 (0)
10	87 (13)	28 (26)	10 (4)	90 (11)
11	95 (6)	23 (12)	60 (36)	91 (4)
12	99 (0)	58 (31)	97 (3)	95 (6)
13	99 (0)	65 (20)	66 (29)	99 (0)
14	98 (1)	99 (0)	99 (0)	98 (2)
15	99 (0)	99 (0)	99 (0)	99 (0)
16	99 (0)	99 (0)	96 (2)	99 (0)
17	99 (0)	98 (2)	99 (0)	99 (0)
18	99 (0)	99 (0)	97 (3)	99 (0)
19	99 (0)	76 (33)	87 (13)	99 (0)
20	99 (0)	88 (16)	99 (0)	99 (0)
21	99 (0)	99 (0)	99 (0)	99 (0)

Table 1.7:

Adsorpion coefficients of diflufenican in six European soils.

Analysis conducted by Bayer CropScience.

Soil (Textural Class)	pH	OM%	K_d (mL/g)	K_d OC (mL/g)
Santilly (Loam)	6.4	0.9	39.9	4428
Kissendorf (Silt Loam)	6.2	1.4	46.3	3306
Chazay (Clay Loam)	6.4	1.9	73.5	3868
Shelley Field (Clay Loam)	5.4	2.4	98.8	4118
Lleida (Clay Loam)	7.7	2.9	88.9	3066
Manningtree (Sandy Loam)	4.1	3.6	267.5	7431

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Chapter 2: Effect of Soil Moisture on Responses of Palmer Amaranth to Diflufenican

Pre-emergent herbicide efficacy is reduced as soil moisture levels decrease. Efficacy of diflufenican on Palmer amaranth was tested on the CA, IA, NY, and WA soils with soil moisture regimes of -0.33, -1, and -4 bar. Soil-water retention curves were developed to determine the gravimetric water content needed to bring each soil to these soil moisture regimes. Linear regression models were fit and Type III ANOVA analysis was run to determine the effect of soil moisture on the number of survivors and dry biomass of Palmer amaranth in untreated and treated pots. Soil moisture did not have an effect on the efficacy of Palmer amaranth in the CA or WA soils. With limitations in study design, the results from the IA and NY soils had to be omitted. Further analysis is needed to determine the effect of soil moisture on diflufenican efficacy in soils with higher organic matter.

INTRODUCTION

Pre-emergent herbicide efficacy is dependent on how much of the active ingredient is available for uptake by emerging shoots. In Chapter 1, it was discussed how important the interaction between soil properties and the pre-emergent herbicide ingredient is for weed control. Soil moisture is also an important factor as it is widely accepted that increased soil moisture often leads to increased pre-emergent herbicide activity (Jursik et al., 2015). If the herbicide has any degree of water solubility, more will become available for plant uptake as soil moisture increases.

Geier et al. (1999) found that pre-emergent control of *Bromus secalinus* with sulfosulfuron was reduced under high soil moisture stress but not affected under moderate soil moisture stress. Nagy (2008) determined that at least 14 mm of rainfall was needed after a pre-emergent application of acetochlor for effective control of *Echinochloa crus-galli* in the field. Inconsistent control was observed at rainfall amounts less than that. Contrastingly, Jursik et al. (2013) found that acetochlor provided excellent broad-spectrum control with and without irrigation applied after application, but control by pethoxamid was significantly reduced without irrigation. Jursik et al. (2015) observed that broad-spectrum control with oxyfluorfen, aclonifen, acetochlor, dimethenamid, and propisochlor did not depend on soil moisture amounts while linuron, prosulfocarb, and pethoxamid did. Stickler et al. (1969) showed that increases in control of *Setaria faberii* with atrazine, EPTC, and amiben could be obtained with increased soil moisture while activity of propachlor and alachlor did not respond to different soil moisture conditions. They also observed that control was reduced under higher soil moisture conditions with trifluralin, demonstrating that sometimes increased soil moisture can have an adverse effect on weed control. It was speculated that the reduction in control was due to increased herbicide

degradation. This demonstrates that increased soil moisture can increase pre-emergent herbicide efficacy, but it is not always needed.

With diflufenican having very low water solubility (0.05 mg L^{-1} at 20˚C) and having adsorption increase in soils with higher soil organic matter (Table 1.7), investigating the impact that combinations of different soil moisture regimes and soil types have on pre-emergent control with diflufenican is important. Sebastian et al. (2017) investigated the interactions of indaziflam and flumioxazin applied to multiple soils at various moisture levels. Their results indicated that herbicide, soil type, and soil moisture have a significant interaction. Specifically, as soil organic matter rose, the soil moisture requirement for herbicide activation rose.

The literature reveals that soil moisture can but does not always impact pre-emergent control. Chapter 1 elucidated that soils with more organic matter can reduce control with diflufenican due to increased adsorption. In utilizing the same soils as Chapter 1 (Table 1.1), the knowledge of factors influencing diflufenican can be built upon by adding the factor of soil moisture. This study examines the effect soil moisture regimes of -0.33, -1, and -4 bar has on the ability of diflufenican to control Palmer amaranth grown in soils collected from CA, IA, NY, and WA.

MATERIALS AND METHODS

Soil Moisture Regime Determination

To determine how much water is needed for each soil to reach our desired soil moisture regimes, the CA, IA, NY, and WA soils were sent to the Colorado State University Soils Testing Laboratory for moisture tension determination analysis. This analysis is conducted using a pressure plate apparatus following the methods set forth by Klute (1986). By subjecting saturated

soils to increasing amounts of pressure, the gravimetric water content can be determined at certain soil moisture tensions. For the CA, IA, NY, and WA soils, gravimetric water content was determined at soil moisture tensions of -0.1, -0.2, -0.33, - 0.5, -1, -2, -4, -6, -10, and -15 bar with 3 replications for each soil at each tension (Table 2.1). The non-linear relationship between gravimetric water content and soil moisture tension was plotted with the ggplot2 package in R (Wickham, 2016) with the soil moisture tension factor log transformed (Figure 2.1). R^2 values for each soil exceeded 93%, indicating the models were well fit.

The soil moisture regimes of -0.33, -1, and -4 bar were chosen as they provided a good distribution from soils at field capacity to soils with drought stress that still allowed for Palmer amaranth survival. Chahal et al. (2018) demonstrated that Palmer amaranth does not survive in soils maintained beneath the permanent wilting point (-15 bar), but it can survive at moisture levels higher than that. These soil moisture regimes were also chosen so that they were spread far enough apart that they could be maintained without easily crossing over each other, which would render any comparisons unreliable.

Experimental Design and Implementation

This experiment was set up as a two-way factorial, investigating the factors of soil moisture and soil type on the number of survivors and above-ground dry biomass of Palmer amaranth. Soils were sieved to < 6 mm , spread out in the greenhouse, and turned over every few days for 2-3 weeks before the execution of this study to allow ample time for the removal of bioavailable soil moisture.

Soils were carefully measured to equal mass (±1 g) so that any difference in mass in future recordings would be due to moisture loss and not differences in initial soil mass.

Palmer amaranth seeds (30 for IA, NY, and WA; 40 for CA) were then planted 5 mm deep. More seed was planted in the CA soils to account for poorer germination observed in previous studies.

One day after pot filling and planting, soils were sprayed using a Generation 4 Research Track Sprayer (Devries Manufacturing, Hollandale, MN) calibrated to deliver 187 l ha^{-1}. The CA and WA soils were sprayed with 30 g ai ha^{-1} and the IA and NY soils were sprayed with 70 g ai ha^{-1} of diflufenican. These rates were expected to deliver good but not complete control of the Palmer amaranth at field capacity, allowing for the effect of soil moisture to be properly analyzed.

Immediately after spray application water was added via simulated rainfall in the spray chamber to bring each pot to their desired soil moisture regime based on the gravimetric water content measurements obtained from the moisture determination analysis. Pots were re-weighed after the addition of water to ensure that each replication was within ± 2 g of each other.

After herbicide application and rainfall simulation, CA and WA pots with the same soil moisture regime were placed into empty trays (8 pots/tray) so that they could be covered with 30 cm tall, clear, plastic domes. The same measures were taken with the IA and NY soil pots. The trays were then completely randomized a shaded area of the greenhouse, out of direct sunlight. These measures were taken to prevent rapid soil moisture loss, which would cause the soil moisture regimes to cross over each other. Every day, the domes were removed for 1-2 hours to allow for necessary gas exchange processes to occur and to try to alleviate the Palmer amaranth from the humid conditions. Every two days, soil pots were weighed and brought back to their initial mass after water was first added by adding simulated rainfall or adding water with a hand-held spray bottle. After each re-watering event, soil trays were rotated.

RESULTS

Results collected from the CA and WA soils were analyzed separately. Results from the IA and NY soils are not included. Regression models were plotted using the ggplot2 package from R statistical software (Wickham, 2016).

For the WA soil, individual linear regression models were fit with an interaction term between soil moisture and herbicide treatment (0 and 30 g ai ha^{-1}) to the response variables (number of survivors and dry biomass) of Palmer amaranth.

For the CA soil, individual linear regression models were fit for the same responses of Palmer amaranth as a function of soil moisture for untreated soils only. Including an herbicide treatment term would have created an unusable linear model as nearly all treated pots obtained complete control.

Log transformation of the soil moisture variable was applied when model fits improved as a result of this action. Type III ANOVA analysis was run on these models and significance was evaluated at a 0.05 alpha level. Fisher's LSD post hoc analysis was conducted for any significant model terms.

No significant interactions between soil moisture and herbicide treatment were observed when evaluating number of survivors (P=0.129) or dry biomass (P=0.472). The individual soil moisture term was not significant for either response while the treatment term, expectedly, was highly significant (Table 2.2, Table 2.3).

Treated and untreated results in the CA soil were not evaluated with one model like the WA soil as almost complete control with 30 g ai ha^{-1} rate prevented confident analysis with the full model. Unlike the WA soil, the soil moisture term did affect the number of survivors (P<0.001) and dry biomass (P=0.001) in the untreated CA soils (Table 2.4, Table 2.6). Post hoc

analysis revealed that the number of survivors was higher in the soils maintained at -0.33 bar than in soils maintained at -4 bar (Table 2.5). Dry biomass measurements were higher in the -0.33 bar soils than soils maintained at -1 and -4 bar (Table 2.7).

DISCUSSION

Negligible differences were identified in the responses of Palmer amaranth to diflufenican in sandy soils with different soil moisture regimes. Soil moisture is likely to have a less pronounced effect on herbicide performance in sandier soils as they do not possess much organic matter, which is the driving component of herbicide sorption. Thus, these results make sense for diflufenican as it possesses very low water solubility and is in an environment conducive for bioavailability.

The impact of soil moisture on herbicide performance is more critical to examine in soils with higher organic matter. Higher herbicide sorption and reduced efficacy with these types of soils was identified in Chapter 1 which puts higher importance on investigating factors that could influence bioavailability. With diflufenican having high sorption coefficients in high organic matter soils, it could be speculated that increased soil moisture could increase bioavailability and help obtain more effective weed control. On the other hand, with diflufenican having such low water solubility, the impact of soil moisture could be insignificant.

Unfortunately, our study was reliant on maintaining humid conditions in order to reduce rapid soil moisture fluctuation. These humid conditions had an adverse effect on Palmer amaranth growth with and without herbicide presence in the IA and NY soils that had much more soil moisture available to evaporate. In the sandier CA and WA soils, this effect was not observed, allowing for some inferences to be made. Soil moisture did not impact diflufenican

control of Palmer amaranth. This is likely due to diflufenican's low water solubility and the lack of adsorptive surfaces in these soils. As long as a sufficient rate is applied, good control can be expected in sandy soils with soil moisture regimes ranging from -0.33 bar to -4 bar. That sufficient rate proved to be as low as 30 g ai ha^{-1} in this study in the CA soil.

ISSUES ENOUNTERED AND PROPOSED SOLUTIONS

With limited soil quantities left to work with, we were forced to use a much smaller volume of soil to evaluate the response of Palmer amaranth to moisture and herbicide stress. In order to prevent rapid evaporation of the moisture in our soils causing the soil moisture regimes to cross over each other, the study had to be carried out in a very humid environment. Soil pots were placed in trays with 30 cm hoods sealed over top to help hold soil moisture, only being removed for a ~2 hours a day to allow for gas exchange and alleviate the Palmer amaranth from the mass humidity. Soil pots were also kept in a shaded area of the greenhouse that did not receive direct sunlight. These measures appeared to have no effect on the sandier soils but had an adverse effect on the clay soil. The clay-based soils had much more soil moisture that could be evaporated to create a more humid environment. Most of the emerged Palmer amaranth grown in the clay-based soils kept at field capacity wilted and died from the humid conditions, preventing any analysis on the effect of soil moisture and herbicide efficacy. The Palmer amaranth grown in the clay-based soils maintained at -1 and -4 bar suffered from the same issues but to a much lower extent. Even though the Palmer amaranth grown in these pots were able to survive, any results generated must be analyzed with much scrutiny as the humidity could be a contributing factor; thus, these results were not included.

Follow-up studies would need to be conducted in a more realistic environment to get a better sense of the true impact soil moisture has on diflufenican control of Palmer amaranth. A much larger volume of soil to study these interactions would be preferred so that pots could be maintained in an open-air environment that is able to receive direct sunlight. A volume of soil is needed that would allow for these conditions and moisture levels to fluctuate some, but not to the point where they fall below other moisture regimes being studied in the experiment.

The herbicide rates should be adjusted for this study as well. A seven-dose, four-replication dose response study was executed with diflufenican to determine the GR80 rate for each soil maintained near but likely above field capacity. The dose response study also had to be conducted in smaller pots These factors ultimately led to unreliable results that did not translate to this study. This led us to having to use results from other greenhouse research studies to ascertain a rate that would deliver Palmer amaranth control near 80%. The diflufenican rate of 30 g ai $^{-1}$ was a little too high for the CA soil and a little too low for the WA soil. The diflufenican rate of 70 g ai ha^{-1} appeared to be close to the intended outcome for the IA and NY soils, but it was hard to truly determine that under such humid conditions. The same dose response study conducted under conditions similar to what would be used for the soil moisture regime study is needed for proper rate determination.

Overall, this study design doesn't support the conditions necessary to evaluate the effect of soil moisture on herbicide efficacy across a broad range of soils. This study design only allowed for accurate information into this effect with sandy soils. This effect needs to be accurately evaluated on soils that possess high amounts of organic matter. In order to do this, I believe considering the alterations recommended previously in this section is necessary.

Table 2.1:

Results from moisture determination analysis conducted by the Colorado State University Soils Laboratory

Results presented as averages for the three replications with standard deviations.

Gravimetric Water Content (%) for a Given Soil Moisture Tension (Bar)										
Soil	-0.1	-0.2	-0.33	-0.5	-1	-2	-4	-6	-10	-15
CA	6.9	6.7	6.4	5.9	5.1	4.8	4.4	3.8	3.2	3.1
	(0.05)	(0.08)	(0.05)	(0.08)	(0.05)	(0.08)	(0.05)	(0.08)	(0.08)	(0.05)
IA	26.7	23.9	19.5	17.4	14.5	13.8	12.2	10.7	9.8	9.6
	(0.29)	(0.08)	(0.17)	(0.12)	(0.05)	(0.05)	(0.17)	(0.12)	(0.05)	(0.05)
NY	26.8	23.9	20.4	17.8	16.3	14.3	12.9	11.6	11.2	10.9
	(0.12)	(0.45)	(0.24)	(0.08)	(0.21)	(0.05)	(0.09)	(0.12)	(0.08)	(0.08)
WA	7.4	7.2	6.8	6.3	5.9	5.0	5.0	4.7	4.6	4.4
	(0.08)	(0.14)	(0.12)	(0.08)	(0.08)	(0.05)	(0.09)	(0.05)	(0.08)	(0.12)

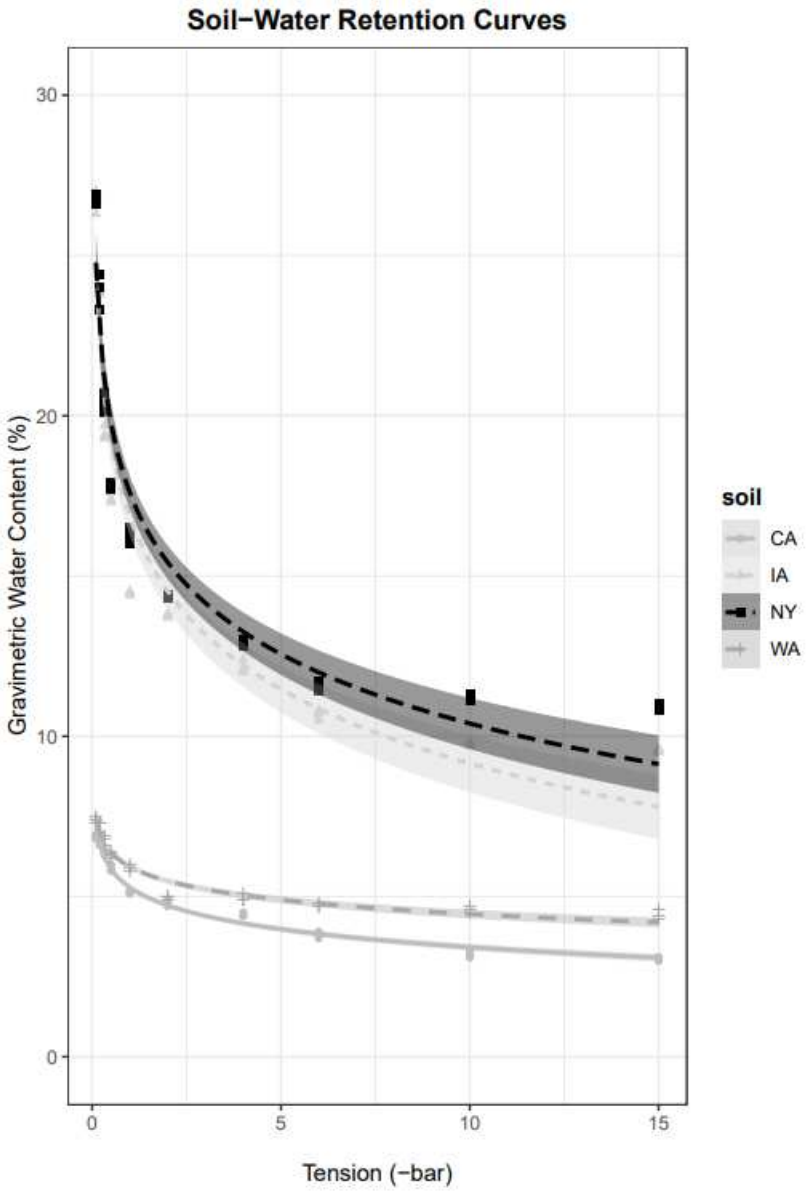

Figure 2.1:

Regression plot with 95% confidence interval bands of gravimetric water content for CA, IA, NY, and WA soils as a function tension..

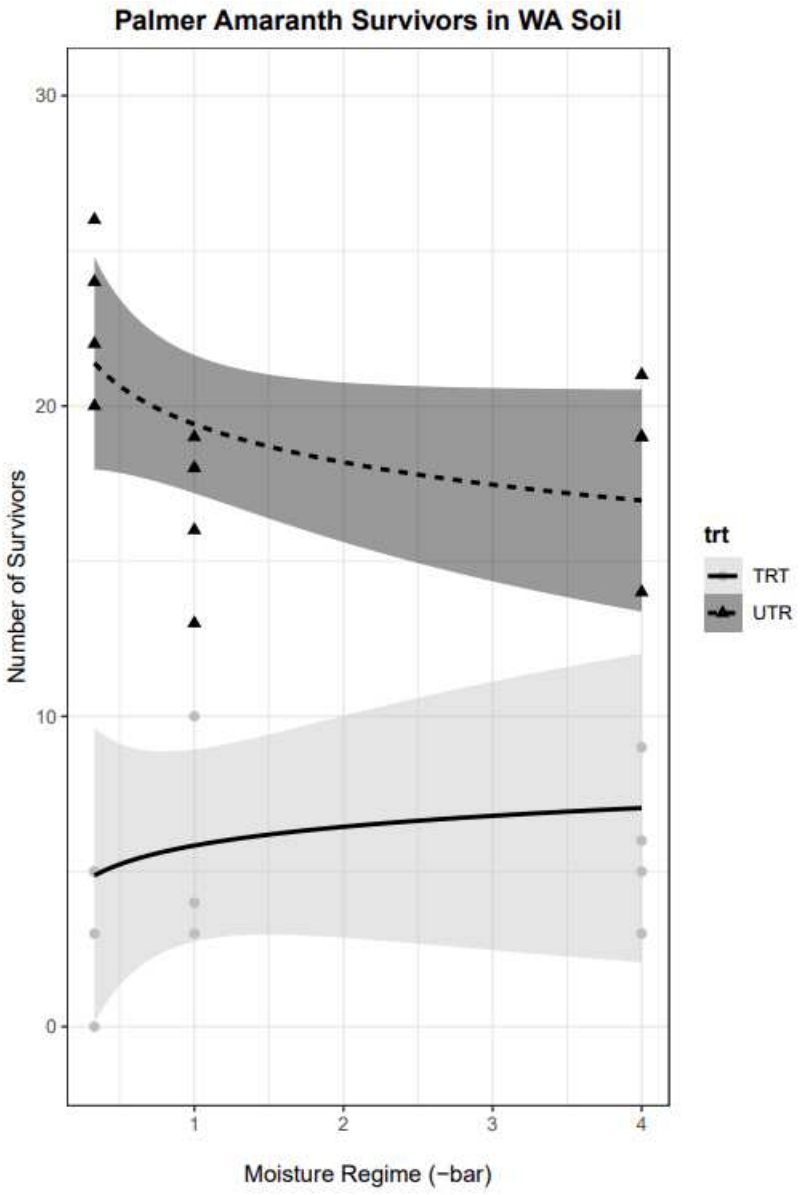

Figure 2.2:

Regression plot with 95% confidence interval bands of Palmer amaranth survivors in WA soil as a function of the interaction between soil moisture regime and herbicide treatment.

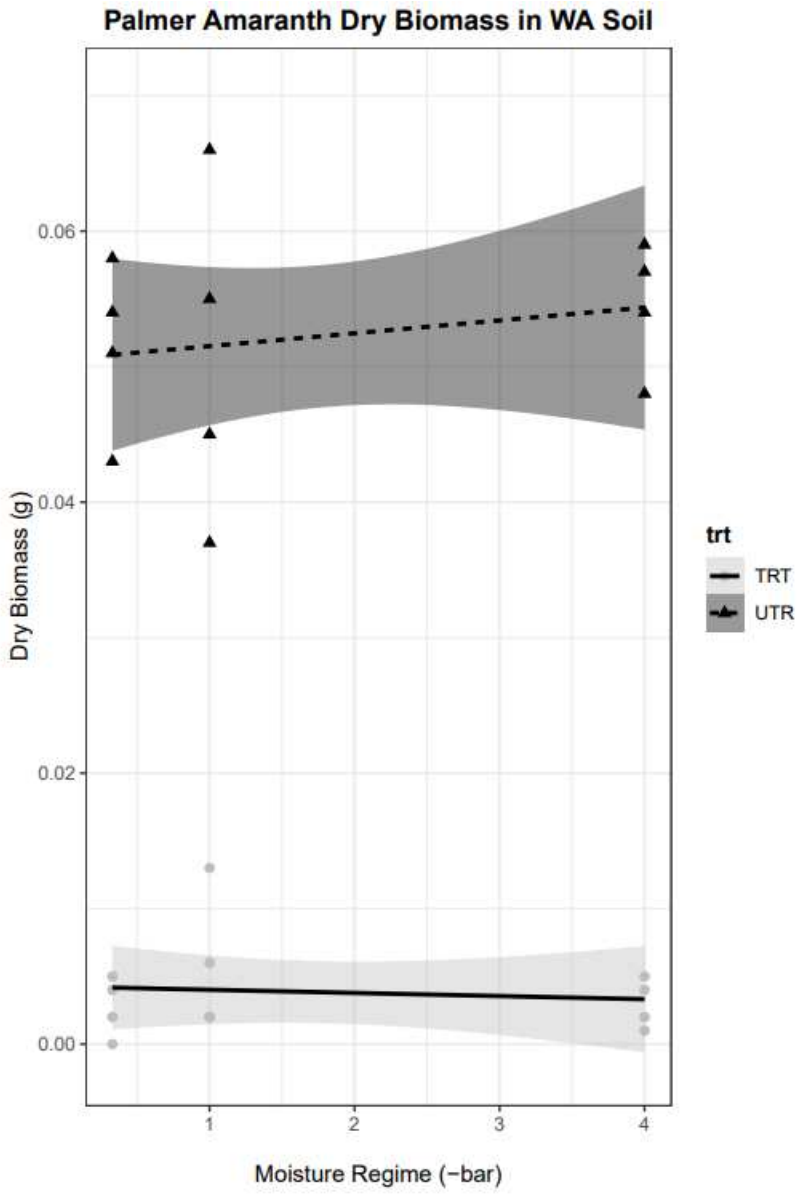

Figure 2.3:

Regression plot with 95% confidence interval bands of Palmer amaranth biomass in WA soil as a function of the interaction between soil moisture regime and herbicide treatment.

Table 2.2:

Fixed-Effects ANOVA results using Palmer amaranth survivors in WA soil as the criterion

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\ \eta^2$	$_{\text{partial}}\ \eta^2$ 95% CI [LL, UL]
(Intercept)	1.79	1	1.79	0.10	.752		
logbar	9.51	1	9.51	0.55	.469	.03	[.00, .25]
trt	179.52	1	179.52	10.31	.004	.34	[.04, .57]
logbar x trt	43.76	1	43.76	2.51	.129	.11	[.00, .37]
Error	348.32	20	17.42				

Table 2.3:

Fixed-Effects ANOVA results using Palmer amaranth biomass in WA soil as the criterion

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\ \eta^2$	$_{\text{partial}}\ \eta^2$ 95% CI [LL, UL]
(Intercept)	0.00	1	0.00	2.44	.134		
bar	0.00	1	0.00	0.04	.840	n/a	[.00, .14]
trt	0.01	1	0.01	145.00	.000	1.00	[.74, .92]
bar x trt	0.00	1	0.00	0.54	.472	n/a	[.00, .25]
Error	0.00	20	0.00				

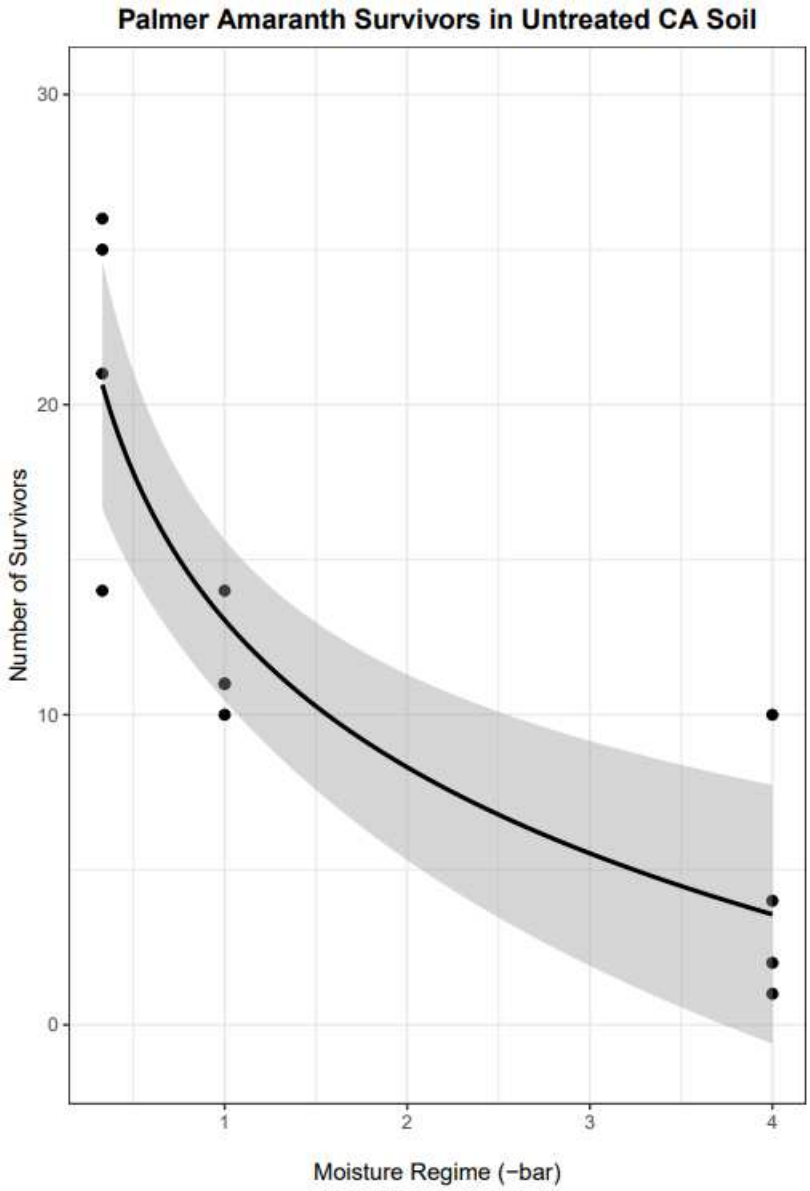

Figure 2.4:

Regression plot with 95% confidence interval bands of Palmer amaranth survivors in untreated CA soil as a function of soil moisture regime.

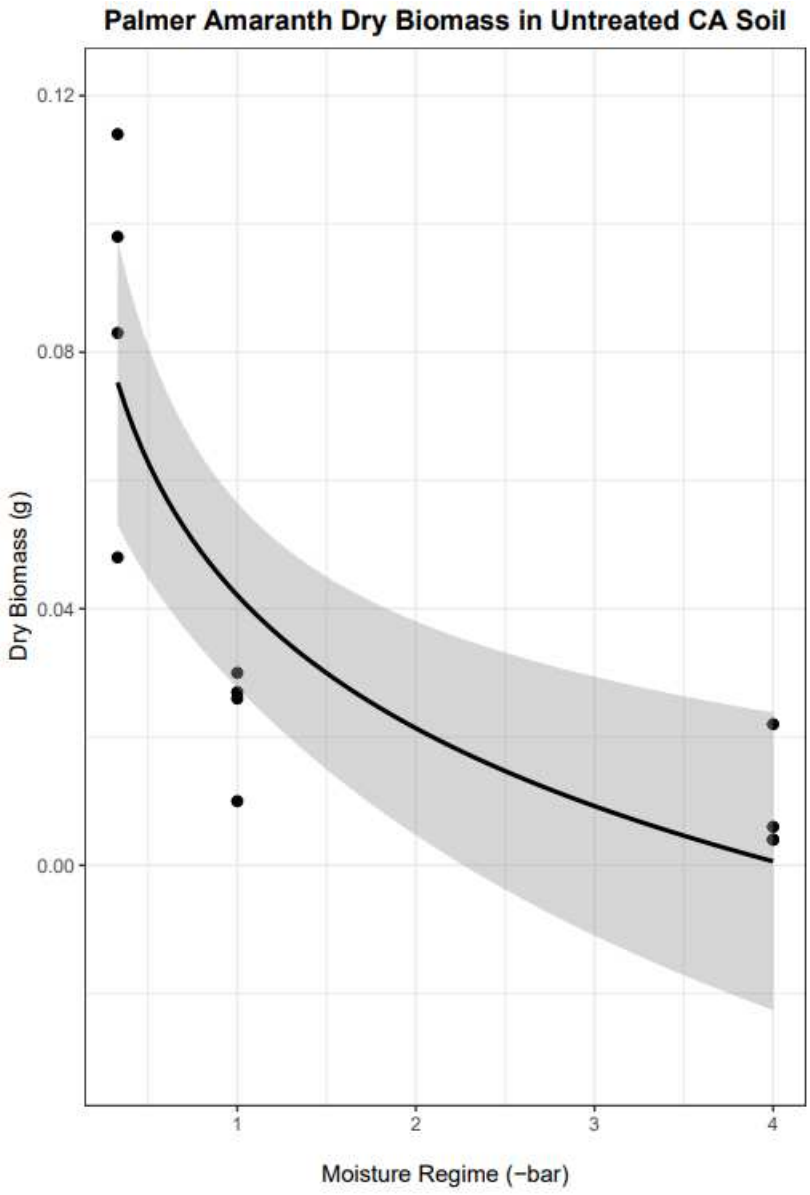

Figure 2.5:

Regression plot with 95% confidence interval bands of Palmer amaranth dry biomass in untreated CA soil as a function of soil moisture regime.

Table 2.4:

Fixed-Effects ANOVA results using Palmer amaranth survivors in untreated CA soil as the criterion

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\,\eta^2$	$_{\text{partial}}\,\eta^2$ 95% CI [LL, UL]
(Intercept)	1074.63	1	1074.63	66.65	.000		
bar	585.69	1	585.69	36.33	.000	.78	[.38, .88]
Error	161.23	10	16.12				

Table 2.5:

Post hoc comparisons of the response (Palmer amaranth survivors in untreated CA soil) to soil moisture regimes.

No adjustment

Term	y	Group 1	Group 2	df	Statistic	p	p.significance
bar	survivors	-0.33	-1	21	1.245	0.227	ns
bar	survivors	-0.33	-4	21	2.170	0.042	*
bar	survivors	-1	-4	21	0.925	0.365	ns

Table 2.6:

Fixed-Effects ANOVA results using Palmer amaranth biomass in untreated CA soil as the criterion

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\,\eta^2$	$_{\text{partial}}\,\eta^2$ 95% CI [LL, UL]
(Intercept)	0.02	1	0.02	35.06	.000		
bar	0.01	1	0.01	22.42	.001	1.00	[.22, .82]
Error	0.00	10	0.00				

Table 2.7:

Post hoc comparisons of the response (Palmer amaranth dry biomass in untreated CA soil) to soil moisture regimes.

No adjustment

Term	y	Group 1	Group 2	df	Statistic	p	p.significance
bar	biomass	-0.33	-1	21	2.102	0.048	*
bar	biomass	-0.33	-4	21	2.579	0.017	*
bar	biomass	-1	-4	21	0.477	0.638	ns

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Chapter 3: Effect of Corn Residue Cover on Pre-emergent Control with Diflufenican

Herbicide droplets are intercepted by plant residues that cover the soil surface. The impact this has on weed control with pre-emergent herbicides has been variable. This is an important question to answer with diflufenican as it is being developed for corn and soybean systems that are often managed with practices that leave high amounts of residue cover on the soil surface. Visual control of redroot pigweed, lambsquarter, and wild-proso millet with diflufenican applied at 90 and 180 g ai ha^{-1} was assessed in a field study with corn residue surface densities of 0, 1, 2, and 3-tons ha^{-1}. A follow-up greenhouse study was conducted to evaluate the impact of 0, 20, 40, and 60% corn residue coverages on efficacy of diflufenican applied at 70 g ai ha^{-1} to redroot pigweed and Palmer amaranth. Linear regression models were fit, and Type III ANOVA analysis was run to determine if corn residue cover had an effect on diflufenican in the field or greenhouse.

No significant interactions between corn residue density and diflufenican rate were identified in the field study. Excellent control of redroot pigweed was obtained with both rates while insufficient control of lambsquarter and wild-proso millet was observed with both rates.

Corn residue coverage did not impact diflufenican control of redroot pigweed. Significantly more Palmer amaranth survivors were identified in treated soil trays with 60% corn residue coverage in comparison to treated soil trays with 0% residue coverage. This indicates that control failures with diflufenican due to residue cover is possible at lower rates. If adequate rates of diflufenican are utilized, good control of susceptible species can still be expected.

INTRODUCTION

Researching the impact of crop residue on the performance of pre-emergent herbicide applications is important in corn and soybean systems where reduced tillage practices leaving high amounts of crop residue on the surface are common. Surveys revealed that conservation tillage (no-till, strip-till, and mulch-till) was utilized on around 70% of soybean hectares in 2012 and on around 65% of corn hectares in 2016 (Claassen et al., 2018). The survey results also indicated that no-till, specifically, was practiced on 45% of all soybean hectares in 2012 and 27% of all corn hectares in 2016. In reduced tillage practices, pre-emergent herbicides are the primary option relied upon to control early-season weeds that can compete with the emerging crop. A poor pre-emergent herbicide application can not only affect the early-season growth and year-end yields but impart high selection pressure on post-emergent herbicides to control the escapes plus the later-emerging weeds it was expected to control.

Plant residue will intercept herbicide droplets. The impact this has on weed control is variable. Koppatschek et al. (1989) observed corn residue have no impact on weed control with a combination of metribuzin and metolachlor. Erbach and Lovely (1975) did not observe significant reductions in weed control with atrazine or alachlor when applied at label rates to corn residue under no-till management. Chauhan and Abugho (2012) observed both non-significant and significant effects of rice residue on control of grass species with oxadiazon and pendimethalin. Control of *Chloris virgate* and *Echinochloa colona* was mostly reduced for pre-emergent herbicides applied to increasing sorghum residues in comparison to bare soil treatments (Mobli et al., 2020).

The type of residue on the soil surface can have an impact on herbicide binding in some cases. Shaner (2013), showed differential binding of atrazine, metolachlor, and pyroxasulfone to

different plant parts of corn, sorghum, and wheat. Khalil et al. (2018) investigated the impact of different crop residues and different ages of the residue on weed control with prosulfocarb, pyroxasulfone, and triflualin. Their findings were that the impact these variables had was mostly due to how effectively they could increase soil surface coverage rather than the actual composition of the different residues at different ages

The ability of a herbicide to release from the residue surface and be incorporated into the soil for uptake of emerging shoots is a key component of a herbicide being effective in high residue coverage situations. Ghadiri et al. (1984) detected that 60% of an atrazine application was initially intercepted by wheat stubble covering 80-90% of the soil surface. Three weeks later, the amount of atrazine in the soil beneath the residue increased two-fold due with assistance from 50 mm of rain that had fallen. Martin et al. (1978) measured less than 2% of alachlor, atrazine, cyanazine, and propachlor, applied separately to near 100% coverage of corn residue, reached the filter paper below. After 3.5 cm of simulated rainfall, they measured that 60-89% of the herbicide initially on the residue was washed off, with around half of that amount washed off with the first 0.5 cm of rainfall. Dang et al. (2016) observed near complete wash-off of a number of herbicides applied to 100% sugarcane residue coverage after 100 mm of simulated rainfall. Around 80% of the wash-off occurred in the first 30 mm of rainfall. Carbonari et al. (2016) found that 77% of sulfentrazone could be washed off of 5 t ha^{-1} of sugarcane residue, decreasing incrementally as residue densities increased up to 20 t ha^{-1}, where 64% was washed off. Almost all of the wash-off occurred during the first 20 mm of irrigation.

It is important to consider how soon after a pre-emergent herbicide application to a residue-covered soil surface will a rainfall or irrigation event occur. Dang et al. (2016) displayed that herbicide wash-off was reduced when rainfall was delayed from 1 day after application to 8

or 40 days after application. Carbonari et al. (2016) showed that significant drop-offs in wash-off were observed when rainfall was applied one and two months after herbicide application, instead of one day after application. When they applied subsequent rainfall applications at one and two weeks after the initial rainfalls at 1, 30, and 60 days after application, only very small amounts of sulfentrazone was released.

Some herbicides simply do not possess the properties that allow them to be washed off of plant residue surface once contact has been made. Gaston et al. (2003), determined less than 1% of pendimethalin had washed off cover crop residues after applying 3, 2-cm rainfall events; a product of the high sorption coefficients that pendimethalin had to the variety of residue sources in their study. Khalil et al. (2019), detected differential wash-off of pyroxasulfone, prosulfocarb, and trifluralin from wheat residue. Pyroxasulfone has a water solubility coefficient of 5 mg L^{-1} at 20˚C and washed off the wheat residue enough so that good control could potentially be obtained. Trifluralin has a water solubility coefficient of 0.22 mg L^{-1} at 20˚C and minimal wash-off was observed, which would lead to a reduction in control under increasing residue coverages.

Diflufenican is a herbicide that highly adsorbs to organic material (Table 1.7) and possesses very low water solubility (0.05 mg l^{-1} at 20˚C). These properties appear conducive to a pre-emergent application of diflufenican being susceptible to high droplet interception and poor release from residue cover. This chapter investigates pre-emergent weed control performance of diflufenican under increasing corn residue situations in the field and the greenhouse.

MATERIALS AND METHODS

Field Study

A seven treatment, two-factor, randomized complete block study evaluating the impact of increasing corn residue densities on pre-emergent control of weeds with of diflufenican was implemented at the Colorado State University field research farm in Fort Collins, CO (soil properties given in Table 3.1).

The field site was tilled the day before the study was implemented to ensure the site was weed-free. Whole plots (3 x 9 m) were sprayed with either 90 or 180 g ai ha^{-1} of diflufenican. Whole plots were split in half with the first half (3 x 4.5 m) being residue free and the back half having either 1, 2, or 3 tons ha^{-1}. For 3 x 4.5 m plots, the amount of corn residue needed to equate 1, 2, and 3 tons ha^{-1} was 1.3, 2.6, and 3.9 kg. Untreated, residue-free plots were included as well. There were three replications for each herbicide rate and residue surface density combination.

The residue was spread out in the designated plots the morning of the spray application. The spray applications were applied at 280 l ha^{-1}. Immediately after the spray application, the entire plot area was incorporated with 25 mm of water applied from a linear irrigation system. Irrigation was applied in the same manner every seven days after.

Redroot pigweed was planted down the center of each plot as the main weed species of interest. Lambsquarter (*Chenopodium album*) and wild-proso millet (*Panicum miliaceum*) were also prominently featured at this field site. Visual control data on a scale of 0-100% (Jursik et al., 2015) was collected 27 days after application for all three weed species.

Greenhouse Study

A greenhouse study was conducted after the field study to further evaluate the response of redroot pigweed to diflufenican applied to various amounts of corn residue coverage. Palmer amaranth was also included in this study as it could not be evaluated in the field. A single rate

(70 g ai ha^{-1}) of was diflufenican applied to four corn residue coverages (0, 20, 40, and 60%). There were three replications for each residue coverage treated with diflufenican and three replications for each residue coverage that was untreated.

The soil used in this study was collected from the Colorado State University field research station near the area where the field study was conducted. The corn residue was collected from a field on the research farm. Trays with 25 x 50 cm dimensions were filled with soil to a depth of 4 cm. Half of the tray (25 x 25 cm) was shallowly planted with redroot pigweed seed and the other half planted with Palmer amaranth, both targeting around 200 emerged seedlings. Corn stalks and leaves were chopped and spread to mimic the soil coverages that were implemented in the field study. The residue coverages were determined (± 2%) using particle analysis in ImageJ software (Ferreira and Rasband, 2012). Images collected with a Nikon® D810 camera were loaded into the software, converted to 8-bit, and made binary. These steps allowed the residue "particles" to be counted and calculated as percent area of the soil surface (Figures 3.1, 3.2, 3.3). Though the results of the particle analysis resulted in soil coverages of 20, 40, and 60%, these numbers are lower than what these residue amounts would measure in the field using traditional methods. Utilizing particle analysis to determine residue coverage was deemed a more reliable and reproduceable method for this greenhouse study.

Diflufenican was applied at 70 g ai ha^{-1} using a Generation 4 Research Track Sprayer (Devries Manufacturing, Hollandale, MN) calibrated to deliver 187 l ha^{-1}. The herbicide was incorporated with 12 mm of simulated rainfall immediately after application. Soil trays were completely randomized in the greenhouse and rotated every three days. Soil trays were watered every day, over the top, to ensure adequate moisture was maintained. Number of survivors were

counted, and above-ground biomass was harvested 27 days after application. Biomass of each species for each treatment was oven-dried for 72 hours at 72˚C.

RESULTS

Field Trial

Individual linear regression models were fit with an interaction term between residue density and herbicide rate for the response of each species. A blocking term was included without interaction. All models passed a Shapiro-Wilk test of normality and visual inspection of diagnostic plots. Type III ANOVA analysis were run on these models and significance was evaluated at a 0.05 alpha level. Fisher's LSD post hoc analysis was conducted for any significant model terms.

Redroot pigweed was effectively controlled by diflufenican at both rates, across all corn residue densities (Figure 3.4). The interaction between herbicide rate and corn residue density was not significant in our model (P=0.161), nor was the herbicide rate (P=0.128) term (Table 3.2). The corn residue density term was significant with post hoc analysis elucidating a significant difference in percent control of redroot pigweed between plots with 0- and 2-tons ha^{-1} of residue.

Insufficient control of lambsquarter and wild-proso millet was observed with both rates of diflufenican across all corn residue densities (Figures 3.5, 3.6). The interaction between herbicide rate and corn residue density did not impact the control of either of these species (lambsquarter, P=0.593; wild-proso millet, P=0.752)(Tables 3.3, 3.4). Herbicide rate (lambsquarter, P=0.416; wild-proso millet, P=0.923) and corn residue density (lambsquarter, P=0.933; wild-proso millet, P=0.788) terms did not have an effect either.

With weed control in this study either being very good (redroot pigweed) or inadequate (lambsquarter and wild-proso millet), model fits were low (R^2 < 43%) as much of the variation in the response data was not captured with our independent variables. A significant interaction with corn residue density and diflufenican application rate at an alpha level of 0.05 was not identified.

Greenhouse Trial

Redroot pigweed and Palmer amaranth were analyzed separately with separate linear models fit for each of the response variables (number of survivors, dry biomass) to test the interaction between corn residue coverage and herbicide treatment (0 and 70 g ai ha^{-1}). Square root transformations were applied to response variables of any model that did not pass a Shapiro-Wilks normality test and visual analysis of diagnostic plots. Type III ANOVA analysis was run on these models and significance was evaluated at a 0.05 alpha level. Fisher's LSD post hoc analysis was conducted for any significant model terms.

The number of redroot pigweed survivors was not significantly affected by the interaction of corn residue coverage and herbicide treatment (P=0.096) or corn residue coverage (P=0.823) (Table 3.5) (Figure 3.7). As expected, the application of diflufenican was highly significant (P<0.001). Significance of the same terms did not change when analyzing the dry biomass of the redroot pigweed survivors (Figure 3.8). Corn residue coverage (P=0.477) and its interaction with herbicide treatment (P=0.824) were not significant while the presence of diflufenican was highly significant (P<0.001) (Table 3.6).

Unlike with redroot pigweed, corn residue coverage impacted the responses of Palmer amaranth. The interaction of corn residue coverage and herbicide treatment was significant (P=0.014) on the number of Palmer amaranth survivors, as were the individual corn residue coverage (P=0.017) and herbicide treatment (P<0.001) terms (Table 3.7) (Figure 3.9). Post hoc

analysis revealed that the number of Palmer amaranth survivors in the treated soil trays with 60% residue coverage was more than in treated soil trays with 0% residue coverage. A significant decrease was identified in untreated soil trays with 60% residue coverage in comparison to soil trays with 40% residue coverage (Table 3.8).

The interaction of corn residue coverage and herbicide treatment was also significant when analyzing the dry biomass of Palmer amaranth (P=0.008) (Table 3.9) (Figure 3.10). The individual herbicide treatment term was significant (P<0.001) while the individual corn residue coverage term was not (P=0.338). Post hoc analysis found all significant interactions to be with the untreated soils trays with different residue coverages. Significant increases in Palmer amaranth dry biomass was seen when residue coverages increased from 0 and 20% to 40 and 60% (Table 3.10).

DISCUSSION

Weed species that diflufenican effectively and ineffectively controls were not impacted by herbicide rate, corn residue density, or their interaction in the field. It was understood in the design of this study that redroot pigweed is a weed species that diflufenican effectively controls. Herbicide rates of 90 and 180 g ai ha^{-1} were chosen as they closely resemble the range at which this herbicide would be used in U.S. corn and soybean systems. Thus, it would be important to know if control of a susceptible weed is maintained at a robust rate or suffers at a lower rate. This study gleans that at 180 g ai ha^{-1}, almost complete control of redroot pigweed can be maintained under increasing residue densities. At 90 g ai ha^{-1}, it appears that a slight negative trend in redroot pigweed control occurs as residue density increases, but effective control was still obtained, rendering differences in control with plots sprayed with 180 g ai ha^{-1} insignificant.

Control evaluations of lambsquarter and wild-proso millet were collected as they were prominently featured in this study site. These weed species are less susceptible to diflufenican than redroot pigweed is. It could be hypothesized that since these weeds are less susceptible that the effect of increasing corn residue densities would be more pronounced. In this study, control of these species was insufficient and variable, preventing any interaction to be seen.

No significant interactions were identified between diflufenican rate and corn residue coverage in the field, but variation in our data was not well explained with our variables. The greenhouse study was executed to further investigate this question in a more controlled environment.

In our previous experiences with diflufenican, control has been seen to be enhanced in the greenhouse in comparison to field experiments. In the corn residue density field experiment, control of redroot pigweed was at a level that made it hard to truly assess if residue amount can impact weed control. With those two things in mind, the rate of diflufenican was dropped to 70 g ai ha^{-1}. The goal of this decision was to create a study more conducive to treatment effects occurring. Redroot pigweed was included as it was the main species of interest in the field study and Palmer amaranth was included as it is a species of more importance in U.S. corn and soybean systems.

With no residue coverage, almost complete control of both species was obtained with diflufenican at 70 g ai ha^{-1}. In alignment with the field study, corn residue had no significant impact on control of redroot pigweed. It appears that even if the residue cover intercepts a large proportion of spray droplets, redroot pigweed is susceptible at such low rates of diflufenican that effective control can be obtained.

Including untreated soil trays with the same residue coverages and replications as the treated soil trays allowed for evaluation of the growth of these weeds under various residue coverages. In general, redroot pigweed was seen to have emerged a few days later than Palmer amaranth and grow at a slower rate. Our analysis indicated that redroot pigweed did not respond differently growing under different residue densities. In general, Palmer amaranth grew with much more vigor than the redroot pigweed, which has been proven before (Horak and Loughin, 2000).

Even with significantly less individuals counted in the untreated soil trays with 60% residue coverage in comparison to untreated soil trays with 40% coverage, more Palmer amaranth dry biomass was measured in untreated soil trays with 40 and 60% residue coverage in comparison to untreated soil trays with 0 and 20% residue coverage. Mobli et al. (2020) identified increased weed emergence and biomass under higher sorghum residue density treatments in their study. Higher residue coverage helps retain soil moisture and help contribute to higher crop yields (Verhulst et al., 2011). In this study, it appears that Palmer amaranth benefited from the increased moisture retention of soils under residue cover as well as possible increased protection from greenhouse insects. The more vigorous growth and increased herbicide interception assisted Palmer amaranth to have more individuals survive under 60% residue coverage in comparison to 0% residue coverage. These results indicate that control failure due to residue interception of diflufenican can occur.

One thing that could be done to help improve the performance of herbicides that tightly adsorb to plant residue is to increase the carrier volume of the spray application. Borger et al. (2013), demonstrated that increasing the carrier volume increased the spray coverage of pyroxasulfone and trifluralin leading to significant improvements in control at three of four test

sites. The exception occurred due to abnormally low rainfall with high weed densities. As shown in literature previously described, pyroxasulfone can wash-off residue, while trifluralin does not. Increased carrier volume could be implemented with diflufenican to help safe guard from control failures happening under high residue cover situations.

Overall, performance of diflufenican on controlling *Amaranthaceae* species was excellent. The one instance in which control was reduced was when a low rate was applied to Palmer amaranth grown under the highest residue coverage studied in a greenhouse setting. This does show that control failures of susceptible species can occur under the right conditions. Our results do show though, that effective control of susceptible species under high residue situations can be expected if an adequate rate is utilized.

Table 3.1:

Properties of soil at the Colorado State University Field Experiment Station in Fort Collins, CO. Analysis conducted by Midwest Laboratories in Omaha, NE.

pH	CEC (meq/100g)	OM %	Sand %	Silt %	Clay %
7.9	3.4	2.6	34	24	42

Figure 3.1:

Pre- and post-processed images revealing 20% corn residue coverage.

Figure 3.2:

Pre- and post-processed images revealing 40% corn residue coverage.

Figure 3.3:

Pre- and post-processed images revealing 60% corn residue coverage.

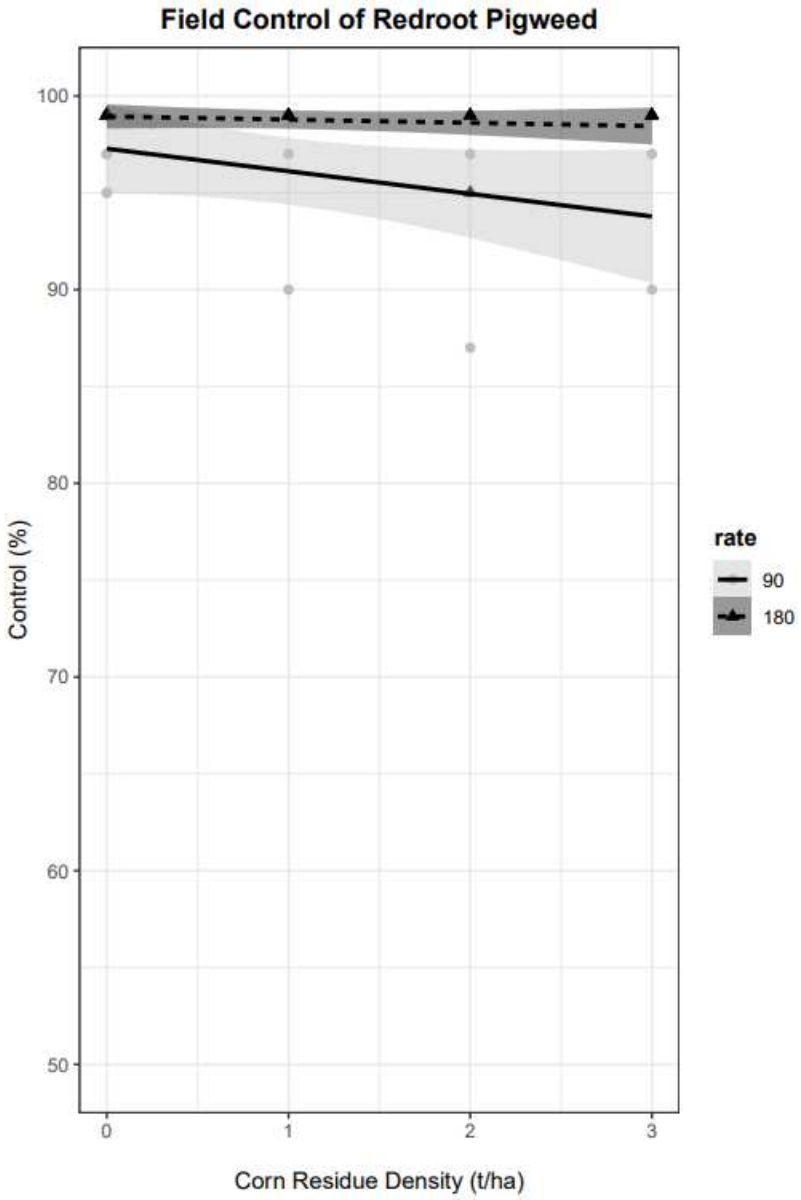

Figure 3.4:

Regression plot with 95% confidence interval bands of redroot pigweed percent control in the field as a function of the interaction between corn residue density and herbicide rate.

Table 3.2:

Fixed-Effects ANOVA results using redroot pigweed control as the criterion.

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\,\eta^2$	$_{\text{partial}}\,\eta^2$ 95% CI [LL, UL]
(Intercept)	62435.64	1	62435.64	10723.68	.000		
rate	14.29	1	14.29	2.45	.128	.08	[.00, .28]
residue	32.67	1	32.67	5.61	.024	.16	[.00, .38]
block	30.89	2	15.45	2.65	.087	.15	[.00, .35]
rate x residue	12.00	1	12.00	2.06	.161	.06	[.00, .27]
Error	174.67	30	5.82				

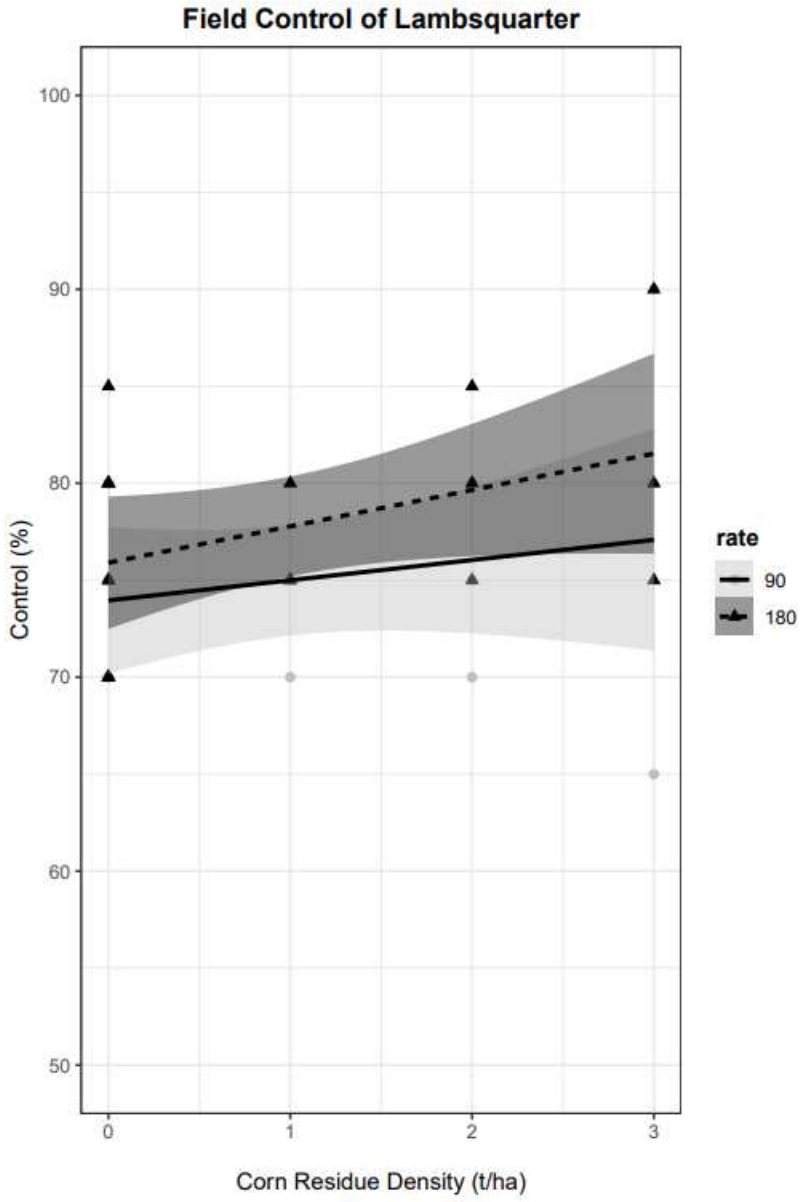

Figure 3.5:

Regression plot with 95% confidence interval bands of lambsquarter percent control in the field as a function of the interaction between corn residue density and herbicide rate.

Table 3.3:

Fixed-Effects ANOVA results using percent control of lambsquarter as the criterion.

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	partial η^2	partial η^2 95% CI [LL, UL]
(Intercept)	37297.00	1	37297.00	1304.64	.000		
rate	19.44	1	19.44	0.68	.416	.02	[.00, .20]
residue	26.04	1	26.04	0.91	.347	.03	[.00, .21]
block	93.06	2	46.53	1.63	.213	.10	[.00, .28]
rate x residue	8.33	1	8.33	0.29	.593	.01	[.00, .16]
Error	857.64	30	28.59				

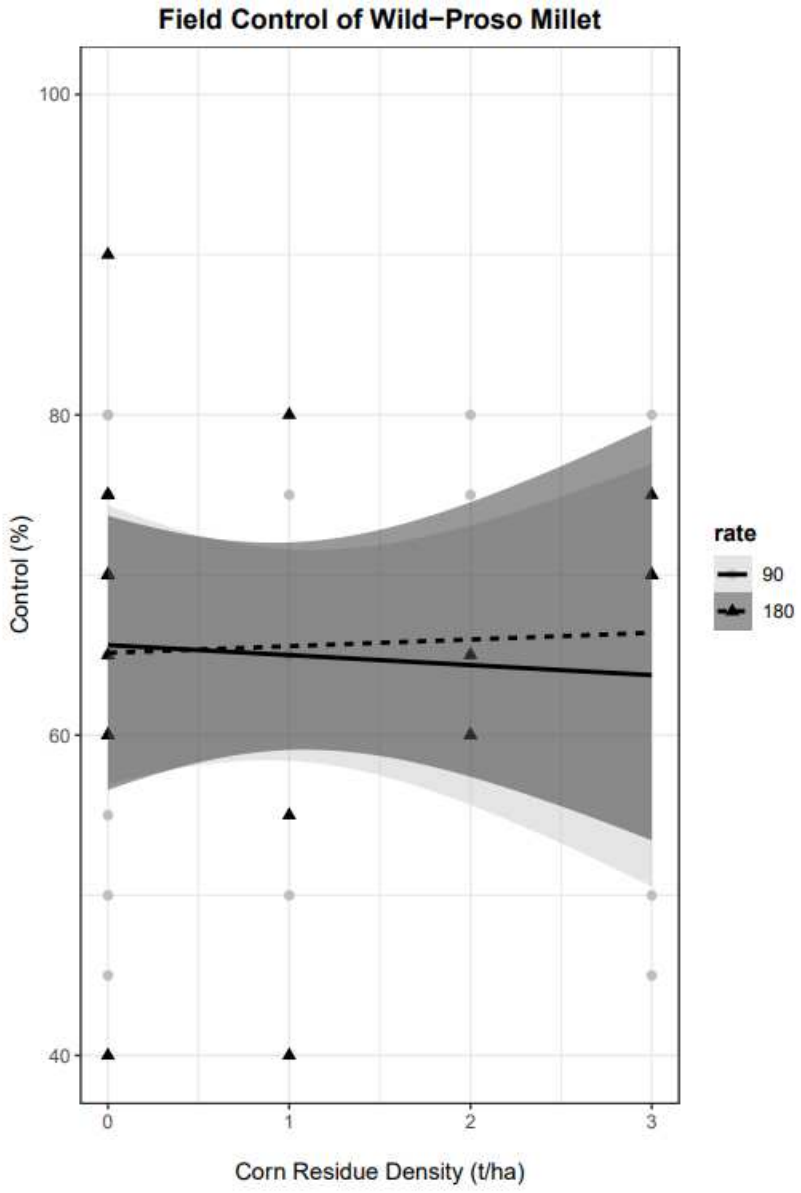

Figure 3.6:

Regression plot with 95% confidence interval bands of wild-proso millet percent control in the field as a function of the interaction between corn residue density and herbicide rate.

Table 3.4:

Fixed-Effects ANOVA results using percent control of wild-proso millet as the criterion.

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\,\eta^2$	$_{\text{partial}}\,\eta^2$ 95% CI [LL, UL]
(Intercept)	20966.70	1	20966.70	163.89	.000		
rate	1.22	1	1.22	0.01	.923	.00	[.00, .07]
residue	9.38	1	9.38	0.07	.788	.00	[.00, .12]
block	1643.06	2	821.53	6.42	.005	.30	[.04, .49]
rate x residue	13.02	1	13.02	0.10	.752	.00	[.00, .13]
Error	3837.85	30	127.93				

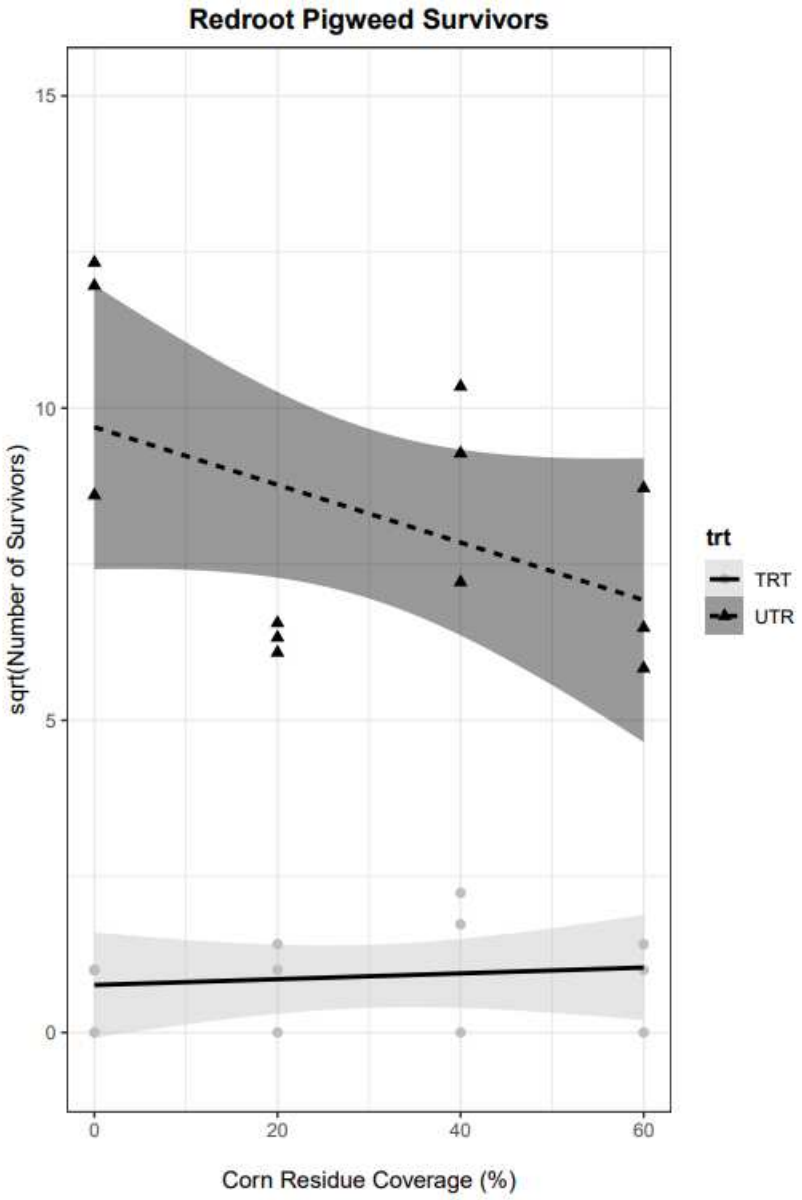

Figure 3.7:

Regression plot with 95% confidence interval bands of redroot pigweed survivors in the greenhouse as a function of the interaction between corn residue coverage and herbicide treatment.

Table 3.5:

Fixed-Effects ANOVA results using sqrt(redroot pigweed survivors) as the criterion.

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\,\eta^2$	$_{\text{partial}}\,\eta^2$ 95% CI [LL, UL]
(Intercept)	2.47	1	2.47	0.97	.335		
coverage	0.13	1	0.13	0.05	.823	.00	[.00, .15]
trt	171.08	1	171.08	67.35	.000	.77	[.53, .85]
coverage x trt	7.76	1	7.76	3.05	.096	.13	[.00, .39]
Error	50.81	20	2.54				

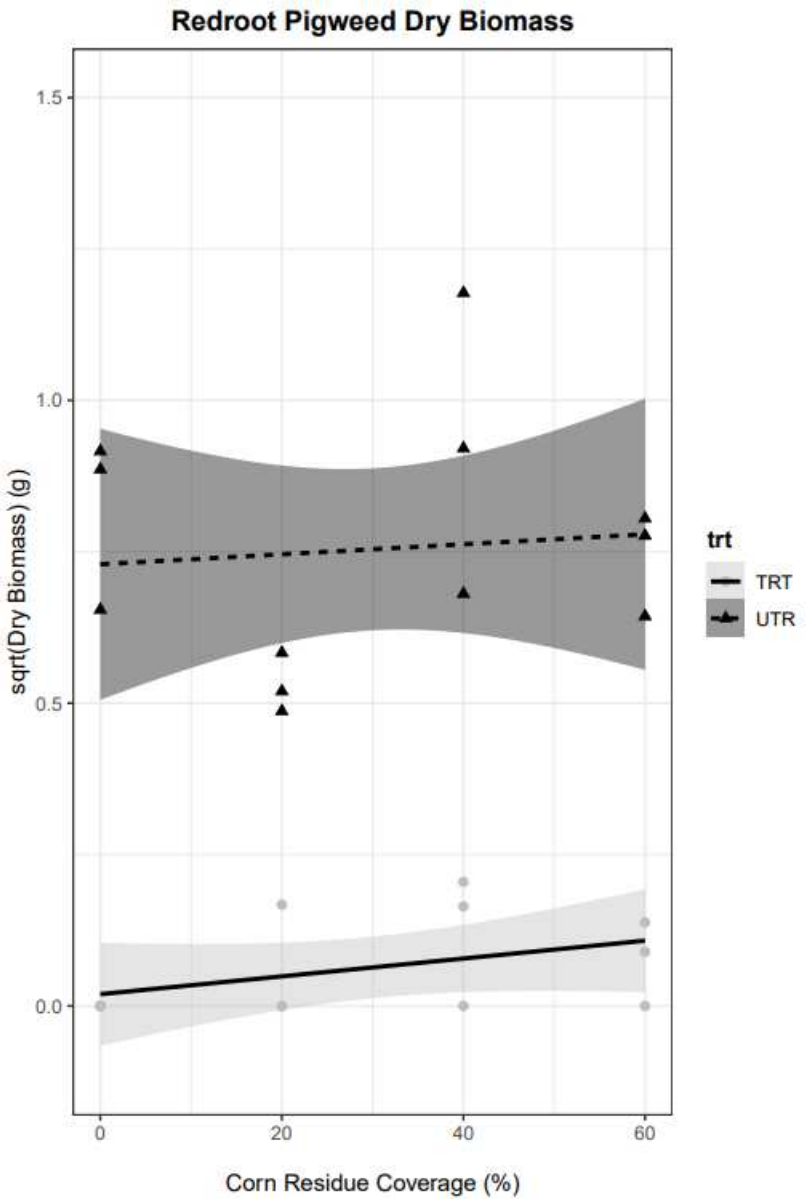

Figure 3.8:

Regression plot with 95% confidence interval bands of redroot pigweed dry biomass in the greenhouse as a function of the interaction between corn residue coverage and herbicide treatment.

Table 3.6:

Fixed-Effects ANOVA results using sqrt(redroot pigweed dry biomass) as the criterion.

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\,\eta^2$	$_{\text{partial}}\,\eta^2$ 95% CI [LL, UL]
(Intercept)	0.00	1	0.00	0.07	.800		
coverage	0.01	1	0.01	0.53	.477	.02	[.00, .25]
trt	1.08	1	1.08	43.61	.000	.68	[.39, .80]
coverage x trt	0.00	1	0.00	0.05	.824	.00	[.00, .15]
Error	0.50	20	0.02				

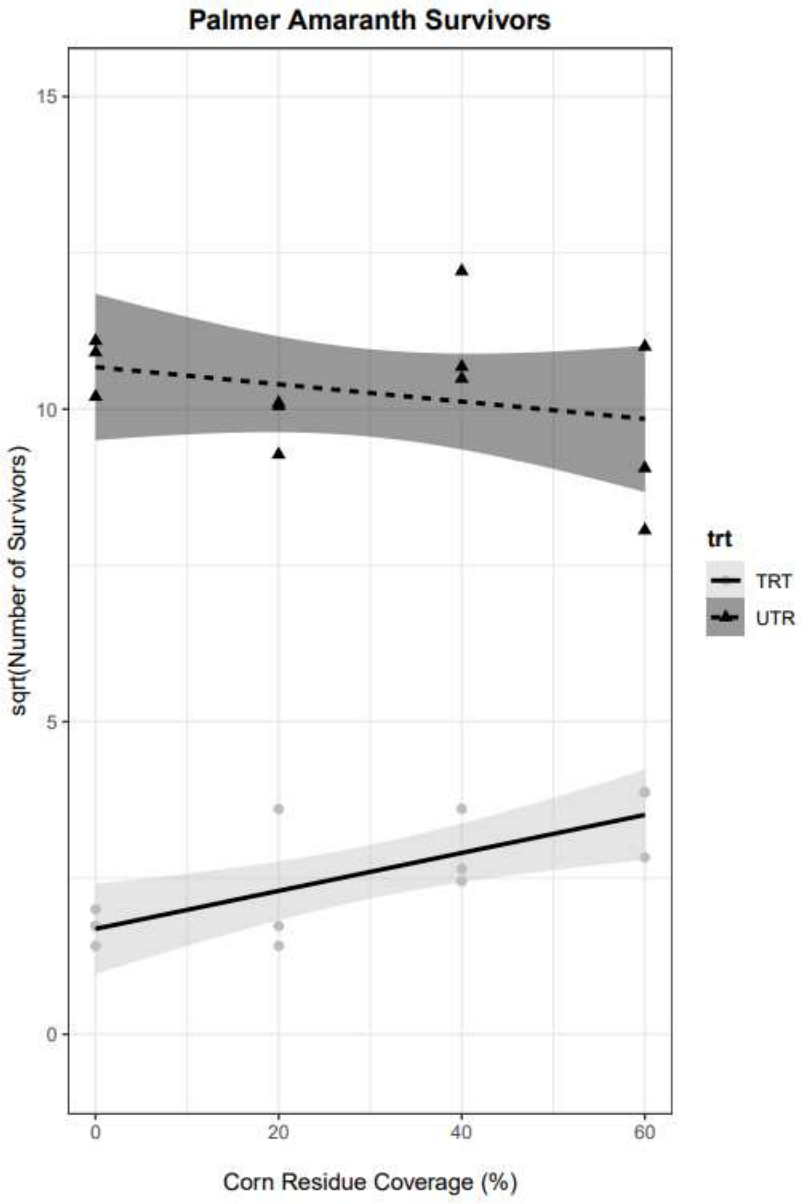

Figure 3.9:

Regression plot with 95% confidence interval bands of Palmer amaranth survivors in the greenhouse as a function of the interaction between corn residue coverage and herbicide treatment.

Table 3.7:

Fixed-Effects ANOVA results using sqrt(Palmer amaranth survivors) as the criterion.

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\,\eta^2$	$_{\text{partial}}\,\eta^2$ 95% CI [LL, UL]
(Intercept)	12.18	1	12.18	14.92	.001		
coverage	5.54	1	5.54	6.78	.017	.25	[.01, .50]
trt	173.09	1	173.09	211.94	.000	.91	[.81, .94]
coverage x trt	5.86	1	5.86	7.18	.014	.26	[.01, .51]
Error	16.33	20	0.82				

Table 3.8:

Post hoc comparisons of the response (square root of Palmer amaranth survivors) to corn residue coverage averaging over treatment effect.

No adjustment.

Trt	Term	y	Group 1	Group 2	df	Statistic	p	p.significance
TRT	coverage	sqrt (PA survivors)	0	20	16	-0.770	0.452	ns
TRT	coverage	sqrt (PA survivors)	0	40	16	-1.705	0.107	ns
TRT	coverage	sqrt (PA survivors)	0	60	16	-2.604	0.019	*
TRT	coverage	sqrt (PA survivors)	20	40	16	-0.935	0.364	ns
TRT	coverage	sqrt (PA survivors)	20	60	16	-1.834	0.085	ns
TRT	coverage	sqrt (PA survivors)	40	60	16	-0.899	0.382	ns
UTR	coverage	sqrt (PA survivors)	0	20	16	1.331	0.202	ns
UTR	coverage	sqrt (PA survivors)	0	40	16	-0.563	0.581	ns
UTR	coverage	sqrt (PA survivors)	0	60	16	1.957	0.068	ns
UTR	coverage	sqrt (PA survivors)	20	40	16	-1.894	0.076	ns
UTR	coverage	sqrt (PA survivors)	20	60	16	0.626	0.540	ns
UTR	coverage	sqrt (PA survivors)	40	60	16	2.521	0.023	*

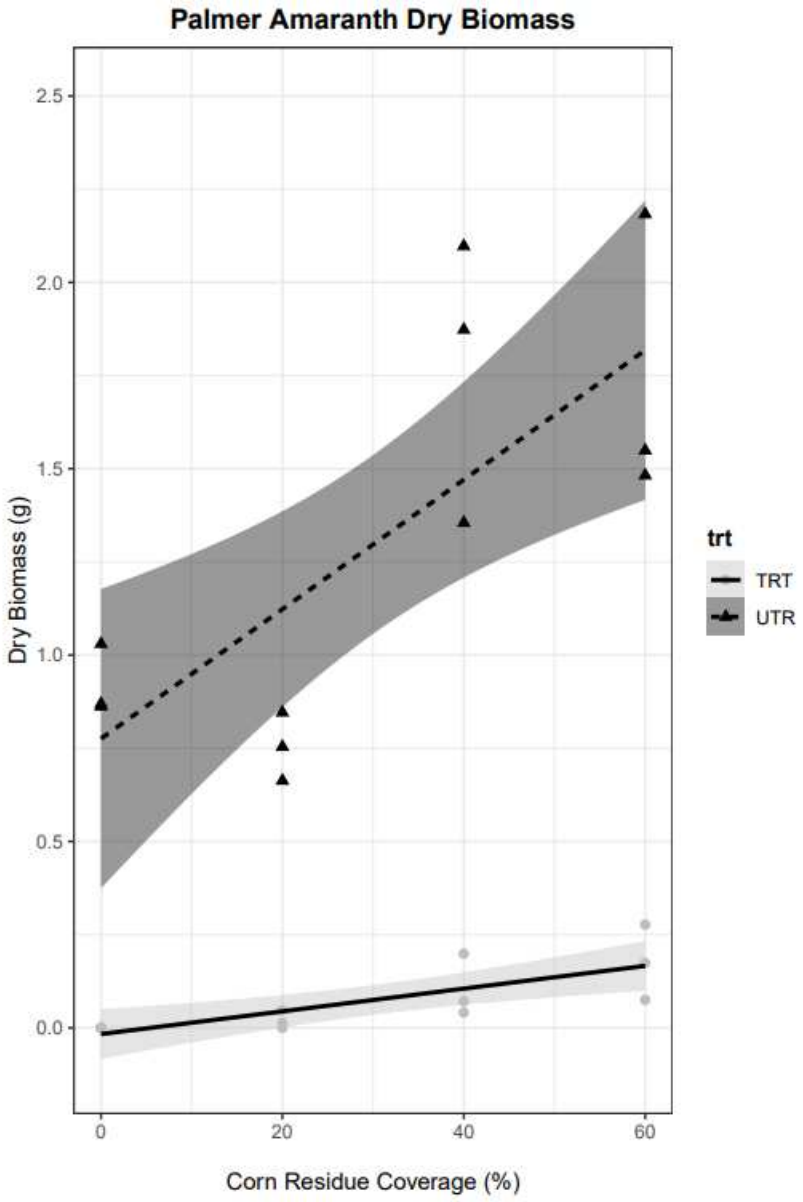

Figure 3.10:

Regression plot with 95% confidence interval bands of Palmer amaranth dry biomass in the greenhouse as a function of the interaction between corn residue coverage and herbicide treatment.

Table 3.9:

Fixed-Effects ANOVA results using Palmer amaranth biomass as the criterion.

LL and UL represent the lower-limit and upper-limit of the partial η^2 confidence interval, respectively.

Predictor	Sum of Squares	*df*	Mean Square	*F*	*p*	$_{\text{partial}}\,\eta^2$	$_{\text{partial}}\,\eta^2$ 95% CI [LL, UL]
(Intercept)	0.00	1	0.00	0.02	.898		
coverage	0.06	1	0.06	0.78	.388	.04	[.00, .27]
trt	1.35	1	1.35	18.82	.000	.49	[.14, .67]
coverage x trt	0.62	1	0.62	8.60	.008	.30	[.02, .54]
Error	1.43	20	0.07				

Table 3.10:

Post hoc comparisons of the response (Palmer amaranth dry biomass) to corn residue coverage (%) averaging over treatment effect.

No adjustment.

Trt	Term	y	Group 1	Group 2	df	Statistic	p	p.significance
TRT	coverage	PA biomass	0	20	16	-0.121	0.905	ns
TRT	coverage	PA biomass	0	40	16	-0.625	0.541	ns
TRT	coverage	PA biomass	0	60	16	-1.058	0.306	ns
TRT	coverage	PA biomass	20	40	16	-0.505	0.621	ns
TRT	coverage	PA biomass	20	60	16	-0.937	0.363	ns
TRT	coverage	PA biomass	40	60	16	-0.432	0.671	ns
UTR	coverage	PA biomass	0	20	16	1.001	0.332	ns
UTR	coverage	PA biomass	0	40	16	-5.156	0.000	****
UTR	coverage	PA biomass	0	60	16	-4.933	0.000	***
UTR	coverage	PA biomass	20	40	16	-6.157	0.000	****
UTR	coverage	PA biomass	20	60	16	-5.934	0.000	****
UTR	coverage	PA biomass	40	60	16	0.223	0.826	ns

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