Integrated Weed Management in Small Grain Production Systems

A Thesis

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by Chandra Maki

Approved by:

Major Professor: Albert Adjesiwor, Ph.D.

Committee Members: Jared Spackman, Ph.D.; Karen Launchbaugh, Ph.D.;

Kurtis Schroeder, Ph.D.

Department Administrator: Juliet Marshall, PhD.

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Abstract

Small grain systems make up a large portion of Idaho's agricultural production, and just like any other crop, have weed pressures. Using different methods of weed control such as cultural, mechanical, and chemical has been proven to be an effective way to help control different types of weeds. The main objectives of this thesis project were to evaluate alternative pre-plant herbicides for weed control in small grains, 2) assess the use of herbicides and crop rotations for integrated weed management, and 3) evaluate weed control and weed pressure impacts on alfalfa, one of the most important rotational crops in small grain production systems. For chapter 1, a 2-year field study was conducted to evaluate the efficacy of alternative preplant burndown herbicide treatments as compared to glyphosate treatments, the industry standard. An economic analysis and crop injury observation were also conducted. Most herbicide treatments achieved 90% or more control of the predominant weed species. In the economic analysis, at least six different herbicide treatments were equivalent to the cost of glyphosate at $26.50 per hectare. No observable damage from herbicide treatments was present, and crop yield was not affected by the treatments. All these factors show that there are alternatives to preplant burndown that are just as effective as glyphosate treatments. With combinations of herbicides, each having a different site of action, weed control can be achieved while simultaneously reducing the risk of herbicide-resistant weeds spreading.

For chapter 2, a 4-year crop rotation study was initiated in 2021 at the University of Idaho Kimberly Research and Extension Center to evaluate weed control and seedbank dynamics in wheat-alfalfa vs wheat-annual crop (corn and dry bean) rotations. There were three herbicide treatments: non-treated, postemergence (POST) only, and preemergence (PRE) + POST. After the first year, there was no difference in seedbank density among treatments. After two years, weed seedbank density was reduced from 2,227 viable seeds m^2 in the non-treated to 1,344 seeds m^2 in the PRE + POST treatments, representing nearly a 40% difference in seedbank density. There was also a trend of PRE + POST treatments slightly reducing weed seedbank density compared to POST-only treatment. Weed density within the crops during the growing season was influenced by the type of crop as well as the herbicide treatment. Both POST-only and PRE + POST treatments reduced weed density compared to the non-treated and the PRE + POST treatments reduced weed density in each crop compared to the POST-only treatment. Weed control treatments did not affect alfalfa yield. However, herbicide application (POST only and PRE + POST) improved corn and dry bean yield. The combination of fewer weeds and greater crop yield in the PRE + POST treatments holds promise for reducing weed seedbank and potentially improving long-term crop productivity and economics.

In chapter 3, field studies were conducted in Idaho in 2021 and 2022 to evaluate the effect of weed control treatments on alfalfa forage accumulation, weed biomass, and nutritive value. In addition, the relationship between the proportion of individual weed species biomass and alfalfa nutritive value was assessed. These studies included eight different herbicide and herbicide combination treatments, including the non-treated check. Treatments were comprised of pre-emergence incorporated, early postemergence (after 80% alfalfa emergence), and postemergence (third trifoliate alfalfa) herbicide applications. Data collection included weed control efficacy, weed and alfalfa biomass, and alfalfa nutritive value. Additional samples were collected and combined in the following alfalfa to weed biomass proportions (% by weight): 0:100, 20:80, 40:60, 60:40, 80:20, and 100:0, for wet chemistry analysis of forage nutritive value to evaluate the relationship between the proportion of individual weed species biomass and alfalfa nutritive value. The acetochlor-only treatment provided less than 50% weed control while the EPTC-only treatment provided 54 to 81% weed control. The control provided by acetochlor and EPTC were less than treatments containing imazamox and imazamox plus bromoxynil. Weed biomass in forage (23 to 55% of total biomass) due to poor or no weed control reduced crude protein, increased fiber concentrations, and reduced the relative feed value. The relationship between the proportion of individual weed species biomass and alfalfa nutritive value was linear for all weed species evaluated.

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Dedication

I would like to dedicate this work to my husband Nixxon and my family. Their support has allowed me to come this far in my career. Without them pushing me to continue with my education, I would not have seen the potential that my education in agriculture has given me.

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Statement of Contribution

Chandra Maki – Chapter 3 Data collection, data entry, writing original draft, review.

Albert Kwarteng – Chapter 3 data collection, and review.

Dr. Albert Adjesiwor – Chapter 3 conceptualization, study design, data collection, data analysis, writing and review.

Chapter 1: Economics, efficacy, and crop response to pre-plant burndown herbicides

Abstract

The value of glyphosate to growers practicing minimum or no-till farming has been primarily a function of three factors: improved weed control with glyphosate compared to other herbicides; lack of residual effect or injury from glyphosate; and relatively cheap cost of glyphosate. It is widely known that repeated use of the same herbicide is the primary factor leading to herbicide resistance in weeds. A 2-year study was conducted in 2021 and 2022 at the University of Idaho Research and Extension Centers at Kimberly and Aberdeen, Idaho. The study objective was to evaluate the efficacy of alternative preplant burndown herbicide treatments as compared to glyphosate treatments, the industry standard. An economic analysis and crop injury observation was also conducted. Most herbicide treatments achieved 90% or more control of the predominant weed species. At least six different herbicide treatments were economically equivalent to the cost of glyphosate at $26.50 per hectare. No observable damage from herbicide treatments was present, and crop yield was not be affected by the treatments. These factors indicate that there are alternatives to preplant burndown herbicides that are equally effective as glyphosate. With combinations of herbicides, each having a different site of action, weed control can be achieved and at the same time reduce the risk of weeds with herbicide resistance spreading.

Introduction

Weed control is one of the most important management practices in small grain production systems. Recent estimates from North America have shown that uncontrolled weeds can cause 2.9 to 34.4% yield loss in winter wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) (Flessner et al., 2021). This translates into $0.19 to $2.19 billion in value annually (Flessner et al., 2021). in

One of the most common and best weed management practices in small grain production is to start "clean". Weeds should be controlled before planting crops to reduce weed competition and potential yield loss. Wheat growers, especially in no-till systems rely heavily on herbicides for pre-plant weed control, with glyphosate being one of the most used herbicides (Givens et al., 2009). However, the overreliance on glyphosate has resulted in the selection of herbicide-resistant weeds (Heap & Duke, 2018). In Idaho, there are confirmed cases of glyphosate resistance in kochia, cheatgrass, and Italian ryegrass. In addition, there are unconfirmed cases of glyphosate resistance in species such as common lambsquarters, barnyard grass, and Russian thistle. To protect the value of glyphosate in small grain production systems, it is important to identify effective alternative herbicides and mixtures for weed control.

The ideal pre-plant burndown herbicide must provide effective broad-spectrum weed control, have little to no residual effect or injury on the crop, and be economical. Thus, any possible alternatives to glyphosate must satisfy at least some of these conditions if they were to be adopted by growers (Givens et al., 2009). Further, using combinations of different burndown herbicides can help reduce the risk of selection for resistance and control a broader range of weed species. Combinations of herbicides with multiple sites of action ensure that weeds that are not controlled by one herbicide are controlled by the other herbicides in the mixture.

One other important factor to consider is crop response to these alternative herbicide treatments. While using these alternative herbicide treatments may help reduce the weed populations, consideration must be made for how the wheat and barley will be affected by the treatments. Some herbicides can persist in the soil for longer periods of time and affect subsequent crops (Muola et al., 2021; Rose et al., 2022) Thus, it is important to ensure that pre-plant herbicides do not accumulate residues at levels that will be phytotoxic to wheat or barley.

Economics is one of the primary considerations when choosing an herbicide for weed control (Gianessi, 2005). As herbicide-resistant weed pressure increases, U.S. farmers are increasing the rate of herbicide application along with the diversity of herbicides, which has resulted in increased financial costs (Swinton & Van Deynze, 2017). Prices of agricultural inputs, including herbicides, have increased drastically over the past few years (Kraehmer, 2012; Hurley & Frisvold, 2016). For example, the price of glyphosate increased >250% from approximately $5.3 per liter in 2014 to over $13.2 per liter in 2023 (Jhala et al. 2014; Knezevic et al. 2023). Thus, the choice of pre-plant herbicide can have a significant impact on weed control costs and farm profits. To provide the science-based guidelines growers need to make an informed management decision on effective alternative pre-plant burndown herbicides and mixtures, this study was designed to: 1) Evaluate the efficacy of pre-plant burndown herbicides and mixtures, 2) Assess the safety of pre-plant burndown herbicides and mixtures on wheat and barley, and 3) Quantify the economics of using alternative pre-plant burndown herbicides and mixtures on wheat.

Materials and Methods

Field experiments were conducted at the University of Idaho Research and Extension Centers in Kimberly Center and Aberdeen, Idaho in 2021 and 2022, to evaluate weed control, crop response, and economics of different herbicide programs. At Kimberly, the soil was a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids). The soil at Aberdeen was a Declo loam (Coarse-loamy, mixed, superactive, mesic Xeric Haplocalcids). Selected soil physical and chemical properties are presented in Table 1.1. The average field location air temperature and relative humidity for the 2 weeks after herbicide spraying in 2021 and 2022, were retrieved from the AgriMet Cooperative Agricultural Weather Network Database (https://www.usbr.gov/pn/agrimet/agrimetmap/) (Figure 1.1).

The wheat and barley studies were established side-by-side at each location. For each crop, there were 18 different herbicide and herbicide combination treatments, including the untreated check (Table 1.2). Treatments were arranged in a randomized complete block with four replications. Each plot was approximately 3 m wide by 9 m long. Herbicides were applied using a CO_2-pressurized bicycle sprayer delivering 144 L ha^{-1} at 207 kPa with TeeJet 11002DG nozzles on August 25th, 2021, and September 14th, 2022 in Kimberly, and September 2, 2021, and September 15th, 2022 in Aberdeen. At the time of herbicide application, the average weed heights in Kimberly in 2021 and 2022 were common lambsquarters (12, 3 cm), kochia (14, 3 cm), redroot pigweed (12, 3 cm), green foxtail (8, 3 cm). In Aberdeen, common lambsquarters, kochia, redroot pigweed, and green foxtail were about 3 to 6 cm tall in both years.

Each year and for each crop, weed control efficacy (by weed species) was visually assessed at 7 days and 14 days after treatment on a scale of 0 to 100%, with 0% being no weed control and 100% being complete weed control. Within 28 days after herbicide applications, winter wheat ("Brundage") and winter barley ("Charles") were planted at a rate of 112 kg ha^{-1}. In the spring of 2022 and 2023, visible crop injury was assessed on a scale of 0 to 100% with 0% being no crop injury and 100% being total crop destruction. Immediately following crop injury assessments, all plots were sprayed with post-emergence herbicides to control emerging weeds and eliminate or reduce competition from weeds. This was done to ensure that any growth or yield reduction was due to crop response to herbicides and not weed competition. The costs of the weed control programs were calculated using the average unit herbicide cost from local agrochemical dealers (Table 1.3).

Data Analysis

All data analyses were performed in R statistical language version 4.2.2 (R Core Team, 2023) using the lme4, lmerTest, and emmeans packages (Bates et al., 2015; Kuznetsova et al., 2017; Lenth, 2022). The effect of weed control treatments on wheat and barley was analyzed using a linear mixed-effects model, where herbicide treatments were considered fixed and location, crop, and block, and their interactions were considered random effects. Estimated marginal means were calculated from the model and posthoc Tukey-adjusted pairwise treatment comparisons were performed at an alpha of 0.05 using the emmeans and multcomp packages (Hothorn et al., 2008; Lenth, 2022).

Results and Discussions

Kimberly and Aberdeen, ID climates are semi-arid and characterized by cold winters and springs and warm, dry summers (Figure 1.1). The production of winter wheat and barley are either rainfed or irrigated to supplement precipitation. This study was conducted under sprinkler irrigation. Air temperatures were slightly warmer in 2021 than in 2022 (Figure 1.1A) and relative humidity in 2022 was greater than in 2021 (Figure 1.1B). Cumulative precipitation within the first two weeks after herbicide application was negligible in 2021 (0.25 mm) and 2022 (0.75 mm) in Kimberly, and 2021 (0.25 mm) and 2022 (0.75 mm) in Aberdeen.

Effective alternatives to glyphosate for pre-plant weed control

Weed control was influenced by herbicide treatments (Figures 1.2-1.5). The majority of the herbicide treatments applied alone or in mixtures provided weed control statistically similar to glyphosate (Figures 1.2 to 1.5). Effective control of common lambsquarters was achieved with the majority of the herbicide treatments used for this experiment (Figure 1.2). Glufosinate, paraquat, tiafenacil, and topramezone applied alone as well as the low rate of glyphosate provided less than 90% control of common lambsquarters (Figure 1.2). However, mixtures containing these herbicides provided very good (>90%) control of common lambsquarters. This demonstrates the importance of herbicide tank-mixtures for effective weed control. Similar results were found in (Eubank et al., 2008) with tank-mixture treatments of paraquat and glufosinate having better control of broadleaf weeds as opposed to these treatments on their own. There was herbicide by location interaction effect on common lambsquarters control (Table 1.4). This was possibly due to differences in weed size and weather conditions (Figure 1.1) at the two locations.

Redroot pigweed control was also significantly influenced by herbicide and the herbicide by year by location interaction (Table 1.4). The interaction effect of these factors on redroot pigweed control was due to weed size and weather condition differences across years and experimental sites (Figure 1.1). Only topramezone applied alone provided less weed control compared to glyphosate (Figure 1.3). All other herbicides, whether applied alone or in mixtures provided similar weed control as glyphosate (Figure 1.3). We can infer that almost all these treatments would be good preplant burndown treatments for a field that had a high population of redroot pigweed. Since redroot pigweed grows later in the growing season, having a burndown in the late summer to early fall is ideal, especially if redroot pigweed is a predominant weed in the field.

Nearly all herbicide treatments except for topramezone applied alone provide very good (>90%) control of kochia (Figure 1.4). Topramezone was the least effective herbicide for kochia control. Only around 50% kochia control was achieved with the topramezone treatment. This was also found by Kumar & Jha (2015). Mixtures of topramezone with other herbicides provided better kochia control. There was no effect of year, location, or their interactions on kochia control (Table 1.4).

One characteristic that makes glyphosate an ideal preplant burndown herbicide is its ability to control both grassy and broadleaf weeds. While there are multiple herbicide options for broadleaf weed control before or after planting small grains, grassy weed control remains very challenging. It was observed that glyphosate remains one of the best options for grassy weed control (Figure 1.5). Interestingly, green foxtail control was much more effective with topramezone compared to the broadleaf weeds. Similar findings were also found by Soltani et al. (2012). Nonetheless, the results showed that there are other effective alternatives to glyphosate for pre-plant grassy weed control (Figure 1.5). For example, glufosinate, paraquat, and their mixtures provided similar green foxtail control as glyphosate (Figure 1.5).

Safe alternatives to glyphosate for pre-plant weed control

After herbicide treatments were applied, the wheat and barley were evaluated for crop injury to determine if the herbicide treatments were as safe as glyphosate treatments. As shown in Figure 1.6, wheat and barley were not damaged by the herbicide treatments. No physical signs of herbicide damage were observed, and the growth of both the wheat and barley was observed as normal. Crop yield was evaluated in 2022, and there were no effects of herbicide treatments on wheat or barley yield (data not shown). Wheat yield was 7,666 kg ha^{-1} in the untreated check and 6,927 to 8,877 kg ha^{-1} in the herbicide treatments. Barley yield was 8743 kg ha^{-1} in the untreated check and 6,591 to 9,550 kg ha^{-1} in the herbicide treatments. Visible injury evaluations in the spring of 2023 also showed that there were no injuries from the pre-plant herbicide applications. Thus, these herbicide alternatives have all been shown to be safe alternatives for pre-plant burndown weed control in these cereal crops.

Economical alternatives to glyphosate for pre-plant weed control

The cost of the pre-plant herbicide programs are compared to the price of glyphosate . due to glyphosate being the standard pre-plant burndown herbicide treatment that growers use for weed control. Table 1.3 shows the results of that economic analysis, depicting the application rate, the unit cost of the herbicides, and the overall dollar amount per hectare. The prices of each treatment per hectare are accurate as of 2023, but it must be noted that product prices change regularly from year to year. It is observed that there were at least six other treatments that may be economical alternatives to glyphosate for pre-plant weed control. The cheapest treatment was paraquat at $15.9 ha^{-1} and depending on the weed species had between 85 to 99% control. This proves that there are indeed cheaper alternatives to glyphosate that still have high levels of control for all the weed species in this study. While more money might be spent on herbicide mixtures in the short term, there is a long-term benefit as a proactive herbicide resistance management strategy.

Conclusions

After comparing the effectiveness of the different herbicide treatments and the economic analysis of the different herbicides used, there are multiple alternatives to glyphosate for pre-plant weed control in wheat and barley. There are at least six different treatments that are just as effective as glyphosate and economical alternatives to glyphosate. The six treatments were paraquat, tiafenacil, glufosinate, paraquat + pyraflufen, paraquat + tiafenacil, and paraquat + bromoxynil. None of these treatments affected the growth and yield of either wheat or barley. It is therefore concluded that there are effective, safe, and economical alternatives to glyphosate for pre-plant weed control in wheat and barley for the weeds evaluated in this study. It is recommended that future research should evaluate the efficacy of these herbicides against other common weeds in small grain productions systems.

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Table 1.1 Soil physical and chemical properties of the 2021 and 2022 experimental sites in Aberdeen and Kimberly, ID USA

Year	Soil texture	Sand	Silt	Clay	OM[a]	pH	CEC[a]
		--------------------%---------------------					meq/100 g
			Aberdeen				
2021	Loam	50	40	10	2.14	8.0	18.7
2022	Loam	40	45	15	1.39	8.2	15.8
			Kimberly				
2021	Silt loam	23	58	19	2.06	7.8	18.8
2022	Silt loam	22	72	6	1.97	8.1	18.6

[a] OM, organic matter; CEC, cation exchange capacity

Table 1.2. Herbicide treatments, rates, and adjuvants used in the pre-plant weed control study from 2021 to 2023, Kimberly and Aberdeen, ID USA

Trt #	Herbicide	Product rate (L ha^{-1})	Rate (g a.i. or a.e. /ha)	Adjuvants
1	Untreated	-	-	-
2	*topramezone* (Impact[a])	0.03	24.5	HSOC[j] + UAN[k]
3	*topramezone* (Impact)	0.03	24.5	HSOC +
	tiafenacil (Reviton[b])	0.06	49.6	UAN
4	*paraquat* (Gramoxone 2.0 SL[c])	0.95	560	NIS[l]
5	*tiafenacil* (Reviton)	0.06	49.6	HSOC
6	*glufosinate-ammonium* (Liberty 280 SL[d])	0.86	594	AMS[m]
7	*paraquat* (Gramoxone 2.0 SL)	0.95	560	NIS
	carfentrazone-ethyl (Aim EC[e])	0.06	35	
8	*paraquat* (Gramoxone 2.0 SL)	0.95	560	HSOC +
	saflufenacil (Sharpen[f])	0.06	50	UAN
9	*paraquat* (Gramoxone 2.0 SL)	0.95	560	NIS
	pyraflufen-ethyl (Vida[g])	0.06	3.64	
10	*paraquat* (Gramoxone 2.0 SL)	0.95	560	NIS
	tiafenacil (Reviton)	0.06	49.6	
11	*paraquat* (Gramoxone 2.0 SL)	0.95	560	NIS
	*bromoxyni*l (Maestro 2EC[h])	0.71	420	
12	*tiafenacil* (Reviton)	0.06	49.6	NIS
	*bromoxyni*l (Maestro 2EC)	0.71	420	
13	*glufosinate-ammonium* (Liberty 280 SL)	0.86	594	AMS
	saflufenacil (Sharpen)	0.06	50	
14	*glufosinate-ammonium* (Liberty 280 SL)	0.86	594	AMS + NIS
	tiafenacil (Reviton)	0.06	49.6	

Table 1.2 Cont'd

15	*topramezone* (Impact)	0.03	24.5	HSOC +
	glufosinate-ammonium (Liberty 280 SL)	0.86	594	AMS
16	*topramezone* (Impact)	0.03	24.5	HSOC +
	*bromoxyni*l (Maestro 2EC)	0.71	420	AMS
17	*glyphosate* (Roundup PowerMax[i])	0.65	870	AMS
18	*glyphosate* (Roundup PowerMax)	0.95	1260	AMS

[a]Impact®, AMVAC Chemical Corporation, Newport Beach, CA USA

[b]Reviton®, HELM Agro, Tampa, FL, USA.

[c]Gramoxone® SL 2.0, Syngenta Crop Protection, LLC, Greensboro, NC, USA

[d]Liberty® 280 SL, Bayer CropScience, St. Louis, MO USA.

[e]Aim® EC, FMC Corporation, Walnut Street, PA USA

[f]Sharpen®, BASF Corporation Research Triangle Park, NC USA

[g]Vida®, Gowan Company, Yuma, AR USA

[h]Maestro® 2EC, Nufarm Inc., Alsip IL USA

[i]Roundup® PowerMax, Bayer CropScience, St. Louis, MO, USA.

[j]HSOC, high surfactant oil concentrate (Superb® HC With CornSorb® Inside, WinField Solutions, St. Paul, MN USA) at 1% v/v.

[k]UAN, Urea-ammonium nitrate solution (32-0-0), Agrium U.S. Inc. (A Subsidiary of Nutrien Ltd.), Loveland, CO, USA.

[l]NIS, nonionic surfactant (Preference®, WinField Solutions, St. Paul, MN USA) at 0.25% v/v.

[m]AMS, Ammonium sulfate (Ultra Pro®, Loveland Products Inc., Greeley, CO USA) at 2.5% v/v.

Table 1.3 Economic analysis of herbicide treatments used in the pre-plant weed control study from 2021 to 2023, Kimberly and Aberdeen, ID USA

Herbicide[a]	Product rate (L ha^{-1})	Active ingredient rate (g a.i. ha^{-1})	Unit price ($ L^{-1} product)	Cost (US $ ha^{-1})
topramezone	0.03	24.5	507.21	37.11
topramezone	0.03	24.5	507.21	65.12
tiafenacil	0.06	49.6	187.67	
paraquat	0.95	560	7.13	15.91
tiafenacil	0.06	49.6	187.67	28.01
glufosinate	0.86	594	14	28.43
paraquat	0.95	560	7.13	46.72
carfentrazone	0.06	35	214.72	
paraquat	0.95	560	7.13	46.72
saflufenacil	0.06	50	207.96	
paraquat	0.95	560	7.13	38.31
pyraflufen	0.06	3.64	152.84	
paraquat	0.95	560	7.13	43.92
tiafenacil	0.06	49.6	187.67	
paraquat	0.95	560	7.13	38.93
bromoxynil	0.71	420	13.74	

Table 1.3 Cont'd

tiafenacil	0.06	49.6	187.67	51.03
bromoxynil	0.71	420	13.74	
glufosinate	0.86	594	14	59.24
saflufenacil	0.06	50	207.96	
glufosinate	0.86	594	14	56.44
tiafenacil	0.06	49.6	187.67	
topramezone	0.03	24.5	507.21	65.54
glufosinate	0.86	594	14	
topramezone	0.03	24.5	507.21	60.13
bromoxynil	0.71	420	13.74	
glyphosate	0.65	870	17.17	26.5
glyphosate	0.95	1260	17.17	38.54

See table 1.2 for a detailed description of herbicide treatment.

Table 1.4 Summary of p-values from the analysis of variance. Herbicide was fixed factor in the model while all other factors and their interactions were random.

Factor	Common lambsquarters	Kochia	Redroot pigweed	Green foxtail
	------------------------ p-value	--------------------------		
Fixed				
Herbicide	< 0.001	<0.0001	<0.0001	<0.0001
Random				
Year	0.99	0.19	0.47	0.01
Location	0.99	0.30	0.97	0.87
Herbicide x Year	0.99	0.26	0.99	0.90
Herbicide x Location	<0.0001	0.08	0.99	0.85
Herbicide x Year x Location	0.99	0.70	<0.0001	<0.0001

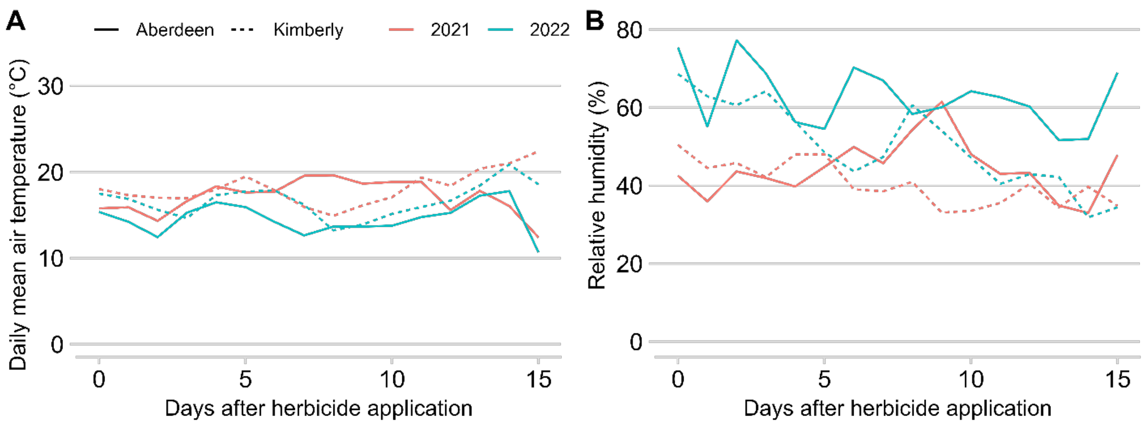

Figure 1.1 Air temperatures (A) and relative humidity (B) 0 to 15 days after herbicide application in 2021 and 2022, Kimberly and Aberdeen Idaho, USA. Data from the AgriMet Cooperative Agricultural Weather Network Database (https://www.usbr.gov/pn/agrimet/agrimetmap/). Herbicides were applied on August 25, 2021, and September 14, 2022 in Kimberly and on September 2, 2021 and September 15, 2022 in Aberdeen.

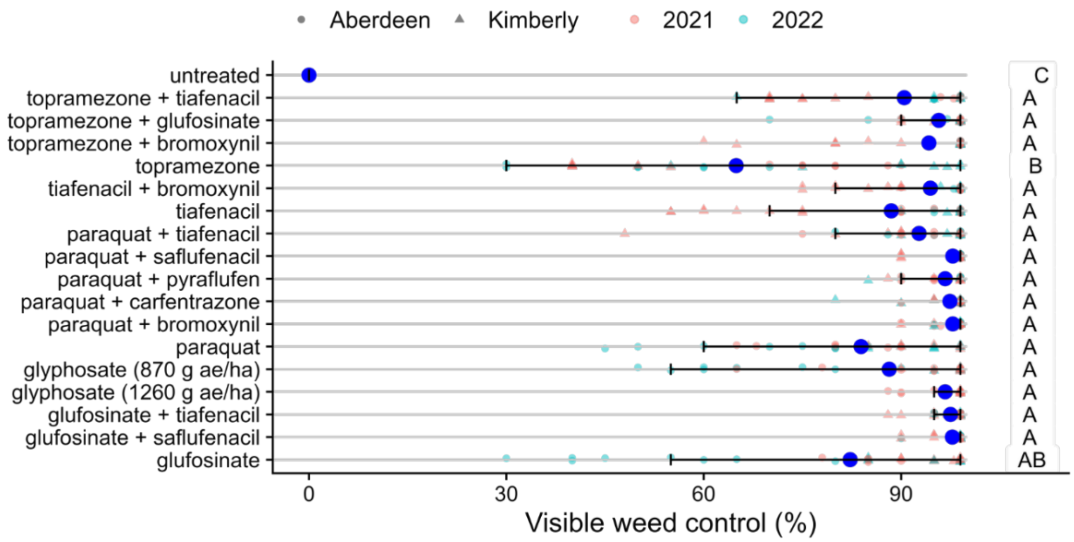

Figure 1.2. Visible common lambsquarters control 2 weeks after herbicide application in 2021 and 2022 at Aberdeen and Kimberly ID, USA. Treatments with the same letters were not statistically different according to Tukey's HSD at alpha of 0.05. See table 1.2 for a detailed description of herbicide treatment.

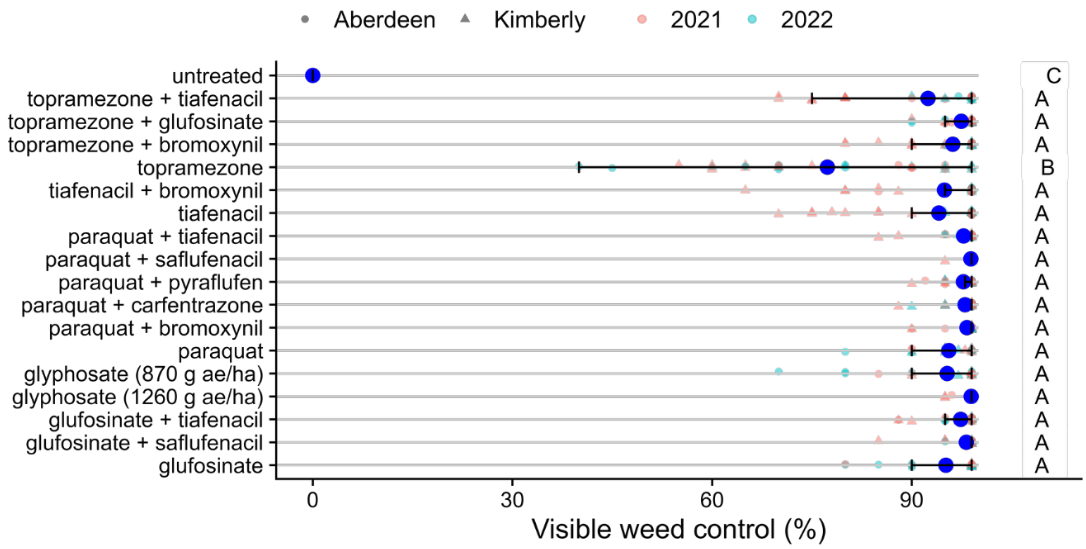

Figure 1.3. Visible redroot pigweed control 2 weeks after herbicide application in 2021 and 2022 at Aberdeen and Kimberly ID, USA Treatments with the same letters were not statistically different according to Tukey's HSD at alpha of 0.05. See table 1.2 for a detailed description of herbicide treatment.

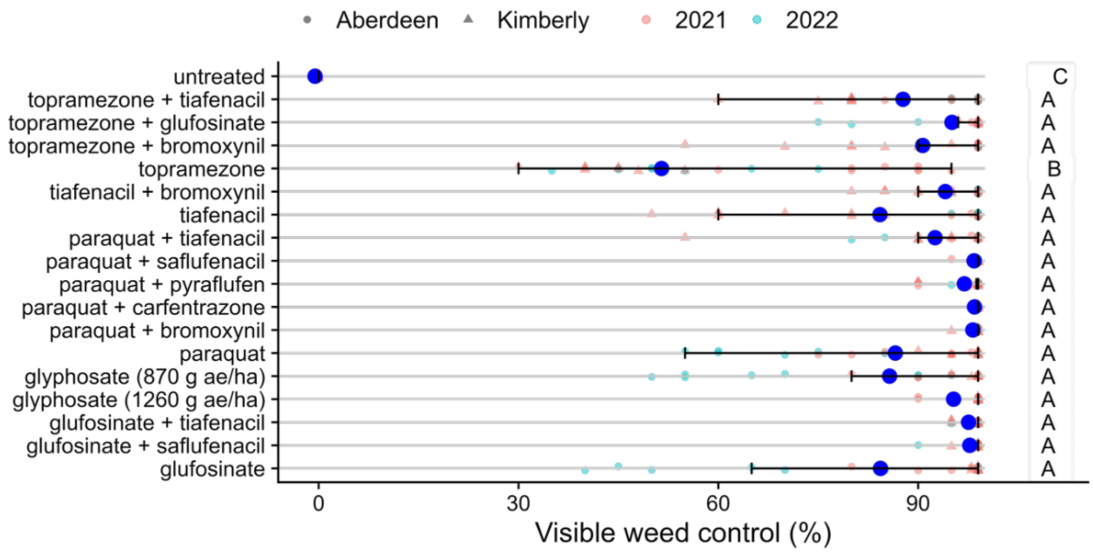

Figure 1.4. Visible kochia control 2 weeks after herbicide application in 2021 and 2022 at Aberdeen and Kimberly ID, USA. Treatments with the same letters were not statistically different according to Tukey's HSD at alpha of 0.05. See table 1.2 for a detailed description of herbicide treatment.

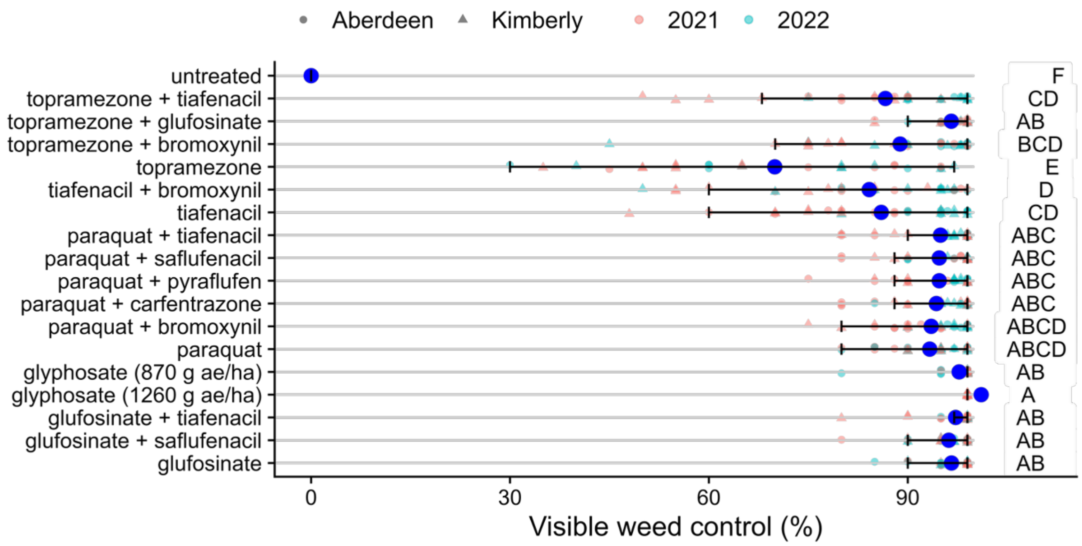

Figure 1.5. Visible green foxtail control 2 weeks after herbicide application in 2021 and 2022 at Aberdeen and Kimberly ID, USA. Treatments with the same letters were not statistically different according to Tukey's HSD at alpha of 0.05. See table 1.2 for a detailed description of herbicide treatment.

Figure 1.6 View of the first replicate showing no herbicide injury from any of the herbicide treatments. Photo from Rockland ID where similar herbicide treatments were applied but data excluded from analysis because of lack of consistency in weed species presence and distribution.

Figure 1.7 Visual weed control 14 days after herbicide application

Chapter 2: Weed Seed bank Control in Rotational Crops for Proactive Herbicide Resistance Management

Abstract

Herbicide-resistant weed populations are evolving rapidly and threatening the sustainability of crop production. A 4-year crop rotation study was initiated in 2021 at the University of Idaho Kimberly Research and Extension Center to evaluate weed control and seedbank dynamics in wheat-alfalfa vs wheat-annual crop (corn and dry bean) rotations. There were three herbicide treatments: non-treated, postemergence (POST) only, and preemergence (PRE) + POST. After the first year, there was no difference in seedbank density among treatments. After two years, weed seedbank density was reduced from 2,227 viable seeds m^{-2} in the non-treated to 1,344 seeds m^{-2} in the PRE + POST treatments, representing nearly 40% reduction in seedbank density. There was also a trend of PRE + POST treatments slightly reducing weed seedbank density compared to POST-only treatment. Weed density within the crops during the growing season was influenced by the type of crop as well as the herbicide treatment. Both POST-only and PRE + POST treatments reduced weed density compared to the non-treated and the PRE + POST treatments reduced weed density in each crop compared to the POST-only treatment. Weed control treatments did not affect alfalfa yield. However, herbicide application (POST only and PRE + POST) improved corn and dry bean yield. The combination of fewer weeds and greater crop yield in the PRE + POST treatments holds promise for reducing weed seedbank density and potentially improving long-term crop productivity and economics.

Introduction

Herbicide-resistant weed populations are evolving rapidly and threatening the sustainability of global crop production. There are currently 131 confirmed unique cases of herbicide-resistant weeds in the United States (Heap, 2023). In Idaho, there are 11 documented cases of herbicide resistance in seven common weed species including kochia, Italian ryegrass, mayweed chamomile, prickly lettuce, redroot pigweed, Russian thistle, and wild oat. These resistance cases encompass at least seven herbicide sites of action, including 5-enolpyruvylshikimate-3-phosphate synthase inhibitors, ACCase inhibitors, acetolactate synthase inhibitors, lipid synthesis inhibitors, very-long chain fatty acid inhibitors, auxin mimics, and photosystem II inhibitors (Heap, 2023). Herbicides with these sites of action are commonly used in economically important crops in Idaho such as alfalfa, barley, corn, dry beans, potatoes, sugar beet, and wheat. Herbicides will undoubtedly remain an important weed management tool well into the future, but even the most ardent supporters of herbicides acknowledge the necessity of reducing reliance on herbicides through integrated weed management practices.

Crop rotations have always been an important cultural practice in crop production. Crop rotations have been used for many reasons including weed control, insect control, disease control, soil nutrient conservation, or even soil health improvement (Pavlychenko and Harrington, 1934). Whatever the reason may be, crop rotations are an important part of healthy cropping systems. When it comes to weed control in crop rotation, the different crop options allow for the use of different herbicides and cultural practices for integrated weed management (Brainard et al., 2008). The weed seed bank, defined as "weed seeds in the soil" is a crucial factor that must be considered when creating a weed management plan. The weed seed bank can be made up of many different species of plants ranging from both weeds and volunteer crops, as this is related to the history of the field (Buhler et al., 1997). Most annual weeds produce numerous seeds with a significant proportion that can remain dormant for several years, depending on the species. This allows weeds to spread germination over time which can create short to long-term weed management issues for growers. Crop rotation is a crucial practice to break up the pattern of the same environmental factors that could stimulate a flush of specific weed species (Buhler et al., 2001). Crop rotations including grass and broadleaf crops have been shown to be an effective strategy for weed management as planting timing, growth patterns, and crop competitiveness can be leveraged for cultural weed management (Hosseini et al., 2014). In addition, the differences in planting and harvest timing help reduce the germination of certain weed species and reducing the production of seeds (Gardarin et al., 2011). Since seed dispersal from weed escapes in one of the major inputs to the weed seedbank, preventing weed species from producing seed is crucial for depleting the weed seed bank. The goal of this research is to provide the foundational knowledge needed by stakeholders to adopt and integrate best management practices for weed seedbank control in crop rotations. The specific objectives were to: 1) Compare weed seedbank densities in wheat-alfalfa and annual crop rotations, and 2) Evaluate residual herbicide programs for effective weed seedbank management within crop rotations.

Materials and Methods

A field study was established under sprinkler irrigation at the University of Idaho Kimberly Research and Extension Center, Kimberly, ID. The soil at the site was Portneuf silt loam composed of 23% sand, 59% silt, and 18% clay with a pH of 7.8, an OM content of 2.29%, and a CEC of 20.7 meq/100 g soil. This experiment was laid out as a split-plot, randomized complete block design with four replications.

Main plot (Crop rotation): Main plots were approximately 13 m wide by 9 m long and consisted of four crop rotations ranging in diversity and complexity (Figure 2.1). There were four replicates of each main plot. Rotation 1 (wheat – alfalfa) incorporates multiple biomass removal events and extended crop canopy presence for enhanced crop competition and suppression of weed seed germination. Rotation 2 to 4 represented annual crop rotations with varied planting/harvest dates and more options for chemical weed control.

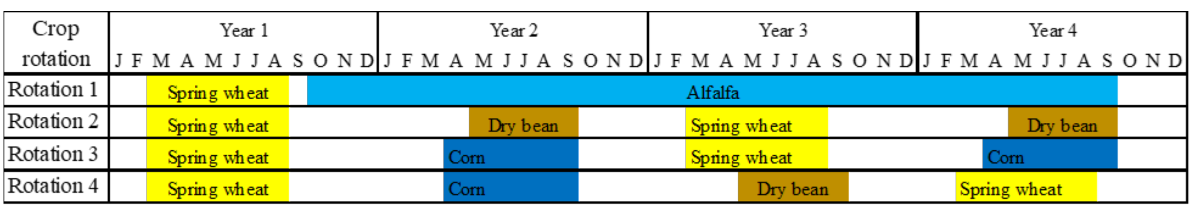

Figure 2.1. The 4-year crop rotation sequence used in the study. Year 1 corresponds to 2021. Data presented for the first 2 years of the study.

Split-plot (herbicide): Split-plots measuring 4.6 m wide by 9 m long were established within each crop rotation (main plot). The first herbicide treatment will rely on a combination of preemergence and postemergence herbicides that would provide the greatest weed control and allow rotation to the next crop. This will allow us to determine the effect of herbicide mixtures on weed management. The second treatment relied solely on a postemergence herbicide program to mimic what most Idaho growers would do. The third treatment had no-herbicide treatment that allowed us to determine the sole effect of crop rotation on weed seedbank density. For wheat, the preemergence (PRE) herbicide was pyroxasulfone (Zidua®) at 89 g ai ha^{-1} and the postemergence (POST) herbicide was bromoxynil + fluroxypyr + pyrasulfotole

(Huskie FX®) at 312 g ai ha^{-1} + fenoxaprop-p-ethyl + pinoxaden (Axial Bold®) at 90 g ai ha^{-1}. In dry bean, PRE herbicide was ethalfluralin + dimethenamid-p (Sonalan® HFP + Outlook®) at 1050 + 950 g ai ha^{-1} and the POST herbicide was bentazon + imazamox (Varisto®) at 587 g ai ha^{-1}. In corn, PRE herbicide was acetochlor (Warrant®) at 1680 g ai ha^{-1} and the POST herbicide was glyphosate (Roundup PowerMax®) at 1260 g ai ha^{-1}. For alfalfa, the herbicide was pendimethalin (Prowl®) at 1,120 g ai ha^{-1} and the POST herbicide was imazamox (Raptor®) at 44 g ai ha^{-1}.

Crop establishment and management: Spring wheat ("UI cookie") was planted at 90 kg ha^{-1} on April 7, 2021. After wheat harvest in 2021, the field was disked after soil sampling and alfalfa ("WL354") was planted in wheat-alfalfa rotational plots at a rate of 22 kg ha^{-1} on September 16, 2021, using a Great Plains 3P806NT no-till drill (Great Plains Ag, Salina, KS, USA). Roundup Ready silage corn ("DKC54-74RIB) was planted at about 88,000 seeds ha^{-1} on May 11, 2022. Dry bean (Pinto bean) was planted on June 2, 2022, on 56 cm row spacing. The crop was irrigated with a solid-set overhead sprinkler as needed.

Data collection: Weed density by species was measured in each plot by counting all weeds in a randomly placed 0.5 m^2 quadrat about 3 weeks after the final herbicide application. Crop yields were determined by harvesting the center rows (3 m long) for dry bean and corn, and 1.5 m x 7.6 m for spring wheat each year. Alfalfa was harvested 3 times a year at approximately 10 to 30% bloom stage, oven-dried at 70 C, and weighed to determine forage biomass yield. Because weed biomass can contribute significantly to the dry matter yield of whole plots, a quadrat (0.5 m^2) was randomly placed within each plot, and aboveground biomass (alfalfa and weeds) within the quadrat area was clipped using rice knives, leaving a stubble of about 12 cm. This was hand separated into weed and alfalfa biomass to enable evaluation of alfalfa and weed contribution to total forage biomass yield.

In late fall each year (after crop harvest), 10 soil samples were collected to a depth of ~15 cm in each split-split-plot using a 1.75 cm diameter soil core, and samples from each plot were bulked. The soil was frozen immediately at -20 C to prevent seeds from germinating. The soil samples were thawed in the spring of the following year and spread thinly (~ 2 cm) in flats filled with potting soil for exhaustive germination in the greenhouse to estimate weed seedbank density (Figure 2.2). Seedlings were counted and removed weekly for 4 months or until no weeds emerged for 2 continuous weeks and the cumulative emergence count was used as an estimate of weed seed bank density.

Data Analysis

All data analyses were performed in R statistical language version 4.2.2 (R Core Team, 2023) using the lme4, lmerTest, and emmeans packages (Bates et al., 2015; Kuznetsova et al., 2017; Lenth, 2022). This was a linear mixed-effects model. Herbicide treatments and crops were considered fixed effects. Block was considered random effect. Means were separated using Tukey's HSD at alpha=0.05 using the emmeans and multcomp packages (Hothorn et al., 2008; Lenth, 2022).

Results and Discussions

Weed densities within crops

Weed density was affected by the types of crops grown during the season and the herbicide treatment used. In Figure 2.3, year 1 weed density in spring wheat was reduced by the herbicide treatment. Better control was achieved in the PRE + POST herbicide treatments than a single POST herbicide treatment or the untreated check. Both herbicide treatments had lower weed density than the untreated control. The untreated control had over double the number of weeds compared to the herbicide treatments. This is an example of why it is important to have multiple types of control, in this case, both chemical and cultural.

Weed density was less in the alfalfa than corn and dry bean. Alfalfa grows densely which can help reduce weeds due to competition and lack of sunlight. In addition, alfalfa is harvested multiple times in a growing season (between 2-4 times in Idaho). Thus, including perennial forage crops like alfalfa in rotations allows for the elimination of annual weed seed production through multiple crop harvests (Goplen et al., 2017; Meiss et al., 2010). These results demonstrate that alfalfa remains an important rotational crop for weed control.

Observations of weed density and diversity within each crop indicate that the different crops have different weed issues. Common lambquarters and prickly lettuce (*Chenopodium album* L.) were the most prevalent in the alfalfa stand and are commonly found in alfalfa production

(Swan, 1972; Wilson & Burgener, 2009). Planting timing is different for wheat, however, resulting in the emergence of different weed species. Besides wheat planting being early spring, it has a different growing pattern than alfalfa resulting in different weeds to be present. The most prevalent weeds in the wheat were barnyard grass and kochia. Both kochia and barnyardgrass emerge early in the spring as well. This shows that weed pressures can differ depending on planting and ecology (Chin, 2001). Wheat and barnyard grass being grasses and having similar growth pattern and root architecture means that barnyardgrass may be very competitive with wheat (Wilson & Read, 2006). Corn, on the other hand being a late spring planted crop has different pressures even though both corn and wheat are both grass crops. The major weed pressures for corn are green foxtail and lambsquarters, with green foxtail being the most common weed. If not effectively controlled, green foxtail can compete with corn, drastically reducing yield (Figure 2.4). Similar results were also observed by Staniforth (1961) when herbicides were not applied to effectively control weeds.

Dry bean is planted late spring to early summer and thus, it tends to select for late-emerging weeds like green foxtail, redroot pigweed, and hairy nightshade. Green foxtail was the predominant weed in dry bean. This weed grows quickly and if not controlled early, it can cause significant yield reductions (Figure 2.4). Green foxtail is a common problematic weed in dry beans and a low density can reduce dry bean yield (Mesbah et al., 2004). All these different planting times and ecological growing patterns of each specific crop causes different weeds to be present at different densities in each crop. It shows that different crops can either successfully compete with or suppress different weeds.

Weed seedbank densities in wheat-alfalfa and wheat-corn/dry bean rotations

After the first year of the exhaustive germination study, there is no statistically significant difference between the different herbicide treatments for 2021 (Figure 2.5). This is expected in the first year of this trial since a seedbank can build up multiple generations of weed seeds in the soil. In the PRE + POST treatment had the lowest seed bank density (Figure 2.6). The relatively low weed seed bank density in the PRE + POST shows promise for the next two years of the study to possibly start seeing a reduction in the seed bank.

Alfalfa was not influenced by herbicide treatments while corn and dry beans were significantly increased by herbicide treatments (Figure 2.4). The alfalfa did not have any statistical difference in yield; however, this is due to the way the alfalfa is harvested. Alfalfa forage is harvested by cutting down the whole crop, so any weeds in the harvested forage would be added to the overall yield. Since corn and dry beans are harvested for grain or seed, the competition with weeds will greatly affect the yield as a stressed plant will normally produce less grain or seed (Gallandt & Weiner, 2015).

Besides the yield and weed seed bank being affected by the rotation and herbicide treatments there is the other benefit of herbicide resistance management. With a constant rotation of herbicides that are specific to each crop, there is a constant change in the herbicide site of action. Some of these crops have the same weed pressures, for example, the corn and dry beans both have a high pressure of green foxtail. However, different herbicide modes of action were applied in dry beans and corn. Research has shown that it is beneficial for crops that have different effective herbicide sites of action for weed control to follow each other in the rotation for proactive herbicide resistance management (Brunharo et al., 2022) The different herbicide sites of action also allow for control of any green foxtail or any other weed that could have resistance or tolerance to an herbicide that was previously used.

It is important to have two modes of action when applying herbicides in a crop for just one year. In Figure 2.7 there is a greater reduction of weed density with PRE + POST. This could be for multiple reasons, one being that any weeds that emerged later in the season were controlled with the second spraying. The other reason would be that any weeds that had resistance were controlled with the second treatment that had a different site of action (Löbmann et al., 2019). Having these two sites of action ensures that weed control is achieved in the first year, having a crop that has different ecology allows for different herbicides with even more sites of action to be used to control any that made it to the next year. With some weeds having long dormancy periods in the seed bank (Bajwa et al., 2022), it is crucial to have all these options for herbicide resistance management. A weed with tolerance or resistance could stay dormant in the soil for decades, so always having resistance management practices in use will help stop the spread of resistance over multiple years.

Conclusion

With the combination of higher crop yields from the PRE + POST herbicide treatments and the lower weed seedbank density 2 years after initiation of the study, the use of PRE + POST herbicides might be an economically positive resistance management practice. Alfalfa has been shown to be a good rotational crop for weed management. This study is still in progress with 2023 being the third year. Results are promising regarding the use of crop rotations and herbicide to manage weed seed banks.

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Figure 2.2. Exhaustive germination of seedbank from soil collected from plots.

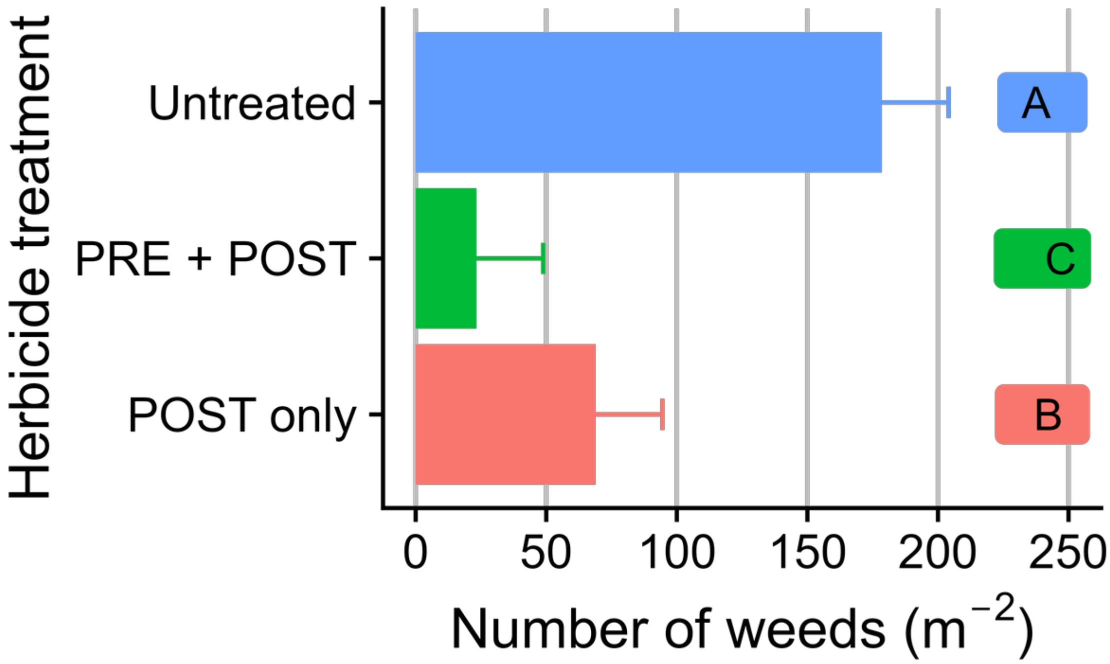

Figure 2.3. Year 1 (2021) weed density within spring wheat 3 weeks after postemergence herbicide application. POST only involved one-time application of a postemergence herbicide, PRE + POST involved the application of a preemergence herbicide followed by a postemergence herbicide.

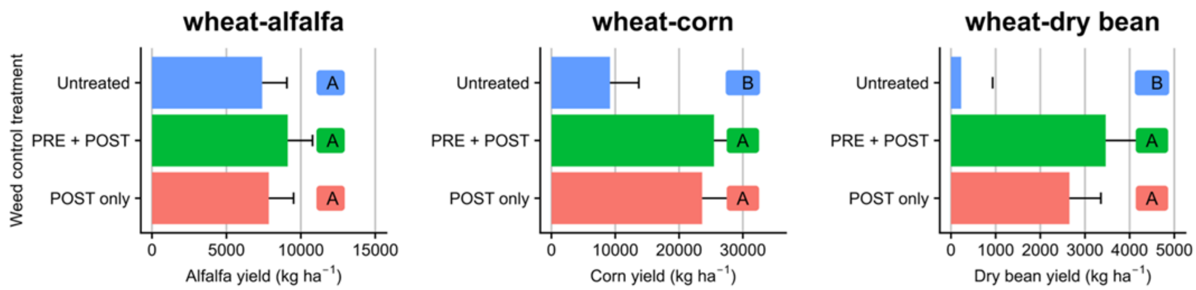

Figure 2.4. Crop yield in year 2 (2022). POST only involved one-time application of a postemergence herbicide, PRE + POST involved the application of a preemergence herbicide followed by a postemergence herbicide. Treatments with the same letters were not statistically different according to Tukey's HSD at alpha of 0.05.

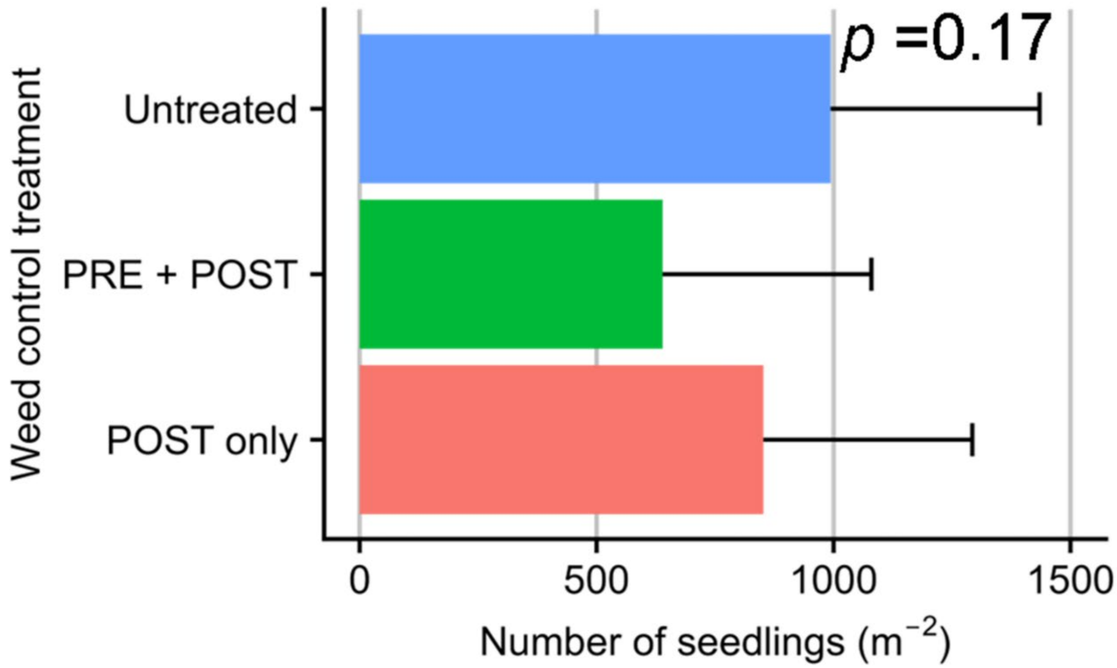

Figure 2.5. Seedbank density of soils collected from fall of 2021. POST only involved one-time application of a postemergence herbicide, PRE + POST involved the application of a preemergence herbicide followed by a postemergence herbicide.

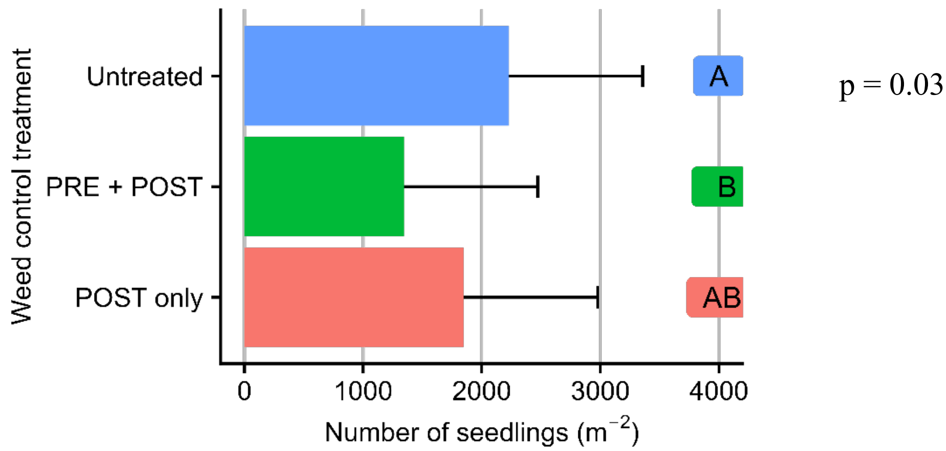

Figure 2.6. Seedbank density of soils collected from fall of 2022**.** POST only involved one-time application of a postemergence herbicide, PRE + POST involved the application of a preemergence herbicide followed by a postemergence herbicide. Treatments with the same letters were not statistically different according to Tukey's HSD at alpha of 0.05.

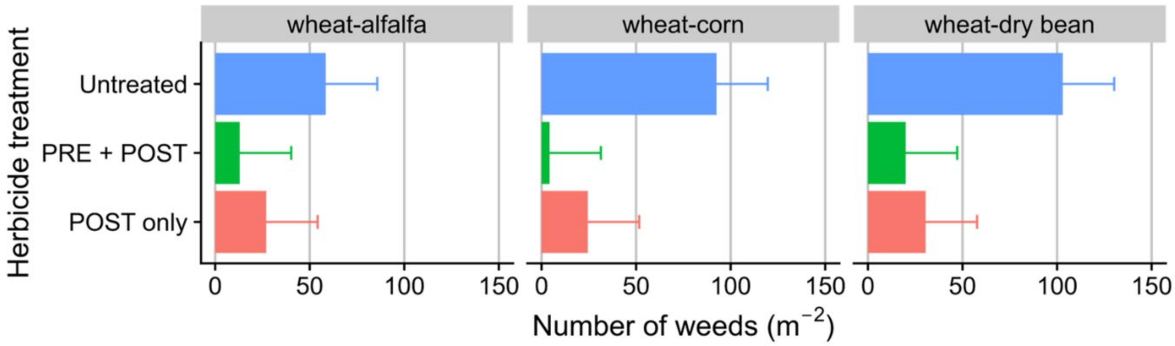

Figure 2.7. Year 2 (2022) Weed density within crops in the rotation**.** POST only involved one-time application of a postemergence herbicide, PRE + POST involved the application of a preemergence herbicide followed by a postemergence herbicide.

Figure 2.8. Weed density in corn in 2022. From left to right: untreated, postemergence (POST) only, and preemergence (PRE) + POST).

Chapter 3: Weed Impacts on Alfalfa Forage Accumulation and Nutritive Value

Abstract

Weeds can influence the economics of alfalfa (*Medicago sativa* L.) production by reducing forage yield, and nutritive value or by contaminating hay. Field studies were conducted in Idaho in 2021 and 2022 to evaluate the effect of weed control treatments on alfalfa forage accumulation, weed biomass, and nutritive value. In addition, the relationship between the proportion of individual weed species biomass and alfalfa nutritive value was assessed. These studies included eight different herbicide and herbicide combination treatments, including the untreated check. Treatments were comprised of pre-emergence incorporated, early postemergence (after 80% alfalfa emergence), and postemergence (third trifoliate alfalfa) herbicide applications. Data collection included weed control efficacy, weed and alfalfa biomass, and alfalfa nutritive value. Additional samples were collected and combined in these alfalfa to weed biomass proportions (% by weight): 0:100, 20:80, 40:60, 60:40, 80:20, and 100:0, for wet chemistry analysis of forage nutritive value to evaluate the relationship between the proportion of individual weed species biomass and alfalfa nutritive value. The acetochlor only treatment provided less than 50% weed control while the EPTC only treatment provided 54 to 81% weed control. The control provided by acetochlor and EPTC were less than treatments containing imazamox and imazamox plus bromoxynil. Weed biomass in forage (23 to 55% of total biomass) due to poor or no weed control reduced crude protein, increased fiber concentrations, and reduced the relative feed value. The relationship between the proportion of individual weed species biomass and alfalfa nutritive value was linear for all weed species evaluated.

Introduction

Weed management is one of the most important practices in alfalfa (*Medicago sativa* L.) production, particularly in newly established alfalfa (Bradley et al., 2010; Dillehay et al., 2011). Established alfalfa is able to tolerate different herbicides and therefore, there are multiple herbicide options (e.g., carfentrazone, diuron, flumioxazin, hexazinone, imazethapyr, MCPA, metribuzin, pendimethalin, paraquat, saflufenacil, terbacil, etc) for effective weed control in alfalfa after the first harvest or established stands (Adjesiwor &

Prather, 2022). Thus, weed control before the first harvest remains one of the critical practices in alfalfa production. Weeds tend to be more problematic in spring-seeded alfalfa compared to summer or fall-seeded alfalfa, as summer annuals often emerge at the same time as the alfalfa (Bradley et al., 2010). Although late-summer or fall seeding often reduces competition from summer annual weeds, winter annual weeds and late-emerging weeds can still be problematic i newly established alfalfa (Adjesiwor et al., 2017; Hall et al., 1995). Weed control is, therefore, important in newly seeded alfalfa to reduce weed competition, increase establishment success as well as subsequent alfalfa forage accumulation and nutritive value (Bradley et al., 2010; Hall et al., 1995; Roberts et al., 2023). For example, weed control using herbicide application increased alfalfa forage accumulation by 36 to 39% compared to the nontreated plots (Roberts et al., 2023). Weed control has also been found to increase alfalfa stand persistence and productivity over the life of the stand (Dowdy et al., 1993). Dillehay et al. (2011) reported that under severe weed infestations, weed control must be initiated before the 7 trifoliate growth stage of alfalfa to prevent economic yield loss. However, because weeds nearly always produce harvestable aboveground biomass, poor weed control or the absence of weed control tends to increase total forage (alfalfa + weeds) biomass under heavy weed pressure (Cosgrove & Barrett, 1987; Moyer & Acharya, 2006; Temme et al., 1979). Studies have found that in some instances, effective weed control reduces forage accumulation of the whole stand due to herbicide injury to the alfalfa or the absence of weed biomass (Bradley et al., 2010; Dowdy et al., 1993; Moyer & Acharya, 2006). Nonetheless, when weeds are present in large quantities in alfalfa, there is a trend of reduced alfalfa dry matter and reduced alfalfa yields overall as the weeds tend to take up more of the biomass (Pike & Stritzke, 1984; Temme et al., 1979). This may affect the nutritive value of hay, depending on the kind of weed present and the proportion of weed biomass in the hay. Studies have shown that weeds vary greatly in their nutritional composition (Bosworth et al., 1986; Frost et al., 2008; Khan et al., 2013). For example, Temme et al. (1979) found that weeds like *Chenopodium album* L. and *Ambrosia artemisiifolia* L. had similar or greater crude protein and digestibility to alfalfa. This tendency of some weed species to contribute to the biomass of the whole stand without significantly reducing forage nutritive value has led to arguments that it may be time to change attitude and view weeds as friends of the agroecosystem rather than as foes

(Gholamhoseini et al., 2013). While arguments like this are important for sustainable weed management, no thresholds have been established for weed biomass or compositions that optimize forage accumulation without reducing forage nutritive value. In addition, weeds from certain genera such as *Amaranthus, Chenopodium, Solanum*, etc., may accumulate compounds such as nitrates, which may be toxic to livestock if the nitrate levels exceed certain thresholds (Bolan & Kemp, 2003; Ekwealor et al., 2019). The objectives of this study were to: 1) evaluate the effect of weed control treatments on alfalfa forage accumulation, weed biomass, and nutritive value of first cutting of spring-planted alfalfa and 2) assess the relationship between the proportion of individual weed species biomass on nutritive value components and nitrate accumulation of the forage mixture.

Materials and Methods

Study #1: Forage accumulation and nutritive value as influenced by weed control treatments

Field experiments were conducted at the University of Idaho Kimberly Research and Extension Center, Kimberly, ID USA (42.549877, -114.349615) in 2021 and 2022 to evaluate the effect of weed control treatments on alfalfa forage accumulation, weed biomass, and nutritive value. The soil was a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) with 23% sand, 58% silt, and 19% clay. In both 2021 and 2022 study years, the soil had a pH of 8.0, organic matter (OM) content of 2.4 %, and a cation exchange capacity (CEC) of 19.8 meq / per 100 g soil. The average field location air temperature and relative humidity from planting to harvest in 2021 and 2022, was retrieved from the AgriMet Cooperative Agricultural Weather Network Database (https://www.usbr.gov/pn/agrimet/agrimetmap/twfida.html) and presented in Figure 3.1. Alfalfa ("WL354") was planted into a well-prepared seedbed at a rate of 22 kg ha^{-1} on April 16, 2021, and April 26, 2022, using a Great Plains 3P806NT no-till drill (Great Plains Ag, Salina, KS USA). Plots were uniformly irrigated using a sprinkler irrigation system.

These studies included eight different herbicide and herbicide combination treatments, including the untreated check. In both years, treatments were arranged in a randomized complete block design with four replications. Treatments comprised of herbicide applied pre-emergence and incorporated, early postemergence (after 80% alfalfa emergence), or postemergence (third trifoliate alfalfa) (Table 3.1). Individual plot size was 3.0 x 9.1 m. Herbicides were applied using a CO_2-pressurized bicycle sprayer delivering 144 L ha^{-1} at 207 kPa with TeeJet 11002DG nozzles and swath width of 3 m.

Weed control efficacy, herbicide injury, forage accumulation, and weed control cost

Immediately before plot harvest each year, weed control efficacy (by weed species) was visually assessed in each plot on a scale of 0 to 100%, with 0% being no weed control and 100% being complete weed control. A quadrat (0.5 m^2) was randomly placed within each plot, and aboveground biomass (alfalfa and weeds) within the quadrat area was clipped using rice knives, leaving a stubble of about 12 cm. This was hand separated into weed and alfalfa biomass to enable evaluation of alfalfa and weed contribution to total forage accumulation.

The 2021 and 2022 seedings were harvested on July 9, 2021, and July 18, 2022, respectively. A 1.5 x 7.6 m area was harvested at about 10% bloom, using a Wintersteiger Cibus F forage plot harvester (Wintersteiger AG., Ried, Austria) and fresh weight was recorded. Forage was harvested only once each year because, in newly established alfalfa, the first harvest often has the highest weed density (Renz, 2015). Subsamples were collected from the harvester, weighed, and oven-dried to a constant weight at 60 ^{o}C for 72 h to quantify dry harvestable weight and dry matter. Estimated moisture from the subsamples was used to adjust plot weights and forage accumulation was expressed in kg dry matter ha^{-1}.

Oven-dried subsamples were ground in a Wiley Mill (Model 4, Thomas Wiley, Laboratory Mill, Thomas Scientific, Swedesboro, NJ USA) to pass through a 1-mm mesh. Samples were scanned for crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) using near-infrared reflectance spectroscopy (NIRS, Foss InfraXact analyzer, Silver Spring, MD USA) that was calibrated using reference samples from wet chemistry analyses. Relative feed value (RFV) was calculated from the relation (Equation 1) (Belyea et al., 1993):

$$RFV = \frac{DDM \times DMI}{1.29} \qquad [1]$$

Where DDM = digestible dry matter and calculated from the relation: DDM= 88.9- (0.779 × %ADF), and DMI = dry matter intake, and calculated from the relation: DMI = 120/ %NDF (Belyea et al., 1993).

The DDM is an estimate of the total digestibility of the feed, and it is calculated from percent ADF. The DMI is an estimate of the amount of feed an animal will consume in percent of body weight, and this is calculated from percent NDF.

The cost of weed control programs was calculated using average unit herbicide cost from local agrochemical dealers as follows: \$14.53 L^{-1} of Eptam® 7E (*EPTC*), \$10.14 L^{-1} of Warrant® (*acetochlor*), \$154.53 L^{-1} of Raptor® (*imazamox*), and \$14.9 L^{-1} of Maestro® 2EC (*bromoxynil*).

Study #2: Relationship between selected weed species biomass contribution and overall mixed stand nutritive value

To assess the relationship between the proportion of individual weed species biomass and nutritive value of the mixed stand (alfalfa + weeds), a second field study was established in 2022. Four plots of alfalfa ("WL354", 9 x 18m) were planted into a well-prepared seedbed at a rate of 22 kg ha^{-1} on April 26, 2022, using a Great Plains 3P806NT no-till drill (Great Plains Ag, Salina, KS, USA). Each plot was considered a replicate. Plots were uniformly irrigated using a sprinkler irrigation system. No herbicide was applied in this study to permit adequate weed biomass production. On July 20, 2022, a quadrat (0.5 x 1 m) was randomly placed at 10 locations within the midportion of each strip (replicate), and aboveground biomass in the quadrat area was clipped using rice knives. Clipped samples were hand separated into alfalfa and the dominant and uniform weed species: common lambsquarters, kochia (*Bassia scoparia* (L.) Schrad.,), field bindweed (*Convolvulus arvensis* L.), shepherd's-purse (*Capsella bursa-pastoris* (L.) Medik), and green foxtail (*Setaria viridis* (L.) P. Beauv.). At sampling on July 20, 2022, alfalfa was 43±1.8 cm tall (±standard error of the mean) and 10% bloom, common lambsquarters was 73±1.8 cm tall and 15% bloom, kochia was 83±1.8 cm tall and 5% bloom, field bindweed was 27±3.2 cm tall and 5% bloom, shepherd's-purse was 58±1.2 cm tall and 95% bloom, and green foxtail was 36±2.9 cm tall and 5% bloom. Harvested samples were oven-dried and ground as previously described.

Dried and ground samples were weighed and combined for these alfalfa to weed biomass (individual weed species) proportions (% by weight): 0 : 100, 20 : 80, 40 : 60, 60 : 40, 80 : 20, and 100: 0, and sent to Ward Laboratories, Inc. (Kearney, NE USA) for wet chemistry analysis of forage nutritive value following standard forage testing procedures.

Data analysis

Study #1: Forage accumulation and nutritive value as influenced weed control treatments

All data analyses were performed in R statistical language version 4.0.2 using the *lme4, lmerTest*, and *emmeans* packages (R Core Team, 2022; Bates et al., 2015; Kuznetsova et al., 2017; Lenth, 2022). Effects of weed control treatments on alfalfa, weed and total biomass, and nutritive values of the whole stand was estimated using a mixed-effects model, herbicide treatment identified as a fixed effect, and year, year x herbicide treatment, and block as random parameters. Estimated marginal means were calculated from the model and post-hoc Tukey-adjusted pairwise treatment comparisons were performed at alpha of 0.05 using the *emmeans* and *multcomp* packages (Hothorn et al., 2008; Lenth, 2022). To evaluate the relationship between weed biomass proportion and whole stand nutritive value, linear regression analyses were performed using the *lm* function in R. In addition, polynomial regression (using the *lm* function) and non-linear regression using the *drm* function from the *drc* package (Ritz et al., 2015). The best model was selected by comparing the various models using Akaike Information Criterion (AIC) function in R. The linear regression equation for each whole stand nutritive value was obtained from the linear regression model.

Study #2: Relationship between selected weed species biomass contribution and overall mixed stand nutritive value, and nitrate concentration

The relationship between weed biomass proportion of selected weed species and forage nutritive values parameters and nitrate concentration was estimated through linear regression analyses using the *lm* function in R (R Core Team, 2022). In addition, polynomial regression (using the *lm* function) and non-linear regression using the *drm* function from the *drc* package (Ritz et al., 2015). The best model was selected by comparing the various models using Akaike Information Criterion (AIC) function in R. The linear regression equation for each weed species and whole stand nutritive value parameters (CP, ADF, NDF, TDN, and RFV) and nitrate concentration was obtained from the linear regression model.

Results and Discussion

The Kimberly, ID area is semi-arid, characterized by cold winter and spring, warm and dry summer (Figure 3.1). Production of alfalfa is heavily reliant on irrigation to supplement precipitation. Air temperatures were slightly warmer in 2021 than 2022 (Figure 1A). Although precipitation in 2022 was greater than in 2021 (Figure 3.1B), the difference in moisture was negated through irrigation.

Study #1: Weed control efficacy, alfalfa herbicide injury, forage accumulation, and weed control cost

Herbicide treatment significantly affected weed control ratings but had no impact on alfalfa injury rating (Table 3.2). The most dominant weeds were common lambsquarters > kochia > green foxtail > shepherd's-purse > redroot pigweed. The year x treatment interaction was significant for redroot pigweed control ratings because of a greater density of redroot pigweed in 2021 compared with 2022 (Table 3.2). Herbicide treatments explained more of the variance in weed control ratings compared to year or year x herbicide treatment (data not shown). The acetochlor-only treatment provided less than 50% weed control while the EPTC only treatment provided 54 to 81% weed control. The control provided by acetochlor and EPTC treatments was less than for treatments containing imazamox and imazamox plus bromoxynil (Table 3.2). Acetochlor is a preemergence herbicide that controls imbibed seeds that are germinating (Adjesiwor & Prather, 2022). Thus, delayed application (after 80% alfalfa emergence) is likely to be less effective since a significant proportion of the weeds would have germinated or emerged at the time of application. The poor weed control from acetochlor-only and EPTC-only treatments increased the amount of weed biomass in the forage at harvest (Table 3.3). Forage accumulation from the acetochlor-only treatment was comprised of 53% weed biomass which was similar to that of the untreated check (55%) (Table 3.3). Weed biomass was 23% of the forage accumulation in the EPTC-only treatment (Table 3.3). In contrast, weed biomass was less than 9% of the forage accumulation in treatments containing imazamox and imazamox plus bromoxynil (Table 3.3). Treatments containing imazamox plus bromoxynil were highly effective at controlling weeds, but they resulted in nearly 20% alfalfa injury within two weeks after application (data not shown). Although the alfalfa recovered from injury (leaf chlorosis) caused by these herbicide treatments by the time of harvest, this resulted in stunting and reduced alfalfa forage accumulation (Table 3.3). This confirms a previous observation that effective weed control may reduce forage accumulation due to alfalfa injury from herbicides and the absence of weed biomass (Moyer & Acharya, 2006). Although effective weed control was obtained at a cost of \$56 ha^{-1} by applying imazamox only (Table 3.2), this herbicide must be combined with one or more effective herbicide sites of action to reduce the chances of herbicide resistance evolution (Beckie, 2006; Kniss et al., 2022). As observed in this study, the addition of other herbicides to imazamox substantially increased the cost of weed control (Table 3.2). For example, the addition of bromoxynil increased the cost of weed control by \$USD 26 ha^{-1} while the addition of EPTC increased the cost of weed control by \$USD 51 ha^{-1} (Table 3.2).

Study #1: Whole stand nutritive value as influenced by weed control treatments and weed biomass

Herbicide treatments affected whole stand forage CP, NDF, and RFV (Table 3.3). Whole stand nutritive value was not affected by year or year x treatment interaction (Table 3.3). Herbicide treatments explained more of the variance in whole stand nutritive value compared to year or year x herbicide treatment. Poorer weed control and increased weed biomass reduced whole stand forage CP and RFV, and increased NDF. Weed biomass did not increase ADF and thus, DDM and TDN were not different among treatments (Table 3.3). The linear model of the relationship between % weed biomass and forage nutritive value showed that a percentage unit increase in weed biomass reduced forage CP by 1 g kg^{-1}, DDM by 0.34 g kg^{-1} TDN by 0.47 g kg^{-1}, and RFV by 0.58 g kg^{-1} (Figure 3.2). The reduction in DDM, TDN, RFV were due to increased ADF and NDF with increase in weed biomass (Figure 3.2). Previous studies have shown that weeds such as shepherd's-purse, green foxtail and redroot pigweed tend to have less CP concentrations compared to alfalfa (Bosworth et al., 1980; Temme et al., 1979). Thus, high density of these weeds may reduce CP of the whole stand.

Study#2: Relationship between weed biomass proportion and forage nutritive value of the artificial mixtures

From the nutritive value analyses of individual weed species, we observed that kochia and common lambsquarters had similar CP concentration as alfalfa (Figure 3.3A). Thus, increasing proportions of kochia and common lambsquarters biomass did not decrease the CP of the forage mixture. Conversely, an increasing proportion of field bindweed, shepherd's-purse, and green foxtail biomass decreased CP of the forage mixes because these species contained significantly lower CP concentration compared to alfalfa (Figure 3.3A). In a previous study, Temme et al. (1979) reported that shepherd's-purse harvested at green seed stage had 6 g kg^{-1} less CP than alfalfa at early bloom stage, and 45 g kg^{-1} less CP when shepherd's-purse was harvested at the seed stage compared to alfalfa at early bloom stage. Similarly, CP concentration in yellow foxtail (*Seteria pumila* (Poir.) Roem. & Schult), a grassy weed closely related to green foxtail, was 35 g kg^{-1} less harvested at early seed stage and alfalfa was harvested at the early bloom stage. The difference in CP concentration was 63 g kg^{-1} when yellow foxtail harvest was delayed until the seed stage (Temme et al., 1979). This suggests that delaying alfalfa harvest may result in further reduction in forage nutritive value due to faster decline in the nutritive value of some weed species.

Acid detergent fiber concentration was lower in common lambsquarters compared to alfalfa, thus increasing the proportion of common lambsquarters decreased ADF concentration of the forage mixture (Figure 3.3B). However, increasing proportions of kochia and field bindweed biomass did not affect the ADF of the forage as these weed species had similar ADF concentrations to alfalfa (Figure 3.3B). Only shepherd's-purse and green foxtail increased ADF concentration with an increasing proportion of biomass (Figure 3.3B). Kochia, common lambsquarters, and field bindweed had similar NDF concentrations as alfalfa, and therefore, increasing the biomass proportion of these weed species did not affect NDF concentration of forage mixture (Figure 3.3C). In contrast, shepherd's-purse and green foxtail contained significantly greater NDF concentrations than alfalfa and thus, increasing the biomass proportion of these weed species linearly increased NDF concentration in the forage mixture (Figure 3.3C). This was expected as weeds such as shepherd's-purse and foxtails (*Setaria* spp) have been shown to have greater fiber concentration compared to alfalfa (Cosgrove &

Barrett, 1987; Temme et al., 1979). It was reported in a previous study, grassy weeds such as foxtails can dramatically increase mixed forage NDF and thus have the most potential to reduce forage nutritive value when present in high density (Becker et al., 1998). In these instances, weed control may increase overall forage nutritive value in first harvest of the establishment year (Becker et al., 1998; Cosgrove & Barrett, 1987).

Common lambsquarters had a greater concentration of TDN than alfalfa, and therefore increasing the proportion of common lambsquarters linearly increased the TDN concentration of the mixed alfalfa forage (Figure 3.3D). Kochia and field bindweed had similar TDN concentrations as alfalfa and therefore, increasing the biomass proportion of these weed species did not affect TDN concentration of mixed alfalfa forage (Figure 3.3D). Shepherd's-purse and green foxtail on the other hand linearly decreased alfalfa TDN with increasing biomass proportions. Like TDN (Figure 3.3D), only common lambsquarters had greater RFV than alfalfa, resulting in a linear increase in RFV with increasing proportion of the mixed forage biomass (Figure 3.3E). Kochia, and field bindweed had similar RFV as alfalfa, and thus, increasing the biomass proportion of these weed species did not affect the RFV of mixed alfalfa forage (Figure 3.3E), whereas an increasing proportion of shepherd's-purse and green foxtail linearly decreased alfalfa RFV (Figure 3.3E).

Study #2: Relationship between weed biomass proportion and nitrate accumulation of the artificial mixtures

Nitrate in hay may persist after harvest and drying and can result in poisoning and mortalities in livestock (Costagliola et al., 2014). Generally, forage with nitrate concentration of 0 to 3,000 mg kg^{-1} (parts per million, on dry matter basis) is safe for cattle; 3,000 to 5,000 mg kg^{-1} is safe for non-pregnant cattle but low risk for pregnant cattle (Puschner, 2017; Strickland et al., 2017). Hay with 5,000 to 10,000 mg kg^{-1} nitrate concentration presents moderate risk of toxicity to cattle and may cause mid to late-term abortions, reduce milk production, and weak calves (Puschner, 2017; Strickland et al., 2017). Nitrate concentrations > 10,000 mg kg^{-1} is potentially toxic for all cattle, and could lead to acute toxicity, abortions, and even death (Puschner, 2017; Strickland et al., 2017). In this discussion, we chose the threshold of 3000 mg kg^{-1} because below this threshold, no health effects would be expected for any class of cattle. Above 3000 mg kg^{-1} nitrate, the forage could potentially be unsafe for some livestock.

The pure alfalfa without any weed biomass contained nitrate concentration of 1,014 mg kg^{-1}. However, common lambsquarters contained nitrate concentration of 5,700 mg kg^{-1}. Thus, the nitrate concentration of the forage mixture increased as the proportion of common lambsquarters in the mixture increased (Figure 3.4). At 60% or greater proportion of common lambsquarters biomass in the forage mixture, nitrate concentration increased above the 3,000 mg kg^{-1} threshold (Figure 3.4), presenting some toxicity risk to some classes of cattle if consumed in high quantities. Up to 15, 000 mg kg^{-1} nitrate concentration was observed in common lambsquarters in a previous study (Davison et al., 1965). Thus, under certain conditions, common lambsquarters may accumulate significantly greater amounts of nitrate. Kochia also contained nitrate concentration of 4,400 mg kg^{-1} and thus, the nitrate concentration of the forage mixture increased in proportion to the amount of kochia in the mixed forage (Figure 3.4). At more than 60% proportion of kochia biomass in the forage mixture, nitrate concentration increased above the 3,000 mg kg^{-1} threshold (Figure 3.4), which presents some toxicity risk to some livestock if consumed in high enough quantities. Shepherd's-purse had nitrate concentration of about 3,700 mg kg^{-1} and therefore, the nitrate concentration of the forage mixture increased when the proportion of Shepherd's-purse in the mixture increased (Figure 3.4). However, the nitrate concentration of the forage mixture only increased above the 3,000 mg kg^{-1} threshold when the proportion of shepherd's-purse biomass in the forage mixture exceeded 80% (Figure 3.4). Field bindweed and green foxtail had nitrate concentrations of 1,500 mg kg^{-1} and 840 mg kg^{-1}, respectively. Thus, the presence of these weeds in the forage mixture did not increase nitrate concentration to toxic levels (Figure 3.4). Although no stress conditions that would be expected to increase nitrate concentrations were observed in this study, it must be noted that conditions which may reduce plant growth (e.g., drought) can increase nitrate accumulation and the risk of livestock poisoning (Bolan & Kemp, 2003; J. O. Hall, 2018; Olson et al., 2002). Research has also shown that nitrate accumulates more in the vegetative tissue, particularly in the stems (Bedwell et al., 1995). Delaying harvest may increase stem tissue and possibly increase the nitrate concentration of the forage mixture.

Conclusions

Alfalfa hay producers who manage their fields for high nutritive value forage will benefit from the application of effective herbicides before first harvest to reduce weed competition during alfalfa establishment and the proportion of weed biomass at harvest. The effect of weeds on total forage accumulation and nutritive value is dependent on the weed species present and their proportion of the stand at harvest. Early maturing weeds like shepherd's-purse and grassy weeds such as foxtails can dramatically increase forage fiber concentration and reduce crude protein and thus, have the most potential to reduce forage nutritive value. Although weeds like common lambsquarters and kochia can add to whole stand forage accumulation without reducing forage nutritive value drastically, these weeds can accumulate significant amounts of nitrate at levels that can be toxic to livestock. Thus, it is highly recommended control these weed species in alfalfa to reduce the amount of biomass from these weed species.

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Table 3.1 Weed control treatments used in the experiments in study #1 in 2021 and 2022, Kimberly, Idaho USA.

Treatment	Rate (g ai/ha)	Commercial product
Untreated	-	-
EPTC[a]	2940	Eptam® 7E
Acetochlor[b]	1260	Warrant®
Imazamox	44	Raptor®
Imazamox[c] *+ bromoxynil*[c]	44 + 420	Raptor® + Maestro® 2EC
EPTC fb imazamox	2940 *fb* 44	Eptam® fb Raptor®
EPTC fb imazamox + bromoxynil	2940 *fb* 44 + 420	Eptam® *fb* Raptor® + Maestro® 2EC
Acetochlor fb imazamox	1260 *fb* 44	Warrant® *fb* Raptor®

[a]Applied pre-plant incorporated (with 2.5 cm of irrigation); [b]Early postemergence (80% alfalfa emergence), [c]Postemergence (3rd trifoliate alfalfa). Postemergence applications included urea ammonium nitrate (2.5 % V/V) and non-ionic surfactant (0.25 %v/v).

fb = followed by

Table 3.2. Broadleaf and grassy weed control and alfalfa injury ratings from herbicide treatments and approximate cost of herbicide programs from study#1 in 2021 and 2022, Kimberly, Idaho USA.

Factor/Treatment[a]	Common lambsquarters	Kochia	Redroot pigweed	Shepherd's -purse[c]	Green foxtail	Alfalfa injury	Cost of control
	---------- P-value ----------						
Year	0.25	0.99	0.27	-	0.16	0.23	-
Herbicide	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.18	-
Year x herbicide	0.10	0.99	**0.01**	-	0.09	0.07	-
Herbicide	---------- % ----------						USD ha^{-1}
Untreated	0 d[b]	0 e	0 c	0 d	0 c	0	0
EPTC	59 bc	59 c	66 ab	81 b	64 ab	2	50.98
Acetochlor	29 cd	33 d	43 b	48 c	43 b	1	35.58
Imazamox	84 ab	73 bc	88 a	95 ab	90 a	4	56.46
Imazamox + bromoxynil	94 a	92 a	95 a	95 ab	88 a	8	82.61
EPTC fb imazamox	91 a	83 ab	92 a	97 a	87 a	6	107.44
EPTC fb imazamox +	95 a	92 a	95 a	96 a	88 a	8	133.58
Acetochlor fb imazamox	85 ab	81 ab	88 a	93 ab	87 a	5	92.05

[a]Herbicide treatment was identified as a fixed effect, and year, year x herbicide treatment as random parameters in the data analysis.

[b]Within a column, means followed by the same letters are not different at 0.05 probability level according to Tukey's HSD.

[c]Shepherd's-purse was only evaluated in 2022 because it was not uniformly present at the study site in 2021.

Table 3.3. Forage accumulation and whole stand nutritive value (crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), total digestible nutrients (TDN), digestible dry matter (DDM), and relative feed value (RFV)) from study#1 in 2021 and 2022, Kimberly, Idaho USA.

Factor/Treatment[a]	Alfalfa	Weed (% by weight of total biomass)	Total
	---------------------- *P-values* --------------------		
Year	0.04	0.86	**0.002**
Herbicide	**0.006**	**0.04**	**0.01**
Year x herbicide	0.06	**<0.001**	0.30
Herbicide effect	---------------------kg ha^{-1}--------------------		
Untreated	1,535 c[b]	1,895 (55) a	3,430 a
EPTC	2,086 abc	624 (23) ab	2,711 ab
Acetochlor	1,640 bc	1,816 (53) a	3,456 a
Imazamox	2,381 a	115 (5) b	2,496 b
imazamox + bromoxynil	1,566 c	126 (7) b	1,692 c
EPTC fb imazamox	2,272 a	49 (2) b	2,321 bc
EPTC fb imazamox + bromoxynil	2,177 ab	178 (8) b	2,355 bc
acetochlor fb imazamox	2,254 a	107 (5) b	2,361 bc

[a]Herbicide treatment was identified as a fixed effect, and year, year x herbicide treatment as random parameters in the data analysis.

[b]Within a column, means followed by the same letters are not different at 0.05 probability level according to Tukey's HSD.

Table 3.3. Cont'd

Factor/Treatment[a]	CP	ADF	NDF	TDN	DDM	RFV
	--------------------------- *P-values* ------------------------------					
Year	0.99	0.99	0.03	0.99	0.99	0.16
Herbicide	**<0.001**	0.05	**<0.001**	0.05	0.05	**0.001**
Year x herbicide	0.58	0.99	0.99	0.99	0.99	0.99
Herbicide effect	--------------------g kg^{-1}----------------------					
Untreated	197 b	342	451 a	607	623	148 b
EPTC	237 ab	308	402 abc	643	649	172 ab
Acetochlor	199 b	332	440 ab	618	630	155 b
Imazamox	249 a	310	383 abc	641	647	182 ab
imazamox + bromoxynil	277 a	283	346 c	670	669	214 a
EPTC fb imazamox	261 a	305	368 abc	647	652	188 ab
EPTC fb imazamox + bromoxynil	271 a	293	353 bc	659	661	205 a
acetochlor fb imazamox	256 a	310	379 abc	642	648	183 ab

[a]Herbicide treatment was identified as a fixed effect, and year, year x herbicide treatment as random parameters in the data analysis.

[b]Within a column, means followed by the same letters are not different at 0.05 probability level according to Tukey's HSD.

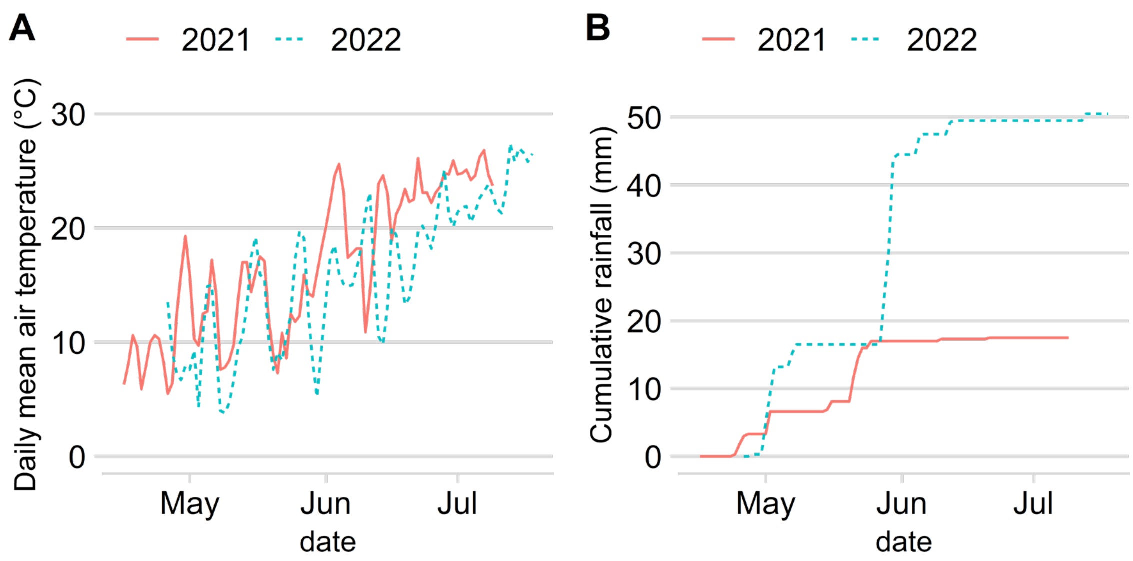

Figure 3.1. Mean daily air temperatures (A) and cumulative precipitation (B) from planting to harvest in 2021 and 2022, Kimberly, Idaho USA. Data from the AgriMet Cooperative Agricultural Weather Network Database (https://www.usbr.gov/pn/agrimet/agrimetmap/twfida.html)

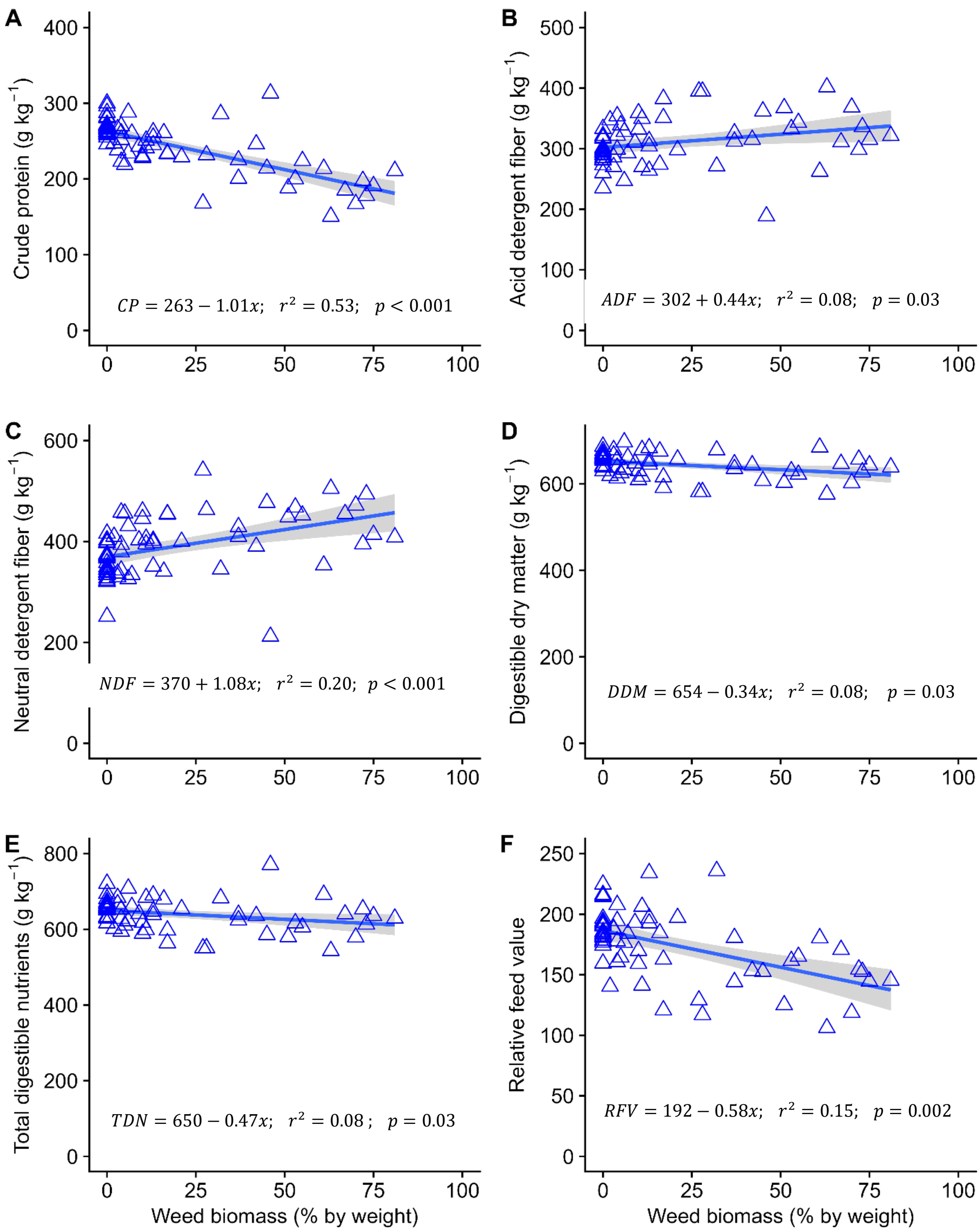

Figure 3.2. Linear relationships between weed biomass proportion (% by weight) and nutritive value of the whole stand forage at first harvest in 2021 and 2022 from study#1, Kimberly, ID USA. Shading around the regression line are the 95% confidence intervals.

Values are the means of two years, each a separate planting, and four replicates in each planting.

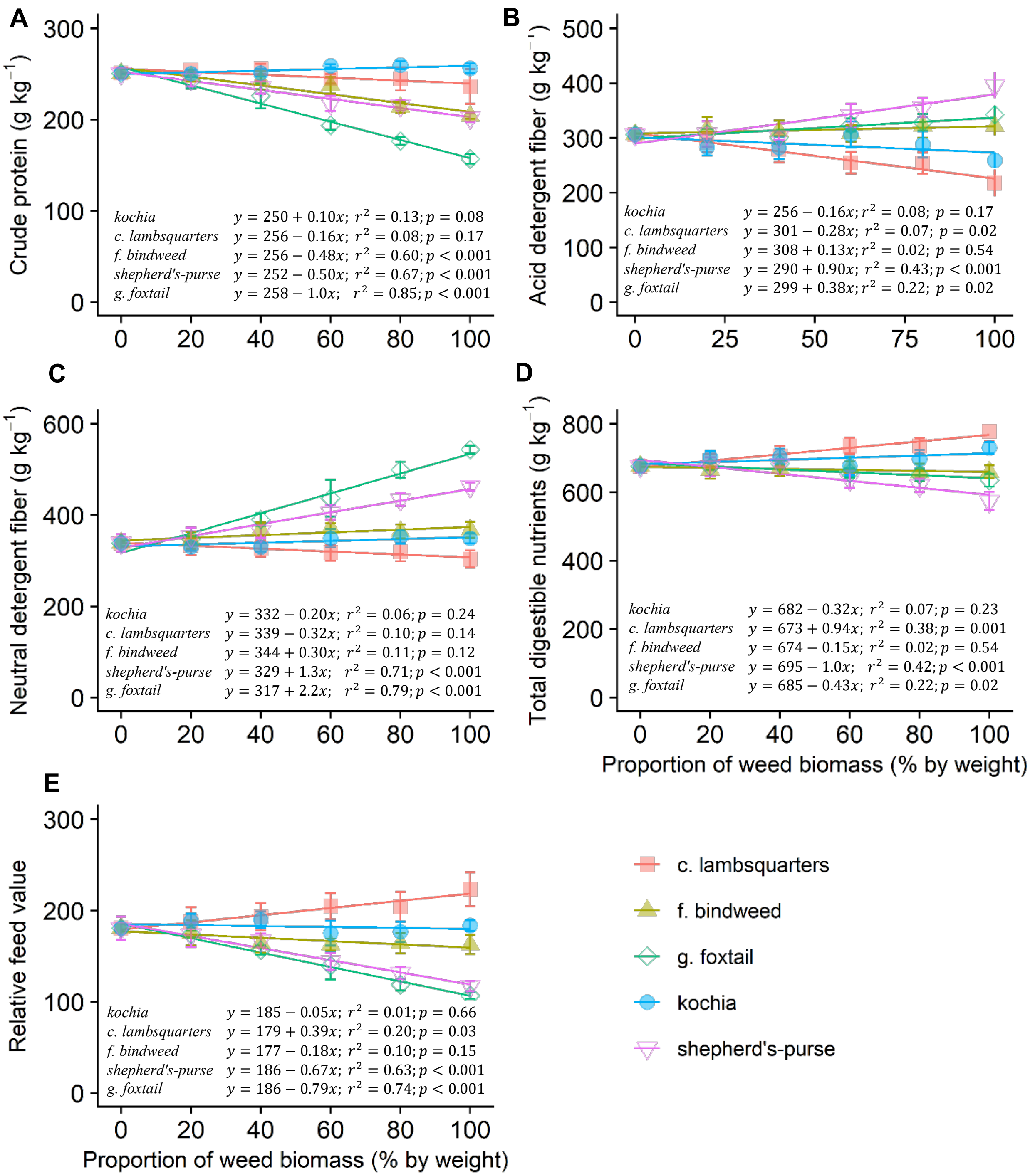

Figure 3.3. Linear relationships between the biomass proportion (% by weight) of individual weed species (kochia, common lambsquarters, field bindweed, shepherd's-purse, and green foxtail) and nutritive value of artificially created forage mixtures at first harvest in 2022 from

study#2, Kimberly, ID USA. The 0% represent the nutritive value of pure alfalfa. Each point is the mean of four replicates.

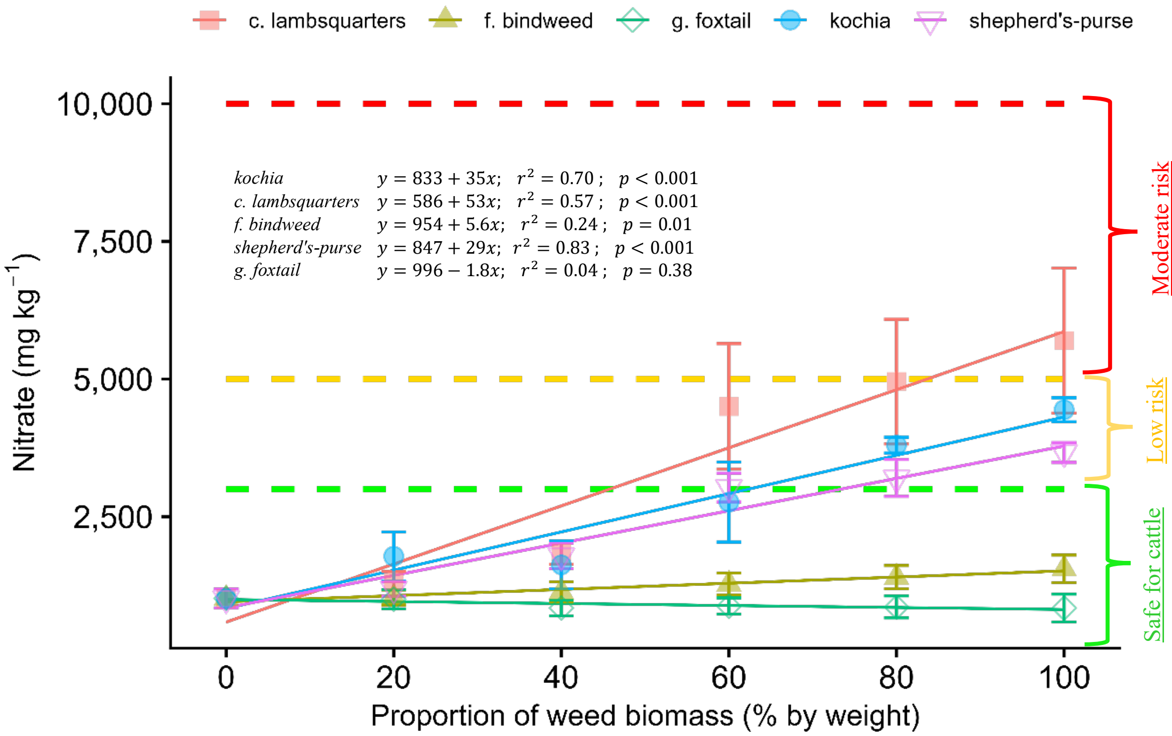

Figure 3.4. Linear relationships between the biomass proportion (% by weight) of individual weed species (kochia, common lambsquarters, field bindweed; shepherd's-purse, and green foxtail) and nitrate concentration of the artificially created forage mixtures at first harvest in 2022 from study#2, Kimberly, ID USA. The 0% represent the nitrate concentration of sole alfalfa. Each point is the mean of four replicates.

Chapter 4: Summary and Conclusions

The projects described have shown that weed management remains an important management practice in small grains and rotations crops. In Chapter 1 results showed that there are different alternatives to preplant burndown herbicides other than the normal glyphosate burndown treatments. No crop damage was observed from the herbicide treatments and none of the herbicide treatments reduced the yield of wheat and barley. Besides these two factors, the economic analysis showed that there are treatments that are comparable to glyphosate in terms of the cost of weed control. These results show that different options are available for growers to help reduce the risk of herbicide resistance.

In Chapter 2 while no significant reduction in weed seed bank density has been observed after two years, the PRE + POST herbicide treatment has the lowest seed bank density among the herbicide treatments. We have observed differences in weed density among the crop rotation which may likely impact weed seed bank density in the coming years. As stated in the study, this is an ongoing study currently in year three. The weed seedbank would most likely show reduction as the study progresses into year 3 or year 4. Overall, the current data is promising and shows that the combination of crop rotation along with herbicide treatments can control weeds, reduce weed densities, and help increase crop yields.

Having identified alfalfa as a good rotational crop to small grains, in chapter 3 we evaluated weed control within the establishment year of alfalfa to maximize weed control and reduce weed seed bank densities in subsequent crops. Alfalfa hay producers who manage their fields for high nutritive value forage will benefit from the application of effective herbicides before the first harvest to reduce weed competition during alfalfa establishment and the proportion of weed biomass at harvest. The effect of weeds on total forage accumulation and nutritive value is dependent on the weed species present and their proportion of the stand at harvest. Early maturing weeds like shepherd's-purse and grassy weeds such as foxtails can dramatically increase forage fiber concentration and reduce crude protein and thus, have the most potential to reduce forage nutritive value. Although weeds like common lambsquarters and kochia can add to whole-stand forage accumulation without reducing forage nutritive value drastically, these weeds can accumulate significant amounts of nitrate at levels that can be toxic to livestock. Thus, it is highly recommended to control these weed species in alfalfa to reduce the amount of biomass from these weed species.