SHEEP AS A POTENTIAL TOOL FOR IN-SEASON COTTON WEED MANAGEMENT

A Thesis

by

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ABSTRACT

Increased reliance on herbicides in crop production has led to many weed species becoming resistant to multiple herbicide modes of action. Sheep herbivory may be a viable alternative weed control method, as sheep have the potential to preferentially graze weeds and be averse to eating the cotton plant due to the presence and concentration of gossypol. Common weeds such as Palmer amaranth and field bindweed are major competitors with cotton plants in western Texas but are also palatable to sheep. Field research on the integration of sheep into cotton systems was performed at the Texas AgriLife extension and research center in San Angelo, Texas during the 2022 and 2023 seasons. Treatments included three different cotton growth stages to initiate grazing (4-leaf, 8-leaf, and mid-bloom) and three different levels of grazing intensity based on weed removal (approximately 70%, 90%, and 100%) with presumably greater cotton damage with increasing intensity. Treatment effects were quantified through monitoring sheep grazing activity, assessments of weed biomass removal, cotton damage, and cotton yield.

During the 4-leaf, 8-leaf, and mid-bloom initiation for both years, sheep spent 87%, 86%, and 93% of feeding time, respectively, grazing on weeds rather than cotton. Final cotton biomass was not influenced by year, intensity, or timing of treatments. Final weed biomass was affected by year ($P > 0.069$) and timing ($P > 0.036$). The year 2022 had less final weed biomass than 2023 and grazing initiated at the 4-leaf stage resulted in

greater weed biomass at the end of the growing season when compared to grazing initiated at the 8-leaf stage. This trial emphasizes the challenge of extrapolating small-scale findings to field conditions, where sheep grazing may occur at different times. While small-plot research is valuable, its limitations highlight the need for field-scale observations. Integrating sheep grazing into production systems shows promise for farmers seeking reduced herbicide/organic management, but further refinement and consideration of economic impacts are necessary. Future research may assess grazing preferences relative to sheep age and breed to provide greater insight into integrated crop-livestock management practices.

DEDICATION

To my father and mother, Chris and Nancy Stewart.

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Contributors

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NOMENCLATURE

SGM	Sheep Grazing Minutes
SGH ha^{-1}	Sheep Grazing Hours per Hectare
kg ha^{-1}	Kilograms per hectare
mm	Millimeter
m	Meter

TABLE OF CONTENTS

Page

List of Figures

LIST OF TABLES

CHAPTER I INTRODUCTION

Weed management options independent of chemical control are necessary for modern agriculture systems. An overreliance on herbicides and reduced rotation between modes of action, has resulted in resistant weeds and dwindling chemical control options (Duke 2022). Weeds are often the most limiting factor to crop yield and herbicides account for a sizable portion of a farmer’s annual budget (Green 2014). Incorporating more cultural and biological weed control methods bears potential to improve overall weed management systems, prolong the effective life of useful herbicides, and slow or inhibit further development of herbicide-resistant weeds. This project focuses on evaluating the introduction of sheep during the cotton growing season as a means of biological weed control.

In recent years, Texas has accounted for 40% of American cotton production (USDA 2022). To maintain this production status into the future, Texas cotton farmers will be combatting an increasing number of production challenges each year. Weed research is evolving to meet the needs of farmers to control their weeds. Integrated pest management (IPM) is an umbrella term for using multiple methods to control pests. The simple definition includes two parts: the use of multiple control tactics and the integration of pest biology into the management system (Buhler, 2002). Within IPM, integrated weed management (IWM) has the same principal objectives, but with the focus on weeds. By using mechanical, cultural, and biological systems along with chemical systems, herbicides will hopefully not be overused and remain effective (Moss, 2019). Common components of IWM could include prevention, crop rotation, intercropping, tillage, and cover crops (Buhler, 2002). An optimal system will require integration of multiple methods of weed control to oppose these pests (Vulchi et al. 2022)

This integrated crop-livestock system coined “sheep weeding” has sparked recent interest and experimentation among cotton farmers in west Texas; although, integrating livestock into cropping systems is not a new concept. Hatfield et al. (2005), found that sheep are useful to control weeds in Montana’s fallow wheat fields through selection of younger, greener weeds to graze rather than the wheat stubble. In 1984, sheep grazing was the most widespread biological control on dryland farms in Victoria, Australia (Amor, 1984). These sheep suppressed weeds on fallow fields and then controlled weeds as a “burndown” prior to planting. Over a 14-year period, Alves et al. (2020) studied the effect of rotation between winter pasture and summer cropping (corn or soybeans) in a no-till system. They found that the lowest intensity (lower stocking rate) rotation resulted in an increased corn yield., striking a balance between nitrogen accumulation in the soil from previous crop residue, and the addition of nutrients from sheep defecation.

Unlike the conditioned aversion method observed in some integrated systems, such as olive tree orchards utilizing sheep for undergrowth grazing and dosing livestock with lithium chloride upon ingestion of targeted species (Manuelian et al., 2010), this project relies on the natural aversion to gossypol inherent in all parts of the cotton plant (Gadelha et al., 2014). Leveraging this potential natural aversion instead of relying on conditioned aversion offers a simpler and more resource-efficient approach. The objective of this study was to assess the viability of sheep grazing as a weed control method throughout the cotton growing season, particularly for farmers interested in adopting organic or reduced herbicide systems. This work focused on the impact of initiating sheep grazing at different cotton growth stages throughout the season. Three distinct growth stages—4-leaf, 8-leaf, and mid-bloom—were selected to represent early, middle, and late initiation, respectively. Grazing was implemented at three intensities according to weed removal: 70%, 90%, and 100% (categorized as low, moderate, and high, respectively). This investigation aimed to characterize critical thresholds of cotton maturity and grazing intensity at which weed control is optimized with the least damage to the cotton crop. Additionally, the research aims to identify a threshold for weed pressure, indicating when sheep grazing transitions from consuming weeds to potentially damaging the cotton crop.

CHAPTER II

LITERATURE REVIEW

Challenges facing weed management

Herbicide resistant crops have given farmers an advantage over the natural world since their introduction. Glyphosate is the most widely used (Dayan, 2019), with 93% of soybeans and 85% of corn planted, being resistant (Green 2014). Glyphosate resistant (GR) crops give farmers the ability to spray a non-selective herbicide on top of their crops and only affect the weeds. This allows farmers to spend less time managing weeds while still achieving effective control. However, a heavy reliance on glyphosate (since the introduction of GR crops in 1996) has increased resistance due to selection pressure (Green 2014). While the advantages that herbicide technologies have are invaluable, alternatives are necessary to combat resistance. Within herbicide development, there is currently a significant need for a new mode of action to be introduced (Duke 2001). This causes a dependence on old modes of action where resistance may have already developed.

Tillage as a means for weed control is common among cotton growers. However, the side effects of tillage including damage to soil structure, compaction, and soil erosion must be considered before tilling to determine if the positives outweigh the negatives (Amanullah 2010). Usman et al. (2009) found a mixture of tillage and hand weeding was effective at controlling weeds in wheat but the increase in labor and fuel costs caused this practice to be impractical for smaller farms. Manual weeding is also more prone to human error. As laborers make their way through a field, it is likely that improper technique could damage the crop when trying to target the weeds. This results in a direct loss in yield and is difficult to fully prevent. These farmers were left with chemical control as the most affordable and practical option.

Economic opportunity in organic systems

Due to the nature of this project as a non-chemical weed management method, organic growers seem to be the most interested. Consumers are becoming more aware of their food and fiber sources and are willing to pay the organic premium for those products (Carrigan and de Pelsmacker, 2009). This has the potential to offset the increased costs of production, which is a common drawback for producers interested in making the transition from conventional to organic. Farmers with small land holdings can use organic production to make the most profit from their acreage with more reasonable and intensive management than large operations. Sizeable farms could benefit from transitioning part of their land and diversifying their markets and income streams.

As sheep graze and deposit manure into the field, it is good to consider the nutrient benefits this may have for the soil. Moreno-Caselles et al. (2007) found sheep manure to have an NPK value of 1.9-1.3-4.1 with a normal diet. This can be utilized to add nutrients and reduce the costs of fertilizer applied.

Herbivory as a potential tool

The “sheep weeding” system is based on the sheep’s natural aversion to gossypol. Gossypol is a secondary metabolite found in cotton stems, seeds, leaves, and flowers (Gadelha et. al., 2014). The proposed idea is that gossypol presence in the leaves increases as the cotton matures and therefore lessens the palatability of the cotton plant. The inherent ability of sheep to selectively graze weeds instead of cotton is key to this project having potential applications across regions. Gossypol poisoning is recorded in both monogastrics and ruminants. Symptoms include respiratory distress, impaired weight gain, anorexia, weakness, apathy, and possible death after several days of ingestion (Gadelha et. al., 2014). Heart failure was also found due to gossypol in lambs (Morgan et al. 1988)

Many weeds that negatively impact yield in cotton are also palatable to sheep, including Palmer amaranth (*Amaranthus palmeri*), field bindweed (*Convolvulus arvensis*) (Stahler et al., 1047), prostrate pigweed (*Amaranthus blitoides*), Jungle rice (*Echinochloa colona*), Johnsongrass (*Sorghum halepense*), and Italian ryegrass (*Lolium multiflorum*). These weeds have an established seedbank in our field site and have been the target weed species of sheep. Alternatively, due to toxicity risks, sheep will not graze buffalo gourd (*Cucurbita foetidissima*) (DeVeaux Shultz, 1985), Carolina horsenettle (*Solanum carolinense)* (Gorrell et al., 1981), devils' claw (*Proboscidea parviflora)*, and silverleaf nightshade (*Solanum elaeagnifolium*) (Molnar and McKenzie, 1976). Which are common in west Texas.

Endozoochorous weed seed dispersal is cause for concern with the integrated crop-livestock system. Ovesi et al., (2020) showed that after 120 hours in the digestive tract of ruminants, every weed species evaluated had a viability of 98% or higher. Field bindweed (*Convolvulus arvensis*) is a common weed in west Texas and had a viability of 100% after 120 hours inside the animal. Introducing new weeds from one field into another would be an additional management consideration for this system to limit spread. A quarantine period could be beneficial before moving sheep from field to field.

CHAPTER III

FROM PASTURE TO FIELD: INVESTIGATING THE EFFECTS OF SHEEP GRAZING ON COTTON GROWTH AND WEED SUPPRESSION

Introduction

In modern agriculture, overuse of herbicides and a lack of rotation strategies have led to the rise of herbicide-resistant weeds, diminishing the effectiveness of chemical solutions (Duke, 2022). This poses a significant challenge to crop yields, with herbicides often consuming a sizable portion of farmers' inputs (Green, 2014). To address this issue, there is a growing recognition of the need to incorporate cultural and biological weed management methods, which can not only extend the lifespan of herbicides but also mitigate the development of resistance. A pioneering initiative in this regard involves the integration of sheep into cotton farming during the growing season.

In Texas, a key player in American cotton production, maintaining productivity faces mounting challenges and weed management strategies must evolve. Integrated Pest Management (IPM), which integrates various control methods tailored to pest biology, serves as a model. Within IPM, Integrated Weed Management (IWM) shares similar goals, emphasizing diverse strategies including mechanical, cultural, biological, and chemical methods (Moss 2019; Buhler 2002). These approaches aim to prevent weed proliferation, promote crop rotation, and utilize cover crops and intercropping to maintain soil health and suppress weed growth (Vulchi et al. 2022).

The concept of "sheep weeding" has garnered interest among cotton farmers in west Texas, although livestock integration in cropping systems is not a new concept.

Research findings demonstrate the effectiveness of sheep grazing in controlling weeds, as observed in Montana where sheep grazed weeds over wheat stubble in fallow fields (Hatfield et al. 2005). In Victoria, Australia, sheep were the dominant strategy for biological weed control (Amor, 1984). Furthermore, the potential benefits of integrating sheep grazing into crop rotations include enhancing soil fertility and weed suppression (Alves et al. 2020). A low intensity stocking rate in rotation with corn showed an increase in grain yield (Alves et al. 2020).

This research aims to evaluate the viability of sheep grazing as a weed control method in cotton farming, particularly for those seeking organic or reduced herbicide approaches. Establishing a weed pressure threshold is crucial to ensuring the balance between weed control and potential damage to cotton plants. The concept revolves around the notion that as cotton matures, the amount of gossypol increases throughout the plant (Gadelha et. al., 2014), thereby reducing the plant's palatability. Central to the success of this project is the innate ability of sheep to selectively graze weeds over cotton, a characteristic that holds promise for widespread application. Gossypol poisoning poses a threat to both monogastric and ruminant animals (Gadelha et. al., 2014). Specific stages of cotton growth, the 4-leaf, 8-leaf, and mid-bloom stages, are targeted for grazing initiation. This includes two vegetative growth stages and a reproductive stage. Varied intensities of 70%, 90%, and 100% weed removal will be examined to determine optimal grazing practices.

Materials and Methods

Field research trials were coordinated in 2022 and 2023 in San Angelo, Texas at the Angelo State University Management, Instruction, and Research (MIR) center. The trial site was previously planted with sorghum-sudangrass, and the soil is an Angelo clay loam (Fine-silty, mixed, superactive, thermic, Aridic Calciustoll). This location was chosen due to its proximity to the Texas A&M AgriLife Extension center and with the unique nature of this project, it was necessary to be near the center for supplies, resources, and access to sheep pens. Sheep were transported to and from the research site every day treatments were applied. During the summer of 2022, plots measured 12.2m × 25.6m (40ft × 84ft) with a total area of 312.3 m^2. Eighteen sheep were used within each plot in 2022. In 2023, plots measured 7.9m × 12.2m (26.6ft x 40ft) with a total area of 96.4 m^2. Grazing selectivity declines with increasing sheep density per area, therefore, sheep number was reduced from 18 in 2022, to 10 sheep per plot in 2023. Treatments included a 3 × 3 factorial with three grazing initiation timings (4-leaf, 8-leaf, and mid-bloom) and three grazing termination indicators (70%, 90%, and 100% weed removal), as well as a weedy control and weed free check for a total of 11 treatments. The weedy control received no weed management practices throughout the season, and the weed-free check was controlled chemicals and hand weeding.

Cotton was planted on June 6th in 2022 and June 7th in 2023 at 92,405 seeds per hectare (37,636 seeds per acre) with a 40-inch row spacing. PHY 480 W3FE was used for the trial because it is a common cultivar grown in this region and is noted for good establishment and early vigor. There was a 3 meter (~10-foot) alley between each range in 2022 which accommodated maneuvering livestock trailers between alleys and plots to place the sheep as near as possible to the next plot. This also allowed room for the traveling irrigator to water between ranges, and providing space for sheep to move from one treatment to another. Notably, due to a reduced plot size, two ranges could now be accommodated in the same area that previously held a single range in the preceding year. This adjustment optimized space utilization while maintaining the necessary conditions for effective sheep management.

Rambouillet ewes were chosen for this project, as they represent a dominant dual-purpose (wool and meat) commercial breed in the region. The Texas A&M AgriLife center in San Angelo houses the extension sheep and goat specialist and many research projects to benefit sheep ranchers in Texas. The sheep used for this trial are from the herd maintained by faculty at the San Angelo AgriLife research center. After treatments, sheep were returned to nearby pastures to graze freely. These sheep were completely naïve to cotton at the beginning of this research project in 2022. Between the end of the 2022 research season (September 2022) to the beginning of the 2023 treatments (July 2023), sheep grazed open pasture.

Before sheep were introduced, irrigation access and fencing for each plot was constructed. To water the trial, a traveling irrigator (VCI-Mk1 Irrigator, Vaughn Irrigators, Henderson NV) with a range of nearly 110’ (depending on wind conditions) was deployed throughout the season. After each pass, the irrigator was moved to another alley and prepared to run the next day allowing for total trial coverage each week. The fencing system (Premier1 ElectroNet® (Standard, Plus & Pro) 9/35/12 Electric Netting) relied on solar powered batteries to energize the electric fences and prevent sheep from moving to different plots. Forty-four fences were installed to cover the entire trial and batteries were moved from plot to plot as needed during treatments.

During each grazing treatment, notes were taken on five-minute intervals to differentiate the number of sheep grazing weeds, grazing cotton, and how many were idle in the plot. These numbers were converted to Sheep Grazing Minutes to determine, in scalable units, a level of grazing intensity required to accomplish the same amount weed removal, and to quantify time spent grazing weeds vs. cotton. In the first and second initiation timings, sheep were grazed in the plots two or one more time, respectively, during the season for plot maintenance. SGM was recorded for these maintenance treatments as well and added to the total SGM for each plot. SGM was converted to Sheep Grazing Hours per Hectare (SGH ha^{-1}) to remove the effect of plot size. For instance, in 2022, 45 SGM were typical for both moderate and most intense grazing intensities. This translates to 24 SGH ha^{-1} in a plot covering 312 m^2. Conversely, in 2023, the same 45 SGM would equate to 72 SGH ha^{-1}, given the smaller plot size of 104 m^2.

Overhead imagery collected before and after grazing events was used to calculate weed canopy removal, cotton canopy removal, and percentage of plot area covered by weeds and/or cotton. Images were taken around noon the day before treatment and around noon on the last day of each treatment. Imagej (National Institutes of Health) software was used to analyze photos to separate green canopy from shadows and soil.

Cotton biomass was harvested on 09/30/2022 and 11/06/2023. With the severe drought that Texas experienced in both years, it was not possible to measure or analyze any lint yield data. This was likely due to insufficient irrigation in combination with extreme temperatures and drought. To measure final cotton biomass for both years, all cotton plants were harvested from a 3-m length of two center rows per plot. To measure final weed biomass for both years, all weeds (palatable and unpalatable) between the rows in the same area were collected. Samples were weighed fresh and subsamples of ~500 grams were weighed and dried to calculate biomass per hectare.

Statistical analysis

Responses underwent analysis using mixed models in SAS 9.4. While all variables were evaluated within sheep treatments, certain variables were solely assessed where non-sheep checks were irrelevant. These included SGH ha^{-1} for both weeds and cotton after each treatment, SGH ha^{-1} for weeds and cotton throughout the season, and the percentage of weed reduction attributed to sheep treatment. Conversely, other responses were examined within sheep treatments and compared to the non-sheep checks. These included weed and cotton percentage over the plot area, the percentage of canopy represented by weeds and cotton, and final weed biomass (kg ha^{-1}) and final cotton biomass (kg ha^{-1}). Among sheep treatments, fixed effects were year, grazing initiation timing, grazing intensity, and all interactions. When compared to the checks, fixed effects were year and treatment. In both cases, random effects were block nested within year, and plot range-row coordinates as covariates nested within year to best account for within-field variability among weed populations. When needed, power transformations were applied to responses according to the Box-Cox method to meet the assumptions of normality and homogenous variance (Box and Cox, 1964). Model estimates were back-transformed for presentation and interpretation. Significant differences were declared at $P < 0.1$ according to Fisher's Protected LSD.

Results

The cotton growing seasons during both years of this research trial were abnormally hot and dry. The 2022 season was one of the driest years on record, and both years had higher average monthly temperatures during summer months compared to the previous year (Figure 3.1). Notably, June 20th, 2023, a new record of 45ºC was set. 2022 experienced a 184 mm precipitation reduction compared to the 30-year average (Figure 3.2), with the growing season (June-November) experiencing a 47 mm deficit.

Sheep Grazing Behavior

The initial amount of time sheep spent grazing weeds (SGH ha^{-1}) was influenced by the year ($P = 0.0028$), cotton growth stage ($P < 0.0001$), and grazing intensity ($P = 0.0008$). In 2022, each treatment required an average of 43% fewer SGH ha^{-1} compared to 2023 (Table 3.1). The mid-bloom initiation timing necessitated 36% and 55% more SGH ha^{-1}, respectively, than the 8-leaf and 4-leaf treatments to achieve targeted weed removal

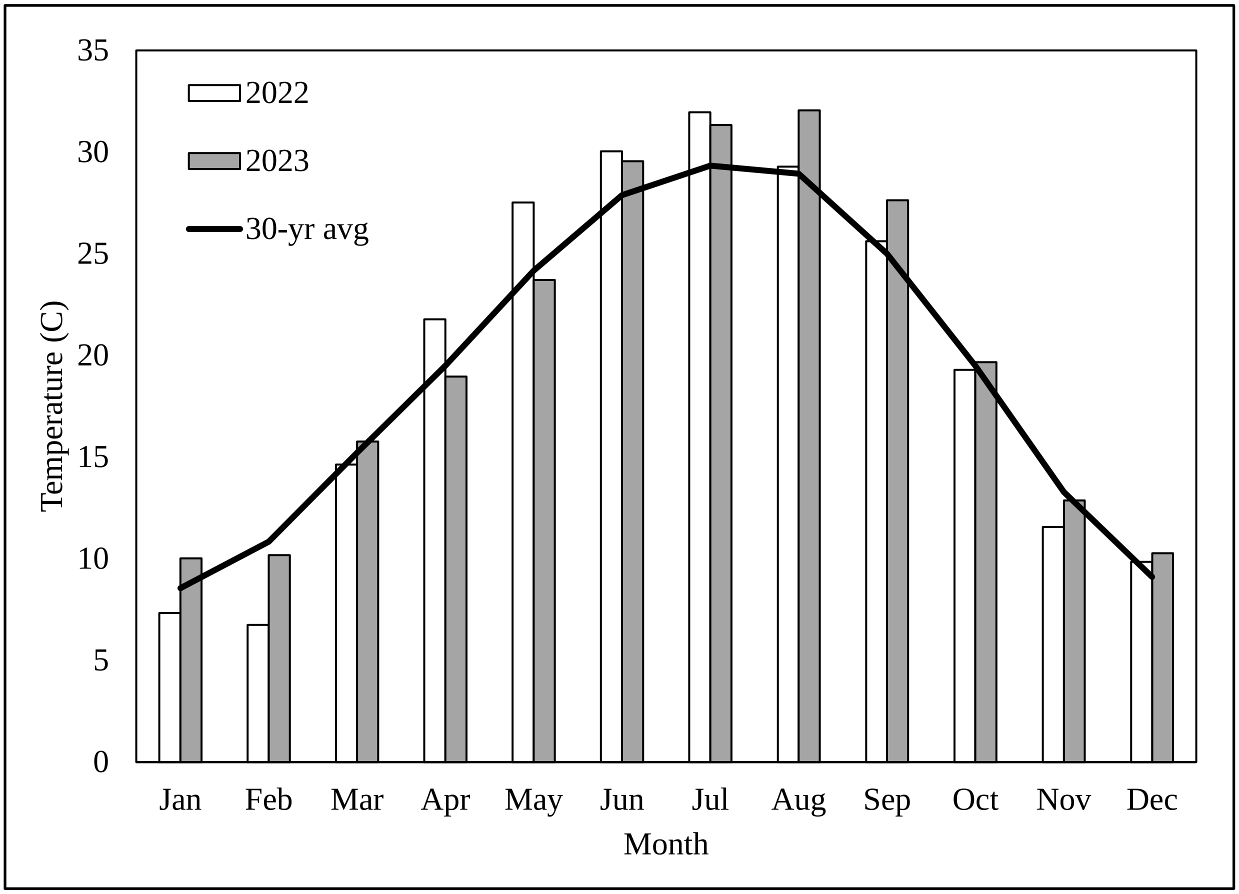

Figure 3.1 Average monthly temperature during experimental years (2022-2023) compared to the 30-yr average in San Angelo, Texas.

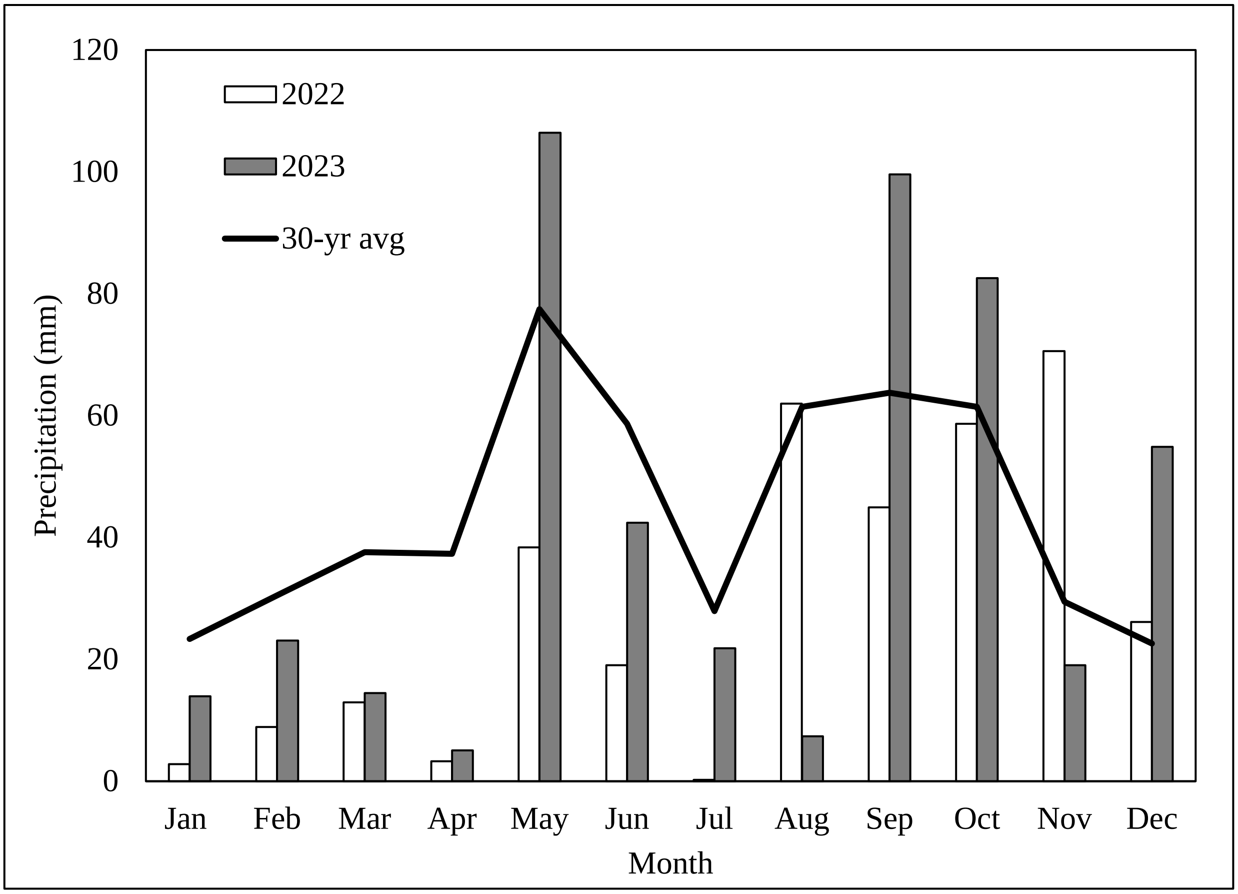

Figure 3.2 Average monthly precipitation during experimental years (2022-2023) compared to the 30-yr average in San Angelo, Texas.

(Table 3.3). Similarly, the most intense grazing required 33% and 43% more SGH ha^{-1} than the moderate and least intense treatments, respectively (Table 3.3). Initial cotton SGH ha^{-1} was affected by year (P = 0.0111) and timing by year (P = 0.036). Sheep grazed cotton 83% less in 2022 than in 2023 (Table 3.1). Initiation at the 8-leaf cotton stage resulted in 22 SGH ha^{-1} compared to the 4-leaf cotton stage with 7 SGH ha^{-1} in 2022, and time spent grazing cotton did not differ between the 4-leaf and mid-bloom stages. In 2023, the initial time spent grazing cotton was not different between cotton growth stages (Table 3.9). Initiation timing (P = 0.0021) influenced the percentage of total SGH ha^{-1} devoted to weeds rather than cotton. The relative percentage of time spent grazing weeds vs cotton was similar between the 4-leaf and 8-leaf initiation timings, but sheep did spend a greater percentage of time grazing weeds vs. cotton at the mid-bloom growth stage (Table 3.5).

Season total weed grazing time was influenced by year (P = 0.007), timing ($P <$ 0.0001), and year by intensity (P = 0.03). Achieving target herbage removal required 35% less SGH ha^{-1} in 2022 than in 2023 (Table 3.1). Grazing initiated at the 8-leaf and 4-leaf growth stages required 41% and 57% less SGH ha^{-1}, respectively, than the mid-bloom stage. The 8-leaf and 4-leaf initiation timing resulted in 41% and 57% less SGH ha^{-1}, respectively, than the mid-bloom initiation (Table 3.2). Grazing intensity did not affect total SGH ha^{-1} in 2022, however the most intense grazing required 67% more SGH ha^{-1} than the moderate intensity in 2023 (Table 3.4). Season total cotton SGH ha^{-1} was affected by year (P = 0.0002) and year by intensity (P = 0.0173). Sheep spent 76% less time grazing cotton in 2022 than in 2023 (Table 3.1). Grazing intensity did not affect SGH ha^{-1} specific to cotton grazing for 2022 (Table 3.4). In 2023, the moderate intensity experienced 38% less SGH ha^{-1} towards cotton, than the most intense grazing (Table 3.4).

The 4-leaf and 8-leaf growth stages resulted in no difference in percentage of time spent grazing weeds for both initial and season long grazing measurements (Table 3.7). Sheep spent a greater percentage of time grazing weeds vs cotton at the mid-bloom initiation timing (Table 3.7). The percentage of time grazing weeds vs. cotton was greater for both initial and season total measurements in 2022 than 2023 (Table 3.8).

Sheep Grazing Effects on Weed reduction

Weed area reduction during grazing treatments was affected by year (P = 0.010) and timing (P = 0.004). There was 15% greater weed reduction due to sheep grazing in 2023 (4% of plot area) than in 2022 (3.5%) (Table 3.8). The 4-leaf grazing initiation resulted in 8% greater weed reduction than the mid-bloom treatment (Table 3.5). There were no differences in weed reduction per plot between the mid-bloom and 8-leaf treatments (Table 3.5).

Final Biomass Measurements and Canopy Area

Among sheep-weeding treatments, the final weed area was affected by year (P = 0.047) and year by intensity (P = 0.072). In 2022, the weed percentage of plot area was 56% less than in 2023 (Figure 3.11). Grazing intensity did not affect the final weed area in 2023 (Table 3.12). In 2022, the weed area percentage in the least intense grazing was 49% more than the moderate intensity (Table 3.12). Final weed area was not different between the moderate and most intense treatments in 2022 (Table 3.12).

When compared with the checks, year (*P* = 0.047) and treatment (*P* = 0.001) affected weed percentage of plot area. Final weed area was 61% less in 2022 than in 2023 (Table 3.11). Weed area was mostly similar among treatments (Figure 3.5). Among the moderate intensities, the latest initiation had the greatest weed area coverage (18.5%). The weed-free check had the least area covered by weeds (Figure 3.5).

Timing (*P* = 0.041) affected the final cotton canopy percentage among the sheep-weeding treatments. The mid-bloom initiation (13% of plot area) resulted in 64% more cotton canopy per plot than the 4-leaf initiation (8% of plot area) (Table 3.6) Cotton area was not different between the 8-leaf initiation and the other timings. The weed-free check had the least percentage of weeds compared to all treatments except the mid-bloom initiation timing with the most intense grazing.

Among sheep treatments, year (*P* = 0.073) affected percent weed cover of total canopy vegetation. Final weed canopy was 35% less in 2022 than in 2023 (Table 3.8). Year (*P* = 0.080) and treatment (*P* = 0.017) affected weed canopy percentage when compared with the checks (Table 3.11). Many treatments were not different (Figure 3.6). However, the latest initiation with the most intense grazing resulted in 33% less canopy than the earliest initiation with the least intense grazing (Figure 3.6). The weed-free check had the least percentage of weeds compared to all treatments except the mid-bloom initiation timing with the most intense grazing (Figure 3.6)

Final weed biomass was influenced by year (*P* = 0.069), timing (*P* = 0.036), and year by intensity interactions (*P* = 0.026). 2022 resulted in 68% less final weed biomass than 2023. The 8-leaf grazing initiation resulted in 51% less weed biomass than the 4-

leaf timing (Table 3.6) Weed biomass was not different with the mid-bloom initiation timing compared to the 4-leaf and 8-leaf initiation timings (Figure 3.4). The weed-free check had less weed biomass than all treatments (Figure 3.4)

Treatment (P = 0.009) also affected weed biomass when compared with checks. Most treatments did not affect final weed biomass. However, the latest initiation timing with moderate grazing intensity resulted in 56% less biomass than the earliest initiation at the least intense grazing (Figure 3.4).

There was no sheep effect on final cotton biomass among sheep grazing treatments. There was, however, a treatment effect (P = 0.055) on final cotton biomass between sheep grazing treatments and the checks. The moderate intensity at the mid-bloom stage yielded greater cotton biomass (700 kg ha^{-1}) than the least and moderate intensities at the 4-leaf stage (277 and 208 kg ha^{-1}, respectively) and the most intense grazing at the 8-leaf stage (260 kg ha^{-1}) (Figure 3.3). The weed free check resulted in greater cotton biomass than all treatments except mid-bloom at the moderate intensity (Figure 3.3).

Table 3.1 Year effect on sheep grazing time (SGH ha^{-1}) allocated to weeds vs cotton at the initial grazing event and season total (including maintenance grazing).

Year	Weed		Cotton	
	Initial	Season	Initial	Season
2022	186b	329a	10b	19b
2023	327a	215b	60a	78a

Table 3.2 Effect of cotton growth stage on SGH ha^{-1} allocated to weeds and cotton at the initial grazing and season long grazing with maintenance included at each growth stage.

Growth Stage	Weed	
	Initial	Season
4-leaf	168c[a]	179c
8-leaf	238b	245b
Mid-bloom	373a	414a

[a] Means within the same column followed by the same letters are not significantly different at the 10% probability level.

Table 3.3 Grazing intensity effect on sheep grazing time (SGH ha^{-1}) allocated to weeds at initial grazing.

Intensity	Weed

	Initial
70%	194b[a]
90%	229b
100%	373a

[a] Means within the same column followed by the same letters are not significantly different at the 10% probability level.

Table 3.4 Grazing intensity by year effect on sheep grazing time (SGH ha^{-1}) allocated to weed vs cotton throughout the season (including maintenance).

Intensity	Season weed SGH		Season cotton SGH	
	2022	2023	2022	2023
70%	209a[a]	229b	23a	59b
90%	199a	297b	22a	69b
100%	238a	504a	14a	110a

[a] Means within the same column followed by the same letters are not significantly different at the 10% probability level.

Table 3.5 Cotton growth stage effect on percentage of sheep grazing time (SGM) weeds and weed reduction percentage.

Growth stage	Weed SGM %	Weed Reduction %[b]
4-leaf	85b[a]	3.96a

8-leaf	84b	3.45b
Mid-bloom	94a	3.67b

[a] Means within the same column followed by the same letters are not significantly different at the 10% probability level.
[b] Percent reduction of the total plot area.

Table 3.6 Effect of cotton growth stage at grazing initiation on final weed biomass and final cotton area.

Growth stage	Weed (kg ha^{-1})	Final cotton area (%)
4-leaf	330a[a]	8b
8-leaf	164b	10ab
Mid-Bloom	218ab	218ab

[a] Means within the same column followed by the same letters are not significantly different at the 10% probability level.

Table 3.7 Effect of growth stage on percentage of sheep grazing time (SGH ha^{-1}) eating weeds for initial and season measurements.

Growth stage	Weed SGH%	
	Initial	Season

4-leaf	87b[a]	82b
8-leaf	86b	81b
Mid-bloom	93a	91a

[a] Means within the same column followed by the same letters are not significantly different at the 10% probability level.

Table 3.8 Year effect on initial and season total sheep grazing time (SGM) percentage associated with weeds, weed reduction between both years, and percentage of final canopy consisting of weeds.

Year	Weed SGM%		Weed reduction %	Weed percentage of canopy
	Initial	Season		
2022	87b	82b	3.5b	39b
2023	86b	81b	4a	60a

Table 3.9 Cotton growth stage effect on sheep grazing time (SGH ha^{-1}) among the two different growing seasons.

Growth stage	Cotton SGH
	Year

	2022	2023
4-leaf	7b[a]	73a
8-leaf	22a	59a
Mid-bloom	5b	50a

[a] Means within the same column followed by the same letters are not significantly different at the 10% probability level.

Table 3.11 Year effect on weed percentage of area and weed percentage of canopy.

Year	Weed percentage of area	Weed percentage of canopy
2022	7.5b	39b
2023	16.4a	60a

Table 3.12 Grazing intensity effect on weed percentage of plot area at harvest among the two different growing seasons.

Intensity	Weed percentage of plot area

	Year	
	2022	2023
70%	10.4a[a]	16.6a
90%	6.9b	14.8a
100%	5.6b	18a

[a] Means within the same column followed by the same letters are not significantly different at the 10% probability level.

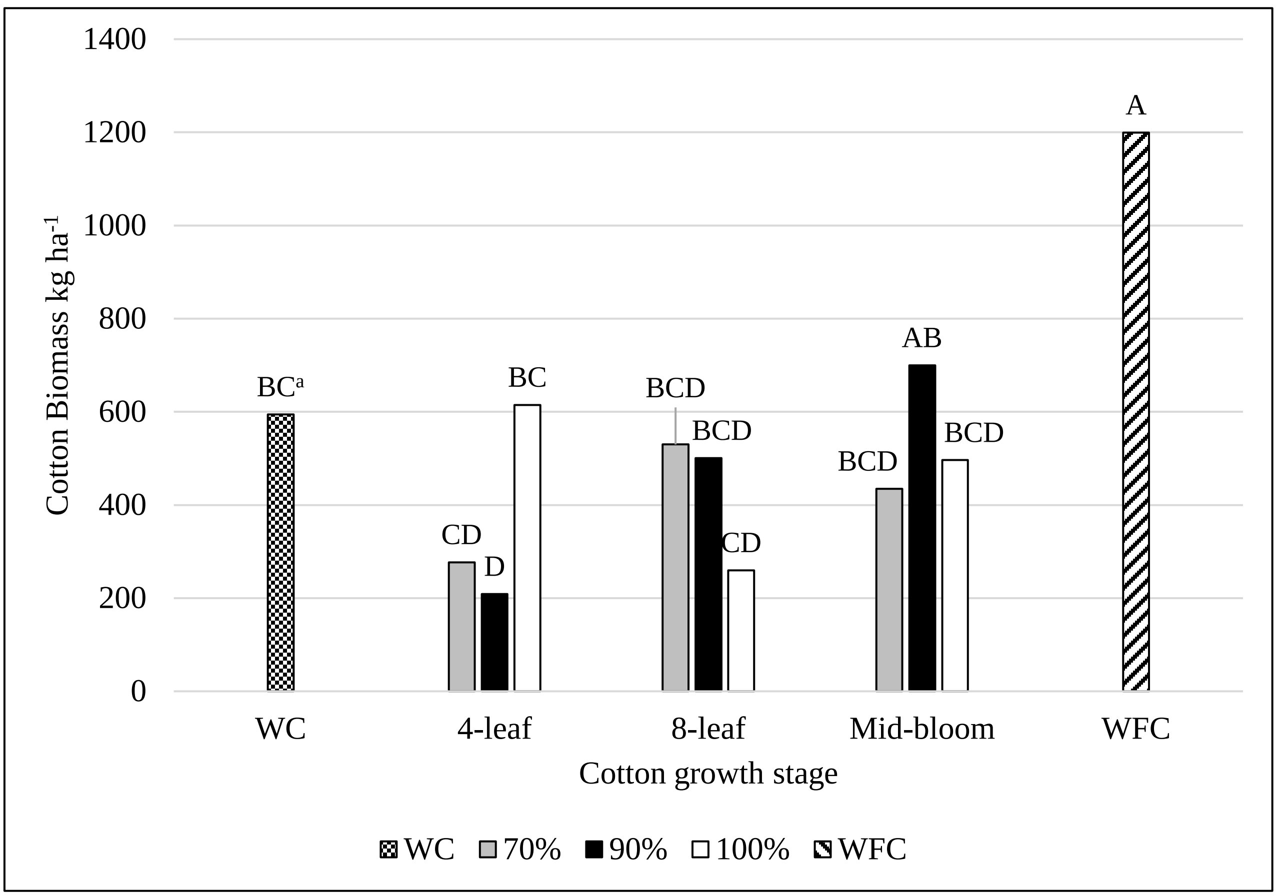

Figure 3.3 Sheep grazing treatment effect on final cotton biomass in San Angelo, TX (2022-2023).
[a] Bars with the same letters are not different (P > 0.1).

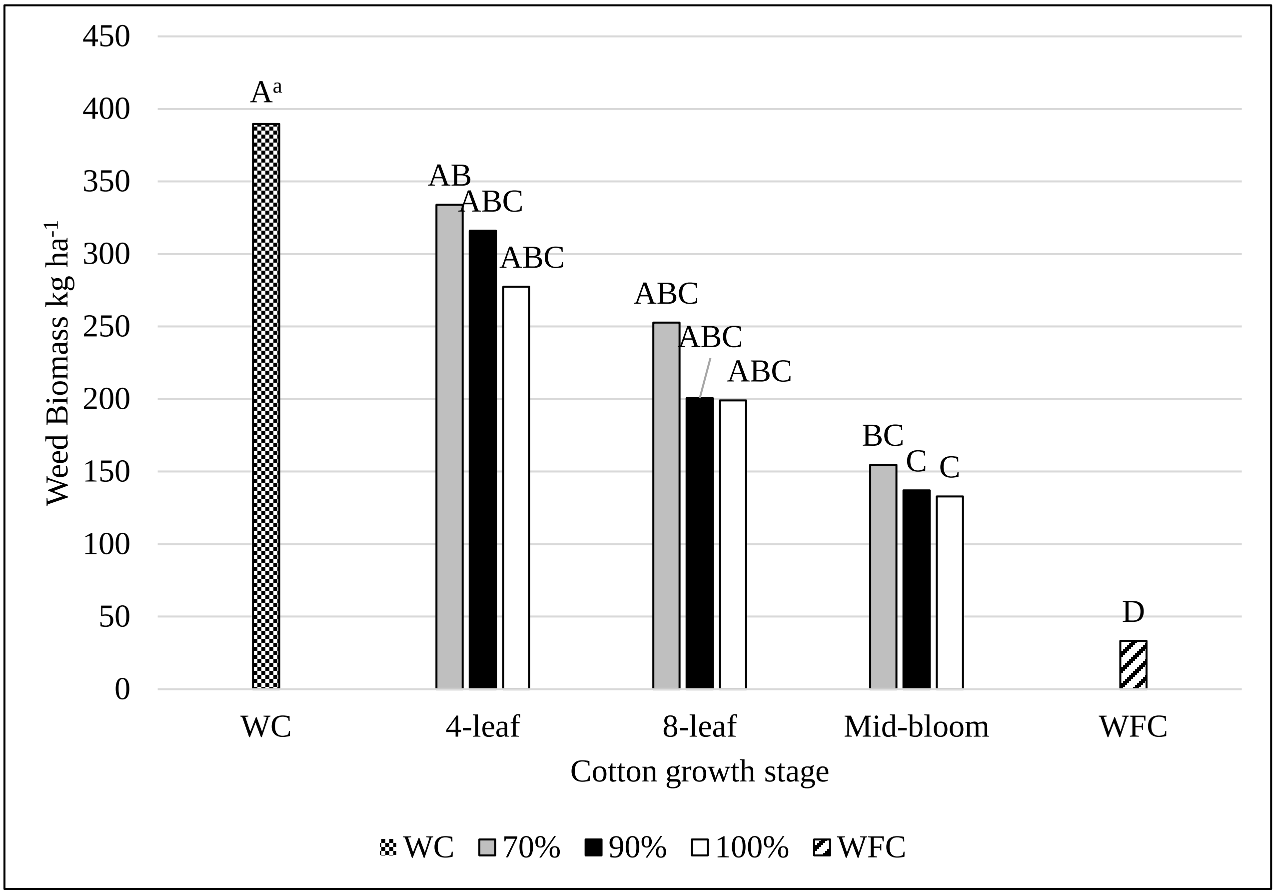

Figure 3.4 Sheep grazing treatment effect on final weed biomass in San Angelo, TX (2022-2023).
[a] Bars with the same letters are not different (P > 0.1).

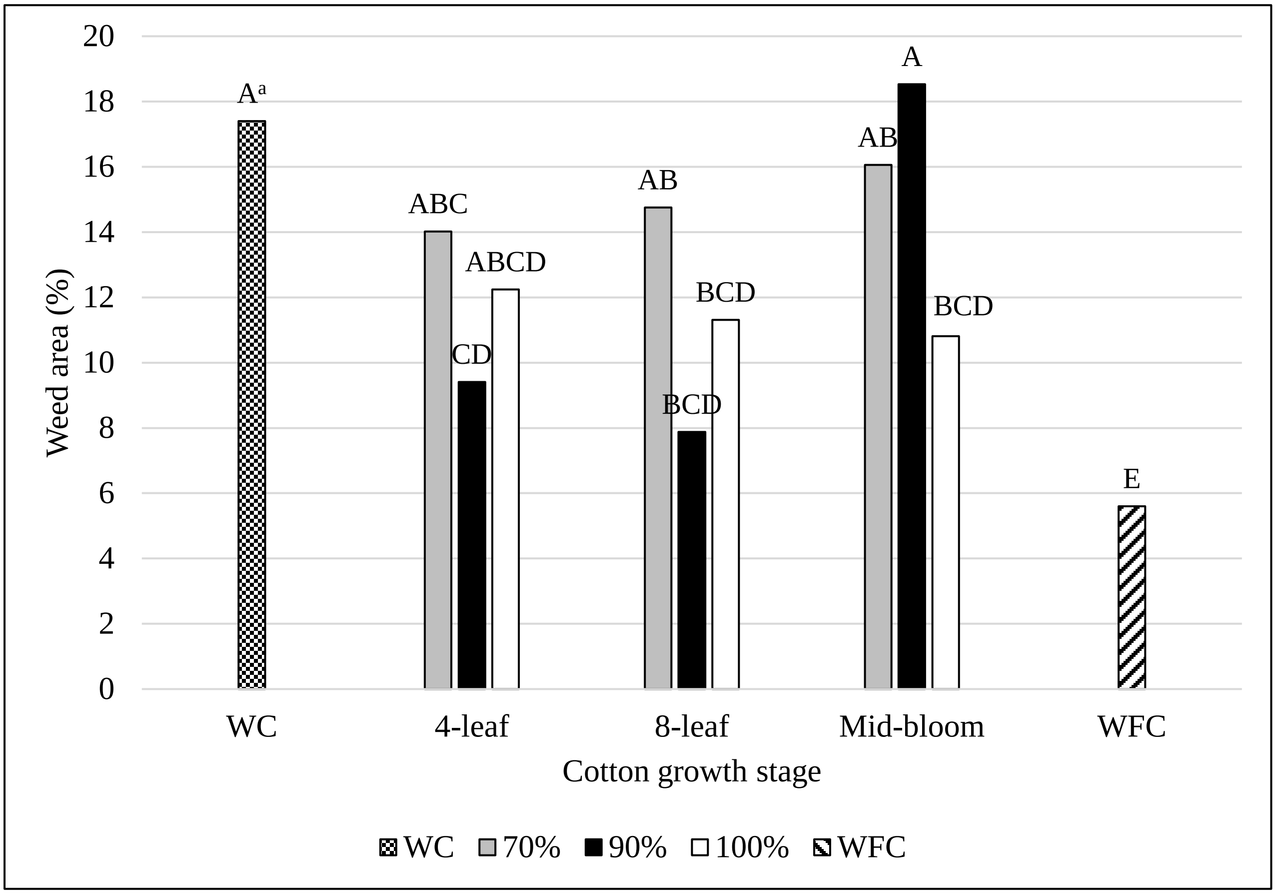

Figure 3.5 Sheep grazing treatment effect on percentage of plot area covered by weeds in San Angelo, TX (2022-2023).

[a]Bars with the same letters are not different ($P > 0.1$).

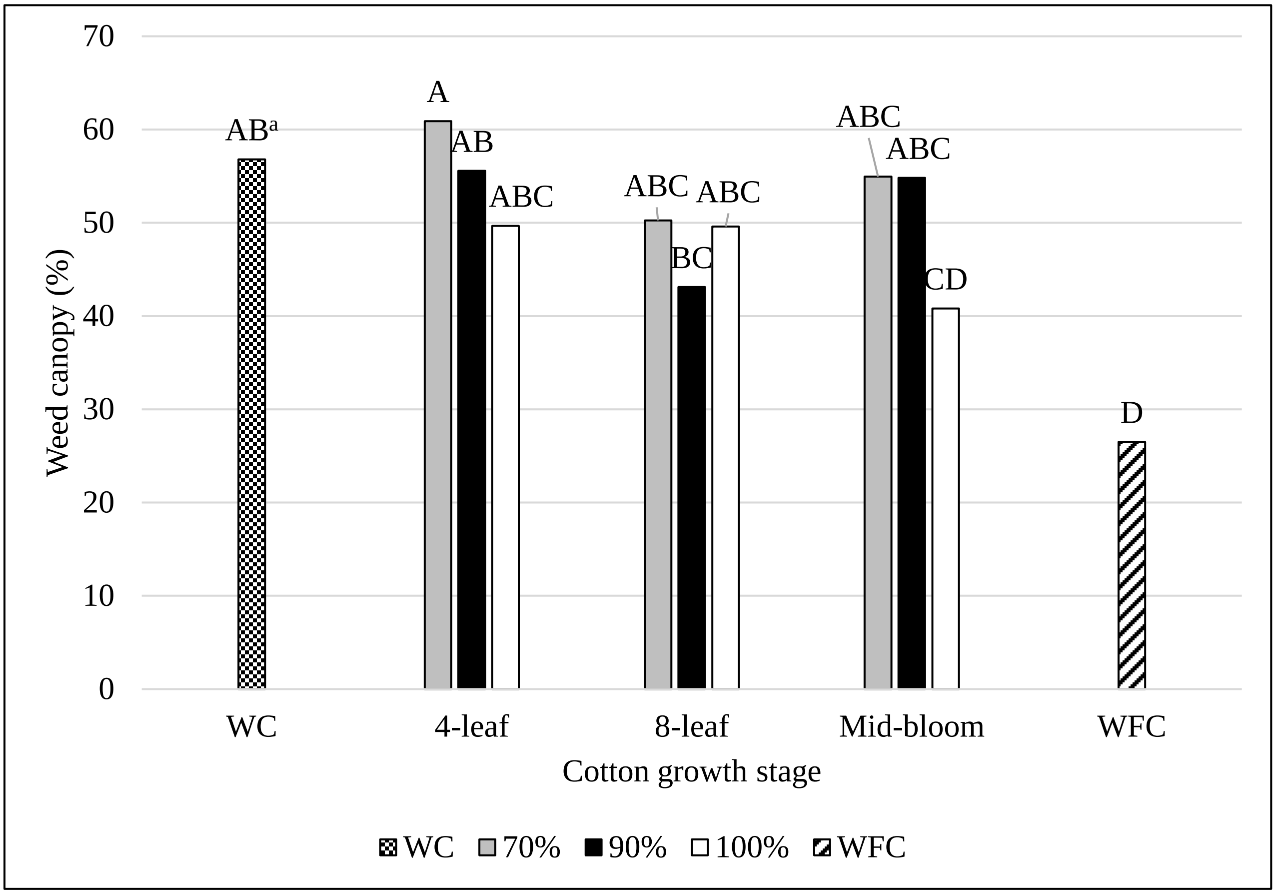

Figure 3.6 Sheep grazing treatment effect on percentage of total canopy consisting of weeds in San Angelo, TX (2022-2023).

[a] Bars with the same letters are not different (*P* > 0.1).

Discussion

The findings of this experiment, influenced by drought and high temperatures in both years, provide valuable insights into the complexities of integrated crop-livestock systems within controlled small-plot research settings. While irrigation sustained measurable crop and weed growth, the suboptimal environmental conditions hindered cotton development and lint yield. The observed impact of weather on sheep activity within the plot underscores a critical limitation of small-plot research in fully capturing real-world agricultural dynamics. As the season progressed, the escalating weed density necessitated increased grazing time, exacerbated by the sheep's slower grazing pace and prolonged resting periods in response to elevated temperatures as observed in previous studies (Thomas 2008).

With the basis of the process being a natural aversion to cotton plants due to the presence of gossypol rather than a condition aversion, greater selectivity towards weeds as opposed to cotton was studied. Final weed biomass at mid-bloom initiation with moderate and most intensive grazing was significantly different than the least intense grazing at the 4-leaf stage (Figure 3.4). While cotton biomass was similar among many treatments, this finding supports a natural selectivity towards the weeds.

The initiation timings of 4-leaf, 8-leaf, and mid-bloom growth stages were chosen to establish thresholds of when is “too early” and when is “too late”. The 4-leaf stage showed little selectivity between weeds and cotton (Figure 3.7). As a result, the 4-leaf stage at moderate intensity had greater cotton removal when compared to the moderate intensity at mid-bloom.

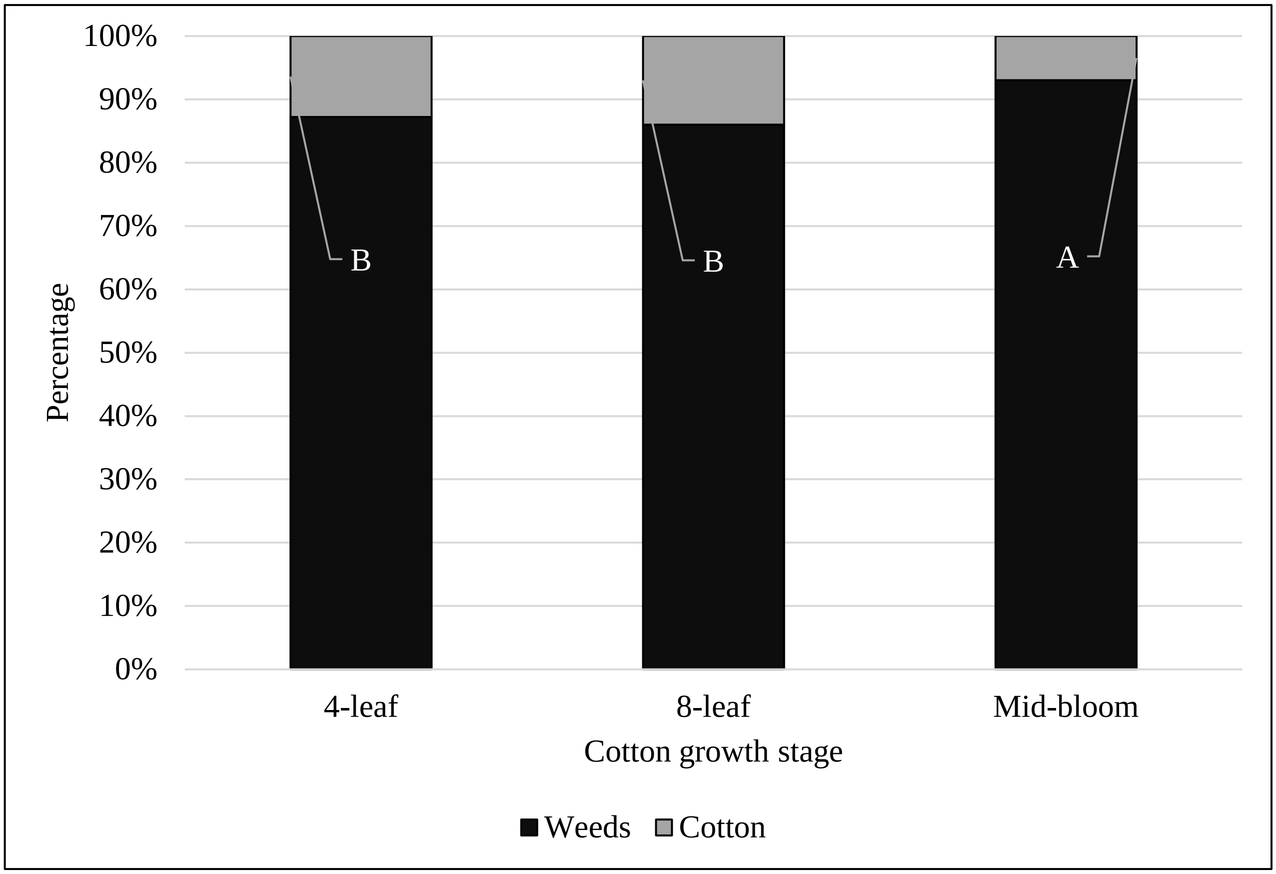

Figure 3.7 Change in sheep selectivity towards weeds vs cotton throughout at each growth stage.

[a] Calculated from SGM.

Figure 3.8 Mature Palmer amaranth stripped of leaves and seeds after treatment.

Figure 3.9 Weed population difference between grazed (right) and non-grazed(left) plot in 2022.

Xi-feng (2012) states that the critical weed free period in cotton is 4-8 weeks after planting. By the time the mid-bloom plots will receive treatments (~2.5-3 months after planting) weeds have already influenced yield and a sheep weeding treatment may only carry risk towards the cotton crop.

Animut et al. (2005), found that increased stocking rate and smaller areas resulted in reduced selectivity among forage. This was the reason for the stocking rate reduction when plot size decreased. Initial protocol was to regulate grazing intensity by releasing a different stocking rate per plot with the least, moderate, and most intense receiving 3, 6, and 9 sheep, respectively. The gregarious habits of sheep were evident as they jumped and ran over fences to socialize with others in adjacent plots. To solve this issue, a set number of sheep were placed in each plot at each intensity. Then, as they grazed, observed visual differences were used to determine sufficient weed removal at each intensity.

A common inquiry into the application of this system is the necessary stocking rate. This number is currently unavailable as the weed density per plot is susceptible to change. For this system to be successful, it will require management while the sheep are in the field to prevent outstanding cotton damage if weeds are not prevalent, and they transition to grazing cotton. Ideally in a field setting, sheep would have the ability to come and go throughout the field as desired with access to water and hay.

The increase in cotton consumption relative to weeds during treatments in 2023 suggests a notable shift in grazing behavior, potentially influenced by favorable weather conditions and the emergence of new growth. The absence of direct contact between sheep and cotton outside of the growing season highlights the significance of seasonal dynamics in grazing behavior. The lack of exposure to cotton plants outside of the designated grazing periods suggests that sheep may exhibit an increased affinity for cotton after exposure in the previous year. This hypothesis aligns with the documented preference of herbivores, such as sheep, towards actively growing vegetation, which may have contributed to the observed increase in cotton consumption.

As selectivity towards weeds increases throughout the season, this could be beneficial for targeting late season weed escapes (Figure 3.7). Seed rain from these plants leads to persistence and increased weed seedbank numbers. Werner et al (2020), reported Palmer amaranth (*Amaranthus palmeri*) could deposit 13.9 million seeds ha^{-1} in a field with 5.1-8.1% infestation. Palmer amaranth is the most prevalent late season weed escape (Werner 2020) and is also palatable to sheep (Figure 3.8). An integrated system could benefit a conventional herbicide program where sheep can be used to target late season weed escapes and reduce seed rain.

Conclusion

Results of the study demonstrate the potential for sheep grazing treatments in mitigating weed growth, as evidenced by reductions in final weed biomass observed across both years. The nuanced influence of timing and intensity of grazing on weed management outcomes highlights the importance of careful consideration of these factors to optimize weed control efficacy. Sheep as a sole method of weed control may not be advised at this point.

However, the study also revealed challenges and limitations associated with sheep grazing as a weed management approach. Variability in weed reduction outcomes across different treatments and growing seasons suggests the need for further refinement of grazing strategies. While sheep grazing presents promising prospects for weed reduction, further research is needed to address potential trade-offs with crop productivity and improve grazing strategies. Integration with conventional systems may offer a smoother transition and benefit producers with access to sheep.

CHAPTER IV

CONCLUSIONS

This trial highlights a fundamental challenge: extrapolating findings from small-scale experiments to the field scale, where sheep could potentially graze earlier in the mornings and later in the evenings. The discrepancy between experimental conditions and real-world scenarios requires cautious interpretation of results and prompts speculation about potential outcomes on a broader scale. While small-plot research serves as a valuable tool for hypothesis testing and preliminary investigations, its inherent limitations reveal the importance of complementing such studies with field-scale observations and experiments to provide a more comprehensive understanding of this dynamic system.

Results of this study indicate that integrating sheep grazing into production systems could be a potential tool to help farmers interested in reduced herbicide/organic weed management practices. Further refinements of grazing intensities and timings as well as an analysis of the farmers' needs is necessary when considering adoption. This research identifies that there is greater selectivity towards weeds as cotton matures. With that being the case, there is still more to understand about how to best coordinate this system so that weed removal is achieved while minimizing cotton damage.

Economic impacts outside of weed management should also be considered with this project. If farmers currently own sheep, adoption of this program may be more feasible than a farmer who does not raise sheep. The possibility of renting or buying sheep will have to be weighed against the benefits they could experience. This should be determined in a specific case by case basis rather than a general application so that unnecessary changes are made that could cost the farmer if this program is not the best fit for their operation.

Future research will explore variations of this project. Difference in cotton varieties (Pima and upland) may shed light on the sheep's response to lower gossypol concentrations. Studying lamb vs ewes could capitalize on the greater toxicity towards lambs and if that plays a role in even greater weed removal rather than cotton. During this research only one sheep breed was used for both years. Trials will also analyze differences of breeds to compare grazing habits and preferences. Both studies will help to advance the development of integrated crop-livestock systems.

REFERENCES

Animut, G., Goetsch, A., Aiken, G., Puchała, R., Detweiler, G., Krehbiel, C., Merkel, R., Sahlu, T., Dawson, L., Johnson, Z., & Gipson, T. (2005). Performance and forage selectivity of sheep and goats co-grazing grass/forb pastures at three stocking rates. *Small Ruminant Research*, 59, 203-215. https://doi.org/10.1016/J.SMALLRUMRES.2005.05.015.

Amanullah, M. M., Srikanth, M., & Muthukrishnan, P. (2010). Soil compaction and deep tillage–A REVIEW. *Agricultural Reviews*, *31*(2), 105-112.

Amor. R. L. (1987). Non-chemical weed control in Victorian dryland crops-the dream and the reality. Proc.: Aust. Weeds Conf. 8:24-26.

Box, G. E., & Cox, D. R. (1964). An analysis of transformations. *Journal of the Royal Statistical Society Series B: Statistical Methodology*, *26*(2), 211-243.

Buhler, D. D. (2002). 50th Anniversary—Invited Article: Challenges and opportunities for integrated weed management. *Weed Science*, *50*(3), 273-280.

Carrigan, M., & De Pelsmacker, P. (2009). Will ethical consumers sustain their values in the global credit crunch?. *International Marketing Review*, *26*(6), 674-687.

DeVeaux, J. S., & Shultz, E. B. (1985). Development of buffalo gourd (Cucurbita foetidissima) as a semiaridland starch and oil crop. *Economic Botany*, *39*(4), 454-472.

Duke, S. O. (2012). Why have no new herbicide modes of action appeared in recent years?. *Pest management science*, *68*(4), 505-512.

Duke, S. O., & Dayan, F. E. (2022). The search for new herbicide mechanisms of action: Is there a ‘holy grail’?. *Pest Management Science*, *78*(4), 1303-1313.

Gadelha, I. C. N., Fonseca, N. B. S., Oloris, S. C. S., Melo, M. M., & Soto-Blanco, B. (2014). Gossypol toxicity from cottonseed products. In *Scientific World Journal* (Vol. 2014). The Scientific World Journal. https://doi.org/10.1155/2014/231635

Gorrell, R. M., Bingham, S. W., & Foy, C. L. (1981). Control of Horsenettle (Solarium carolinense) Fleshy Roots in Pastures. *Weed Science, 29*(5), 586-589.

Green, J. M. (2014). Current state of herbicides in herbicide-resistant crops. *Pest Management Science*, *70*(9), 1351-1357.

Hatfield, P. G., Lenssen, A. W., Spezzano, T. M., Blodgett, S. L., Goosey, H. B., Kott, R. W., & Marlow, C. B. (2007). Incorporating sheep into dryland grain production systems: II. Impact on changes in biomass and weed density. *Small Ruminant Research, 67*(2-3), 216-221.

Lucas Aquino Alves, Luiz Gustavo de Oliveira Denardin, Amanda Posselt Martins, Cimélio Bayer, Murilo Gomes Veloso, Carolina Bremm, Paulo César de Faccio Carvalho, Debora Rubin Machado, Tales Tiecher (2020). The effect of crop rotation and sheep grazing management on plant production and soil C and N stocks in a long-term integrated crop-livestock system in Southern Brazil. Soil and Tillage Research, 203.

Manuelian, C., Albanell, E., Salama, A., & Caja, G. (2010). Conditioned aversion to olive tree leaves (Olea europaea L.) in goats and sheep. *Applied Animal Behaviour Science,* 128, 45-49. https://doi.org/10.1016/J.APPLANIM.2010.09.011.

Molnar, V. M., and D. N. McKenzie. 1976. Progress report on silverleaf nightshade research. Pamphlet No. 61. Vermin and Noxious Weeds Destruction Board, Dept. of Crown Lands and Survey, Victoria, Australia.

Moreno-Caselles, J., Moral, R., Perez-Murcia, M., Perez-Espinosa, A., & Rufete, B. (2002). Nutrient value of animal manures in front of environmental hazards. *Communications in Soil Science and Plant Analysis*, *33*(15-18), 3023-3032.

Morgan, S., Stair, E. L., Martin, T., Edwards, W. C., & Morgan, G. L. (1988). Clinical, clinicopathologic, pathologic, and toxicologic alterations associated with gossypol toxicosis in feeder lambs. *American journal of veterinary research*, *49*(4), 493-499.

Oveisi, M., Ojaghi, A., Rahimian Mashhadi, H., Müller-Schärer, H., Reza Yazdi, K., Pourmorad Kaleibar, B., & Soltani, E. (2021). Potential for endozoochorous seed dispersal by sheep and goats: Risk of weed seed transport via animal faeces. *Weed Research*, *61*(1), 1-12.

Stahler,L. M.and Carlson,A. E., 19471901505, English, Journal article, 39, Journal of the American Society of Agronomy, (56–64), Controlling field bindweed by grazing with sheep.

Thomas, D., Wilmot, M., Alchin, M., & Masters, D. (2008). Preliminary indications that Merino sheep graze different areas on cooler days in the Southern Rangelands of Western Australia. *Animal Production Science*, 48, 889-892. https://doi.org/10.1071/EA08061.

USDA ERS - Cotton Sector at a Glance. (2023, October 11). https://www.ers.usda.gov/topics/crops/cotton-and-wool/cotton-sector-at-a-glance/

Usman, K., & Khan, M. A. (2009). Economic evaluation of weed management through tillage, herbicides and hand weeding in irrigated wheat. *Pakistan Journal of Weed Science Research*, *15*(4).

Vulchi, R., Bagavathiannan, M., & Nolte, S. A. (2022). History of herbicide-resistant traits in cotton in the US and the importance of integrated weed management for technology stewardship. *Plants*, *11*(9), 1189.

Xi-feng, L. (2012). Mixed Weeds and Competition with Directly Seeded Cotton,North Henan Province,China. *Cotton Science*.