THE IMPACT OF EQUIPMENT AND METHODOLOGY ON HERBICIDE EFFICACY FOR CONTROLLING SMUTGRASS (*SPOROBOLUS INDICUS VAR. INDICUS)*

A Thesis

by

MASON TRANT HOUSE

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Chair of Committee,	Scott Nolte
Committee Members,	Steve Hague
	Chris Skaggs
Head of Department,	David Baltensperger

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ABSTRACT

Smutgrass (*Sporobolus indicus*) is an aggressive, perennial bunchgrass that invades introduced and native pastures primarily in the southeastern part of the United States. It is problematic to agriculture in range and pasture and is not usually found in row crops. Smutgrass' prolific seed production allows it to overpower desirable grasses by simply outnumbering them, and its size allows it to outcompete for sunlight. It invades grazed pastures and hay fields making the land difficult to traverse for humans, equipment, and for the animals inhabiting the land. Smutgrass is also undesirable as a food source for cattle. The broad range of variables involved in herbicide applications can make achieving effective weed control challenging. These include application timing, equipment, methodology, weather and many other factors. The impact of these variables has been researched extensively on several weed species; however, no research has been published evaluating application equipment type and the methodology to determine if it can impact herbicide efficacy in smutgrass. There are four primary objectives of this research endeavor. First, determine which herbicides are most effective on smutgrass in individual plant treatments. Second, determine if the inclusion of a pre-emergent, residual herbicide with common post-emergent treatments can increase smutgrass control. Third, determine if nozzle type will impact the efficacy of herbicides in broadcast smutgrass control. Lastly, determine whether different methods of individual plant treatment impact the efficacy of herbicides, including aerial application, foliar ground-based and post-directed ground-based application. Individual plant applications of various rates of glyphosate, liquid hexazinone, solid hexazinone and glyphosate + imazapic, at all rates used, provided 100% control of smutgrass within thirty days and continued to cause complete necrosis to ninety days. Liquid hexazinone treatments, half hexazinone tablets and the low rate of glyphosate alone tended to be the safest to the desirable grasses, recovering to 100% by the end of the study. The bermudagrass treated with the middle

rate of glyphosate and low rate of glyphosate + imazapic was highly variable in recovery, with both having 30% or more difference in recovery between locations after ninety days, the high rate of glyphosate recovered poorly to 25-50% and middle and high rate of glyphosate + imazapic were highly injurious and bermudagrass recovered to a maximum of 55%, and a minimum of 0%. Including indaziflam as a pre-emergent following a post-emergent herbicide did not cause a significant difference in the number of newly emerged seedlings. Prior to the indaziflam applications, three treatments received labeled rates of hexazinone, and one received glyphosate. Glyphosate reliably controlled the smutgrass in both years while also causing severe damage to desirable grasses, only being tolerated by 3% of desirable grass in the plots four weeks after application. However, the desirable grass recovered to 53-75% by 18 weeks after PRE-applications. Hexazinone applications failed to adequately control smutgrass the first year, concluding at 25% control, while providing 96-100% control the second year. However, the desirable grasses at both locations fully recovered in both years by 18 weeks after PRE applications. When evaluating control by nozzle selection, there was no significant difference within herbicides by nozzle selection in this research. However, this study showed that an application of glyphosate three to four weeks before an application of hexazinone significantly increased smutgrass control at 98%, compared to hexazinone alone at 89-90% control. Glyphosate followed by hexazinone (59-60%) was significantly more injurious to desirable grasses than hexazinone alone (84-85%) at 40 weeks. By 46 weeks, glyphosate followed by hexazinone recovered to 76-79% and was not significantly different than hexazinone alone (87-88%) at the conclusion of the study. When applying hexazinone to individual plant treatments, targeting the foliage caused 100% necrosis in all plants by thirty days and continued to 240 days, but applying hexazinone post-direct did not cause 100% necrosis until springtime, 240 days after treatment. Applying post-direct to target the smutgrass roots also caused significantly more

damage to desirable grasses around the plant (37% tolerance) at 75 days compared to foliar application (84% tolerance). Both methods recovered to 100% bermudagrass tolerance by 240 days. Lastly, when applied as individual plant treatments, hexazinone and glyphosate + hexazinone provided similar levels of smutgrass control regardless of whether applied from the ground or the air. Hexazinone applied alone to smutgrass resulted in NDVI readings of 32-22 and 91-94% control, while desirable grass tolerance was 93-95% and significantly better than any other herbicide and not significantly different than the untreated check. Smutgrass treated with Glyphosate + hexazinone had NDVI readings of 16-30 and provided 94-100% control with a significant amount of injury to desirable grass (73-74% tolerance). Glyphosate alone applied by hand (17-20) did cause significant reduction in smutgrass NDVI readings compared to glyphosate applied from a UAS (26-30), but there was no significant difference by method for smutgrass control or desirable grass tolerance.

DEDICATION

This thesis is dedicated to Deanna and Steve Cox.

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First and foremost, thank you to my mom and stepdad Deanna and Steve Cox. Without their emphasis on my education, I would not have made it this far. There were times I was not sure I would finish a bachelor's degree, now I am here getting my master's degree. However, this is not the end of my journey, this is hardly even the beginning.

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very late to the party starting as a junior. It also made me realize that I could excel in Agronomy (or anything else) if I tried, which “trying” was also a foreign concept to me at that point. After that class, the next step was the professional development trip to Mississippi, which I forgot to take my cell phone. I’m sure your ears needed a few rest days after being in a vehicle with me for that long without a cell phone. Thank you for always being at the forefront of making me feel like part of the Agronomy family, even though it was not my major (I hope getting a master’s degree in it fixes my poor decision of not making it my undergraduate major).

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Below is a scene from Night at the Museum that has bounced around my head a million times in the last few days of this degree:
Teddy Roosevelt:
You're done your job. It's time for your next adventure!
Larry Daley:
I have no idea what I'm going to do tomorrow.
Teddy Roosevelt:
How exciting.

It is time to start my tomorrow.

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Contributors

This research was conducted under the supervision of the thesis committee consisting of Dr. Scott Nolte (advisor) of Texas A&M University, Dr. Steve Hague of Texas A&M University and Dr. Chris Skaggs of Texas A&M University.

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NOMENCLATURE

AI	Air Induction
DAA	Days after A-Application
DAB	Days after B-Application
DAT	Days After Treatment
g	Gram
ha	Hectare
kg	Kilogram
L	Liter
LSD	Fishers protected least significant difference
NDVI	Normalized Difference Vegetation Index
PDIR	Post Direct
PRE	Pre-emergent Herbicide
POST	Post-emergent Herbicide
TTJ	Turbo Twin-Jet Bi-Directional Nozzle
TTI	Turbo Tee-Jet Induction Uni-Directional Nozzle
UAS	Unmanned Aerial Sprayer
WA	Weeks After
XR	Extended Range Nozzle

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CHAPTER I INTRODUCTION AND LITERATURE REVIEW

Smutgrass and Impacts to Pasture Forages

Smutgrass (*Sporobolus indicus)* is an aggressive perennial bunch-type grass that invades introduced and native pastures primarily in the southeastern part of the United States; however, it has been found also in Oregon and New Jersey (McCaleb and Hodges, 1971). According to the USDA (2018), smutgrass has been identified in 54 counties across Texas. Smutgrass was introduced to the United States from tropical Asia (Hitchcock and Chase, 1951). The name smutgrass is given for the dark-colored fungus (*Bipolaris* spp.) that often infects the inflorescence of the plant and gives it a black, sooty appearance (McCaleb et al. 1963; Mislevy et al. 2002). Smutgrass may produce more than 1,400 seeds per panicle and 45,000 seeds per plant in a single growing season, with seed production taking place continually throughout the growing season (Currey et al. 1973). The seeds favor 25-35°C temperatures, ample moisture, and being placed on the soil surface rather than being buried to germinate (Rana et al. 2017b). Smutgrass is not favorable for cattle diets, however, if seeds are ingested, they can be dispersed by cattle (Andrews, 1995). Andrews (1995) also found that 19% of smutgrass seeds were viable after ingestion and that 100% of seeds had fully passed through the cattle's digestive system within 7 days. However, Andrews (1995) determined that the seeds do not readily germinate in the manure after excretion and must be dispersed, and that seeds sticking to the livestock's hair for transportation contributes to more smutgrass spread than through cattle excrement. Mature plants grow in tufts up to 1 m long with leaves 8-30 cm long and 3-5 mm wide (University of California, 2016). Cattle will eat smutgrass while the foliage is immature and tender, however after around 2 weeks it becomes less palatable and cattle will generally avoid mature smutgrass plants altogether (Mullahey, 2000). When the foliage is managed intensely to remain in the window where cattle will eat it, the weight gain and forage quality is similar to bahiagrass (*Paspalum notatum)*; one reason it does not make a high-quality grazing forage is the amount of intense management it requires relative to bahiagrass or bermudagrass (*Cynodon dactylon)* (Mullahey, 2000). Ferrell, et al. (2006) found that, compared to low densities (<20% groundcover), medium densities (20%-70%) of giant smutgrass reduced bahiagrass yield by 49%, and high densities reduced bahiagrass yield by 87%. Soil pH also plays a role in smutgrass competition. Rana, et al. (2017a) found that at pH of 4.5 to 6.5, giant smutgrass would outcompete bahiagrass, but at 4.5 to 5.5 pH, bahiagrass would outcompete small smutgrass. Smith, et al. (1974) found that bermudagrass production decreased as smutgrass density and size increased, he also found that the quality of the bermudagrass also improved. However, the bermudagrass was not harvested for yield data and to date, no yield data has been published to measure smutgrass' impact on bermudagrass yield loss. Increased reductions in desirable forage from smutgrass lead to increased inputs into the cattle that depend on forage, including extra feed to avoid low calving percentages or low weaning weights (Ferrell et al. 2006). Given these characteristics of the plant and its ability to reduce land economic value and nutritional value of livestock forages, research was conducted to experiment with variables to control smutgrass.

Herbicides for Smutgrass Control

Many methods have been attempted to control smutgrass, such as mowing, cultivation, intense grazing and herbicides. In Florida, mechanical methods including mowing and cultivation did not control smutgrass, but a single application of the herbicide active ingredient dalapon at 5.6 kg ha^{-1} provided 85% control (McCaleb et al. 1963; McCaleb and Hodges, 1971). According to the Pesticide Action Network North America, dalapon's EPA registration was approved on May 14, 1971 and cancelled Aug 19, 1988 (Pesticide Action Network, n.d.). To fill the void of dalapon, which was the only selective herbicide for smutgrass from the 1950s to the 1980s, selective herbicidal control of smutgrass has been available since hexazinone received federal registration for pastures in 1989 (Ferrell and Mullahey, 2006). Hexazinone (3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4(1H,3H)-dione) is an s-triazine herbicide that is readily absorbed by both roots and foliage (Vencill, 2002). It is a photosystem II inhibitor with low adsorption potential, high mobility potential and soil half-life of 90 days (Tu et al. 2001; Table I-1). It is sold for range and pasture use under the trade names Velpar DF (dry flowable, Bayer Environmental Science), Velpar L VU (liquid, Bayer Environmental Science) and Pronone Power Pellet (tablet, Pro-Serve Inc.), but in total twenty end-use pesticide products and one technical grade manufacturing use product containing hexazinone were included in the 1994 Registration Eligibility Decision (EPA, 1994). Brecke (1981) found that 1.7 and 2.2 kg ha^{-1} provided over 95% control one year after treatment. Brecke (1981) also found that 3.4 kg ha^{-1} provided 100% control five months after treatment. However, despite the fact that these rates work to control smutgrass, they would make it difficult to realize a profitable return on investment in most cow-calf operations, and the 1.26 kg ha^{-1} federal grazing restriction would require all the cattle to be moved out of the area for sixty days, according to the Velpar L VU label (Bayer, 2015). Adequate control can be achieved with rates between 0.56 and 1.12 kg ha ^{1}, but they are highly variable and unreliable (Ferrell, et al. 2006; Mislevy, et al. 199; Mislevy, et al. 2001; Wilder, et al. 2011). Another common herbicide in weed control that can be effective on smutgrass is glyphosate (Meyer and Baur, 1979). Glyphosate is a non-selective, systemic herbicide that inhibits 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase, a key enzyme in the shikimic acid pathway (Hoagland and Duke, 1982). It has high adsorption potential, low mobility potential and a soil half-life of 47 days (Tu et al. 2001; Table I-1). Glyphosate was registered in the United States in 1974 and is contained in over 750 products in the United States (Henderson et al. 2010). In a study conducted by Meyer and Baur (1979) on smutgrass near Caldwell, TX, glyphosate at 2.2 kg ha^{-1} in September and October was more effective than atrazine or bromacil. Riewe et al. (1975) found that 1.12 kg ha^{-1} of glyphosate can also provide significant smutgrass control. Research using glyphosate in a roller wiper at 50% glyphosate solution and wiping bi-directionally achieved 90% control and no damage to the desirable grass and the bermudagrass began to colonize the spot where the smutgrass plant was controlled 11 months after application (Lemus et al. 2013).

The herbicides described above are primarily focused on post-emergent control of smutgrass. Pre-emergent smutgrass control could be beneficial, due to the fact that a single plant can produce 45,000 seeds per year (Currey et al. 1973). Of these 45,000 seeds, 1-9% will germinate under normal field conditions, while scarification improves germination to 98% (Currey et al. 1973). Indaziflam has been used in perennial cropping systems previously (such as turfgrass) but the registration for use in bermudagrass forage under the trade name Rezilon (indaziflam, Bayer Environmental Sciences) was only recently approved in 2020. There is currently no published field level data documenting the control of smutgrass with pre-emergence applications of indaziflam. In a greenhouse experiment, Howard (2020) found that rates even down to 0.25X the lowest recommended labeled rate still controlled smutgrass seedlings. Indaziflam has shown in previous research to control other notable weeds in central Texas including smooth crabgrass (*Digitaria ischaemum*), annual bluegrass (*Poa annua*) (Brosnan and Breeden, 2012) and southern sandbur (*Cenchrus echinatus* L.) (Nolte et al. 2020). The addition of a pre-emergent such as indaziflam in order to advance towards an integrated weed management program could prove advantageous for controlling smutgrass.

Aside from determining whether the herbicide simply works, another important aspect is economic threshold. Ferrell et al. (2006) found that although 1.1 kg ha^{-1} was able to reduce the density of smutgrass, it created a net loss of $11.30 ha $^{-1}$ in low level infestations. However, it resulted in a net gain of $26 and $47 ha $^{-1}$ in medium and high-level infestations, respectively. In a cow-calf operation, the primary source of income is cattle being sold by weight. Therefore, a reduction in available desirable forage results in a reduction in cattle weight and reduced income. The cost of these infestations when uncontrolled was $92.52 ± 10 ha^{-1} for medium infestation and $114.15 ± 14 ha $^{-1}$ at high infestation in 2006. However, average adult beef cattle and calf prices have increased from $1.71 and $2.64 kg^{-1}, respectively, in 2006, to an average of $2.53 kg $^{-1}$ for adult cattle and calves at $3.74 kg $^{-1}$ in 2018 (USDA, 2007; USDA 2019c). While this increase in price per kilogram does lead to increased revenue, profit margins must also take into account an increase in the cost of herbicide. In April 2017, hexazinone was approximately $21 L^{-1} (Ferrell and Sellers, 2017), and has risen 14% per year to a price of approximately $37 L^{-1} in 2021 (Forestry Suppliers, 2021; Table I-2). It is also important to remember this is not a single year investment, and while applying hexazinone may cause a loss in the first year, it is possible to increase profit in subsequent years, due to recovered forage production. Therefore, it is important to think critically about the how and why of herbicide use and doing everything possible to reduce cost and amount in order to allow farmers and ranchers to generate more profit. Experimentation presented in this thesis studies ways different equipment and application methods impact herbicide efficacy in order to gain maximum benefit from the herbicides.

Herbicide Application Methodology

The oldest method of herbicide application known occurred in AD 460, which occurred in Rome and consisted of common salt being applied to plants (Smith and Secoy, 1976).

Selective removal of one species or a group of species while excluding other species was only achievable by the human applicator deliberately applying the herbicide to the species they targeted until 1896-1897, when agricultural scientists discovered copper salts selectively killed broadleaf weeds in cereals, which then lead to workers the realization that other inorganic chemicals such as sodium nitrate and iron sulfate had similar effects (Peterson, 1967). In 1942, a patent was filed for 2,4-D, which industrialized selective weed control and took herbicidal weed control from an approximately $2 million industry in 1940 to a nearly $271 million industry in 1962 (Peterson, 1967). However, the selective nature of 2,4-D allows for control of broadleaves in grasses but controlling broadleaves in broadleaves or grasses in grasses still required ingenious use of equipment and methodology. In the 1950s, one of the ideas to change application style to achieve desired results was to wrap sponges of herbicide around spray booms, which would target the taller weeds in the shorter crops (Dale, 1980). The problem with this was the dripping onto the crop caused damage, so the ideas was improved by impregnating wax bars with 2,4-D and attaching those to the boom, in an attempt to control sesbania in soybeans (McWhorter, 1966). This idea of rubbing herbicide onto target plants was industrialized by Dale (1978) developing the “ropewick” which is an applicator with a reservoir filled with herbicide, and ropes attached to the reservoir, causing the ropes to become soaked with herbicide then be rubbed on the target plants. The ropewick gives us some of the first examples of how application equipment and methodology can impact herbicide efficacy. Leafy spurge *(Euphorbia esula*) control required 75% less picloram and johnsongrass *(Sorghum halepense*) required 85% less glyphosate for control compared to spraying the herbicides (Dale, 1979b). Being able to control weeds, while reducing herbicide input into the environment is a desirable outcome, however, technology has changed since 1978, namely, the number of herbicides available, and the types of equipment available to applicators, so it is important to consider using methodology to increase weed control efficacy.

The most common method of application for herbicides is spraying. There are five phases of spraying, outlined by Combellack (1984): 1. Addition of herbicide to diluent to make the spray solution, 2. Droplet production over the target plant/area, 3. Movement of droplets from the nozzle on to the target plant/area, 4. Impingement and retention of the droplet on the plants, 5. Achievement of biological requirement/result. Any change in any of these 5 phases will change the efficacy of the weed control. The optimum spraying parameters needed to achieve control must be defined in relation to the level and duration of weed control desired, based on criteria such as weed density (Dew, 1972; Gilbey, 1974; Reeves, 1976; Wells, 1979: and Zimdahl, 1980) and an estimate of the economic impact of the weed (Ferrell, 2006; Elliot, 1978; Vere and Campbell, 1979: and Zimdahl, 1980). The potential of noxious weeds to spread or re-invade should also be considered (Amor and Twentyman, 1974; Parsons, 1973). These factors would then be related to the tolerance of the crop to the herbicide under consideration. Three of the most common parameters that cause the herbicide to be ineffective, or “lost”, fall into the droplet production and movement of droplet categories, such as droplet size, spacing and placement, and these must be optimized so that a minimal amount of spray solution misses the target (Combellack, 1984). The two types of “losses” in application are classified as “endo-losses”, which are losses within the target area, which is commonly a selective herbicide landing on the tolerant crop in close proximity to the weed and “exo-losses” which are losses outside the target area such as wind drift or volatilization. Once the droplet is retained on the plant, Combellack (1984) says there are five factors that govern the efficacy of an herbicide at controlling the target species: 1. Quantity of herbicide, 2. persistence of herbicide, 3. form of deposit (how evenly the herbicide molecules distribute within single spray solution droplets), 4. distribution of herbicide (how evenly multiple droplets disperse across the leaf) and 5. placement of the herbicide on the target. There has already been some research conducted on certain variations of herbicide application on smutgrass (Mislevy, 1999; Wilder 2009). Mislevy (1999) experimented with mowing the plants before applying hexazinone, which did not increase control. Wilder (2009) found that adjuvants did not increase control with hexazinone. However, one variation that did create significant difference is that mid-summer and fall applications of hexazinone provided significantly better control than late-spring applications, most likely due to smutgrass' perennial nature and the movement of carbohydrates towards the root system during these times immediately prior to dormancy, which would also carry hexazinone to the roots (Howard, 2020). Research outside of smutgrass on methodology variables includes Hunter et al. (2020) finding that pesticide coverage from a UAS at 1 m s $^{-1}$ ranged from 30% to 60%, while applications at 7 m s $^{-1}$ dropped coverage down to 13-22%. Creech et al. (2015) also found that an increase from a 11003-orifice to a 11005-orifice increased VMD by 8%, and that glyphosate increased VMD 11% compared to water when all other variables were the same and concluded that effects on VMD from least to greatest are nozzle, operating pressure, herbicide, orifice volume and carrier volume. The research in this thesis primarily focuses on variations in application methodology in order to evaluate their possible effectiveness for an agriculture producer looking to control smutgrass. This research will focus on 5 variations in equipment and methodology to assess their influence on herbicide efficacy- 1: Individual plant treatment (IPT) by hand also referred to as "spot spraying" to determine efficacy differences in different rates of herbicide. 2: Broadcast applying post-emergent herbicides through different nozzles to assess nozzle impact on efficacy. 3: Broadcast spraying post-emergent herbicides followed by pre-emergent herbicides to assess efficacy of adding a pre-emergent to a smutgrass control program.

4: Applying hexazinone to different target areas on the plant to assess the impact of target area on efficacy. 5. Aerial applications made from an Unmanned Aerial Sprayer (UAS) or “drone” to determine how efficacy varies from applications made by a human on the ground.

Critical Analysis of Herbicide Application Methodology

Individual plant treatment is the method of walking or driving in an off-road vehicle to each plant and applying a measured amount of herbicide mixture onto the target plant, while minimizing the amount of herbicide solution sprayed onto desirable crops around the target. A benefit of this method is the ability to selectively apply non-selective herbicides such as glyphosate to a specific target to minimize the amount of damage to surrounding vegetation because the applicator can ensure that the herbicide is targeted only at the weed, thus greatly reducing both endo and exo-losses. Secondly, an applicator can spray a selective herbicide, such as hexazinone, ensuring the target species receives an effective dose while again minimizing yield losses to the desirable grass around it. Because a selective herbicide is being used, accuracy is not as critical due to the limited injury a selective herbicide will cause on non-target species, but injury to non-target plants is still possible. Increased accuracy using a selective herbicide can be desirable due to the cost of selective herbicides, and inefficient use will ultimately cost the applicator money. Ferrell et al. (2006) provided three classifications of giant smutgrass infestation level- “low”: (<20% groundcover), “medium” (<20-70% groundcover) and “high” (>70% groundcover). Although these classifications were made in giant smutgrass, in combination with the size total target area, are helpful for creating recommendations for which methods and herbicides are more feasible and will provide the best control given the circumstances. Individual plant treatment experiments are conducted at less than 50% groundcover. Treating 5000 1 m^2 ha^{-1} plants is 50% groundcover, therefore is a “medium” infestation level. Treating these 5000 plants with 35 ml plant $^{-1}$ of solution equates to 175 L ha^{-1} of solution applied. Considering that common herbicide broadcast rates for smutgrass are 280-421 L ha^{-1} it is reasonable to believe that individual plant treatments can be a more water efficient treatment system if the smutgrass density is less than 8,000 plants ha^{-1}. Spot treating 8,000 plants ha^{-1} with 35 ml plant^{-1} would require more water than broadcast spraying 280 L ha $^{-1.}$ This resource efficiency of individual plant treatments can be attributed to significant reduction in exo-losses and endo-losses by applying the solution directly to the plant to keep endo-losses off of surrounding plants, and also being able to apply close to the plant to limit exo-losses from wind drift. Also, individual plant treatments area also available in tablets, which provide even more reduction in exo-losses. Beyond recommendations that can lead to efficiency, there are some rules that must be followed, which are detailed in the herbicide label. In terms of labelled restrictions on the herbicides being used, the label for RoundUp ProMax (Bayer Environmental Sciences) states the following:

> "For spot treatments or wiper application methods using rates of 2 quarts of this product per acre or less, the entire field or any portion of it may be treated. When spot treatments or wiper applications are made using rates above 2 quarts of this product per acre, no more than 10 percent of the total pasture may be treated at any one time. (Bayer Environmental Science, 2018)"

Since this formulation is equivalent to 540 grams of the acid glyphosate L^{-1}, the rate of 2 quarts A^{-1} of product in the label equates to 2.5 kg ha $^{-1}$ of glyphosate. Considering the rates used in the experimentation for this thesis, an applicator could treat the following number of plants per hectare with two quarts per acre of solution: 13227 plants, 6613 plants or 2645 plants at 0.19 g plant $^{-1}$ (1% product solution), 0.38 g plant $^{-1}$ (2% product solution) or 0.94 g plant $^{-1}$ (5%

product solution) respectively. By staying below, the number of plants with the corresponding rate, there is no limit to the amount of area that can be treated. Similar to the above restrictions for using glyphosate, comparable federal limits livestock grazing following applications of hexazinone at rates of 1.26 kg ha $^{-1}$ or higher (Bayer Environmental Science, 2015). For IPT treatments, at a rate of 1.26 kg ha $^{-1}$ an applicator can legally treat 15750 plants ha^{-1} at 0.08 g plant $^{-1}$ (1% product solution), 7875 plants per hectare at 0.16 g plant $^{-1}$ (2% product solution) and 3150 plants per hectare at 0.40 g plant $^{-1}$ (5% product solution) to continue grazing cattle unrestricted. In terms of hexazinone tablets, an applicator can legally use 1320 tablets per hectare per season, so they can treat 2640 plants ha^{-1} with one-half tablet plant^{-1} or 1320 plants ha^{-1} with one full tablet plant^{-1}. While this method can be tedious and time consuming it has the potential to reduce the amount of herbicide needed for adequate control since little to no herbicide is lost off target. Minimal herbicide is lost because the solid tablet is not subject to wind drift or evaporation like a liquid herbicide is. As stated previously, the variables assessed related to individual plant treatments were the rate of herbicide applied and how target area on the plant impacts efficacy.

Broadcast spraying in agronomy is the practice of using a tractor or off-road vehicle, fitted with a spraying setup that covers the entirety of a width (usually 2 to 10 m) in an equal amount of herbicide, while the applicator is driving the vehicle forward. This method does not allow for precise measuring of herbicide per plant, rather it measures an amount of herbicide applied over an area, measured in gallons per acre or liters per hectare (GPA; L ha^{-1}). Two types of broadcast sprayers are boom-sprayers and boomless sprayers. Boom sprayers have arms that extend the length of the spraying swath width. They allow for less exo-loss and more even coverage but are cumbersome in rough or densely vegetated terrain. Boomless sprayers spray solution from the middle of the sprayer, they tend to be easier to maneuver through a pasture, but the coverage is not as precise and allow for more exo-loss. For this experimentation, broadcast applications were done using a handheld boom system to simulate an application made by equipment. Variables in the broadcast spraying experiments were herbicides and nozzle selection, to determine the results of different combinations. Benefits of this method are timeliness and the ability to make applications from inside an environmentally controlled cabin of a tractor. Since a broadcast application is inherently designed to deliver a consistent rate of herbicide over a broad area, this method is more suited for treating weed populations of a more even distribution, while spot spraying allows for precise targeting and dosage rates of herbicide depending on the density of the target population. Another challenge with broadcast application is that range and pasture lands are diverse landscapes that may contain vegetation with dense crowns such as smutgrass, anthills, or other features that make the ground area rough and therefore more difficult to traverse, especially while attempting to maintain a constant speed for consistent output. Broadcasting equipment does not have the suspension capabilities of off-road vehicles, which can lead to equipment problems from the jarring effects of driving a constant speed over a pasture infested with smutgrass. Broadcast spraying is still held to the same federal grazing restriction levels for hexazinone application (no restriction under 1.26 kg ha $^{-1}$). Glyphosate contains no grazing restriction below 2.5 kg ha $^{-1}$ but requires livestock to be removed and the forage not be used for any livestock feed for eight weeks when this threshold is exceeded. Removal of livestock or supplemental feed may still be necessary when applied under the grazing restriction limit, due to the non-selective nature of glyphosate and the damage it can cause to the livestock’s forage. The broadcast treatments in this thesis are conducted at medium (20-70% groundcover) to high (>70% groundcover) infestation levels. Because the herbicide is being applied over a target area and the federal restrictions are based on the amount of active ingredient per hectare, the number of smutgrass plants being treated does not impact an applicator's ability to stay below the threshold. The variable assessed in this research were how differences in nozzles can impact the herbicide's efficacy in a boom-broadcast application, and how a pre-emergent application fits in with post-emergent broadcast applications.

The final application method this experiment will evaluate is aerial application from a drone. Unmanned Aerial Vehicles (UAV) are aerial vehicles, which come in wide varieties, shapes, and sizes and can be remotely controlled or can fly autonomously through software-controlled flight plans in their embedded systems working on the basis of GPS (Simelli and Tsagaris 2015). Research has been done in smutgrass sensing/mapping using multispectral imagery (Howard, 2020). Experimentation in Chapter V will explore using the aerial vehicle to apply herbicide to the smutgrass. Aerial vehicles have mapped weed populations in corn fields in an effort to support herbicide applications (Castaldi et al. 2017). This is a new technology, and the gap in knowledge of drone applications is large. It is expensive to do research with a drone, which is one reason there has been limited research with this new technology. However, the price has dropped substantially. In 2005, an unmanned helicopter for agriculture cost around $100,000 (Sugiura, Noguchi & Ishii, 2005). Since 2005, technologies have become much more compact as well, and much more feasible for a farmer or rancher to learn to operate and can be purchased. For example, the range of agricultural UAS pricing is around $649 (Arris Hobby, 2021) up to $18,000 dollars (Empire Drone). They can go up more in price depending on options and features, but they are relatively cheaper than they were fifteen years ago. UAS applications are subject to the same limitations as the individual plant treatments above, which are 1.26 kg ha^{-1} for hexazinone and 2.5 kg ha^{-1} for glyphosate. A main benefit of the UAS method is that ground features do not impede application nearly to the extent that they impede ground operated vehicles or walking. Technology is available now for the operator to set the height of the UAS manually or set a distance from the ground and the UAS will use a radar to scan the ground to ensure that it maintains a constant application height. Disadvantages of this system include having to spray from approximately two meters in the air, in order to reduce the risk of accidentally hitting the ground. This makes it more tedious to apply accurately than hand applied IPT, but this research will focus on whether these perceived disadvantages are enough to cause significant difference in herbicide efficacy.

The method of herbicide application an applicator chooses will have pros and cons. In theory, individual plant treatments can save water, herbicide and money, at the expense of time and labor. Individual plant treatment within itself has variables. Variables include spraying from a UAS or spraying by hand, and whether the applicator should direct the herbicide at the foliage or root system. Broadcast spraying is nearly the opposite in terms of theoretical tradeoffs- it allows an applicator to apply herbicide from the safety and luxury of a tractor which can be climate controlled, while not adjusting herbicide or water output to adjust to weed density changes throughout the field which can lead to over- or under-application. Therefore, the specific objectives of this research were to: 1) determine which herbicide and rate applied as individual plant treatments (IPT) provides the greatest smutgrass control and least injury to desirable forage species; 2) determine the impact of root versus foliar IPT herbicide placement on smutgrass control and forage tolerance; 3) evaluate indaziflam for pre-emergence control of smutgrass; 4) evaluate the impact of various nozzle types on smutgrass control; and 5) evaluate IPT methods using an unmanned aerial vehicle versus traditional IPT application.

Table I-1. Environmental activity, toxicity and fate of herbicides.

Herbicide	Water Solubility (ppm)	Adsorption Potential	Primary Degradation Mechanism	Soil Half-Life (days)	Mobility Potential	Dermal LD50 (mg kg-^{1})^{a,b}	Oral LD50 (mg kg^{-1})^{c}	LC50 (mg L $^{-1}$)^{d}
Hexazinone	33,000	Low	Slow Microbial Metabolism	90	High	>6000	1690	370
Glyphosate	900,000	High	Slow Microbial Metabolism	47	Low	>5000	5600	120

[a] Abbreviations: LD50, Lethal dose to 50% of test subjects; LC50, Lethal concentration to 50% of test subjects.

[b] In rabbits (*Oryctolagus cuniculus*)

[c] In rats (*Rattus norvegicus)*

[d] In bluegill sunfish (*Lepomis macrochirus)*

Table II-2. Cost of herbicides.

Herbicide	Cost L^{-1} (US Dollars)	Cost ha^{-1} to broadcast (US Dollars)	Cost to spot treat 5000 emerged plants with 1% solution (US Dollars)
Hexazinone	39.73	208 (1.26 kg ai ha)	70
Glyphosate	11.41	65 (2.5 kg ai ha)	20
Indaziflam	296.92	65 (0.04 kg ai ha)	N/A

CHAPTER II EVALUATION OF HERBICIDAL CONTROL OPTIONS FOR SMUTGRASS UTILIZING INDIVIDUAL PLANT TREATMENTS

Introduction

The oldest method of individual plant treatment herbicide application known occurred in AD 460 in Rome and consisted of common salt being applied to plants (Smith and Secoy, 1976). Selective removal of one species or a group of species while excluding other species was only achievable by the human applicator deliberately applying the herbicide to the species they targeted until 1896-1897, when agricultural scientists discovered copper salts selectively killed broadleaf weeds in cereals, which then lead to workers realizing other inorganic chemicals such as sodium nitrate and iron sulfate had similar effects (Peterson, 1967). In 1942, a patent was filed for 2,4-D, which industrialized selective weed control and took herbicidal weed control from an approximately $2 million industry in 1940 to an almost $271 million dollar industry in 1962 (Peterson, 1967). However, the selective nature of 2,4-D allows for control of broadleaves in grasses but controlling broadleaves in broadleaves or grasses in grasses still required ingenious use of equipment and methodology. In the 1950s, one of the ideas to change application style to achieve desired results was to wrap sponges of herbicide around spray booms, which would target the taller weeds in the shorter crops (Dale, 1980). The problem with this was the dripping onto the crop caused damage, so the ideas was made better by impregnating wax bars with 2,4-D and attaching those to the boom, in an attempt to control sesbania in soybeans (McWhorter, 1966). This idea of rubbing herbicide onto target plants was industrialized by Dale (1978) developing the “ropewick” which is an applicator with a reservoir filled with herbicide, and ropes attached to the reservoir, causing the ropes to become soaked with herbicide then be rubbed on the target plants. The ropewick gives us some of the first examples of how application equipment and methodology can impact herbicide efficacy. Leafy spurge *(Euphorbia esula*) control required 75% less picloram and johnsongrass *(Sorghum halepense*) required 85% less glyphosate for control compared to spraying the herbicides (Dale, 1979b). Being able to control weeds, while reducing herbicide input into the environment is a desirable outcome, however, lots of things have changed since 1978, namely, the number of herbicides available, and the number of different pieces of equipment at an applicator's disposal, so it is important to take a look at this idea of using methodology to increase efficacy. Therefore, the objective of this experimentation is to utilize both selective and non-selective herbicides and apply them directly to targeted individual plants to evaluate weed control and forage tolerance.

Materials and Methods

Experiment Locations

Field experiments were conducted in 2019, near Anderson, TX (30.4989161°N, -95.8623963°W) in Grimes County and at a second location in Montgomery County near Richards, TX (30.512417ºN, -95.815667ºW). The Anderson location consists of an Annona fine sandy loam (Fine, smectitic, thermic Vertic Paleudalfs) with a pH of 6.4. Its mean annual precipitation is 100-120 cm, the mean annual air temperature is 17-20°C degrees, and it is frost free 230-280 days per year. It is moderately well drained, very high runoff class and does not flood or pond and the soil's water available water capacity is considered moderate (USDA Web Soil Survey). The Richards location consists of a Kaman series clay soil with pH of 5.9. It receives 120 to 160 cm of precipitation per year, averages 17-20°C and is frost free for 240-300 days per year. This soil is somewhat poorly drained, high runoff class and experiences frequent flooding and the available water capacity is moderate (USDA Web Soil Survey). The Anderson location consists primarily of centipedegrass (*Eremochloa ophiuroides*) and a light to medium infestation of smutgrass with 20-40% groundcover, while the Richards location consists of medium to heavy smutgrass infestation (50-90% groundcover), dense common bermudagrass (*Cynodon dactylon*) along with Pensacola bahiagrass and common carpetgrass (*Axonopus fissifolius*). Both locations were previously stocked with cattle; however, the cattle were able to be closed out of the Anderson location and the Richards location had a fence built around the trial to keep cattle out. In short, the Anderson location is a drier location on a hillside in loamy soil and the primary forage is centipedegrass, while the Richards location is more of a marsh area, with clay soil and healthy bermudagrass with other grasses mixed in.

Experiment Establishment and Design

Both locations were completely randomized designs (CRD), with single smutgrass plants being the individual experimental unit for each treatment and were replicated four times at each location. Treatments included glyphosate at 0.19, 0.38 and 0.94 g ai plant $^{-1}$, hexazinone at 0.08, 0.16 and 0.40 g ai plant $^{-1}$, imazapic + glyphosate at 0.04 + 0.06, 0.07 + 0.11, 0.18 + 0.28 g ai plant $^{-1}$ respectively, and hexazinone tablets at 0.24 g dissolved in 250 ml of water, 0.24 g solid and 0.48 g plant $^{-1}$. All liquid herbicide treatments were applied using a single nozzle CO_2-powered backpack sprayer calibrated to apply 35 ml of solution per plant. Depending on the type of solid tablet treatment, the tablet was dissolved in water and poured into the crown of the plant or the solid tablet was placed into the crown of the plant. Herbicide applications were made on 12 and 16 April 2019 at Anderson and Richards locations, respectively.

Smutgrass Control and Forage Tolerance Evaluations

Evaluations were made in three ways, 1: visual evaluation of % control, 0% as fully healthy, green plant and 100% as complete death; 2: visual evaluation of % of desirable grass tolerant to herbicide, 0% being complete death and 100 % being completely tolerant. Lastly 3: measured area, in centimeters, of desirable grass showing injury at 30 days after treatment. The combination of visual evaluation and numerical measurement of desirable grass tolerance provides not only degree of injury, but off target movement level of the herbicide as well. Evaluations were taken for smutgrass control and desirable grass tolerance 30, 60 and 90 days after treatment. Data were analyzed using SAS 9.4 (SAS Institute, Cary, N.C.). Data were subject to ANOVA and were analyzed for treatment by location interaction. Means were separated using the LSD test function within PROC GLM in SAS at alpha=0.05.

Results and Discussion

Smutgrass Control

There was no significant treatment by location interaction (P=1 at 30, 60 and 90 DAT) and all treatments were significantly different than the untreated check (Table II-1). All treatments provided 100% necrosis of smutgrass at 30, 60 and 90 DAT in every replication at both locations, with no green regrowth or seedhead growth (Table II-2, Figures II-1,2,3,4).

Forage Tolerance

The visual evaluation of desirable grass tolerance significant treatment by location interaction at all three evaluation timings (P<0.0001 at 30, 60 and 90 DAT; Table II-1), therefore treatment means were evaluated separately by location. There were significant differences in the herbicide treatments' injury level to the desirable grasses, which are primarily centipedegrass in

Anderson and primarily bermudagrass with bahiagrass and carpetgrass in Richards (Table II-3). The measurement of damaged area also showed significant treatment by location interaction ($P<0.0001$; Table II-1) therefore this evaluation is separated by location for analysis.

Thirty Days After Treatment

The Anderson location showed no treatment being less injurious than an untreated check. One-half hexazinone tablet dissolved in 250 ml of water caused the least amount of injury at 75% tolerance. Next was the low rate of liquid hexazinone with 66% tolerance, which significantly outperformed all other treatments excluding the dissolved one-half tablet. The solid one-half tablet was next best tolerated at 59% and was significantly more injurious than the previous two herbicides, but significantly less injurious than the rest. The low rate of glyphosate (25%), low rate of hexazinone (25%), low rate of imazapic + glyphosate (28%) and whole hexazinone tablet (25%) were not significantly different from each other but were more injurious than the previously listed treatments. The middle and high rate of glyphosate, high rate of hexazinone and the middle and high rate of imazapic + glyphosate all showed 0% tolerance at this location (Table II-3). Aside from visually evaluating the percentage of grass damaged, the distance of desirable grass showing damage for each treatment was measured. All treatments caused a significant damaged area compared to the untreated check. Both rates of one-half tablet (2 cm dissolved, 4.5 cm undissolved) and the low rate of liquid hexazinone (3 cm) damaged significantly less area than all other treatments. One whole tablet (9 cm), the middle rate of hexazinone (7 cm), high rate of hexazinone (8 cm), low rate of glyphosate + imazapic (8 cm), middle rate of glyphosate + imazapic (8.5 cm) and low rate of glyphosate (8.5 cm) were significantly more injurious than the previously listed treatments, but not significantly different from each other. The middle rate of glyphosate (13 cm) was significantly more injurious than the previously listed treatments but damaged a significantly smaller area than the high rate of glyphosate and high rate of glyphosate + imazapic, which both damaged 18 cm (Table II-4).

The desirable grass at the Richards location was 100% tolerant to all applications of hexazinone and not significantly different than the untreated check. All formulations of liquid hexazinone and the low rate of glyphosate + imazapic were tolerated by 50% of the desirable grass, which is significantly more injurious than the hexazinone tablets but caused significantly less injury than the other treatments. The middle rate of glyphosate + imazapic was tolerated by 25% of grasses while the low rate of glyphosate alone caused significantly more injury and was tolerated by 20% of grasses. The middle and high rate of glyphosate and the high rate of glyphosate + imazapic were tolerated 0% and significantly less than all other treatments (Table II-3). Aside from visually evaluating the percentage of grass damaged, the distance of desirable grass showing damage for each treatment was measured. In Richards, all liquid treatments damaged a significant area, but all tablet treatments (0 cm damaged) did not damage a significant area compared to the untreated check. The high rate of imazapic + glyphosate caused damage significantly farther off target than any other herbicide, measuring 21 cm of damage away from the smutgrass plant. The high rate of glyphosate and the middle and low rate of glyphosate + imazapic damaged significantly less area than the high rate of glyphosate + imazapic (13, 13 and 14 cm, respectively). The high rate of hexazinone damaged a significantly smaller area than the high rate of glyphosate + imazapic (12, 14 cm respectively). The middle rate of glyphosate (9.5 cm) and middle rate of hexazinone (8 cm) caused significantly less damage than all glyphosate + imazapic treatments, and the high rates of glyphosate and hexazinone. The low rate of glyphosate (6.5 cm) and low rate of hexazinone (7 cm) were the least injurious liquid treatments, causing less damaged area than the high and middle rates of glyphosate and hexazinone, and less damage than all glyphosate + imazapic treatments but were significantly injurious compared to hexazinone tablets and the untreated check (Table II-4).

After thirty days, the importance of grass species to determine herbicide tolerance is important. The healthy bermudagrass in Richards tolerated treatments as well or better than the struggling centipedegrass in Anderson. The Richards location tolerated all liquid hexazinone rates equally and all solid hexazinone rates equally. Meanwhile the Anderson location showed significantly more damage with each rate increase. Sellers et al. (2009) warns that bahiagrass will turn yellow 15-20 days after spraying Velpar and return to dark green within approximately forty days, while bermudagrass will turn yellow with some necrosis and take approximately thirty days before returning to green. The middle and high rates of glyphosate and the high rate of imazapic + glyphosate was tolerated by 0% of grasses at both locations, meaning that extreme care should be used with these formulations to ensure herbicide is not lost off the target weed onto the desirable forage. The low rate of glyphosate was tolerated poorly at both locations but did not cause complete necrosis. The high rate of hexazinone and middle rate of imazapic + glyphosate caused complete necrosis at the Anderson location, but a significant level of tolerance at the Richards location. The high rate of glyphosate + imazapic damaged the highest area of desirable grass at both locations, while one-half hexazinone tablet dissolved damaged the lowest area at both locations. The low rate of glyphosate, low rate and middle rate of liquid hexazinone and all three rates of liquid hexazinone caused less than 10 cm of damage at both locations. The middle rate of glyphosate, low and middle rates of glyphosate + imazapic and high rate of liquid hexazinone all caused less than 10 cm of damage at only one location. The high rate of glyphosate and high rate of glyphosate + imazapic caused damage over 10 cm of area at both locations.

Sixty Days After Treatment

This evaluation at the Anderson Location showed one-half hexazinone tablet not causing significant injury compared to the untreated check (93% tolerance dissolved, 95% solid). The low rate of liquid hexazinone (80%), low rate of glyphosate (75%) and full hexazinone tablet (70%) caused significantly more injury than ½ tablet treatments, but significantly less injury than all other treatments. The middle rate of glyphosate and the middle and high rate of hexazinone were tolerated 50%. The high rate of glyphosate was statistically the same as the low rate of imazapic + glyphosate (31% and 30% tolerance respectively). The middle and high rate of imazapic + glyphosate was tolerated 0%.

At the Richards location sixty days after treatment, all forms of hexazinone tablets were tolerated 100% and not significantly injurious compared to the untreated check. The low and middle rates of liquid hexazinone caused more injury than the tablets but were significantly less injurious than all other treatments (90% tolerance for both treatments). The low rate of glyphosate, high rate of hexazinone and low rate of imazapic + glyphosate caused significantly more damage than the previous treatments (all 75% tolerance). All remaining herbicides in order of tolerance were middle rate of imazapic + glyphosate (55%), middle rate of glyphosate (45%), high rate of glyphosate (20%) and imazapic + glyphosate (0%), with every treatment being significantly more injurious than the treatment before it (Table II-3).

Sixty days after treatment is the first evaluation showing any treatments not causing significant injury in Anderson, which are the two treatments of one-half hexazinone tablet both solid and dissolved. These two treatments were also not significantly injurious in Richards, along with the full tablet. In Anderson, the low rates of hexazinone and glyphosate plus the whole hexazinone tablet separated from the rest of the treatments and were significantly less injurious than all treatments besides the one-half tablets. In Richards, the low rate of glyphosate caused the same amount of injury as in Anderson, but many treatments were tolerated more in Richards which moved it farther away from the tablets and untreated check in terms of tolerance. The low rate of hexazinone is the only herbicide to be tolerated better than any other liquid herbicide at both locations. All rates and formulations of hexazinone were better tolerated in Richards than Anderson, most likely due to the heavy bermudagrass and bahiagrass presence in Richards, which are both within the hexazinone label for safety; whereas the Anderson location is primarily centipedegrass which is not contained in the hexazinone label.

Ninety Days After Treatment

The desirable grasses at the Anderson location fully recovered to 100% from the low and middle rate of glyphosate, all rates of liquid hexazinone and both treatments of one-half hexazinone tablet after 90 days. The full hexazinone tablet was tolerated 60%, which was significantly more than all the treatments not previously listed. The high rate of glyphosate and low rate of imazapic + glyphosate were both tolerated 50%, and the middle and high rate of imazapic + glyphosate were both tolerated by 0% of desirable forage (Table II-3).

At the Richards location, the low rate of glyphosate, all rates of liquid hexazinone and all rates of solid hexazinone were tolerated by 100% of desirable grasses and not significantly injurious compared to the untreated check. The low rate of imazapic + glyphosate (80%) was more injurious than the previous listed treatments, but significantly less injurious than all other treatments. The remaining treatments- middle and high rate of glyphosate (60% and 25% tolerance respectively) and the middle and high rate of glyphosate + imazapic (55% and 0% respectively) were all significantly different from other treatments and significantly different from each other (Table II-3).

After ninety days, the low rate of glyphosate, all rates of liquid hexazinone and both treatments of one-half tablet of hexazinone were tolerated by 100% of desirable forage. The middle rate of glyphosate was tolerated 100% only in Anderson, while the whole hexazinone tablet was tolerated 100% in Richards. Conversely, they were both tolerated 60% at the other location ninety days after treatment. The high rate of imazapic + glyphosate was tolerated 0% at both locations and the high rate of glyphosate alone was tolerated less than 50% at both locations. The low rate of glyphosate + imazapic (50%) was tolerated significantly less in Anderson than the middle rate of glyphosate (100%), but was tolerated significantly more in Richards (glyphosate + imazapic: 80%, glyphosate: 60%) (Table II-3).

Conclusion and Economic Analysis

Smutgrass control did not vary by herbicide treatment or location. All herbicide mixtures caused complete necrosis deep into the crown of the plant within thirty days and sustained this through ninety days after treatment. These herbicides were chosen due to their documented ability to control smutgrass in various application methods in multiple studies (Wilder et al. 2011; Howard, 2020; Meyer & Baur, 1979). Smutgrass control evaluations were included in this experiment as a way of confirming that the rates used were adequate to control smutgrass in the environmental conditions presented in this experiment, and the results confirm that the rates were adequate. Controlling the weed is only half the issue, crop tolerance is the other half of herbicide evaluation that must be considered, and desirable grass tolerance varied greatly by location. Considering hexazinone is a selective herbicide, we would generally expect it to cause less injury than a non-selective herbicide such as glyphosate. Wilder et al. (2008) found Tifton-85 bermudagrass recovered to normal growth by 6 weeks after an application of hexazinone in broadcast applications. In this experiment, the low and middle rate of hexazinone had returned to normal by 8 weeks after treatment, but the high-rate treatments were still significantly more injured than the untreated check. This can primarily be attributed to the fact that 0.40 g of hexazinone is an extremely high dose. That is simply too much hexazinone, given the lower rates provide the same amount of control at every rating and the desirable grasses recovered significantly more. Also, the low and middle rates of hexazinone not only damaged a lower percentage of desirable grass, they also damaged significantly smaller areas than the high rate of hexazinone. The treatments of glyphosate and imazapic + glyphosate followed a similar trend. The high rates of both herbicides caused the desirable grass at both locations to never fully recover and remain significantly more injured than the low and middle rates. The low rate of glyphosate made a full recovery to 100% at both locations, while the middle rate recovered to 100% in the primarily bermudagrass location but only 60% in the primarily carpetgrass location. The key advantage that glyphosate has to every other treatment is that it is relatively inexpensive compared to all other treatments. Roundup Pro Max herbicide costs approximately 1.14 cents mL^{-1} (Do My Own, 2021), meaning the low, medium and high rates cost 0.40, 0.80 and 2 cents plant $^{-1}$ respectively. Velpar L VU costs approximately 3.97 cents mL $^{-1}$ (Forestry Suppliers, 2021), meaning the cost more than triples from the cost of glyphosate to 1.39, 2.78 and 6.95 cents plant^{-1}. Plateau costs 4.4 cents mL $^{-1}$ (Forestry Distributing, 2021), so combined with RoundUp, the Plateau + RoundUp treatments cost 0.93, 1.87 and 4.67 cents plant^{-1}. Pronone Power Pellets cost approximately 10 cents pellet^{-1} meaning the one-half tablet treatments cost 5 cents plant^{-1}. It is important to also consider the economic threshold of a medium infestation, which was \$92.52 ha $^{-1}$ (Ferrell, 2006). At this economic threshold, using glyphosate alone, an applicator could treat 23130 plants ha^{-1} at the low rate, 11565 at the medium rate and 4626 plants with the high rate and break even economically, only considering the cost of the herbicide. However, all of these numbers would put the amount of herbicide for that rate over the grazing restriction thresholds of 11987, 5949 and 2378 plants for the low, medium and high rate, respectively. Therefore, using glyphosate, any number of treated plants below the federal grazing restriction will likely also create a gain in profit within one year. Meanwhile with liquid hexazinone, the federal limit allows 15750, 7875 and 3150 plants ha^{-1} to be treated at the low, medium and high rates used in this experiment, but the economic threshold is at 6656, 3328 and 1331 plants ha^{-1}. Therefore, cost would become a prohibiting factor before federal grazing restrictions when using individual plant treatments. By treating more plants than the economic threshold previously stated, the cost of the herbicide becomes more than the loss caused by uncontrolled smutgrass. It is important to remember that this is a multi-year investment, and while it may cause a loss in the first year, it could end up recovering monetarily in subsequent years. When considering hexazinone tablets, the same is true. The legal application amount is 2640 with one-half tablets and 1320 with full tablets, but with more than 1850 one-half tablets or 925 full tablets, the operation is losing money in the first year on the cost of herbicide alone. The ultimate goal of controlling smutgrass is to create more desirable grass for cattle, so the rancher can grow more, bigger cattle. Considering the economic cost and desirable grass damage of imazapic + glyphosate, hexazinone and glyphosate must be considered as much more feasible options. Therefore, individual plant treatments, specifically with glyphosate, present an opportunity to save lots of money and still get effective smutgrass control. Meanwhile, hexazinone is approximately twice as expensive, but the selective nature of the herbicide presents much greater safety to the surrounding forage, especially soon after application.

Photos of Individual Plant Treatments

Figure II-1 (top left): High rate of imazapic + glyphosate 90 DAT at Richards.

Figure II-2(top right): High rate of imazapic + glyphosate 90 DAT at Anderson.

Figure II-3 (bottom left): High rate of hexazinone alone 90 DAT at Anderson.

Figure II-4 (bottom right): One-half hexazinone tablet dissolved, 90 DAT at Richards

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Table II-1. Analysis of variance for experiment 1.

	SG Control[a]			DG Tolerance			DG Area		
	df	P value	SS	df	P value	SS	df	P value	SS
Effect			30 DAT			30 DAT			
Location	1	1	0	1	<0.0001	7047.12	1	<0.0001	311.54
Treatment	12	<0.0001	73846.15	12	<0.0001	114685.1	12	0.5266	985.15
Location X Treatment	12	1	0	12	<0.0001	15946.63	12	<0.0001	449.46
			60 DAT						
Location	1	1	0	1	<0.0001	6231.01			
Treatment	12	<0.0001	73846.15	12	<0.0001	94403.85			
Location X Treatment	12	1	0	12	<0.0001	10784.62			
			90 DAT						
Location	1	1	0	1	<0.0001	553.85			
Treatment	12	<0.0001	73846.15	12	<0.0001	146053.85			
Location X Treatment	12	1	0	12	<0.0001	14946.15			

[a] Abbreviations: SG, Smutgrass; DG, Desirable Grass; DAT, Days After Treatment

Table II-2. Smutgrass control 30, 60 and 90 DAT, by herbicide treatment.

		Locations Combined		
Herbicide	Rate	30 DAT[a]	60 DAT	90 DAT
	– g plant $^{-1}$ –	——————— % Control ——————		
Glyphosate	0.19	100a[b]	100a	100a
Glyphosate	0.38	100a	100a	100a
Glyphosate	0.94	100a	100a	100a
Liquid Hexazinone	0.08	100a	100a	100a
Liquid Hexazinone	0.16	100a	100a	100a
Liquid Hexazinone	0.40	100a	100a	100a
Imazapic + Glyphosate	0.04 + 0.06	100a	100a	100a
Imazapic + Glyphosate	0.07 + 0.11	100a	100a	100a
Imazapic + Glyphosate	0.18 + 0.28	100a	100a	100a
Dissolved one-half Hex. Tablet	0.24	100a	100a	100a
Solid one-half Hex. Tablet	0.24	100a	100a	100a
Whole Hexazinone Tablet	0.48	100a	100a	100a

[a] Abbreviation: DAT, Days After Treatment; Hex., Hexazinone

[b] Means within the same column followed by the same letters are not significantly different at 5% probability level

Table II-3. Desirable grass tolerance 30, 60 and 90 DAT, by herbicide treatment and location.

		30 DAT[a]		60 DAT		90 DAT	
Herbicide	Rate	Anderson	Richards	Anderson	Richards	Anderson	Richards
	—g plant -1–	——————% Tolerance——————					
Glyphosate	0.19	25e[b]	20d	75b	75c	100a	100a
Glyphosate	0.38	0f	0e	50c	45e	100a	60c
Glyphosate	0.94	0f	0e	31d	20f	50c	25e
Liquid Hexazinone	0.08	66c	50b	80b	90b	100a	100a
Liquid Hexazinone	0.16	25e	50b	50c	90b	100a	100a
Liquid Hexazinone	0.40	0f	50b	50c	75c	100a	100a
Imazapic + Glyphosate	0.04 + 0.06	28e	50b	30d	75c	50c	80b
Imazapic + Glyphosate	0.07 + 0.11	0f	25c	0e	55d	0d	55d
Imazapic + Glyphosate	0.18 + 0.28	0f	0e	0e	0g	0d	0f
Dissolved One-Half Hex. Tablet	0.24	75b	100a	93a	100a	100a	100a
Solid One-Half Hex. Tablet	0.24	59d	100a	95a	100a	100a	100a
Whole Hexazinone Tablet	0.48	25e	100a	70b	100a	60b	100a

[a] Abbreviation: DAT, Days After Treatment

[b] Means within the same column followed by the same letters are not significantly different at 5% probability level

Table II-4. Area of damaged desirable grasses 30 DAT by herbicide treatment and location.

Herbicide	Rate	Anderson	Richards
	—g plant $^{-1}$ —	——— Area Showing Damage (cm) ———	
Glyphosate	0.19	8.5c[a]	6.5e
Glyphosate	0.38	13b	9.5d
Glyphosate	0.94	18a	13bc
Liquid Hexazinone	0.08	3de	7e
Liquid Hexazinone	0.16	7c	8de
Liquid Hexazinone	0.40	8c	12c
Imazapic + Glyphosate	0.04 + 0.06	8c	13bc
Imazapic + Glyphosate	0.07 + 0.11	8.5c	14b
Imazapic + Glyphosate	0.18 + 0.28	18a	21a
Dissolved One-Half Hexazinone Tablet	0.24	2ef	0f
Solid One-Half Hexazinone Tablet	0.24	4.5d	0f
Whole Hexazinone Tablet	0.48	9c	0f

[a] Means within the same column followed by the same letters are not significantly different at 5% probability level. Means followed by "a" are not significantly different from the mean.

Table II-5. Herbicide application dates and rainfall amounts through 90 DAT.

		Rainfall[a]					
Location	Application Date	7DBT[b]	7DAT	14DAT	30DAT	60DAT	90DAT
		cm					
Anderson	April 12	0.6	2.8	4.7	23.5	39.9	48
Richards	April 19	0.5	4.6	14.8	26	42	52

[a] Cumulative amount from day of treatment until day specified

[b] Abbreviations: DBT, Days Before Treatment; DAT, Days After Treatment

CHAPTER III EVALUATION OF INDAZIFLAM EFFICACY FOLLOWING A POST EMERGENT HERBICIDE APPLICATION FOR SMUTGRASS CONTROL

Introduction

Each smutgrass plant can produce 45,000 seeds year^{-1} (Currey, et. al, 1973). The average germination in nature is 9%, which means smutgrass plants can produce over 4000 viable seeds year^{-1} (Sellers, et al. 2020). Therefore, it is important to target the seedbank to ensure that once emerged smutgrass is controlled, the seeds waiting to germinate do not take over the newly clean field. Rezilon (indaziflam) was first labeled for use in range and pasture in 2020 by Bayer Environmental Sciences. There is currently no published data documenting the control of smutgrass with pre-emergence applications of indaziflam at the field level, only in the greenhouse with excellent control (Howard, 2020). The rates in this experiment correspond with labeled rates. A common use recommendation for this indaziflam product is 219.1 mL ha^{-1} (0.04 kg ai ha^{-1}) twice per year. Once in the spring for summer annual weeds and once in the fall for winter annual weeds. This product is bound by a 438.2 mL ha^{-1} (0.07 kg ai ha^{-1}) per year restriction. Considering this experimentation is on smutgrass which only germinates in the summer, treatments of the higher 365.1 mL ha^{-1} (0.06 kg ai ha^{-1}) rate are also used, which can only be done once per year to heavily target one particular season’s weeds. Hexazinone and glyphosate have shown in previous studies that they are effective in controlling smutgrass post emergence (Mislevy et al. 1999; Chapter II). The addition of a pre-emergent such as indaziflam in order to advance towards an integrated weed management program could prove advantageous. The formulations of post-emergent herbicides are the maximum amount of hexazinone below the federal grazing restriction, a renovation rate of glyphosate to ensure a clean kill of emerged smutgrass while sacrificing desirable grass tolerance to evaluate the pre-emergent. The pre-emergent herbicide used in this experiment is indaziflam, using a new formulation released in 2020. The objective of this study is to determine whether indaziflam applied in the spring provides pre-emergence control of smutgrass when used after applying hexazinone or glyphosate for post-emergence control the prior fall.

Materials and Methods

Experiment Locations

Field experimentation was conducted in 2019 and 2020, in a different location each year near Bryan, TX in Brazos County. The soil type of the 2019 Bryan location (30.7271342°N, -96.3674128°W) was Tabor fine sandy loam (Fine, smectitic, thermic Oxyaquic Vertic Paleustalfs) with a pH of 6.6. Mean annual precipitation is 95-105 cm, the mean annual air temperature is 18.8 to 20°C, and the frost-free period is 254 to 273 days. It is considered moderately well drained, very high runoff and moderate available water capacity. The 2020 Bryan location (30.7247032°N, -96.3685781°W) was a Spiller loamy fine sand (Fine, mixed, semiactive, thermic Ultic Paleustalfs) with a pH of 6.3. Mean annual precipitation is 80-100 cm, mean annual air temperature is 18.8 to 20 degrees and the frost-free period is 250-280 days. It is considered moderately well drained, high runoff class and moderate available water capacity (USDA Web Soil Survey). Both locations have cattle in the area, but the locations were surrounded by an electric fence to keep the livestock out, which is important due to the grazing restriction caused by the glyphosate rate. Both locations also received adequate precipitation to properly incorporate the herbicides in accordance with the label (Table III-5). The density of smutgrass in both locations would be considered moderate to heavy, ranging from plants approximately every 2 meters (50% groundcover) to plants touching each other. The 2019 Bryan location contained fewer but larger plants. Whereas the 2020 Bryan location had smaller plants at a higher density. The primary desirable grass in the first year is almost exclusively common bermudagrass, the primary desirable grass in the second year is a mixture of common bermudagrass and common carpetgrass and bahiagrass.

Experiment Establishment and Design

All treatments were arranged in a randomized complete block (RCB) design with four replications. Individual plots were 2 by 5 m in size at the 2019-2020 location and 2 by 6 m in size at the 2020-2021 location. Treatments included hexazinone applied post-emergence (POST) at 1.26 kg ha^{-1} followed by a pre-emergence (PRE) application of three rates of indaziflam at 0, 0.04, and 0.06 kg ha^{-1}, and a treatment of glyphosate applied POST at 5.00 kg ha^{-1} followed by indaziflam PRE at 0.06 kg ha^{-1}. In 2019, POST and PRE applications were made on September 13 and February 14, respectively, whereas in 2020, POST and PRE applications were made on September 7 and February 22, respectively. Treatments were applied in 300 L ha^{-1} of solution at 304 kPa for POST and 300 kPa for PRE using a CO^2 powered backpack sprayer and 4-nozzle boom using TTI-11004 (TeeJet Inc.) nozzles for POST and XR8004 (TeeJet Inc.) for PRE applications.

Smutgrass Control and Forage Tolerance Evaluations

Evaluations were conducted 4 weeks after (WA) POST treatment, and then 12 and 18 WA-PRE. Visual estimates of smutgrass control were evaluated on a scale from 0 to 100%, where 0% equals no injury and 100% was equivalent to complete death, whereas visual estimates of forage tolerance were evaluated on a scale from 0 to 100%, where 0% equals complete forage death and 100% was equivalent to no injury. At 12 WA-PRE, emerged seedlings were counted, and data is presented as emerged seedlings per m^2. Data were analyzed using SAS 9.4 (SAS

Institute, Cary, N.C.). Data were subject to ANOVA and were analyzed for treatment by year interaction. Means were separated using the LSD test function within PROC GLM in SAS at alpha=0.05.

Results and Discussion

Post-Emergence Smutgrass Control

There was significant treatment by year interaction for all three evaluation timings for smutgrass control (P=0.0206 4WA-POST, P=0.0014 12 WA-PRE, P=<0.0001 18 WA-PRE, Table III-1), consequently the data were analyzed separately by year.

2019-2020 Experiment

At 4 WA-POST, glyphosate (95%) provided significantly better control than the hexazinone treatments (70-71%). All treatments provided significant control compared to the untreated check. Moving to 12 WA-PRE, glyphosate followed by hexazinone control had increased to 100% and continued to provide significantly better control, while all the hexazinone treatments caused 54-61% control regardless of the amount of indaziflam in the sequential application. At 18 WA-PRE, glyphosate followed by indaziflam still provided 100% control and significantly outperformed all treatments. Hexazinone followed by the high rate of indaziflam provided 50% control and hexazinone followed by the low rate of indaziflam or no indaziflam both provided 25% control. (Table III-2, Figure III-1).

2020-2021 Experiment

Glyphosate followed by indaziflam provided 100% control of emerged smutgrass at all three evaluations. It significantly outperformed all hexazinone treatments (75-78%) at 4 WA-POST. By 12 WA-PRE, there was no significant difference between herbicide treatments due to the hexazinone treatments improving to 85%, 88% and 89% for no indaziflam, low indaziflam and high indaziflam respectively. At 18 WA-PRE, all treatments remained statistically equivalent, with hexazinone and no indaziflam at 96%, hexazinone followed by the low rate of indaziflam at 98% and both glyphosate and hexazinone both followed by the high rate of indaziflam provided 100% smutgrass control (Table III-2; Figures III-2, 3, 4).

Pre-Emergence Smutgrass Seedling Control

There was no significant treatment by year interaction (Table III-1), consequently the years were analyzed together. There was no significant difference between any herbicide treatments and the untreated check (P=0.1636). Therefore, the inclusion of indaziflam created no significant difference on the number of new smutgrass seedling emergents per m^2.

Forage Tolerance

The 4 WA-POST evaluation did not have significant treatment by year interaction (P=0.8584, Table III-1) therefore years are combined for analysis. There was significant treatment by year interaction for 12 WA-PRE and 18 WA-PRE evaluations (P=0.0123, P=<0.0001 respectively, Table III-1), consequently these evaluations were analyzed separately by year.

Years Combined: 4 WA-POST

Both years showed all hexazinone treatments causing significant damage to desirable grasses (72-76% tolerance) but being significantly safer than glyphosate which was only tolerated 3% (Table III-3).

2019-2020 Experiment: 12 WA-PRE and 18 WA-PRE

At 12 WA-PRE, all herbicide treatments were significantly different than the untreated check. There was no significant difference between hexazinone treatments regardless of the rate of indaziflam in the PRE (77-79%), and while more injurious than the untreated check, they were tolerated significantly more than glyphosate (9%). At 18 WA-PRE, all hexazinone treatments recovered to 100% and were not significantly different than the untreated check. Glyphosate tolerance recovered to 75% which was significantly less than hexazinone treatments and the untreated check. 66-69% the second year, while glyphosate was tolerated 9% in the first year and 28% in the second year (Table III-3, Figure III-1).

2020-2021 Experiment: 12 WA-PRE and 18 WA-PRE

At 12 WA-PRE, all herbicide treatments were significantly different than the untreated check (Table III-3). There was no significant difference in tolerance between any of the hexazinone treatments, regardless of the amount of indaziflam in the PRE (66-69%). While all hexazinone treatments did cause significant injury compared to the untreated check, they were all tolerated significantly better than glyphosate (28%). At 18 WA-PRE all hexazinone treatments, regardless of the rate of indaziflam in the b-timing, had recovered 100%, and were not significantly more injurious than the untreated check. The glyphosate treatment recovered to 50% and was tolerated significantly less than hexazinone treatments and the untreated check (Table III-2; Figures III-2, 3, 4).

Conclusion and Economic Analysis

Although the numbers differed by year, there are visible correlations to the trends by year. By the spring following application, glyphosate had managed 100% smutgrass control at both locations, while sacrificing safety to desirable grasses and remaining significantly injurious throughout the entire study for both years. Sellers et al. (2017) recommends the idea of a complete pasture renovation at 70-80% ground coverage. Complete renovation requires three things- 1: complete control of emerged plants, both weeds and “desirable” forage, 2: control of weed seeds in the seedbank and lastly 3: replanting of the desirable forage from seed. The glyphosate rate used in this experiment would not satisfy a complete renovation, due to the desirable grass not being killed to 0% tolerance. A complete renovation would require 0% tolerance to the herbicide. Johnson (1988) experimented with glyphosate on bermudagrass, specifically comparing one, two and three separate applications. The data shows 44-79% tolerance one year after treatment with one application of 4.5 kg ha^{-1} of glyphosate. Johnson (1988) also shows that 2.2 kg ha^{-1} applied twice thirty days apart caused more injury than 4.5 kg ha^{-1} applied in a single application (54% and 34% injury respectively). Lastly, the data shows that expecting to control bermudagrass with a single application of glyphosate is unlikely, no matter how high the rate. In a renovation, after emerged plant control, the weed seedbank must be controlled. Indaziflam has shown utility for controlling weed seeds in other notable Texas weed species such as smooth crabgrass, annual bluegrass and southern sandbur (Brosnan and Breeden, 2012; Nolte et al. 2020). In Howard (2020), indaziflam also showed possible utility for smutgrass pre-emergence control, by providing 100% pre-emergence control in a greenhouse study. However, no rate used in this experiment was significantly different than the untreated check. Lastly in complete renovation, forage grass must be replanted from seed after weed seeds have been controlled. Although the glyphosate treatment in this study would not satisfy a complete renovation, it actually could be used to avoid a complete renovation, considering that it killed 100% of smutgrass but the desirable grass was not completely killed, thus avoiding the necessity of a replant. This possibility hinges on whether indaziflam is capable of controlling smutgrass seedlings in pastures, or whether a different pre-emergent can control smutgrass seedlings. A replant could be helpful in this treatment but is not necessary like it is in a true renovation. The other post-emergent treatments in this study were much safer on desirable grasses with all hexazinone treatments recovering to not significantly different than the untreated check. In the first year, hexazinone provided poor control and the smutgrass continuously recovered throughout the study. Contrary to the first year, hexazinone in the second year gradually increased in control throughout the study. Both years received similar amounts of rainfall, and the incorporation rainfall in the first year would be considered desirable to the second year, so rainfall is likely not the cause. Another aspect that can possibly explain the significant difference by location is the soil type. The hexazinone product label suggests using higher rates in fine-textured soils. The 2019 location's soil is a sandy loam, while the 2020 location's soil is a sand, therefore both are coarse-textured soils. In terms of desirable grass tolerance, Sellers (2008) showed yield of Tifton-85 bermudagrass to be reduced to ~30% after a treatment of 1 kg ha^{-1} of hexazinone when measured 4 weeks after treatment and recovering to ~80% by 6 weeks after treatment. Meanwhile Seller's bahiagrass tolerance research showed 9-34% biomass reduction after an application of 1.12 kg ha^{-1} of hexazinone and bahiagrass yield was significantly lower than the control at both locations in both years. The data presented in this experiment shows much more tolerance than expected from the bermudagrass, but the tolerance in this experiment is within the range expected for bahiagrass tolerance. However, Sellers' evaluations took place for twelve consecutive weeks, while this experiment has a thirty-six-week gap in evaluations due to winter dormancy. In the final rating at 18 WA-PRE, the treatment by year significant difference came from the glyphosate followed by indaziflam treatment. This treatment finalized at 75% tolerance the first year, but 50% in the second. While all hexazinone treatments achieved 100% tolerance by the end of the study in both years. The primary conceivable reason for this being that the first year took place in exclusively bermudagrass, while the second year took place in a mix of bermudagrass, bahiagrass and common carpetgrass. Johnson (1988) found that a single application of glyphosate is unlikely to kill bermudagrass beyond being able to naturally recover. This experiment shows the same result, although the grass was heavily damaged early in the study, it did not end up being completely controlled by the lone application of glyphosate and the bermudagrass, along with the mixed grasses in the second year, continued to improve into the summer. Which was expected considering they are all warm-season perennials. The second year's mixture of grasses was more tolerant at green-up than the first year, but in the following six weeks, did not recover as well as the first year. Lastly, the evaluation of indaziflam was inconclusive of any control, and was not significantly different than the untreated check at any rate. Given that smutgrass is a perennial, it's growth from seed is not common, especially in areas as densely populated with smutgrass as the areas in this experiment were. Macon (2019) says that smutgrass seeds require bare ground to germinate, and the density of the smutgrass reduces the amount of bare ground. Sellers et al. (2012) research shows thatone year after applying hexazinone, smutgrass density was reduced, but two years later the density began to increase. Given these two previous experiments, possible improvements to fieldlevel research on pre-emergent herbicides for smutgrass would be to spread seed onto bare ground instead of using existing plants for seed production, and also evaluating the experiment tobeyond two years after treatment. In terms of economic value, using Ferrell's (2006) valuation ofa medium infestation costing \$92.52 ha $^{-1}$ when uncontrolled, all of the treatments used in this experiment would require multiple years of increased profit to justify. The renovation rate of glyphosate which costs approximately \$130 ha $^{-1}$, followed by the high rate of indaziflam which costs \$108.43 ha^{-1} leads to a total cost of \$238.43 ha^{-1}, which would cause profit loss in the first two years, then begin to cause gain in profit after the third year.

However, this rate of glyphosate is the amount recommended for pasture renovation, meaning it is subject to an 8-week grazing restriction, but is not intended for immediate return of animals, due to the severe damage of the forage. On the other hand, hexazinone costs \$208 ha^{-1} at the rate used in this experiment, which is more expensive, but is not subject to a federal grazing restriction at the rate used. The low rateof indaziflam costs \$65.06 ha^{-1} while the high-rate costs \$108.43 ha^{-1}, bringing the cost of the hexazinone treatments to \$208 ha^{-1} with no indaziflam, \$273.06 using the low rate of indaziflamand \$316.43 using the high rate, meaning it can take anywhere from 2-4 years to pay off the herbicide treatment using a \$92.52 ha^{-1} increase in profit compared to leaving the smutgrass uncontrolled. In conclusion, there are many variables to consider when assessing the best treatment for a specific scenario. While glyphosate provided consistent smutgrass control, it alsocaused consistent damage to the desirable grasses. Hexazinone was not consistent in control but was consistent in being safer on the desirable grasses compared to glyphosate. While the results of this experiment show that indaziflam did not make a significant difference on new seedling emergence, it would make it seem not economically friendly to apply. However, a better evaluation of this herbicide following the recommendations made previously in this paragraph would be a much better indicator of indaziflam’s efficacy and cost-effectiveness. Another suggestion for further research includes using the glyphosate followed by indaziflam treatment from this study, which only contains one application of glyphosate and shows potential for desirable grass recovery and comparing it to a true renovation, which requires multiple glyphosate applications, tillage and replanting bermudagrass. This comparison can provide data on the rate of smutgrass return, long-term bermudagrass return, timeframe of return to full stocking rate and economic analysis.

Photos of Indaziflam Experiment

Figure III-1 (top): Indaziflam Study, 2019-2020 18 WA-PRE.

(Black= UTC, Blue= Hexazinone, Red= Glyphosate)

Figure III-2 (bottom left): Untreated Check, 2020-2021 18 WA-PRE.

Figure III-3 (bottom middle): Hexazinone followed by low rate of indaziflam, 2020-2021 18 WA-PRE.

Figure III-4 (bottom right): Glyphosate followed by high rate of indaziflam, 2020-2021 18 WA-PRE.

Table III-1. Analysis of variance for experiment 2.

	SG Control			DG Tolerance			Seedling Emergence		
	df	P value	SS	df	P value	SS	df	P value	SS
Effect					4 WA-POST				
Year	1	<0.0001	175.78	1	0.3829	50.63			
Treatment	4	<0.0001	43933.75	4	<0.0001	42006.25			
Year X Treatment	4	0.0206	83.59	4	0.8584	83.75			
					12 WA-PRE				
Year	1	<0.0001	3062.50	1	0.1308	330.63	1	0.0121	0.06
Treatment	4	<0.0001	44978.75	4	<0.0001	29640.00	4	0.1636	0.05
Year X Treatment	4	0.0014	2068.75	4	0.0123	2135.00	4	0.0573	0.09
					18 WA-PRE				
Year	1	<0.0001	15210.00	1	<0.0001	4202.50			
Treatment	4	<0.0001	43283.75	4	<0.0001	10628.75			
Year X Treatment	4	<0.0001	10933.75	4	<0.0001	1978.75			

Abbreviations: SG, Smutgrass; DG, Desirable Grass; WA, Weeks After

Table III-2. Smutgrass control 4 WA-POST, 12 WA-PRE and 18 WA-PRE, by herbicide treatment and year.

			4 WA-POST[a]		12 WA-PRE		18 WA-PRE	
Herbicide	Rate	Timing	2019-2020	2020-2021	2019-2020	2020-2021	2019-2020	2020-2021
	–kg ha^{-1}–		% Control					
Hexazinone	1.26	POST	70b[b]	78b	54b	85a	25c	98a
Hexazinone	1.26	POST	71b	78b	61b	88a	25c	99a
Indaziflam	0.04	PRE						
Hexazinone	1.26	POST	71b	75b	59b	89a	50b	99a
Indaziflam	0.06	PRE						
Glyphosate	5.00	POST	95a	100a	100a	100a	100a	100a
Indaziflam	0.06	PRE						

[a] Abbreviations: WA, Weeks After

[b] Means within the same column followed by the same letters are not significantly different at 5% probability level

Table III-3. Tolerance of desirable grass 4 WA-POST, 12 WA-PRE and 18 WA-PRE by herbicide treatment and year

			4 WA-POST[a]	12 WA-PRE		18 WA-PRE	
Herbicide	Rate	Timing	Combined	2019-2020	2020-2021	2019-2020	2020-2021
	—kg ha^{-1} —		% Tolerance				
Hexazinone	1.26	POST	76b[b]	79b	69b	100a	91a
Hexazinone	1.26	POST	72b	79b	68b	100a	91a
Indaziflam	0.04	PRE					
Hexazinone	1.26	POST	73b	77b	66c	100a	88a
Indaziflam	0.06	PRE					
Glyphosate	5	POST	3c	9c	28c	75b	53b
Indaziflam	0.06	PRE					

[a] Abbreviation: WA, Weeks After

[b] Means within the same column followed by the same letters are not significantly different at the 5% probability level

Table III-4. Smutgrass seedling emergence 12 weeks after indaziflam.

Herbicide	Rate	Timing	Combined[a]
	kg ha-1		# Emerged[b]
Hexazinone	1.26	A	0.04[ab]
Hexazinone Indaziflam	1.26 0.04	A B	0.05[ab]
Hexazinone Indaziflam	1.26 0.07	A B	0.02[b]
Glyphosate Indaziflam	5.48 0.07	A B	0.02[b]
Untreated	N/A	N/A	0.13[a]

[a] Number of new emergent seedlings per m^2

[b] Means within the same column followed by the same letters are not significantly different at 5% probability level

Table III-5. Herbicide application dates and rainfall amounts through 18 WA-PRE.

Year	Application Date	Timing	Rainfall[a]				
			7DBT[b]	7DAT	14DAT	12 WA-PRE[c]	18 WA-PRE
			cm				
Year 1	13-Sep-19	A	2	2	3	63.5	71.6
	14-Feb-20	B	2	1.8	1.8		
Year 2	7-Sep-20	A	6.9	5.5	5.7	38.1	63.6
	22-Feb-21	B	0.3	1.5	1.5		

[a] Cumulative amounts from day of treatment until day specified

[b] Abbreviations: DBT, Days Before Treatment; DAT, Days After Treatment

[c] 12 WA-PRE and 18WA-PRE amounts are from date of experiment establishment until day specified

CHAPTER IV EVALUATION OF NOZZLE SELECTION ON HERBICIDE EFFICACY FOR SMUTGRASS CONTROL

Introduction

The objective of this study is to determine whether a bi-direction nozzle impacts smutgrass control compared to uni-directional fan nozzle. Smutgrass control is highly variable, specifically from hexazinone. Wilder et al. (2011) propose that rainfall is an indicator of the level of control to be expected from hexazinone, unfortunately it is impossible to control rainfall. However, there are spraying variables that can be controlled, such as application equipment. With no conclusive data published regarding the level of contact vs systemic action by hexazinone, applications are typically made by non-specific nozzles such as DriftGuard (TeeJet Inc.) or extended range nozzles. However, nozzles such as air induction nozzles exist to create bigger droplets for less drift and are recommended by the manufacturer for systemic herbicides, while dual-orifice bi-directional nozzles are at the opposite end of the spectrum. They produce finer droplets and apply liquid forwards and backwards, for more complete coverage of the plant, which is desirable for contact herbicides. Brecke (1981) achieved 91% and 100% control at two different locations one year after treatment with hexazinone at 1.1 kg ha^{-1} while Meyer and Baur (1979) achieved 68%-98% percent control, with the higher control being in the fall. More recently, Howard (2020) achieved anywhere from 70% in a summer application of 1.26 kg ha^{-1} hexazinone down to 3% control with a spring application using XR-8003 nozzles (Extended Range, TeeJet Inc.). Creech et al. (2015) performed experimentation on how equipment variables effect droplet size. XR nozzles were the smallest volume median diameter (VMD) nozzle and TTI nozzles were the largest, with 176% difference in droplet size between the two (Creech et al. 2015). Creech et al. (2015) also found that an increase from a 11003-orifice to a 11005-orifice increased VMD by 8%, and that glyphosate increased VMD 11% compared to water when all other variables were the same and concluded that effects on VMD from least to greatest are nozzle, operating pressure, herbicide, orifice volume and carrier volume. Ramsdale and Messersmith (2001) found that carfentrazone and imazamox, when applied through drift-reducing nozzles, were equally or more effective than conventional flat-fan nozzles in 95% of comparisons. Carfentrazone and imazamox are contact and translocated respectively, in the experimentation in this chapter both herbicides used are translocated. Research in Palmer amaranth (*Amaranthus palmeri)* by Berger et al. (2014) found that XR and AI (Air Induction, TeeJet Inc.) nozzles varied in coverage on water-sensitive cards, the coverage difference did not cause significant difference in Palmer amaranth control. In Sellers (2019) using hexazinone and glyphosate with a rotary wiper, the three treatments at both locations that provided the most control were applied bi-directionally. A bi-directional nozzle such as the Turbo Twin Jet used in this experiment works to emulate this action that applies herbicide to the front and back of the plant, but while spraying instead of using a rotary wiper. The experiment contained in this chapter evaluates similar variables as described in the literature above, but in smutgrass which has no published literature on how nozzles impact herbicide efficacy.

Materials and Methods

Experiment Locations

Field experiments were conducted in 2019-2020 and 2020-2021 in Brazos County, TX near Bryan. The soil type in the 2019-2020 Bryan location (30.7251095° N, -96.3683308° W) is a Spiller loamy fine sand (Fine, mixed, semiactive, thermic Ultic Paleustalfs) with a pH of 6.3. Mean annual precipitation is 80-100 cm, mean annual air temperature is 18.8 to 20°C and the frost-free period is 250-280 days. It is considered moderately well drained, high runoff class and moderate available water capacity. The 2020-2021 Bryan location (30.7271342° N, -96.3674128° W) is Tabor fine sandy loam (Fine, smectitic, thermic Oxyaquic Vertic Paleustalfs) with a pH of 6.6. Mean annual precipitation is 95-105 cm, the mean annual air temperature is 18.8 to 20°C, and the frost-free period is 254 to 273 days. It is considered moderately well drained, very high runoff and moderate available water capacity. Both locations have cattle in the area, but very few relative to the size of the land (USDA Soil Survey). The first year is within a pasture that is approximately 25 ha and is stocked with 1-5 head of cattle, the second year is within a pasture that is approximately 100 ha and stocked with 10-15 head of cattle. The smutgrass at both locations would be considered heavy infestation, less than one meter between most plants, often leaf tips of plants touching other plants. Noteworthy differences in soil by location is the first year is close to water, loosely packed, ebbs and flows in the topography allow for water holding to infiltrate and it is generally level from one end of the study to the other. While the second location is not within close vicinity to water, the soil is densely packed from cattle traffic, the topography is smooth, but it is sloped, making it good for runoff and bad for water infiltration. The primary desirable grass in the first year is common carpetgrass, along with common bermudagrass and bahiagrass, the primary desirable grass in the second year is common bermudagrass. All treatments received adequate incorporation rainfall (Table IV-5).

Experiment Establishment and Design

Both years were randomized complete block (RCB) designs with 2 m by 6 m plot sizes. The experiment initiated in 2019 was three replications, the experiment initiated in 2020 was four replications. All applications were made with a four nozzle, CO_2-powered backpack sprayer pressurized to 304 kPa. The spray volume of this study was 300 L ha^{-1} for all applications. The nozzles being evaluated are TTJ60-11003 (bi-directional, TeeJet Inc.) and TTI-11004 (uni-directional, TeeJet Inc.). The TTI-11004 nozzles were used at 3.0 mph, the TTJ60-11003 were used at 2.6 miles an hour to ensure both nozzles were applying 300 L ha^{-1} at the same pressure, due to changes in operating pressure being a significant variable in droplet size (Creech et al. 2017). A-POST herbicides were applied 11 September 2019 and 7 September 2020 and B-POST herbicides were applied 4 October 2019 and 28 September 2020. The herbicide treatments include glyphosate at 1.25 kg ha^{-1} mixed with hexazinone at 1.26 kg ha^{-1} at the A-POST timing, glyphosate at 1.25 kg ha^{-1} at the A-POST timing followed by hexazinone at 1.26 kg ha^{-1} at the B-POST timing, hexazinone alone at 1.26 kg ha^{-1} at the A-POST timing and glyphosate alone at 2.50 kg ha^{-1} at the A-POST timing.

Smutgrass Control and Forage Tolerance Evaluations

Evaluations were taken 4 weeks after the A-POST (4 WAA) in late October, 40 weeks after B-application (40 WAB) which was in the late spring as the plants break dormancy, and 46 weeks after B-application (46 WAB) which was in mid-June during summer. Evaluation was made in two ways, 1: visual evaluation of % weed control, 0% as no control and 100% as complete death; and 2: visual evaluation of % desirable grass tolerant to the herbicide, 0% being complete death and 100% being completely tolerant. Data were analyzed using SAS 9.4 (SAS Institute, Cary, N.C.). Data were subject to ANOVA and were analyzed for treatment by year interaction. Means were separated using the LSD test function within PROC GLM in SAS at alpha=0.05.

Results and Discussion

Smutgrass Control

There was a significant treatment by year interaction observed for 4 WAA and 40 WAB (P=0.0021, 0.0036 respectively), however no significant treatment by year interaction was observed for 46 WAB (P=0.2627). Consequently, data were analyzed separately by year for 4WAA and 40WAB and years were combined for 46WAB (Table IV-1).

Four Weeks After A-POST Application

There was no significant difference in smutgrass control between nozzle types within the same herbicide mixture in either year. In 2019, Glyphosate alone through both TTI and TTJ nozzles (87% and 83%, respectively) and hexazinone followed by glyphosate through both TTI and TTJ nozzles (82% and 80%, respectively) significantly outperformed hexazinone through both TTI and TTJ nozzles (72% and 70%, respectively). Hexazinone mixed with glyphosate was not significantly different than any other treatments (76% TTI, 78% TTJ) except hexazinone through TTJ (70%). In 2020, hexazinone mixed with glyphosate and glyphosate alone had 100% control with both nozzles. All treatments that contained glyphosate (all >90% control) significantly outperformed the hexazinone only plots (80% TTI, 78% TTJ). Hexazinone mixed with glyphosate regardless of nozzle (both 100%) provided significantly better control than a sequential application glyphosate followed by hexazinone through TTJ nozzles (90%) but did not provide significantly better control than the sequential application through TTI nozzles (94%). However, there was no significant difference between the sequential applications separated by nozzle. In conclusion, little difference occurred in 2019, with 17% control separating all treatments and no treatments achieving greater than 90% control. However, the 2020 experiment showed four treatments getting 100% control and two more being over 90% control with a total of 22% difference between all treatments 4 WAA. All Treatments were significantly different than the untreated check (Table IV-2).

Forty Weeks After B-POST Application

All treatments provided significant control compared to the untreated check and there was no significant difference by nozzle for any herbicide. The 2019 trial showed glyphosate alone achieving 100% control through both nozzles, glyphosate followed by hexazinone achieving 97% control through both nozzles, glyphosate mixed with hexazinone providing 80-87% control with no significant difference by nozzle, and hexazinone alone providing significantly less control than all treatments at 70-72%, except for glyphosate mixed with hexazinone through TTI nozzles (80%). In the 2020 trial, all treatments were significantly different than the untreated check. All treatments that contain glyphosate provided 98-100% control in year two and provided significantly better control than hexazinone alone regardless of nozzle (89% TTI, 81% TTJ) (Table IV-2).

Forty-Six Weeks After B-POST Application

Treatment by year interaction was not significant for this evaluation; therefore, years are combined (Table IV-1). All treatments were significantly different than the untreated check. Glyphosate alone provided 100% control through both nozzles and glyphosate followed by hexazinone provided 98% through both nozzles. These treatments significantly outperformed hexazinone alone, which provided 90% control through TTI nozzles and 89% control through TTJ nozzles. Glyphosate mixed with hexazinone provided 95% control through TTI and 94%

through TTJ and was not significantly different from any other treatment and the nozzles were not significantly different (Table IV-2; Figures IV-1 to 5).

Forage Tolerance

There was no significant treatment by year interaction for any evaluation timing (P=0.5986 4WAA, P=0.1601 40WAB. P=0.8781 46WAB). Therefore, the years were combined and separated by treatment for analysis (Table IV-1).

Four Weeks After A-POST Application

All treatments caused significant injury to the desirable grass compared to the untreated check and there was no significant difference by nozzle with the same herbicide treatments. Hexazinone alone caused significantly less damage than any other herbicide (64% TTI, 72% TTJ), glyphosate mixed with hexazinone caused significantly more damage than hexazinone alone (24% tolerance for both nozzles) but was significantly less injurious than glyphosate followed by hexazinone through TTJ nozzles (10%) and glyphosate alone (6% TTI, 4% TTJ). Glyphosate followed by hexazinone through TTI nozzles was tolerated by 14% of desirable grasses, which is not significantly different than the same herbicide through TTJ (10%) or the mixture of glyphosate and hexazinone (Table IV-3).

Forty Weeks After B-POST Application

There was no significant difference between the same herbicides by nozzle. Hexazinone alone treatments improved to being not significantly injurious compared to the untreated check (85% TTI, 84% TTJ) and were also tolerated significantly better than all other treatments, which all contain glyphosate. Glyphosate alone was the most injurious at 38% tolerance through both nozzles. Glyphosate either mixed with hexazinone or followed by hexazinone ranged from 59-

61% tolerance, which was significantly more than hexazinone alone but significantly less than glyphosate alone (Table IV-3).

Forty-Six Weeks After B-POST Application

All treatments were not significantly different from each other. Hexazinone alone was the only herbicide mixture that was not significantly injurious compared to the control (87% TTI, 88% TTJ). All treatments that contained glyphosate ranged from 75-82% tolerance and were significantly injurious compared to the control but were not significantly more injurious than hexazinone alone (Table IV-3, Figures IV-1 to 5).

Conclusion and Economic Analysis

The primary objective of this experiment was to determine whether or not the efficacy of these herbicide treatments varied based on nozzle. There was no significant difference for any of the nozzles within herbicides, all differences both in smutgrass control and desirable grass tolerance are attributed to the herbicide treatment. This mirrors what Berger et al. (2014) found in Palmer amaranth, that nozzles did not produce significant difference in control. The control of smutgrass with hexazinone alone at spring green up was 70-72% the first year and 81-89% the second year, while Howard (2019) achieved 70% control with the same rate of hexazinone also applied in summer and rated in the spring using XR-8003 nozzles from TeeJet Inc. at a location in Richards, TX. A key difference between these experiments is the application rate in Howard's (2020) experiment was 185 L ha^{-1} while the application rate for this experiment was 300 L ha^{-1}, along with these experiments all taking place in different soil types. To adequately compare the nozzles used in this research to the XR8003 nozzle, or any other nozzle, it would be important to apply them at the same location using the same mix and application rates to reduce variables. In terms of economic feasibility, using Ferrell (2006) evaluation of approximately \$92 ha^{-1} being lost from cattle operations not controlling smutgrass, the treatment of glyphosate alone at 2.50 kg ha^{-1} would cost approximately \$65 ha^{-1}, which seems as if it would pay for itself in one year (Do My Own, 2021). The severe damage to desirable grasses in the first two evaluations would make the cost-benefit analysis challenging and would require further research to value not only reduced price of calves caused by smutgrass infestation, but also possible reduced value due to the herbicide injuring the grass the livestock feed on. This is important because even though the cattle can remain in the location due to the rate not exceeding the federal restriction, the available forage would still be greatly reduced, and therefore the stocking rate would be greatly reduced. Mixing hexazinone with 1.25 kg ha^{-1} glyphosate was significantly safer early in the study compared to glyphosate alone, but still significantly injurious at 24% tolerance from both nozzles, while also being nearly 6x more expensive at \$240.50 ha^{-1} and not being significantly different in smutgrass control by the end of the study (Do My Own, 2021; Forestry Suppliers, 2021). The herbicide cost of glyphosate followed by hexazinone is the same as these herbicides tank-mixed, \$240.50 ha^{-1}, with an increased cost of making a sequential application. By 46 WAB, there was no significant difference in smutgrass control or desirable grass tolerance between the tank-mix and sequential applications, therefore it seems that the extra time and money involved with making a sequential application is not worth it. However, there was also no significant difference at 46 WAB between the hexazinone + glyphosate mix, glyphosate followed by hexazinone and glyphosate alone, while the treatments containing hexazinone cost \$175 more than the rate of glyphosate used alone. Hexazinone alone at \$208 ha^{-1} provided significantly less control than glyphosate alone and glyphosate followed by hexazinone, but 89-90% control is still considered good control and was significantly safer on desirable grasses until the glyphosate treatments recovered at 46 WAB. Considering that the primary research variable in this experiment was nozzle selection, it is also important to consider the cost of the nozzles. The TTI-11004 (TeeJet Inc.) nozzles cost $8.50 each, while the TTJ60-11003 nozzles cost $7.50 each and XR-8003 used in Howard (2020) cost $3.50. The conclusion on nozzles is that using the TTI or TTJ nozzles will not make a significant difference on smutgrass control or desirable grass tolerance with these herbicides. The TTI nozzles large droplets will cause less wind drift, but neither hexazinone nor glyphosate are considered drift prone in good spraying conditions, so while this should be considered, it is not necessarily important. To assess the value of these nozzles compared to the XR-8003 which is less than half the price, future research suggestions include comparing the XR-8003 to other nozzles in the same experiment, as described previously in this paragraph.

Photos of Nozzle Experiment

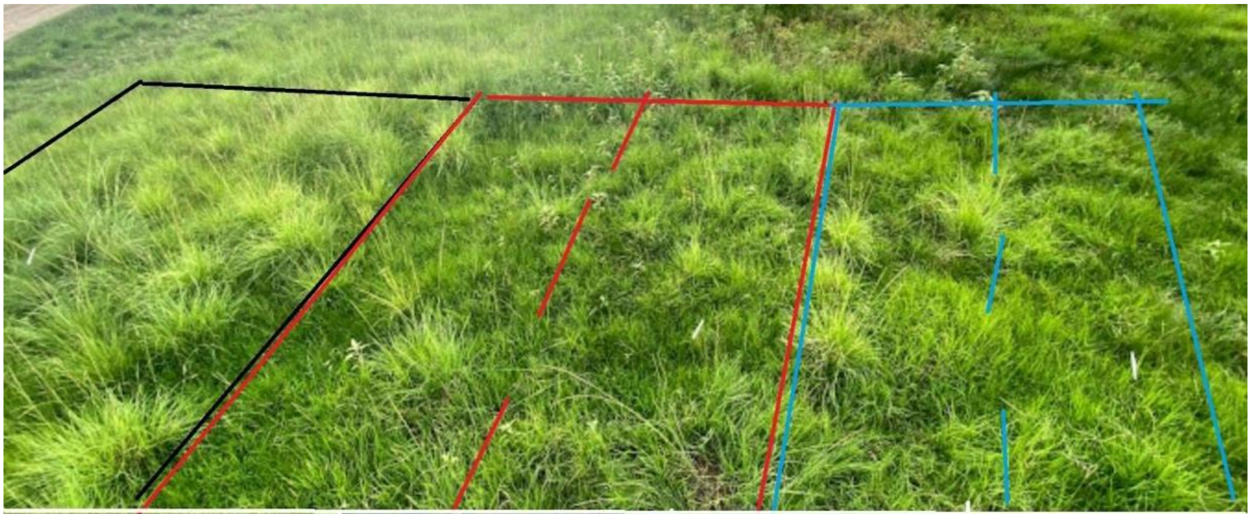

Figure IV-1 (Top): 2019 Nozzle Study 46 WAB (Black=UTC, Red= Gly + Hex, Blue= Gly fb Hex), dashed lines represent separation by nozzle (left = TTI, right = TTJ)

Figure IV-2 (Bottom left): 2020 Nozzle Study- Untreated Check 46 WAB

Figure IV-3 (Bottom middle/left): 2020 Nozzle Study- Hexazinone (Left TTI, Right TTJ) 46 WAB

Figure IV-4 (Bottom middle/right): 2020 Nozzle Study- Glyphosate fb Hexazinone (Left TTI, Right TTJ) 46 WAB

Figure IV-5 (Bottom right) 2020 Nozzle Study-Glyphosate by TTI only 46 WAB

Table IV-1. Analysis of variance for experiment 3.

	SG Control			DG Tolerance		
	df	P value	SS	df	P value	SS
Effect			30 DAT[a]			
Year	1	<0.0001	1601.66	1	0.9131	1.67
Treatment	9	<0.0001	86692.85	9	<0.0001	93042.21
Year X Treatment	9	0.0021	991.93	9	0.5986	1024.23
			40 WAB			
Year	1	0.0003	510.42	1	0.0118	1083.75
Treatment	9	<0.0001	96665.00	9	<0.0001	33294.64
Year X Treatment	9	0.0036	985.00	9	0.1601	2194.52
			46 WAB			
Year	1	0.0094	106.67	1	0.3280	81.67
Treatment	9	<0.0001	88322.50	9	0.0466	1629.27
Year X Treatment	9	0.2627	160.00	9	0.8781	343.33

[a] Abbreviations: SG, Smutgrass, DG, Desirable Grass WAA, Weeks After A-POST: WAB, Weeks After B-POST

Table IV-2. Smutgrass control 4 WAA, 40 WAB and 46 WAB by herbicide treatment and year.

Herbicide	Rate	Timing	Nozzle	4 WAA 2019-2020	4 WAA 2020-2021	40 WAB 2019-2020	40 WAB 2020-2021	46WAB Combined
	–kg ha $^{-1}$ –			% Control				
Glyphosate Hexazinone	1.25 1.26	A	TTI	76bc	100a	80cd	100a	95ba
Glyphosate Hexazinone	1.25 1.26	A	TTJ	78bc	100a	87bc	98a	94ba
Glyphosate Hexazinone	1.25 1.26	A B	TTI	82ba	94ab	97ba	100a	98a
Glyphosate Hexazinone	1.25 1.26	A B	TTJ	80ba	90b	97ba	100a	98a
Glyphosate	2.50	A	TTI	87a	100a	100a	100a	100a
Glyphosate	2.50	A	TTJ	83ba	100a	100a	100a	100a
Hexazinone	1.26	A	TTI	72cd	80c	72d	89b	90b
Hexazinone	1.26	A	TTJ	70d	78c	70d	81b	89b

[a] Abbreviations: WAA, Weeks After A-POST; WAB, Weeks After B-POST

[b] Means within the same column, followed by the same letters are not significantly different.

Table IV-3. Desirable grass tolerance 4WAA, 40WAB and 46 WAB, by herbicide treatment

Herbicide	Rate	Timing	Nozzle	Years Combined 4WAA[a]	Years Combined 40WAB	Years Combined 46 WAB
	–kg ha $^{-1}$ –			% Tolerance		
Glyphosate Hexazinone	1.25 1.26	A	TTI	24c[b]	61c	82b
Glyphosate Hexazinone	1.25 1.26	A	TTJ	24c	60c	82b
Glyphosate Hexazinone	1.25 1.26	A B	TTI	14cd	59c	76b
Glyphosate Hexazinone	1.25 1.26	A B	TTJ	10d	60c	79b
Glyphosate	2.50	A	TTI	6d	38d	80b
Glyphosate	2.50	A	TTJ	4d	38d	75b
Hexazinone	1.26	A	TTI	64b	85a	87ab
Hexazinone	1.26	A	TTJ	72b	84a	88ab

[a] Abbreviations: WAA, Weeks After A-POST; WAA, Weeks After B-POST

[b] Means within the same column followed by the same letters are not significantly different at 5% probability level

Table IV-4. Herbicide application dates and rainfall amounts through 46 WAB.

			Rainfall[a]					
Year	Application Timing	Application Date	7 DBT[b]	7 DAT	14 DAT	21 DAT	40 WAB[c]	46 WAB
			cm					
2019-2020	A-POST	11 September	2.1	2.2	2.9	2.9	63.5	71.6
	B-POST	4 October	0	6.9	8.6	12.9		
2020-2021	A-POST	7 September	6.9	2.2	2.2	5.6	38.1	63.5
	B-POST	28 September	3.4	0.5	0.8	1.27		

[a] Cumulative amount from day of treatment until day specified

[b] Abbreviations: DBT, Days Before Treatment; DAT, Days After Treatment; WA, Weeks After

[c] 40 WAB and 46 WAB amounts are cumulative from trial initiation (A-POST) until day specified

CHAPTER V EVALUATION OF THE IMPACT OF APPLICATION METHOD ON HERBICIDE EFFICACY FOR SMUTGRASS CONTROL IN INDIVIDUAL PLANT TREATMENTS

Introduction

This chapter contains two experiments to assess how methodology impacts herbicide efficacy on smutgrass in individual plant treatments. The effective target area of hexazinone for the greatest efficacy is ambiguous. The label states that the herbicide is absorbed through both the roots and foliage. In terms of foliar uptake, the label recommends applying when weeds are less than 5 cm in height or diameter, applying during temperatures above 26.6 °C with high humidity and good soil moisture. The label also says that symptoms usually appear within two weeks after applications in warm, humid conditions, but if inadequate rainfall is achieved, foliage may recover from the contact effects and continue to grow. In regard to root uptake, the label states that 0.64-1.28 cm of rainfall within two weeks of application will lead to the best results. While Mislevy et al. (1980) discovered that hexazinone is primarily uptaken by the roots, the label does not make recommendations regarding whether foliage or the root system is a more appropriate target area for a hexazinone application. Collecting data with multiple application methods and equivalent herbicide mixtures will help determine which application methods are the most effective. The methods used in this chapter are individual plant foliar application, individual plant aerial application from an unmanned aerial sprayer (UAS) and under the canopy, post-directed individual plant treatment. Experiment 1 (Target Area Experiment) compares the two methods of human applied treatments to address the lack of target recommendation in the hexazinone label. Experiment two (UAS Experiment) compares foliar human applied treatments to UAS applied treatments. Collecting data on aerial application is important due to the impact of smutgrass on topography, mainly the plant's ability to make grasslands nearly impossible to drive through, much less maintain a constant speed. The mechanical fatigue caused on ground equipment by smutgrass can damage the equipment, therefore it would be advantageous to apply herbicide from the air. Many studies have examined the potential of imaging plants from the air (Castillejo-Gonzales & de Castro 2019; Laliberte, 2010; Mirik et al. 2013; Pena et al. 2013). Being able to clearly image, accurately identify and map weeds is a great advancement in weed control, the next logical step is controlling the weeds. Hunter et al. (2020) experimented with applying pesticides from a UAV and determined that pesticide coverage at 1 m s $^{-1}$ ranged from 30% to 60%, while applications at 7 m s $^{-1}$ dropped coverage down to 13-22%. Hunter et al. (2020) concluded that coverage decreased as application speed increased, and that extended range flat spray nozzle coverage declined faster than air induction nozzles. Ahmad et al. (2020) produced a similar experiment and also found that droplet deposition increased as altitude and speed decreased, and that droplet density and coverage decreased with increases in speed and altitude. However, both of these studies, along with many others studying UAS applications, utilized broadcast applications (Tang et al. 2018; Wang et al. 2019; Xinyu et al. 2014). Due to the uneven growing patterns of smutgrass across pastures, individual plant treatments were used in this experiment. Richardson et al. (2020) experimented with an artificial tree to determine the accuracy of a UAS in individual plant treatments. They concluded that the positioning accuracy of the UAV was "excellent", but the droplet sizes were much larger than expected. They utilized targets that were 2 m tall and two different diameters of 1 and 2 m. This is substantially higher than a smutgrass plant, which is approximately 1 m tall to the top of the seed head, but 1 m diameter matches well to the size of a smutgrass plant (University of California, 2016). They found that the application was accurate and consistently hit the center of the target, but also stated that wind was low to none throughout the study. Their experiment varied from the UAS experiment in this chapter due to their use of artificial plants, and their use of a 4-rotor UAS. The experimentation performed in this chapter is on real, living smutgrass plants and utilizes a 6-rotor UAS and is focused on measuring weed control and forage tolerance, not necessarily UAS accuracy. In New Zealand, weed control around crop trees was traditionally done by hand (Richardson et al. 2019). Now, helicopters are being used for individual tree treatment and also to control invasive conifers (Gous et al. 2014). In conclusion, the Target Site Experiment builds upon Mislevy et al. (1980) to determine the best target area for hexazinone on a smutgrass plant. The UAS Experiment builds on Richardson et al. (2020) to determine if spot spraying with a UAS is a viable alternative to applying herbicide by hand.

Materials and Methods

Target Area Experiment

Experiment Locations

Field experimentation was conducted at two locations simultaneously on a cattle ranch in Brazos County near Bryan, TX in 2020. The soil type in the first location, which is a pasture, (30.725833° N, 96.368611° W) is Tabor fine sandy loam (Fine, smectitic, thermic Oxyaquic Vertic Paleustalfs) with a pH of 6.6. Mean annual precipitation is 95-105 cm, the mean annual air temperature is 18.8 to 20°C, and the frost-free period is 254 to 273 days. It is considered moderately well drained, very high runoff and moderate available water capacity. This location is not in close proximity to any water and is densely packed and is a generally dry soil. The second location, which is in a cattle holding pen near a pond, (30.724722° N, -96.368333° W) is a Spiller loamy fine sand (Fine, mixed, semiactive, thermic Ultic Paleustalfs) with a pH of 6.3. Mean annual precipitation is 80-100 cm, mean annual air temperature is 18.8 to 20°C and the frost-free period is 250-280 days. It is considered moderately well drained, high runoff class and moderate available water capacity. This location is in close proximity to a pond, is not notably compacted and retains more moisture than the first location. Both locations are considered light infestations of smutgrass with approximately 20-25% groundcover and the desirable grass at both locations is exclusively common bermudagrass.

Experiment Establishment and Design

This experiment was initiated in the summer of 2020 at both locations in Brazos County, Texas as a completely randomized design (CRD) with individual plants being the experimental unit for each treatment. Both locations contained five replications. The herbicide used in both treatments is hexazinone at 0.08 g plant^{-1}, which is the same mix rate as the "low rate" in chapter II. All herbicide applications were made in 35 ml of solution. Applications were made using a single TG-1.5 Full Cone Nozzle (TeeJet Inc.) powered by a CO_2 backpack calibrated to 206 kPa. The two treatments in this experiment are 0.08 g plant $^{-1}$ applied to the foliage of the plant and 0.08 g plant $^{-1}$ being applied post-direct below the canopy of the plant. Herbicide applications were made on 20 July 2020 at both locations.

Smutgrass Control and Desirable Forage Evaluations

The target area experiment was evaluated in three ways- 1: Visual evaluation of % control- 0% being no control and 100% being complete control, 2: Visual evaluation of % desirable grass tolerance growing within the smutgrass plant (Figure V-2)- 0% being complete death and 100% being completely tolerant, and 3: Visual evaluation of % desirable grass tolerance growing around the smutgrass plant- 0% being complete death and 100% being completely tolerant. Data for both experiments were analyzed using SAS 9.4 (SAS Institute, Cary, N.C.). Data were subject to ANOVA and were analyzed for treatment by year interaction. Means were separated using the LSD test function within PROC GLM in SAS at alpha=0.05.

UAS Experiment

Experiment Locations

Field experimentation was conducted simultaneously in two locations in 2019. One location was in Brazos County, TX (30.7271342° N, -96.3674128° W) in a Tabor fine sandy loam (Fine, smectitic, thermic Oxyaquic Vertic Paleustalfs) with a pH of 6.6. Mean annual precipitation is 95-105 cm, the mean annual air temperature is 18.8 to 20°C, and the frost-free period is 254 to 273 days. It is considered moderately well drained, very high runoff and moderate available water capacity. The second location was in Grimes County, TX (30.5105663° N, -95.8338024° W) in a Huntsburg loamy fine sand (Fine, mixed, semiactive, thermic Aquic Paludalfs) with a pH of 5.2. Mean annual precipitation is 102-122 cm, the mean annual air temperature is 18.9 to 20°C and the frost-free period is 240 to 270 days. It is moderately well drained, very high runoff and moderate available water capacity. Both locations consist exclusively of common bermudagrass as the desirable grass and smutgrass as the target weed. Both locations are considered lightly infested, with smutgrass plants averaging more than one meter from other plants. This light infestation was chosen to ensure that only one smutgrass plant would be receiving herbicide and that losses would be captured by the bermudagrass surrounding the target smutgrass plant. Both locations were in active cattle production prior to the study. Fences were built to keep the livestock out of the trial area, but all treatments used in this experiment would not be subject to any federal grazing restriction.

Experiment Establishment and Design

Field experimentation was conducted simultaneously at two locations in 2019, one location in Bryan, Texas and one location in Richards, Texas. Both locations of this experiment were completely randomized designs (RCD) with four replications of each treatment, with individual plants being the experimental unit of each treatment. The treatments were applied at both locations on 3 October 2019. All herbicides were applied both from the air with a UAS, along with a backpack sprayer to compare the applications methods. The UAS nozzle applies a 1.2-meter diameter circle from the application altitude of 2 meters, while the hand applied treatments were focused to the approximately 0.6 m diameter area of the crown of the plant, with small variation depending on the size of the plant. The coverage area of the UAS must be larger than the plant due to the potential for the UAS to move while in the air. To compensate for this area coverage difference, the UAS applies 70 ml per plant considering the UAS sprays a 1.2 m circle, while mature smutgrass plants grow to approximately 0.6 m in diameter. This means 35 ml of solution is applied to the target, while 35 ml is lost as “endo-losses”. The 35 ml reaching the target matches the hand applied dose and provides the same amount of active ingredient on the target plant as the hand application. The herbicide treatments in this study are glyphosate at 0.38 g plant $^{-1}$, hexazinone at 0.08 g plant $^{-1}$, and glyphosate at 0.19 + hexazinone at 0.08 reaching the plant. Because the UAS applies twice as much solution to an area twice the size of the plant, the concentration reaching the plant matched the hand application. The UAS was outfitted with a 10 L tank and nozzle that fires directly below the aircraft at approximately 30 degrees It is powered by an electric pump and operates at 412 kpa. The hand spraying was applied with a carbon dioxide powered backpack, using a TG-1.5 nozzle at 206 kpa. Applications were made at both locations in this experiment on 3 October 2019.

Desirable Grass and Forage Tolerance Evaluations

This experiment was evaluated using five different methods of evaluation, all at thirty days after treatment. The methods used for evaluation were- 1: Normalized Difference Vegetation Index (NDVI) of the foliage, 2: NDVI of the crown of the smutgrass plant, 3: visual evaluation of % control- 0% as no control and 100% being complete death, 4: NDVI of desirable grasses surrounding the target smutgrass plant, and 5: visual evaluation of % desirable grass tolerant to the herbicide- 0% as complete death and 100% being no visible injury. NDVI was measured using a Trimble Greenseeker (Trimble Inc.). NDVI is used to measure the difference in light absorbed by chlorophyll compared to the amount reflected by the rest of the leaf, which can be an indicator of plant health. However, NDVI varies differently from % control and % tolerance due to NDVI only measuring light reflectance differences, while % control and % tolerance also account for plant height, leaf area, discoloration and seedhead suppression.

Results and Discussion

Target Area Experiment

There was significant treatment by location interaction in desirable grass tolerance, both inside and surrounding the target area 30 days after treatment (P=<0.0156 & 0.008, respectively). There was no significant treatment by location interaction for smutgrass necrosis 30 days after treatment (P=0.3966). At 75 days after treatment there was significant treatment by location interaction for smutgrass necrosis (P=0.0263) but neither desirable grass tolerance inside nor surrounding the target area had significant treatment by location interaction (p=0.5180 inside, p=0.0554 outside). There was no significant treatment by location interaction for smutgrass control or outside desirable grass tolerance 240 days after treatment (both P=1) and no evaluation was made for desirable grass tolerance within the target area at 240 days. Therefore, locations are combined for necrosis 30 and 240 days after treatment and analyzed separately 75 days after treatment. Desirable grass tolerance inside the target is analyzed separately by location at 30 days after treatment and locations are combined for 75 days after treatment. Desirable grass tolerance outside the target is analyzed separately by location 30 days after treatment and locations are combined for 75 and 240 days after treatment (Table V-1).

Smutgrass Control

Foliar hexazinone (100%) caused significantly more necrosis than applying it post-directed below the canopy of the plant (95%) after 30 days (Figures V-1, 2). At 75 days, both treatments provided 100% control near the pond. In the pasture area, foliar hexazinone caused 100% necrosis, which is significantly more than post-direct application which caused 98% control (Figures V-3, V-4). 240 days after treatment, none of the treated plants survived to green up, therefore both methods achieved 100% control at both locations (Figures V-5, V-6). Both methods were significantly different than the untreated check (Table V-2).

Forage Tolerance

Thirty days after treatment in the pasture, neither treatment had any desirable grass regrowth within the smutgrass plant and therefore, were not significantly different from each other but were significantly injurious compared to the untreated check. However, at the pond location thirty days after treatment, there was no desirable grass within the smutgrass plant of any foliar-treated plants (Figure V-1), but multiple plants treated with post-direct hexazinone had bermudagrass growing through the necrotic smutgrass plant (Figure V-2), which resulted in an 87% tolerance assessment for tolerance to post-direct inside the target area. Both methods were significantly injurious compared to the untreated check at this location as well. In the thirty-day rating of desirable grass tolerance immediately surrounding the smutgrass plant, foliar hexazinone (70% pond, 47% pasture) caused significantly less injury than post-direct (32% pond, 21% pasture). At 75 days after treatment, locations were combined, and all treatments were significantly injurious compared to the untreated check. There was no significant difference for tolerance within the smutgrass plant (17% foliar, 21% post-direct), but foliar hexazinone (84%) was tolerated significantly better in the area surrounding the plant than post-direct hexazinone (37%, Figures V-3, 4). By spring green-up at 240 days after treatment, only desirable grass around the target area was evaluated, due to the necrotic smutgrass carcasses covering all of the soil within the target area (Figures V-5, 6). Both methods had recovered to 100% tolerance and were therefore not injurious compared to the untreated check (Table V-3).

UAS Experiment

There was significant treatment by location interaction for foliage NDVI evaluation (P=0.0022). NDVI of the crown (P=0.3668), visual smutgrass control evaluation (P=0.5884), NDVI of desirable grasses (P=0.1172) and visual desirable grass tolerance evaluation (P=0.0643) did not have significant treatment by location interaction. Therefore, the upper-foliage NDVI evaluation is separated by location for analysis, while all other evaluations are combined by location (Table V-5).

Smutgrass Control

NDVI Evaluation of Upper-Foliage

All treatments lowered the NDVI reading of the upper foliage of the target plant compared to the untreated control at both locations. The only significant difference by method at this evaluation came from glyphosate at the Richards location, with the hand application providing a 17 NDVI reading (Figure V-8) while the UAS application provided a 26 (Figure V-7). Glyphosate by hand, and glyphosate + hexazinone regardless of application (16 hand, 17 UAS) method significantly outperformed both glyphosate by UAS (26) and hexazinone by UAS (26), but not hexazinone by hand (22). In Bryan, glyphosate by hand (17) significantly outperformed hexazinone from both application methods (23 hand, 22 UAS; Figures V-11 and V-12) but was not significantly different from glyphosate by UAS (18) or glyphosate + hexazinone regardless of application method (20 hand, 21 UAS; Figures V-9 and V-10) (Table V-6).

NDVI Evaluation of the Crown

There was no significant treatment by location interaction for this evaluation (P=0.3668), consequently the locations are combined for evaluation (Table V-5). All treatments had significantly lower NDVI in the crown than the control (44). The only significant difference by application method was glyphosate by hand (20, Figure V-8) was significantly lower than glyphosate by UAS (30, Figure V-7). Glyphosate by hand also significantly outperformed hexazinone from both application methods (32 hand, 31 UAS). Glyphosate by hand and glyphosate + hexazinone from both application methods (27 hand, 30 UAS) were not significantly different (Table V-6).

Visual Evaluation of Control

There was no significant treatment by location interaction for this evaluation (P=0.1552), consequently the locations are combined for evaluation (Table V-5). When visually evaluated, no treatments were significantly different from each other, but all were significantly different than the untreated check. All treatments provided <90% visual estimated control at 30 days after treatment, which means little to no green remaining, with a high likelihood the plant will end up dying (Figures V-7 to V-12) (Table V-6).

Desirable Grass Tolerance

NDVI Reading of Desirable Grasses

There was no significant treatment by location interaction for either method of evaluating desirable grass tolerance (P=0.1172 for NDVI, P=0.1214 for visual evaluation, Table V-5). All treatments caused significant reduction in NDVI reading of desirable forage surrounding the plant compared to the untreated check (41) Hexazinone caused the least reduction, with an NDVI of 34 from both application methods. Glyphosate (25 for both methods) and glyphosate + hexazinone (26 for both methods) reduced NDVI significantly more than hexazinone alone but were not significantly different from each other (Table V-7).

Visual Evaluation of Desirable Grass Tolerance

There were no significant differences in desirable grass tolerance in the visual evaluation by application method. Hexazinone did not cause significant visual injury compared to the untreated check (95% hand, 93% UAS; Figures V-11,12) and was tolerated significantly more than any of the other treatments. Glyphosate (72% hand, 73% UAS; Figures V-7,8) and glyphosate + hexazinone (74% hand, 73% UAS; Figures V-9,10) all caused significant damage compared to the control and hexazinone only treatments (Table V-7).

Conclusion and Economic Analysis

The objective of this chapter was to determine how application methods impact herbicide efficacy. The target area experiment shows that by 240 days after application, treating a smutgrass plant with 0.08 g plant $^{-1}$ of hexazinone in individual plant treatment will control it, and the desirable grass will recover, regardless of whether you target the foliage or apply as a post-direct below the canopy (Figures V-5 and V-6). The post-direct application did not cause complete necrosis of the smutgrass plant until after winter dormancy, while application to the foliage caused 100% necrosis within thirty days. Applying post-direct did allow bermudagrass to grow into the target area more quickly at one location, at the expense of the bermudagrass surrounding the smutgrass plant (Figure V-2). Conversely, by applying the herbicide to the foliage, any grasses within the target will likely be damaged, while saving forage surrounding the target. At 30 and 75 days, applying the herbicide to the foliage resulted in significantly less damage to the surrounding bermudagrass than applying post-direct below the canopy. Importantly to note, there was no bermudagrass within the target area after green-up, due to the necrotic smutgrass plants essentially creating a mulch in the spot they had been growing in. Therefore, priority should be given to bermudagrass outside the target area, as it is more likely to survive long term, and also accounts for more area of forage. Applying the hexazinone to the foliage of the plant prioritizes the tolerance of the bermudagrass surrounding the target area, and also causes complete necrosis within thirty days, which a post-direct application did not do. While this does not follow hexazinone through translocation to determine where it is actually working at a biological level within the plant, this experiment ultimately concludes that hexazinone is more effective when applied to the foliage with adequate activating precipitation (Table V-4). Further research ideas in this area include, experimenting with whether the smutgrass control and desirable grass tolerance changes in the event of receiving less than adequate rainfall. Another beneficial experiment would be to determine whether lower rates can still provide 100% control and determine if they are safer for desirable grasses, or if there is greater difference depending on target area. While the first experiment compares two ground-based methods, with different target areas, the second experiment compares a ground-based method to an aerial method, both targeting the foliage. Hexazinone alone, and glyphosate + hexazinone performed uniformly, regardless of application methods. There were no significant differences by application method for these herbicides in any of the evaluations. However, glyphosate alone varied significantly by application method in two evaluations- NDVI outside the plant at the Richards location, and NDVI inside the plant with locations combined. Glyphosate by hand averaged a significantly lower NDVI reading in both of these evaluations but did not have a significantly higher control rate when visually evaluated. One possible explanation for this variation is that NDVI only accounts for difference in light reflectance (color) of the plant, while visual evaluation accounts for color (necrosis and chlorosis) plus changes in physiology and morphology of the plant that can be attributed to herbicide, such as changes in leaf shape, seed head suppression and abnormal growth habits. It is important to note, that this study was designed to ensure that the amount of herbicide reaching the target plant was equal by application method, which required twice as much herbicide from the UAS in order to cover twice as much area in the same amount of herbicide. The cost of glyphosate in the hand treatments was 0.80 cents plant $^{-1}$ and hexazinone alone used in hand spraying was 1.39 cents plant $^{-1}$, while the cost of these herbicides sprayed aerially was 1.60 cents and 2.78 cents plant^{-1} respectively due to the necessity to apply twice as much herbicide to cover the target. The mixture of glyphosate + hexazinone costed 1.79 cents plant $^{-1}$ by hand, while applying it aerially costed 3.58 cents plant^{-1}. Along with a higher cost of herbicide, the lowest available cost for a UAS is $1649 from (Arris Hobby, 2021), while the TTA M6E Agriculture Drone (Beijing TTAviation Company LTD.) used in this experiment is approximately $7000. Meanwhile pump-up backpack sprayers cost approximately $59 (www.homedepot.com) and ~80 L electric sprayers to mount on an ATV or truck cost $120-200 dollars (www.northerntool.com), the additional cost of a UAS to an operation looking to control smutgrass is high. However, spending thousands of dollars for an ATV or truck is justifiable in a ranch setting due to the ability of the equipment to not only act as a sprayer, but as a cattle feeder, survey vehicle, hunting vehicle and many other needs, drones can be justified in this same capacity. Drones outfitted to apply herbicide can also be used to image, and a primary advantage of this is to be able to map areas of high weed density from the air to make the herbicide application more efficient. This increase in utility also helps make the cost of the machine more justifiable. Howard (2020) showed an imaging drone identifying smutgrass in bermudagrass with over 85% accuracy. Costs of labor must also be factored in, which are highly variable, considering how much skill and licensing is required to apply herbicide from a UAS, compared to no licensing required to apply the hand treatments in this experiment. In conclusion, there is much more research to be done, to determine other uses of drones, create the most effective herbicide mixtures, and increase the accessibility of them by lowering the price and teaching more people the skills to properly operate the piece of equipment. This research shows that in both hand applied treatments to different target areas, and different methodology altogether, proper operation of any equipment is key. The first step is choosing the correct equipment. “Correct” is different for every applicator and knowing the pros and cons of hand application and aerial application is critical to making the correct choice. Even after choosing the correct equipment, improper operation can increase the amount of time it takes the herbicide to be effective and can cause unnecessary damage to the surrounding grasses. Therefore, it is important to consider the impact of the application variables in this chapter to assist the applicator in making the best decision.

Target Area Experiment Photos






Figure V-1 (top left): Foliar hexazinone 30 days after treatment near pond.

Figure V-2 (top right): Post-direct hexazinone 30 days after treatment near pond.

Figure V-3 (middle left): Foliar hexazinone 75 days after treatment in pasture.

Figure V-4 (middle right): Post-direct hexazinone 75 days after treatment in pasture.

Figure V-5 (bottom left): Foliar hexazinone 240 days after treatment near pond.

Figure V-6 (bottom right): Post-direct hexazinone 240 days after treatment near pond.

UAS Experiment Photos






Figure V-7 (top left): Glyphosate by UAS 30 DAT at Richards.

Figure V-8 (top right): Glyphosate by hand 30 DAT at Richards.

Figure V-9 (middle left): Glyphosate + Hexazinone by UAS 30 DAT at Bryan.

Figure V-10 (middle right): Glyphosate + Hexazinone by Hand 30 DAT at Bryan.

Figure V-11 (bottom left): Hexazinone by UAS 30 DAT at Bryan.

Figure V-12 (bottom right): Hexazinone by hand 30 DAT at Bryan.

Table V-1. Analysis of variance for Target Area Experiment.

	SG Control			DG Tolerance Inside Plant			DG Tolerance Surrounding Plant		
	df	P value	SS	df	P value	SS	df	P value	SS
Effect					30 DAT				
Location	1	0.337	20.83	1	0.0306	3000.00	1	0.0221	750.00
Treatment	2	<0.0001	62518.52	2	<0.0001	56363.63	2	<0.0001	37792.42
Location X Treatment	2	0.3966	41.67	2	0.0156	6000.00	2	0.0008	3020.00
					75 DAT				
Location	1	0.0451	20.83	1	0.1285	520.83	1	0.3387	300.83
Treatment	2	<0.0001	71704.55	2	<0.0001	48078.78	2	<0.0001	18531.29
Location X Treatment	2	0.0263	41.67	2	0.518	271.67	2	0.0554	2251.67
					240 DAT				
Location	1	1	0				1	1	0
Treatment	2	<0.0001	66666.67				2	1	0
Location X Treatment	2	1	0				2	1	0

[a] Abbreviations: SG, Smutgrass; DG, Desirable Grass; DAT, Days After Treatment

Table V-2. Smutgrass control 30, 75 and 240 DAT by application method and location.

			30 DAT[a]	75 DAT		240 DAT
Herbicide	Rate	Method	Combined	Pond	Pasture	Combined
	g plant $^{-1}$		——— % Necrosis ———			
Hexazinone	0.08	Foliar	100a[b]	100a	100a	100a
Hexazinone	0.08	PDIR	93b	100a	98b	100a

[a] Abbreviation: DAT, Days After Treatment

[b] Means within the same column, followed by the same letters are not significantly different.

Table V-3. Desirable grass tolerance 30, 75 and 240 DAT by application method and location.

			30 DAT[a]				75 DAT		240 DAT
			Inside[b]		Outside		Inside	Outside	Outside
Herbicide	Rate	Method	Pond	Pasture	Pond	Pasture	Combined	Combined	Combined
	g plant $^{-1}$		——— % Tolerance ———						
Hexazinone	0.08	Foliar	0c[c]	0b	70b	47b	17b	84b	100a
Hexazinone	0.08	PDIR	87b	0b	32c	21c	21b	37c	100a

[a] Abbreviation: DAT, Days After Treatment

[b] “Inside”, growing up through the crown of the smutgrass plant; “Outside”, surrounding the smutgrass plant

[c] Means within the same column, followed by the same letters are not significantly different.

Table V-4. Application dates and rainfall amounts for target area experiment through 240 DAT.

		Rainfall[a]				
Location	Application Date	7DBT[b]	7DAT	14DAT	75 DAT	240 DAT
		cm				
Pond Area	20 July 2020	0	3.1	5.2	20.3	55.3
Pasture	20 July 2020	0	3.1	5.2	20.3	55.3

[a] Cumulative amount from day of treatment until day specified

[b] Abbreviations: DBT, Days Before Treatment; DAT, Days After Treatment

Table V-1. Analysis of Variance for Experiment 4

	Visual SG Control				Visual DG Tolerance		
Effect	df	P value	SS	30 DAT[a]	df	P value	SS
Location	1	0.4554	114.29		1	0.0018	36.16
Treatment	6	<0.0001	62971.43		6	<0.0001	6502.21
Location X Treatment	6	0.5884	935.7100		6	0.0643	40.71
	Outside NDVI				Inside NDVI		
	df	P value	SS	30 DAT	df	P value	SS
Location	1	0.0548	64.29		1	0.9852	0.02
Treatment	6	<0.0001	1933.36		6	<0.0001	2494.5
Location X Treatment	6	0.0022	477.21		6	0.3668	350.86
	Desirable Grass NDVI						
	df	P value	SS	30 DAT			
Location	1	0.2316	23.14				
Treatment	6	<0.0001	1843.18				
Location X Treatment	6	0.1172	179.61				

[a] Abbreviations: SG, Smutgrass; DG, Desirable Grass; DAT, Days After Treatment; NDVI, Normalized Difference Vegetation Index

Table V-6. Smutgrass control 30 DAT, by treatment and location.

			Inside Crown Greenseeker		Foliar Greenseeker	Visual Evaluation
Herbicide	Rate	Method	Bryan	Richards	Combined	Combined
	g plant $^{-1}$		——— NDVI[a] Reading	———	———	– % Control–
Glyphosate	0.38	Hand	17c[b]	17c	20c	100a
Glyphosate	0.38	UAS	18bc	26b	30b	94a
Hexazinone	0.08	Hand	23b	22bc	32b	94a
Hexazinone	0.08	UAS	22b	26b	31b	91a
Glyphosate Hexazinone	0.19 0.08	Hand	20bc	16c	27bc	100a
Glyphosate Hexazinone	0.19 0.08	UAS	21bc	17c	30bc	94a
UTC	N/A	N/A	30a	42a	44a	0b

a. Abbreviation: NDVI, Normalized Difference Vegetation Index

b. Means within the same column, followed by the same letters are not significantly different.

Table V-7. Desirable grass tolerance, by treatment.

Herbicide	Rate	Method	Greenseeker	Visual Evaluation
	g plant $^{-1}$		–NDVI[a]–	–% Tolerance–
Glyphosate	0.38	Hand	25c[b]	72b
Glyphosate	0.38	UAS	25c	73b
Hexazinone	0.08	Hand	34b	95a
Hexazinone	0.08	UAS	34b	93a
Glyphosate Hexazinone	0.19 0.08	Hand	26c	74b
Glyphosate Hexazinone	0.19 0.08	UAS	26c	73b
UTC	N/A	N/A	41a	100a

[a] Abbreviation: NDVI, Normalized Difference Vegetation Index

[b] Means within the same column, followed by the same letters are not significantly different.

Table V-8. Application dates and rainfall amounts through 30 DAT.

		Rainfall[a]			
Location	Application Date	7DBT[b]	7DAT	14DAT	30 DAT
		cm			
Bryan	3 October 2019	0	6.7	8.6	16.2
Richards	3 October 2019	0.03	0.17	4.5	13.7

[a] Cumulative amount from day of treatment until day specified

[b] Abbreviations: DBT, Days Before Treatment; DAT, Days After Treatment

CHAPTER VI CONCLUSIONS

Glyphosate, glyphosate + imazapic, hexazinone liquid and hexazinone tablets are all effective at controlling smutgrass and provided 100% control in individual plant treatments. The key difference in these treatments is damage to desirable forage grasses, and price. Glyphosate alone worked well, with the plants treated with the low rate fully recovering at both locations and the middle rate fully recovering at one and recovering to 60% at the other. Adding imazapic to glyphosate only increased the cost and damage to desirable forage, so therefore would not be recommended over glyphosate alone at any rate. Plants treated with all three rates of liquid hexazinone and both treatments of one-half tablets fully recovered at both locations. While all of these treatments are more expensive than glyphosate, they did provide significantly higher safety to desirable grasses at comparable rates earlier in the study. The highest rate of liquid hexazinone is simply a frivolous increase in cost and desirable grass damage, and the two lower rates should be considered better options, with the lowest being the most cost effective and safest. One full hexazinone tablet was simply an overkill, doubling the price of application compared to a half tablet and causing significantly more desirable grass damage, as a full tablet is meant to be used for woody species control and smutgrass does not require a full hexazinone tablet. Dissolving half of a hexazinone tablet in water made it safer on desirable grass in the first rating, and also significantly reduced the area of damage compared to placing the tablet on the plant undissolved. However, dissolving each tablet in water then pouring it out, refilling a container and doing it again is much more time consuming than simply placing the undissolved tablet in the plant. Doing this on a large scale is much easier using liquid hexazinone and mixing it in a sprayer. In conclusion, when using glyphosate 1% product rate or 0.19 g plant $^{-1}$ is sufficient for controlling smutgrass and allowing desirable grass to recover and is cost effective. 2% product rate or 0.38 g plant $^{-1}$ glyphosate is also a viable option but increasing the rate and price by 2x is not necessary for complete control. Hexazinone at 1% product rate or 0.08 g plant $^{-1}$ in individual plant treatments is also a high performing option for smutgrass control and desirable grass tolerance, any increase in rate is not necessary due to the cost. Adding imazapic to glyphosate is not recommended due to price and desirable grass damage, and while hexazinone tablets are effective, placing the tablets or pouring the solution is time consuming, plus the tablets are expensive. They are great options however for dense areas of smutgrass (90%+ groundcover), where a tablet in one plant can produce enough herbicide to also kill the surrounding smutgrass plants.

One application of a high rate of glyphosate provided great control of smutgrass at the expense of the desirable grass. However, the desirable grass did return to over 50% within one year at both locations. While the rate used (5.00 kg ai ha^{-1}) could not be grazed immediately due to a federal grazing restriction at that rate, it provided much more consistent smutgrass control than hexazinone and avoided the need to buy seed and replant, which would be necessary in a true renovation. The one year of hexazinone failure to control in this experiment is another example of the herbicide's inconsistency, however in the second year it showed how well it can work while also being safe on desirable grasses. Following these post-emergent herbicides with indaziflam did not cause any significant difference in the number of new seedlings emerged 12 weeks after applying indaziflam.

The nozzle used to apply hexazinone, glyphosate, a mixture of the two or sequential applications does not make a significant difference in terms of smutgrass control or desirable grass tolerance. By 46 WAB, glyphosate alone, glyphosate + hexazinone and glyphosate followed by hexazinone all provided significantly more control than hexazinone alone, but hexazinone alone was far safer on desirable grasses early in the study and it took 46 weeks for other treatments to become not significantly more injurious. If the desirable grass is extremely healthy, adding glyphosate to the hexazinone is a small increase in cost that will provide a significant boost in control. However, it if is not extremely healthy and the landowner does not want to replant desirable grasses, hexazinone alone is the best option. If the grass is not healthy and seeding desirable grasses such as bermudagrass is a possibility, the most cost-effective treatment is glyphosate alone, which will also provide consistent high level of control.

Whether hexazinone is applied to the foliage or the base of the plant impacts how quickly it becomes necrotic, with foliar applications causing complete necrosis by 30 DAT at both locations while it took 240 DAT for both locations of post-direct applications to cause complete necrosis. However, all treatments of both foliar and post-direct did cause complete control. The tradeoffs to this are that post-direct is more time consuming, requiring the applicator to get under the leaves with the sprayer, while foliar is much easier to simply spray the leaves. When spraying post-direct, one location had bermudagrass grow up through the crown of the plant in multiple replications, this was not seen at the other location or in either location of foliar applications. However, this was one stolon of bermudagrass in each smutgrass plant and saving this singular intra-smutgrass stolon of bermudagrass does not replace the damage to many stolons of bermudagrass around the smutgrass plant. Meanwhile, applying to the foliage did ultimately cause less harm to bermudagrass and caused quicker necrosis of the smutgrass plant that lasted the duration of the experiment; therefore, it is recommended to spray the foliage when spot spraying hexazinone instead of spraying post-direct to the crown. Two methods of foliar application were presented in the final chapter, aerial and ground based. While glyphosate showed significant differences by method with hand application reducing NDVI in certain areas more than the UAS application, neither glyphosate + hexazinone or hexazinone alone did. However, the increased cost of buying the UAS, learning how to fly it, getting the licenses, or hiring someone that checks these boxes, only to get lesser or equivalent control using more herbicide is not justified, especially for a rancher. The legal limits on weight and capacity also present great restrictions for using a UAS commercially. It is not unforeseeable with advancements in technology that see-and-spray drones will become common in agriculture, which would greatly improve the efficiency of drone application over the method used in this experiment, which is remote control. It is also likely that they will become less expensive, and that legal restrictions may be reduced after more research is completed. However, spot spraying glyphosate or hexazinone alone by hand will be much more cost effective in the near future and provide equivalent to better results than applications from a UAS depending on the herbicide.

REFERENCES

Ahmad, F., Qiu, B., Dong, X., Ma, J., Huang, X., Ahmed, S., & Chandio, F. A. (2020). Effect of operational parameters of UAV sprayer on spray deposition pattern in target and off-target zonesduring outer field weed control application. Computers and Electronics in Agriculture, 172, 105350.

Amor, R.L. & Twentyman, J.D. (1974). Objectives Of, And Objections To, Australian Noxious WeedLegislation. Journal of the Australian Institute of Agricultural Science 40, 194-203.

Andrade, J. M. D. s. (1979). Smutgrass (*Sporobolus poiretii* [Roem. And Schult.] Hitchc.) control withgrazing management systems. Doctor of Philosophy Dissertation, University of Florida.

Andrews, T. S. (1995). Dispersal of Seeds of Giant *Sporobolus spp* after Ingestion by Grazing Cattle.Australian Journal of Experimental Agriculture, 35(3), 353-356. doi: Doi 10.1071/Ea9950353

Arris Hobby (2021). Price for Arris G06 4 Axis 6L UAV Agricultural Spraying Drone Farm Sprayer. Retreived from https://arrishobby.com/products/arris-g06-4-axis-6l-uav-agricultural-spraying-drone-farm-sprayer

Bayer Environmental Science. (2015). Velpar L VU herbicide label. Research Triangle Park, NC: BayerCorporation, LLC.

Bayer Environmental Science. (2018). Roundup ProMax herbicide label. Research Triangle Park, NC:Bayer Corporation, LLC.

Bayer Environmental Science. (2020). Rezilon herbicide label. Research Triangle Park, NC: Bayer Corporation, LLC.

Berger, S. T., Dobrow, M. H., Ferrell, J. A., & Webster, T. M. (2014). Influence of carrier volume andnozzle selection on palmer amaranth control. Peanut Science, 41(2), 120-123.

Brecke, B. J. (1981). Smutgrass (*Sporobolus poiretii*) Control in Bahiagrass (*Paspalum Notatum*) Pastures. Weed Science, 29(5), 553-555.

Brosnan, J. T., & Breeden, G. K. (2012). Application Placement Affects Postemergence Smooth Crabgrass (*Digitaria ischaemum*) and Annual Bluegrass (*Poa annua*) Control with Indaziflam.Weed Technology, 26(4), 661-665, 665.

Castaldi, F., Pelosi, F., Pascucci, S., & Casa, R. (2017). Assessing the Potential of Images from Unmanned Aerial Vehicles (UAV) to Support Herbicide Patch Spraying in Maize. PrecisionAgriculture, 18(1), 76-94. doi: 10.1007/s11119-016-9468-359

Combellack, J. H. (1984). Herbicide Application: A Review of Ground Application Techniques. CropProtection, 3(1), 9-34.

Creech, C., Henry, R., Fritz, B., & Kruger, G. (2015). Influence of Herbicide Active Ingredient, NozzleType, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics. Weed Technology, 29(2), 298-310. doi:10.1614/WT-D-14-00049.1

Currey, W. L., Parrado, R., & Jones, D. W. (1973). Seed Characteristics of Smutgrass *(Sporobolus poiretii*). Soil and Crop Science Society of Florida, 32, 53-54. Applications. Remote Sensing,10(4), 584.

Dale, J.E. (1978). The Rope Wick Applicator---A New Method of Applying Glyphosate. Proceedings 31st Annual Meeting Southern Weed Science Society, p. 332.

Dale, J.E. (1979a). Advances in Wick Applicator Technology. Proceedings 32nd Annual Meeting Southern Weed Science Society, p. 378.

Dale, J.E. (1979b). Application Equipment for Roundup--The Rope Wick Applicator. Proceedings 3rdCotton Weed Science Research Conference, p. 15.

Dale, J.E: (1980). Rope Wick Applicator--Tool with a Future. Weeds Today, Late Spring, 3-4.

Dew, D.A. (1972). An Index of Competition for Estimating Crop Loss Due to Weeds. Canadian Journal of Plant Science 52, 921-927.

Dias, J. L. C. S. (2019). Implementation of Integrated Strategies to Manage Giant Smutgrass (*Sporobolus indicus var. pyramidalis*) Infestations in Bahiagrass Pastures. Doctorate (Ph.D.)Dissertation, University of Florida, Gainesville, Florida.

Do My Own (2021). Price of RoundUp Pro Max Herbicide 2.5 Gallon. Retrieved from https://www.domyown.com/roundup-pro-max-p-1346.html?gclid=CjwKCAjwrPCGBhALEiwAUl9X0yCJk_jrQ6UXrQXj8a9vsdAdY7vUjJJBT3 IV2AQNTiCKrZcByIMttxoCtUQQAvD_BwE

Elliot, J.G. (1978). The Economic Objective of Weed Control in Cereals. Proceedings 1978 British CropProtection Council Conference--Weeds 3, 829-839.

Empire Drone (2021). Price for DJI Agras T20 Spray Drone Four Battery Bundle. Retrieved from https://www.empiredroneco.com/products/dji-agras-t20-spray-drone-ready-to-fly-bundle

EPA (1994). "Hexazinone Reregistration Eligibility Decision Fact (RED) Sheet." US EPA Archive Document.

Ferrell, J. A., Mullahey, J. J., Dusky, J. A., & Roka, F. M. (2006). Competition of Giant Smutgrass(*Sporobolus indicus*) in a Bahiagrass Pasture. Weed Science, 54(1), 100-1 05. doi: Doi 10.1614/Ws-05-061r1.1

Ferrell, J.A. & Sellers, B. A. (2017). Approximate Herbicide Pricing. Retrieved from https://edis.ifas.ufl.edu/publication/wg056#FOOTNOTE_2

Forestry Suppliers (2021). Price for Velpar L VU Liquid Hexazinone 2.5 Gallon. Retrieved from https://www.forestry-suppliers.com/

Forestry Distributing (2021). Price for Plateau Herbicide 1 Gallon. Retrieved from https://www.forestrydistributing.com/plateau-herbicide-basf

Gilbey, D.J. (1974). Estimating Yield Losses in Wheat Resulting From Infestation By Double Gee (*Emex australis*). Australian Journal of Experimental Agriculture and Animal Husbandry 14,656-657.

Gous, S., Raal, P., & Watt, M. S. (2014). Dense wilding conifer control with aerially applied herbicidesin New Zealand. New Zealand Journal of Forestry Science, 44(1), 1-5.

Henderson, A. M.; Gervais, J. A.; Luukinen, B.; Buhl, K.; Stone, D.; Strid, A.; Cross, A.; Jenkins, J. (2010). Glyphosate Technical Fact Sheet; National Pesticide Information Center, Oregon StateUniversity Extension Services. Retrieved from: http://npic.orst.edu/factsheets/archive/glyphotech.html.

Hitchcock, A. S. & Chase, A. (1951). Manual of The Grasses Of The United States, US Department ofAgriculture.

Hoagland, R. E., & Duke, S. O. (1982). Biochemical Effects of Glyphosate [N-(phosphonomethyl)glycine].

Hoffmann, W., Member, K., & Lan, Y. (2008). Development of an Unmanned Aerial Vehicle-Based Spray System for Highly Accurate Site-Specific Application. Paper Presented at 2008 ASABEAnnual International meeting, June 29 - July 2, 2008. doi: 10.1303one-half013.24628

Howard (2020). Smutgrass (*Sporobolus indicus* Var. *indicus*) Control and Identification in PerennialPasture in Texas. Master's (M.S.) Thesis, Texas A&M University, [College Station, Texas].

Hunter III, J. E., Gannon, T. W., Richardson, R. J., Yelverton, F. H., & Leon, R. G. (2020). Integration of Remote-Weed Mapping and an Autonomous Spraying Unmanned Aerial

Vehicle for Site- Specific Weed Management. Pest Management Science, 76(4), 1386-1 392. doi:10.1002/ps.5651

Jiménez-Brenes, F. M., López-Granados, F., Torres-Sánchez, J., Peña, J. M., Ramírez, P., Castillejo-González, I. L., & de Castro, A. I. (2019). Automatic UAV-based Detection of Cynodon dactylon for Site-Specific Vineyard Management. PLOS ONE, 14(6), e0218132. Doi: 10.1371/journal.pone.021813

Johnson, B. J. (1988). Glyphosate And SC-0224 For Bermudagrass (Cynodon spp.) Cultivar Control. Weed Technology, 20-23.

Laliberte, A. (2010). Acquisition, Orthorectification, and Object-Based Classification of Unmanned Aerial Vehicle (UAV) Imagery for Rangeland Monitoring. Photogrammetric Engineering andRemote Sensing, 76, 661-672.

Lemus, R., Mowdy, M. J., & Davis, A. (2013). Herbicide Evaluation for Smutgrass Control Using TheWeed Wiper Method. 6 (1). Retrieved 9 September, from https://www.nacaa.com/journal/index.php?jid=229

Macêdo, J. F. d. S., Ribeiro, L. S., Bruno, R. d. L. A., Alves, E. U., de Andrade, A. P., Lopes, K. P., daCosta, F. B., Zanuncio, J. C., & Ribeiro, W. S. (2020). Green Leaves and Seeds Alcoholic Extract Controls *Sporobulus* indicus Germination in Laboratory Conditions. Scientific Reports,10(1), 1599. doi: 10.1038/s41598-020-58321-y

Macon, D. (2019) Coping with Smutgrass on Irrigated Pasture. University of California Agriculture &Natural Resources. Retrieved from https://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=31059

McCaleb, J. E., & Hodges, E. M. (1971). Smutgrass Control at Range Cattle Station; Ona, Florida. Southern Weed Science Society Proceedings, 24, 182-1 86.

McCaleb, J. E., Hodges, E. M., & Kirk, W. G. (1963). Smutgrass Control. Florida AgriculturalExperiment Station, Circular S-1 49, 10.

McWhorter, C.G. (1966). Sesbania Control in Soybeans With 2,4-D Wax Bars. Weeds 14, 15~155. Meyer, R., & Baur, J. R. (1979). Smutgrass (*Sporobolus poiretii*) Control in Pastures with Herbicides. Weed Science, 27(4), 361-366. Retrieved May 5, 2021, from http://www.jstor.org/stable/4043184

Meyer, R. E., & Baur, J. R. (1979). Smutgrass (*Sporobolus poiretii*) Control in Pastures with Herbicides. Weed Science, 27(4), 361-366. doi: 165.91.13.79

Mirik, M., Ansley, R. J., Steddom, K., Jones, D., Rush, C., Michels, G., & Elliott, N. (2013). Remote Distinction of a Noxious Weed (Musk Thistle: CarduusNutans) Using Airborne HyperspectralImagery and the Support Vector Machine Classifier. Remote Sensing, 5(2), 612-630. Doi 10.3390/rs5020612

Mislevy, P., & Currey, W. L. (1980). Smutgrass (*Sporobolus Poiretii*) Control in South Florida. WeedScience, 28(3), 316-320.

Mislevy, P., Curry, W. L., & Brecke, B. J. (1980). Herbicide and Cultural-Practices in Smutgrass(*Sporobolus Poiretii*) Control. Weed Science, 28(5), 585-588.

Mislevy, P., & Martin, F. G. (1985). Smutgrass Control and Subsequent Forage Production with FallApplication of Dalapon. Soil and Crop Science Society of Florida Proceedings, 44, 203-205.

Mislevy, P., Martin, F. G., & Hall, D. W. (2002). West Indian Dropseed/Giant Smutgrass (*Sporobolusindicus Var. Pyramidalis)* Control in Bahiagrass (Paspalum Notatum) Pastures. Weed Technology, 16(4), 707-711. doi: Doi 10.1614/0890037x(2002)016[0707:Widgss]2.0.Co;2

Mislevy, P., Shilling, D. G., Martin, F. G., & Hatch, S. L. (1999). Smutgrass (*Sporobolus indicus*)Control in Bahiagrass (Paspalum notatum) Pastures. Weed Technology, 13(3), 571-575.

Mullahey, J. J. (2000). Evaluating Grazing Management Systems to Control Giant Smutgrass (*Sporobolus indicus var. pyramidalis*). [Abstract]. Southern Weed Science Society, 53, 59-60.

Nolte, S. (2019). Grassbur - Identification and Management in Pastures. Texas A&M Agrilife ExtensionSCS-2019-10. Retrieved April 2, 2020, from http://publications.tamu.edu/WEEDS_HERBICIDES/Grassbur-in-pasture-SCS2019-10.pdf

Parsons, W.T. (1973). Noxious Weeds of Victoria. Melbourne, Victoria, Australia: lnkata Press.

Peterson, G. (1967). The Discovery and Development of 2,4-D. Agricultural History, 41(3), 243-254. Retrieved May 19, 2021, from http://www.jstor.org/stable/3740338

Peña, J. M., Torres-Sánchez, J., de Castro, A. I., Kelly, M., & López-Granados, F. (2013). Weed Mapping in Early-Season Maize Fields Using Object-Based Analysis of Unmanned Aerial Vehicle (UAV) Images. PloS one, 8(10), e77151-e77151. doi: 10.1371/journal.pone.0077151

Persad, N. K. (1976). Nutritive Value Components and Yield of Smutgrass and Its Influence on Pensacola Bahiagrass. Master's Thesis, University of Florida, Gainesville, FL.

Pesticide Action Network. (n.d.). "Dalapon." Pesticide Action Network- Pesticides Database

Pro-Serve Inc. (2004) Pronone Power Pellets Label. East Brooks Road, Memphis, TN. Pro-Serve Inc.Ramsdale, B., & Messersmith, C. (2001). Nozzle, Spray Volume, and Adjuvant Effects on Carfentrazone and Imazamox Efficacy. Weed Technology, 15(3), 485-491. doi:10.1614/0890-037X(2001)015[0485:NSVAAE]2.0.CO;2

Rana, N., Sellers, B. A., Ferrell, J. A., MacDonald, G. E., Silveira, M. L., & Vendramini, J. M. (2015). Integrated Management Techniques for Long-Term Control of Giant Smutgrass (*Sporobolus indicus var. pyramidalis*) in Bahiagrass Pasture in Florida. Weed Technology, 29(03), 570-577.doi: 10.1614/wt-d-1 5-00021.1

Rana, N., Sellers, B. A., Ferrell, J. A., MacDonald, G. E., Silveira, M. L., & Vendramini, J. M. (2017a). Impact of Soil pH on Bahiagrass Competition with Giant Smutgrass (*Sporobolus indicus var. pyramidalis*) and Small Smutgrass (*Sporobolus indicus var. indicus*). Weed Science, 61(01),109-1 16. doi: 10.1614/ws-d-1 2-00070.1

Rana, N., Wilder, B. J., Sellers, B. A., Ferrell, J. A., & MacDonald, G. E. (2017b). Effects of Environmental Factors on Seed Germination and Emergence of Smutgrass (*Sporobolus indicus*)Varieties. Weed Science, 60(04), 558-563. doi: 10.1614/wsd-1 1-00208.1

Rango, A., Laliberte, A., Herrick, J., Winters, C., Havstad, K., Steele, C., & Browning, D. (2009).

Unmanned Aerial Vehicle-Based Remote Sensing for Rangeland Assessment, Monitoring, and Management. Journal of Applied Remote Sensing, 3(1), 1-15. doi: 10.1117/1.3216822

Reeves, T.G. (1976). Effect Of Annual Ryegrass (*Lolium rigidum* Gaud) On Yield Of Wheat. Weed Research 16, 57-63.

Richardson, B., Rolando, C., Hewitt, A., & Kimberley, M. (2020). Meeting droplet size specifications for aerial herbicide application to control wilding conifers. New Zealand Plant Protection, 73, 13-23.

Richardson, B., Rolando, C. A., Somchit, C., Dunker, C., Strand, T. M., & Kimberley, M. O. (2020). Swath pattern analysis from a multi-rotor unmanned aerial vehicle configured for pesticide application. Pest management science, 76(4), 1282-1290.

Riewe, M. H., Evera, G. W., & Merkle, M. G. (1975). Smutgrass Control and Winter Grazing Establishment with Herbicides. Proceedings of the Southern Weed Science Society, 28, 218.

Ripper, W.E. (1955). Application methods for crop protection chemicals. Annals of Applied Biology 42,288-324.

Sebastian, D. J., Fleming, M. B., Patterson, E. L., Sebastian, J. R., & Nissen, S. J. (2017).

Indaziflam: ANew Cellulose-Biosynthesis-Inhibiting Herbicide Provides Long-Term Control of Invasive Winter Annual Grasses. Pest Management Science, 73(10), 2149-2162. doi: 10.1002/ps.4594

Sellers, B. A., & Ferrell, J. A. (2012). Managing Bahiagrass in Bermudagrass, Stargrass, and Limpograss Pastures. University of Florida IFAS Extension SS-AGR-257. Retrieved February15, 2020, from https://edis.ifas.ufl.edu/ag243.

Sellers, B. A., Rana, N., & Dias, J. L. C. S. (2012). Smutgrass Control In Perennial Grass Pastures,2018, from http://edis.ifas.ufl.edu/aa2

Simelli, I. & A. Tsagaris (2015). The Use of Unmanned Aerial Systems (UAS) in Agriculture. HAICTA.

Simon, B. K., & Jacobs, S. W. L. (1999). Revision of the Genus Sporobolus (*Poaceae, Chloridoideae*)in Australia. Australian Systematic Botany, 12(3), 375-448. doi: Doi 10.1071/Sb97048

Singh, V., Rana, A., Bishop, M., Filippi, A. M., Cope, D., Nithya, R., & Bagavathiannan, M. V. (2019). Unmanned Aircraft Systems for Precision Weed Detection and Management: Prospects andChallenges. Advances in Agronomy, 153, 93-134. doi: https://doi.org/10.1016/bs.agron.2019.08.004

Smith, A. E. (1982). Chemical Control of Smutgrass (*Sporobolus poiretii*). Weed Science, 30(3), 231-234.

Smith, A.E. & Secoy, D.M. (1976). Early chemical control of weeds in Europe. Weed Science 24, 594-597

Smith, J. E., Cole, A. W., & Watson, V. H. (1974). Selective Smutgrass Control and Forage Quality Response in Bermudagrass-Dallisgrass Pastures. Agronomy Journal, 66(3), 424-426. doi: DOI10.2134/agronj1974.00021962006600030025x’=

Sugiura, R., Noguchi, N., & Ishii, K. (2005). Remote-sensing technology for vegetation monitoringusing an unmanned helicopter. Biosystems engineering, 90(4), 369-379.

Tang, Y., Hou, C. J., Luo, S. M., Lin, J. T., Yang, Z., & Huang, W. F. (2018). Effects of operation height and tree shape on droplet deposition in citrus trees using an unmanned aerial vehicle.Computers and Electronics in Agriculture, 148, 1-7.

University of California Agriculture and Natural Resources (2016). “Weed Gallery: Smutgrass”. Retrieved from http://ipm.ucanr.edu/PMG/WEEDS/smutgrass.html

USDA (1997). “Spiller Series”. USDA-NRCS Soil Series. Retrieved from https://soilseries.sc.egov.usda.gov/OSD_Docs/A/SPILLER.html

USDA (2000). “Annona Series”. USDA-NRCS Soil Series. Retrieved from https://soilseries.sc.egov.usda.gov/OSD_Docs/A/ANNONA.html

USDA (2003). “Huntsburg Series”. USDA-NRCS Soil Series. Retrieved from https://soilseries.sc.egov.usda.gov/OSD_Docs/A/HUNTSBURG.html

USDA (2007). “2006 Livestock Highlights”. Retrieved from https://www.nass.usda.gov/Statistics_by_State/Florida/Publications/Annual_Statistical_Bulletin/2007/D1thru27Lv-2007.pdf

USDA. (2014). "Kaman Series." USDA-NRCS Soil Series. Retrieved from https://soilseries.sc.egov.usda.gov/OSD_Docs/A/KAMAN.html

USDA. (2018). United States Department of Agriculture Natural Resources Conservation Service.Plants Profile for *Sporobolus indicus* (L.) R. Br. var. indicus (smutgrass), Retrieved from https://plants.usda.gov/core/profile?symbol=SPINI2

USDA. (2019a). State Agriculture Overview - Texas. from US Department of Agriculture https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=TEXAS

USDA. (2019b). State Agriculture Overview - Texas Crops - Planted, Harvested, Yield, Production,Price (MYA), Value of Production Sorted by Value of Production in Dollars. from US Department of Agriculture https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=TEXAS

USDA. (2019c). Annual Summary; Livestoc, Dairy, Poultry – USDA NASS. Retrieved from https://www.nass.usda.gov/Statistics_by_State/Florida/Publications/Livestock_and_Poultry/ldpsum18/LDP18ALLc.pdf

Valle, L. S. (1977). Changes in Smutgrass (*Sporobolus Poiretii* [Roem. And Schult.] Hitchc.) GroundCover Induced by Spraying with Molasses and Grazing Management. Doctor of Philosophy Dissertation, University of Florida, Gainesville, Florida.

Vencill, W. K. (2002). Herbicide Handbook 8th ed., Weed Science Society of America.

Vere, D.R. & Campbell, M.H. (1979). Estimating the Economic Impact Of Serrated Tussock (*Nassella trichotoma*) in New South Wales. Journal of the Australian Institute of Agricultural Science 45, 35-43.

Vogler, W. D. (2010). Efficacy of Herbicides on Weedy Sporobolus Grasses in the Glasshouse in Australia. Plant Protection Quarterly, 25(1), 9-14.

Walter, J. H., Newman, Y. C., Gamble, S. F., Mudge, D. M., Deal, P., Baseggio, M., & Fluke, A. (2013). Use of Rotational Stocking in Combination with Cultural Practices for Smutgrass Control—A Florida Case Study. Rangelands, 35(5), 98-103. doi: 10.2111/rangelands-d-1 3-00023.1

Wang, G., Lan, Y., Qi, H., Chen, P., Hewitt, A., & Han, Y. (2019). Field evaluation of an unmanned aerial vehicle (UAV) sprayer: effect of spray volume on deposition and the control of pests anddisease in wheat. Pest management science, 75(6), 1546-1555.

Wells, G.J. (1979). Annual Weed Competition in Wheat Crops: The Effect of Weed Density and Applied Nitrogen. Weed Research 19, 185-192.

Wilder, Sellers, B. A., Ferrell, J. A., & MacDonald, G. E. (2011). Response of Smutgrass Varieties to Hexazinone. Forage and Grazinglands, 9(1), 1-7. doi: 10.1094/fg-2011-0222-02-rs

Wilder, B., Ferrell, J. A., Sellers, B. A., & MacDonald, G. E. (2008). Influence of Hexazinone on 'Tifton 85' Bermudagrass Growth and Forage Quality. Weed Technology, 22(03), 499-501. doi:10.1614/wt-08-008.1

Wilder, B. J. (2009). Seed Biology and Chemical Control of Giant and Small Smutgrass. Master's (M.S.)Thesis, University of Florida, [Gainesville, Fla.] Florida. Retrieved from http://ufdc.ufl.edu/UFE0024543/00001?search=seed+%3dbiology+%3dchemical+%3dcontrol+%3dgiant+%3dsmall+%3dsmutgrass

Xinyu, X., Kang, T., Weicai, Q., Yubin, L., & Huihui, Z. (2014). Drift and deposition of ultra-low altitude and low volume application in paddy field. International Journal of Agricultural andBiological Engineering, 7(4), 23-28.

Zimdahl, R.L. (1980). Weed Crop Competition--a Review. Oregon State University, Corvallis, USA:International Plant Protection Center