NOVEL PEST MANAGEMENT STRATEGIES IN SOUTHERN FORAGE SYSTEMS

by

NICHOLAS JOHN GLEASON SHAY

(Under the Direction of Lisa L. Baxter)

ABSTRACT

Smutgrass (*Sporobolus indicus*) is a non-native warm-season perennial weed that continually invades bahiagrass (*Paspalum notatum*) forage systems in the Coastal Plains Region of the Southeastern United States. A small plot trial was established to evaluate the effectiveness and economics of integrated weed management strategies for controlling smutgrass in bahiagrass grown in Alapaha, GA. Treatment combinations included Indaziflam (PRE), Hexazinone (POST), with fertilizer. Initially, all plots had a similar visual concentration of smutgrass ($P = 0.59$). The combination of PRE- and POST-emergent herbicides with N and K fertilizer resulted in greater reduction of smutgrass and less bahiagrass injury than POST-emergent herbicide alone. A preliminary economic analysis demonstrated that a fully integrated management strategy, unlike the current practice of POST alone, displayed significant savings when compared to complete bahiagrass renovation. Consequently, the fully integrated management plan has both agronomic and economic benefits for producers controlling smutgrass in bahiagrass fields.

INDEX WORDS: Integrated weed management, forages, bahiagrass, smutgrass, hexazinone, indaziflam, preemergence, postemergence, fertilizer, economics

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DEDICATION

I dedicate this work to my wife and daughter, April and Joanna Shay. Your patience, joy, and hope continue to provide encouragement for pressing forward. To my wife, thank you for taking risks, committing to lofty dreams, and being the most amazing mother. I am grateful beyond measure for your prayers, upholding me in my weaknesses and your steadfast faith as we walk side by side in this crazy life. I pray that God’s will be done, and that our purpose is to bring Him honor in all we do. We hope that we can be a blessing to all those around us. To my daughter, your joy radiates the atmosphere easing the many worries of tomorrow. No moment escapes your zeal, constantly remaining in the present and living each moment to the fullest. I cherish every waking moment that we share together, from dancing in the dining room to outlandish bedtime stories where we laugh until we cry. Lastly, to both of you, this achievement is a reflection of your commitment to building a life-lasting legacy. I wouldn’t do this any other way. I love you.

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CHAPTER I

INTRODUCTION

Livestock producers in the Southeastern United States are faced with many challenges. Agriculture in the Coastal Plains region currently thrives thanks to favorable growing conditions and ample precipitation throughout the year. With minimal sub-freezing temperatures, perennial and annual forages have sustained production for long growing seasons to support livestock throughout most of the year. However, uneven distribution and increasingly extreme weather events such as hurricanes and intermittent drought necessitate the need for expanding management strategies as unpredictable weather patterns during the hottest months of the year make it difficult to maintain peak forage performance.

Agriculture in the Coastal Plains region of Georgia relies on perennial, warm-season forages for most of the annual forage production. Most soils in the region have fertility constraints because the sandy texture inhibits nutrient retention. Bahiagrass (*Paspalum notatum*) is common in the more southern parts of this region that are prone to typically higher rainfall and severe summer weather systems (Hancock et al., 2010). Furthermore, it can better tolerate the marginal soils, input limitations, and continuous grazing management than other warm-season perennial forage options such as bermudagrass (*Cynodon dactylon*). This enables bahiagrass to better compete with weed species.

Unfortunately, years of poor management have led to the decline of many bahiagrass pastures and hayfields (Sellers and Ferrell, 2017). Invasive weed species, specifically smutgrass (*Sporobolus indicus*), are beginning to threaten these forage systems as there are limited herbicides available for selective use in bahiagrass. Integrating novel pest management strategies that include both herbicides and fertilizer will allow producers to control smutgrass while minimizing the negative impact on the bahiagrass stand.

Historically, forage systems in South Georgia have been well suited for low-input cow-calf operations or hay production (Table 1.1). However, climate change is driving changes in sward dynamics and shifts in plant and weed populations (Hoberg and Brooks, 2015). When coupled with lower fertilization rates because of increasing fertilizer prices (Quinn, 2021), it is not surprising that southern bahiagrass forage systems are seeing declines in forage production and smutgrass encroachment. This may ultimately result in total loss of bahiagrass stands and the need for costly renovations, a consequence that would be devastating to the region (Table 1.1). Cost-effective strategies are required to safeguard against losses of these bahiagrass stands to weed invasions. Integrating herbicides and fertilizer is a viable option for these producers to prevent total loss of desirable forage species to invasive weeds.

Table 0.1.1 2021 rankings of market value of agricultural products sold in Georgia†.

Commodity	Rank	Cash Receipts
Broilers	1	$4,000,000,000
Cotton	2	$983,600,000
Timber	3	$679,500,000
Beef	4	$666,100,000
Peanuts	5	$663,000,000
Greenhouse	6	$476,500,000
Corn	7	$321,400,000
Hay	8	$306,200,000
Dairy	9	$306,000,000
Pecans	10	$263,400,000

†Adapted from University of Goeriga AgSnapshots, caed.uga.edu (2021).

The use of integrated weed management is not a novel idea. Integrated weed management is a management strategy combining preventative, cultural, mechanical, and chemical techniques for reducing competition from opportunistic weeds. However, the lack of available control options in forages coupled with low-input management does make the situation more challenging. Producers in the Coastal Plains would benefit from a sound management plan that will quickly and economically reduce the presence of smutgrass while enhancing the regrowth of bahiagrass without requiring repeated herbicide applications or other costly inputs. The central focus of this research was to create an economical integrated weed management plan that reduces smutgrass populations by utilizing herbicides and fertilizer to increase bahiagrass recovery and productivity.

Previous research by Mislevy et al. (1999) in Ona, FL, determined that one hexazinone (Velpar) application could control up to 95% of smutgrass. However, the authors also found that bahiagrass suffered herbicidal injury following treatment which led to bare soil areas that presented a window for other opportunistic weeds to emerge. Integrating nitrogen applications can optimize bahiagrass production, possibly doubling forage accumulation across an entire growing season and increasing vigor with competing weeds (Beaty et al., 1960).

Although hexazinone has performed well in smutgrass research trials for the last four decades, diversifying modes of action can lower the risk of herbicide resistance. Incorporating a pre-emergent herbicide can prevent this resistance, by working in combination with hexazinone (Sebastian, 2017). Often seedling emergence of annual weeds and shifts in weed populations follow hexazinone applications. Although broadleaf weeds are relatively easy to control, grass weeds (annual or perennial) are more difficult. Indaziflam is a new broad spectrum herbicidal mode of action (WSSA group 29) with potential for controlling annual weeds. It is unknown the impact in perennial systems and may provide additional weed management options when used in concert with hexazinone.

Hay and livestock production in Georgia are critical to the success of the Southeast's agricultural community. This research can provide novel pest management strategies to serve as an alternative to total renovation of bahiagrass stands that have been infested by smutgrass. Maintaining an improved low-input bahiagrass pasture system will be necessary where rising costs of fuel, herbicides, and fertilizers impact management decisions. The proposed improvements to stand persistence by the economic removal of weeds while potentially limiting injury to bahiagrass will encourage producers to take advantage of an integrated strategy. Adopting novel pest management strategies which include both herbicide diversification and fertilizer treatments are important for sustaining pastures in the Coastal Plains.

Research trials were conducted to evaluate the efficacy and economic potential of novel pest management strategies for controlling smutgrass in bahiagrass systems in South Georgia. These included:

1. Evaluate the interactive effects of herbicides and fertilizer applications for controlling smutgrass
2. Monitor population shifts in species relative abundance and distribution and diversity following indaziflam applications
3. Determine the most efficacious and economical IPM plan for low-input bahiagrass systems

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CHAPTER 2

LITERATURE REVIEW

Forage production systems and challenges in the lower Coastal Plains

In the Southeastern United States, bahiagrass (*Paspalum notatum*) forage production exceeds more than 4 million acres for both livestock grazing and hay production (Wallau et al., 2010). In this region, the temperate climate is home to perennial, warm-season grasses providing producers with an extended growing season. Known for its extreme temperature fluctuations, this region tends to have wet springs, followed by recurring drought-like conditions (flash or prolonged) during the hottest parts of the year in the summer when rainfall is pertinent for maintaining peak forage performance. Unfortunately, these conditions tend to favor annual and perennial weeds that negatively impact desired forages as intraspecific competition limits growth of suitable forages by competing for light, space, and nutrients. Another negative consequence of weed competition is the impact on forage performance, and as a result can reduce animal performance (Rana et al., 2012).

Forage production for livestock becomes a major challenge when peak forage performance does not align with animal needs and does not support their nutrient and energy requirements throughout the year as a result of climate fluctuations from season to season (Blount et al., 2000). With few sub-freezing events, warm-season perennial grasses have long growing seasons to support livestock throughout most of the year in Southern Georgia. However, vegetative production slows once temperatures fall below 20°C and livestock nutrient demands must be supplemented with winter annual or stored forages until vegetative growth resumes near the end of May (Blount et al., 2000; West, 1992). Optimizing forage performance will require a better understanding of bahiagrass and its growth characteristics to assist in improving the relationship between this forage and competing weed species.

Bahiagrass

Bahiagrass is a deep-rooted, sod-forming, warm-season perennial grass native to South America. It was first introduced to the United States around 1913 at the Florida Agricultural Experiment Station by the Bureau of Plant Industry (Hancock et al., 2010; Wallau et al., 2010). Typically known as a low-management pasture forage, it can also be used for moderate to low-quality hay (Hancock et al., 2010). With low fertility requirements, and the ability to tolerate close grazing (depending on cultivar), it proves to be a sufficient option for livestock production in temperate and sub-tropical climates as a highly economically viable forage. Bahiagrass development has focused on improving traits and characteristics throughout the years to meet the demands of livestock producers.

Bahiagrass Development

Originally, the first cultivar known as ‘common’ bahiagrass was grown abundantly in Argentina, Brazil, Eastern Bolivia, and Paraguay (Hancock et al., 2010). Well suited for the Southeast Coastal Plains region of the United States, common bahiagrass was widely used as a low maintenance forage for pastures, although nutrient values are lower than other forage species like bermudagrass (*Cynodon dactylon*). Bahiagrass is a multi-purpose management tool with many uses commonly seen in erosion control, wildlife habitat, pest management within row-cropping such as peanuts, and hay production (Hancock et al., 2010; Rodriguez-Kabana, 1988).

Today, bahiagrass is one of the primary perennial forages in Georgia. Its innate characteristics provide a strong adaptability to regional climatic conditions and a competitive advantage over other forages and weed species during periods of extreme heat or drought. Bahiagrass is known for its ability to grow on upland well-drained sandy soils as well as poorly drained low-land soils found near swamps (Chambliss & Sollenberger, 1991). Livestock producers in the region benefit greatly from the low inputs required for proper management to maintain forage quality. A recognized challenge is that some weed species out compete bahiagrass because they also respond favorably to extreme climatic conditions.

Physiological & Morphological Characteristics

Bahiagrass is unique as it propagates both by rhizomatous growth and seed production for survival, however bahiagrass is typically propagated by seed (Wallau et al., 2010). Once established, propagation occurs rather quickly in bottomlands compared to bermudagrass because of the aggressive rhizomatous production, rapid lateral spread, and seed production over open ground (Peacock, 2017). Known for its characteristically recognizable Y-shaped bifurcated seed-head, the grass grows in an upward pattern reaching approximately 30-63 cm tall (Peacock, 2017; Wallau et al., 2010). Bahiagrass varieties may be divided into two groups, diploid and tetraploid. Diploids are more cold tolerant than tetraploid cultivars and require less photosynthetic energy, and as a result reach maturity earlier especially while enduring unfavorable conditions (Hancock et al., 2010). These diploid cultivars are also less sensitive to photoperiod and vegetative production begins earlier in the spring as early as March and April. Tetraploid varieties take longer to establish due to delayed seedling maturity with optimal growth occurring during the middle of the summer (Vendramini et al., 2013).

Favorable Growing Conditions

Where other warm-season perennial grasses struggle due to rainfall variability in the Coastal Plain region, from drought-like conditions during the summer and seasonal hurricane spells in the fall, bahiagrass can withstand the extremes of both tropical and sub-tropical climates. The large diameter rhizome-root structures enable bahiagrass to store nutrient reserves for access when experiencing these extreme bouts of weather (Blue, 1973). The adaptability of this grass has also done well in saturated soils (Chambliss & Sollenberger, 1991). In some instances, bahiagrass is able to withstand complete submersion in water for up to a week or longer while avoiding permanent degradation (Poore, 2016). Other considerable attributes are the plant's tolerance to shade, close grazing, and heat tolerance where 85% of its production takes place during the hottest part of the year during June through September (Wallau et al., 2010). Additionally, soil pH suitability for bahiagrass growth has a large range from 4.5 to 6.5 with an optimal range of around 5.5 (Silveira et al., 2007). Maintaining a proper pH is a vital component for stand survivability, and cultivar selection is an important factor when selecting attributes that will withstand the regional differences in the environment.

Cultivars

'Pensacola', a shade-tolerant cultivar (Beaty et al., 1960), was first discovered in the 1930s at the port of Pensacola near the old Perdido Wharf (Burton, 1967) in Florida (Hancock et al., 2010). One of the suggested origins of Pensacola has been traced backed to Berduc Island near Santa Fe, Argentina (Burton, 1967). When E.H. Finlayson discovered this diploid cultivar, he was working for the state of Florida as a County Extension agent when he observed this plant growing in empty lots at shipping docs in 1941 (Beaty et al., 1960). Most researchers suggested that this cultivar arrived by running ashore on old ship ballast returning from South America (Burton, 1967). Finlayson thought the cultivar could be beneficial and began collecting seeds to germinate in pastures for the purpose of land conservation (Wallau et al., 2010).

Pensacola is easily identifiable because of its long, narrow leaves and taller seed stalks (Hancock et al., 2010). Pensacola has an ergot disease-resistant trait allowing for low input management (Hoveland, 1961). It is a widely desired cultivar and represents up to 60% of the bahiagrass population in the Southeast (Wallau et al., 2010). While Pensacola is still popular in most of the region, researchers looked for ways to improve dry matter yields, upright growth patterns, and resistance to heavy grazing (Wallau et al., 2010). Furthermore, Pensacola does not compete well with weed species in the spring each season when there is limited access to important resources such as sunlight and fundamental nutrients for breaking winter dormancy.

‘Tifton 9’ was developed by Dr. Glenn Burton of the United States Department of Agriculture (USDA) – Agricultural Research Service (ARS) to address many of the aforementioned shortcoming of Pensacola (Burton, 1989). Tifton 9 is a diploid cultivar selected from Pensacola through restricted, recurrent selection, that has superior yields and seedling vigor compared to Pensacola (Wallau et al., 2010). Tifton 9 became a popular option as a pasture variety, but seed hardness proved to be an undesirable trait amongst producers (Wallau et al., 2010). Therefore, research focused on improving seeds by reducing hardness for increased germination rates, and as a result ‘TifQuik’ was generated. Other tetraploid cultivar varieties that were later developed in the U.S. were ‘Argentine’, ‘UF-Riata’, ‘Paraguay 22’, ‘AU Sand Mountain’, and ‘Wilmington’ (Wallau et al., 2010).

TifQuik was developed through recurrent selection (Wallau, et al., 2010). Maintaining desired vegetative characteristics similar to Tifton 9 with 10-30% more dry matter than Pensacola, selection was focused on those producing fewer hard seeds (Wallau et al., 2010). Additionally, forage accumulation can equate to as much as 3,362 to 11,209 kg ha^{-1} during a growing season with variability in yields based on environmental conditions (Wallau et al., 2010). Improving germination rates is important for continued and longstanding production. Earlier germination leads to earlier emergence, which provides a competitive advantage over other weed species competing for the same resources. Selecting for germination rates and other specific traits reduces dependence on other treatment methods for controlling weeds in pasture and hay systems.

Results and feedback from the industry expressed the advantages of choosing varieties with specific traits for regionality by maximizing the options of selectivity and variability bolstering continued research in Tifton 9. While improvements have been made to herbage accumulation, germination rates, and physiological growth, all varieties stemming from Pensacola still had limitations, one of which was photoperiod sensitivity. To help boost spring and fall production, the goal was to develop a variety that was less sensitive to day length resulting in greater yields during this timeframe and season. As a result, UF-Riata was released in 2009 from the University of Florida (Nordlie, 2008). Although persistence may be impacted when grazed more frequently, as is the case with Tifton 9, decreasing photosensitivity can increase forage yields at the early and late time periods of the season for vegetative growth. Addressing bahiagrass production limitations with varietal selection alone may not suffice as there are external factors contributing to bahiagrass persistence some of which are understanding the most limiting nutrient based on aggregated conditions from pH, soil types, and other environmental factors.

Limiting Nutrients

The decline of bahiagrass in terms of forage quality and yield is severely problematic, given that it is a plant species that already is tolerant to less than optimal soil conditions which most other warm-season perennial grasses cannot tolerate. Bahiagrass prefers a sandier soil structure but this can be a detriment to maintaining minimal fertility requirements for growth and reproduction (Wallau et al., 2010). Nitrogen (N) within bahiagrass is most likely the limiting nutrient in sandy soils (Blue, 1973). Potassium (K) was thought to be another limiting factor for vegetative growth but Yarborough et al., (2017) further supports N as the most limiting nutrient because forage accumulation did not increase with increases in K fertilization. However, it is plausible that some deficiency of K can occur where low recovery levels of K exist as the result of leaching, especially in low pH soils (< 5.5) or heavy rain events (Yarborough et al, 2017). Sollenberger (2019) also reiterates the importance of understanding a balanced fertility management plan. Although producers remained attentive to nitrogen requirements, bahiagrass stands were still declining from neglected K fertilization. Some producers in Florida were failing to adjust P and K treatments with changes to N recommendations. It is also important to understand localized soil types for determining fertility requirements and the needs for bahiagrass.

Fertility Requirements

The fertilization requirements of bahiagrass should always be preceded by a soil test. Yet, a soil test alone may not be enough to capture the full range of nutrient requirements as this process can isolate some of the most limiting nutrients. Sollenberger (2019) discovered declining bahiagrass pastures had high concentrations of phosphorus (P) below the sampled soil layer (> 6 inches) that had accumulated on top of a hard pan over time. The lower rooting zone may also have specific deficiencies as a result of this hard pan that is easily masked or show little to no symptoms of imminent decline for many years (Silveira et al., 2007). Therefore, the total needs of bahiagrass should include examining the entire plant. For this reason, plant tissue analysis is recommended with soil testing every three years for grazing pastures and every year for hayfields to capture all of the nutrient requirements (Sollenberger, 2019).

Nitrogen and Seasonality Responses

It is important to note that moisture is a key factor for increased forage accumulation responses to N fertilization (Beaty et al., 1960) and can be a limiting resource in low-input management systems. There was seasonal forage distribution in Pensacola bahiagrass in response to N fertilization where 64% of forage was produced in June and July (Beaty et al., 1960). Understanding seasonal responses of bahiagrass yields will help to mitigate ill-timed fertilizer losses. With correctly timed N applications at a recommended rate of 112 kg N ha^{-1}, it is possible to see in upwards of 7958 kg forage ha^{-1} compared to 3363 kg ha^{-1} with no added N fertility across an entire growing season (Beaty et al., 1960). The goal of N applications is to optimize bahiagrass yields for animal performance.

Nitrogen applications increased protein fractions and forage quality in bahiagrass resulting in a greater percentage of N in the forage that is useable for ruminant animal digestibility (Beaty et al, 1974; Evans et al., 1961; Johnson et al., 2001; Myer et al., 2011). Although Johnson et al. (2001) found that acid detergent fiber (ADF) and in vitro organic matter digestibility (IVOMD) were not influenced by N fertilization, neutral detergent fiber (NDF) decreased with increasing rates of N. As a result of these lower NDF concentrations in bahiagrass livestock can consume more forage and increase digestibility of nutrients such as sugars, carbohydrates, and proteins for supporting maintenance of energy requirements. Animal performance, such as average daily gains, responds to the quality of forage, and understanding N fertilization requirements is paramount for attaining maximum forage performance.

Nitrogen Requirements

Burton et al., (1997) expressed that a ratio of 4-1-4 (N-P-K) satisfies the fertility requirements of bahiagrass as neither P nor K significantly impacted forage yields. It is recommended that at least one N application be completed at the rate of 60 kg N ha^{-1} for improved forage quality and increased herbage accumulation (Vendramini et al., 2013). Blue (1973) identified that rates exceeding 112 kg N ha^{-1} (224, 448 kg N ha^{-1}) saw a diminished return on investment. Previous research indicates that there is no yield advantage from splitting N applications during the growing season on irrigated hay pastures when applications are applied to loamy sandy soils (Beaty et al., 1974). Current University of Georgia recommendations suggests that a typical fertilization program should include divided applications of N and K at a rate ranging between 112 – 224 kg N ha^{-1} to limit luxury consumption (Hancock et al., 2010). These events should occur in early spring and summer during stages of vegetative growth before going to seed (Wallau et al., 2010).

Phosphorus Requirements

Phosphorus is a growing concern for water quality issues throughout the United States. Limiting environmental impacts could have implications on achieving bahiagrass fertilization requirements, however, Silveira (2010) found that agronomic rates in low input grazing systems did not negatively impact water quality nor raise any environmental concerns. Bahiagrass responses to P fertilization vary depending on environmental conditions (Silveira, 2010). One early study, in particular, indicated a P rate of 112 kg P_2O_5 ha^{-1} was most effectively utilized (Allen, 1977). Wallau et al. (2010) recommends a rate of 28 kg P_2O_5 ha^{-1} should be added when plant tissue levels fall below 0.15%. Taking a balanced approach to fertilization requirements necessitates adding K when required by soil test recommendations.

Potassium Requirements

A complete fertilizer application for improving forage yields is crucial, and omitting one of these elements, as is the case with N, can significantly decrease yields up to 2241 kg ha^{-1} (Allen et al., 1977). Allen (1977) suggests that at a rate of 112 kg ha^{-1}, K concentrations maintained minimum requirements throughout most of the growing season until roughly mid-August. K concentrations regardless of the rate illustrated a steady decline from application until the end of the season (Allen, 1977). In most soils, K is more readily available compared to N and P because of ionic charge (Brady & Weil, 2008). Understanding the complete fertilization relationship is important for recognizing differences in nutrient availability for plant uptake. N and P play a significant role in increased tissue concentrations of K (Yarborough et al., 2017).

Complete Fertilization Relationship

Limited cation exchange concentrations and minimal organic matter in sandy soils, requires N fertilization for stimulating K uptake which develops greater rhizome-root mass of bahiagrass for exploring a larger soil volume for other nutrients (Yarborough et al., 2017). However, it is important to point out that overfertilization with N can have an adverse effect by depleting K supplies in the soil (Evans et al., 1961). Allen (1977) indicates that increasing levels of N and P above 224 kg ha^{-1} and 112 kg ha^{-1} respectively, can decrease optimal K utilization. As previously mentioned, greater rhizome-root development in bahiagrass from N fertilization could potentially increase stand persistence by serving as a storage vessel for nutrients, as well as being a mechanism for translocating carbohydrates, maintaining water concentrations, turgor pressure of its cells, and proper stomata function (Yarborough et al., 2017). Peak forage performance of bahiagrass for livestock production relies heavily on recognizing nutrient limitations and understanding how to adjust accordingly.

Earlier research focused mainly on nitrogen uptake, nitrogen losses, and bahiagrass response to grazing frequency when limiting nitrogen fertilizer (Vendramini et al., 2013). Information pertaining to fertilization timing in Georgia, especially in conjunction with or following herbicide applications, has yet to be thoroughly explored in research. Although input costs are lower than other warm-season perennial grasses, bahiagrass' adaptability lends itself to a wide range of management options. Often, fertilization and management decisions are based on economic projections in the livestock market.

Smutgrass

Smutgrass (*Sporobolus indicus*) originated in the tropical region of Asia (Hitchcock, 1950). The name smutgrass is derived from the observation of a dark-colored fungus (*Drecbslera ravenelii curt*) found on the inflorescence which closely resembled smut from a fireplace or chimney (Mislevy et al., 1999). How this species was introduced into the United States has yet to be discovered and there is no certainty of the source of infection worldwide. Smutgrass is found primarily in the Southeast, but this highly competitive tuft-forming grass has been known to withstand undesirable winter conditions outside the Deep South as far away as Texas and Virginia (Wilder, Ferrell, Sellers, and MacDonald, 2008). The resiliency of smutgrass was assessed in a survey conducted in 2007 by the Florida Beef Forage Program and revealed to be one of the most problematic weeds in South Florida (Crawford and Wiggins, 2007). Two varieties are in existence today, ‘small’ smutgrass (*Sporobolus indicus var. indicus*) and ‘giant’ smutgrass (*Sporobolus indicus var. pyramidalis*) (Sellers et al., 2018). Eradication, management, and smutgrass control trials began in 1955 at the Agricultural Research Center in Ona, Florida but there is still a paucity of information on smutgrass, especially outside of the subtropical region (Mislevy and Martin, 1985).

Geographic Region

As the spread of smutgrass moves more northward, researchers should monitor to the extent that smutgrass has spread as a result of its aggressive nature, high seed vigor, and resiliency in the state of Georgia and possibly beyond. While the regional dispersion of smutgrass ecotypes in Georgia specifically has not yet been determined, small smutgrass has been documented in 23 states from the Pacific Coast to New York and Texas as well as Florida, and giant smutgrass has been limited to Florida and Puerto Rico (Rana et al., 2012). However, movement of giant smutgrass into southern Georgia is plausible as it tends to display more vigorous growth under stressful and undesirable conditions (Rana et al., 2012). Multiple physiological and morphological characteristics give both giant smutgrass, and small smutgrass an advantage over their competitors in low-input forage systems.

Smutgrass Characteristics

A mature smutgrass is described as being a dark green tufted perennial with erect stems that displays leaf blades typically flat to regularly folded towards the base of the plant rounding off as it moves towards the tip of the leaf (Colvin et al., 2010). The leaf blade is smooth and will grow to lengths of 15-48 cm and widths of 1-5 mm, with a small membranous ligule measuring approximately <0.1 mm in length (Wilder, 2009). The aggressive nature of smutgrass lends itself to its ability to grow up to 1.1 m tall at an average clump size of 20-25 cm (Wilder, 2009).

Seedheads are narrow panicles displaying spike-like features that are generally interrupted at around 40 cm from the tip of the stem (Wilder, 2009). Showcasing its resiliency and invasive character, flowering is continuous to allow for seed production to persist from April to December (Currey, Parrado, & Jones, 1973).

Seed Dispersal

As a perennial bunch-type grass, smutgrass infestation is a slow process and may take several years. Seed dispersal by animal and machinery are well-known avenues of distribution and enabled the spread of smutgrass onto roadsides, ditches, residential lawns, and pastures or hayfields of soil with poor quality (Maddox et al., 2021). Currey et al. (1973) discovered while attempting to control smutgrass with mowing that it only intensified dispersal while creating a more uniformed and developed stand. Livestock producers will find difficulty controlling an established stand of smutgrass because animals influence seed dispersion by ingesting seed from mature forages. Those that consume smutgrass seed unintentionally have the potential to spread seed over a vast land area with little variation as a result of regional, national, and global transport of livestock. However, Andrews (1995) found that the seed viability rates decreased to roughly 19% once the seed left a ruminant’s digestive tract and returned to the soil surface. A low percentage could indicate that manure is not the main mechanism of transportation of seeds as their viability is significantly reduced after passing through the digestive system. A more common transmissible seed dispersal is clinging to the coats of animals. Smutgrass becomes sticky when the pericarp has been loosened by moisture allowing for adhesion to animal hair (Andrews, 1995). Severe weather events in southern Georgia are common and increase the risks of seed dispersal through wind, water runoff, and erosion. Transportation through waterways via ditches, roadways, streams, and rivers can introduce the highly invasive weed into neighboring fields.

Seed Characteristics

Most seeds that reach maturity are red and typically free of the black fungus found on immature seeds (Wilder et al., 2008). In a study conducted by Currey et al. (1973), research revealed that each plant is capable of producing roughly 30 seed heads and each panicle is then capable of producing 1,400 seeds. Seed production is continuous throughout the growing season because all cycles occur simultaneously. While seeds are shattering, others are flowering and maturing on each seed head (Mislevy et al., 1999). Seeds have been known to survive predation and undesirable conditions due to a protective husk (Wilder, 2009) remaining viable for up to two years until conditions become optimal to initiate germination (Currey et al., 1973). Even though smutgrass has a vigorous seed production, and an expansive germination range, it does have vulnerabilities.

Seed Germination Requirements

Smutgrass seed germination is vulnerable to cold temperatures (< 15°C) (Wilder, 2009). Susceptibility to cold temperatures is good news for producers in more northern latitudes, which can limit or slow its spread. Diurnal temperature fluctuations are essential to initiate germination with ranges between 22 - 33°C day^{-1} and 11 - 24°C night^{-1} at a rate of 88% germination (Rana et al., 2012). Inhibitions of germination have been found when the seed is dirty, has moisture-imposed stress, and the depth of burial is > 3 cm (Rana et. al., 2012). Smutgrass is highly fecund, but according to Andrews et al. (1996), early sown seeds portrayed a high degree of innate dormancy with only 4% of seedling emergence. More recent research indicates that ensuring the seed is clean (Wilder, 2009), and scarified (Andrews et al., 1996), is even more crucial in impacting germinations rates than temperature, and light, as viability remains dependent on favorable conditions (Rana et al., 2012).

Seed production and seedling emergence differs slightly depending on the species of smutgrass that is present. Husks cover both small and giant smutgrass, which has been linked to decreasing germination rates if not removed (Wilder, 2009). Rana et al. (2012) indicated that removing the husk increased germination from < 9% to > 94%. Differences in germination rates based on cultivar has been recorded in literature. Giant smutgrass is more viable at rates of 11% (giant smutgrass) compared to 7% (small smutgrass) (Wilder, 2009), and can germinate more quickly and at elevated rates when conditions are not ideal (Rana et al., 2012). Additionally, the range of giant smutgrass germination is approximately 85% at warmer temperatures (35°C day, 25°C night) (Wilder, 2009). This is something to keep in mind as global temperatures continue to rise resulting in the continued spread of giant smutgrass northward.

Smutgrass Control

Managing smutgrass populations in a pasture or hayfield setting has traditionally been accomplished by implementing mechanical and chemical strategies. Some of the control options used previously have been mowing, fertility management, herbicide usage, and intensive rotational grazing (Ferrell & Mullahey, 2006). However, a variety of grazing and fertility management options have been trialed with inconsistent results (Rana et al., 2012). To subdue the aggressive nature of smutgrass, there is still heavy dependence on chemical control, although there are limited herbicide options for controlling smutgrass without injury to desirable species. Therefore, there is a need to further explore the combination of these limited treatment options in concert with new methods that can be deployed for effective control.

Developing a strategy to effectively control smutgrass relies on information pertaining to its stage of development, the seasonal environmental conditions, climate, and timing and rate of herbicide application. Because most options available for control of smutgrass are often costly, infestation rates are a key component for implementing management. Under extreme conditions when bahiagrass areas have been infested by smutgrass that has exceeded a coverage of 70-80%, a complete pasture renovation has been required (Sellers et al., 2018). Typical pasture renovation includes stand termination via herbicides and cultivation through tillage (Sellers et al., 2018). This method is also costly and should only be used when all other options have been exhausted. One exploratory option for controlling smutgrass is reducing smutgrass populations by minimizing seed production through PRE- and POST-emergent herbicides, but more research is needed to fully understand these methods to make this a viable option. Until then, mechanical control of smutgrass is still widely used in hay and pasture systems.

Mechanical Control

Mowing

Previous research found mowing was an ineffective method for the reduction of smutgrass populations, and actually increased seed disbursement more rapidly (Mislevy et al., 2002). The physical action of mowing also decreases plant diameter while increasing overall numbers of plants through seed disbursement (Mislevy et al., 1999). Mowing can improve palatability for livestock during early vegetative stages (Ferrell et al., 2006). Although mowing may slow the spread of smutgrass, complete termination and removal are highly unlikely, and once mowing has ceased plants will revert to pre-treatment densities (Mislevy et al., 1999).

Grazing

Grazing can be used as a management tool that mimics mechanical strategies. However, McCaleb et al. (1963) noted that cattle do not consume smutgrass as forage quality decreases and becomes unpalatable as it matures. Rana et al., (2012) further supported this claim by adding that within the first two weeks of growth, smutgrass is tender and palatable to livestock but quickly becomes unpalatable as the plant begins to mature. As a result, overgrazing of desirable forages like bahiagrass causes them to be easily displaced by lowering interspecific competition thereby increasing smutgrass densities (Wilder et al., 2008). Left to complete its life cycle with no intervention or growth regulation from grazing, smutgrass proliferates through the production of seed and rhizomatous propagation.

Renovation

Another popular method of control when densities are severe enough is complete renovation. Tillage is a widely used practice that disrupts rhizomatous growth, exposes roots for termination, and buries weed seed, which cannot survive depths > 3 cm (Rana et al., 2012; 2015). Consequences of tillage have been noted as disturbances can expose buried seed to favorable conditions for germination (Rana et al., 2015). Rana et al. (2015) utilized roller chopping as a potential mechanical option with 89% reduction in smutgrass ground cover percentages, but reinfestation after 36 months was two times higher. Burning also has been used as a management tool but does not affect smutgrass control (Rana et al., 2015). Herbicides remain the most effective option for reducing smutgrass populations.

Chemical Control

There have been multiple chemical herbicide options throughout the years that have been registered for use as an effective treatment option for influencing smutgrass populations. According to Mislevy et al. (1999), the most effective and capable herbicide product on the market for smutgrass control was Dalapon (Dupont Chemical Company, Wilmington, DE). McCaleb et al. (1963) first recommended that Dalapon herbicide be applied at 2.27 kg a.i. in 379 L of water to control smutgrass without serious injury to bahiagrass. Dalapon controlled smutgrass but because it lacks pre-emergent activity and injures bahiagrass, it increased the presence of broomsedge (*Andropogon virginicus*) and dogfennel (*Eupatorium capillifolium*) (Brecke, 1981). Dalapon was federally deregistered for use in pastures in the 1980's. After Dalapon was no longer in use, Dupont filed for a federal label for Hexazinone (Nolte, 2017), and currently is the most effective primary herbicide option for managing smutgrass in pastures and hayfields.

Options for weed control in bahiagrass systems are limited and weed resistance is highly probable with repetitive applications (Hurdle et al., 2020). Before 2021, there were two groups for general weed control in pasture systems, WSSA Group 4 and WSSA Group 5 (hexazinone) for smutgrass specifically. Group 4 broadleaf herbicides, which have no activity on grasses including smutgrass, consist of 2,4-D, aminopyralid, clopyralid, dicamba, fluroxypur, and triclopyr (Hurdle et al., 2020). Given that smutgrass control has been limited to one mode of action, increases the risk for the development of resistance. Expanding potential modes of action will help to mitigate this risk.

Hexazinone Usage and Mode of Action

Hexazinone was registered in 1975 as a non-agricultural herbicide (Sung et al., 1985) and classified in the s-triazine family of herbicides (Rana, 2012). Today this xylem-mobile herbicide is registered for use in agricultural and non-agricultural uses under the trade names Velpar and Velossa (Rana, 2012). Examples of agricultural uses have been on Christmas tree (*Pseudotsuga menziesii*), alfalfa (*Medicago sativa*), sugarcane (*Saccharum officinarum*), and pineapple (*Ananas comosus*) production (Rana, 2012). Research has indicated that hexazinone does not reduce broomsedge nor carpetgrass (*Axonopus fissifolius*) (Brecke, 1981). Hexazinone provides residual control of unwanted weed species for up to two years, including brush, but may require a second application in year two (Rana et al., 2012).

Moisture is important for the efficacy of hexazinone. The amount of precipitation will determine if hexazinone will reach the targeted root-zone in the rhizosphere for plant uptake where it will be absorbed by the roots (Rana, 2012). In some instances, hexazinone can be absorbed by leaf tissues, but has poor translocation throughout the plant because mobility is strictly limited to xylem movement (Wilder, 2009). Again, this is further supported when Rana (2012) noted that foliar applications provided little translocation through phloem mobility. The mechanism of action occurs by inhibiting photosynthesis, RNA, and lipid synthesis (Hatzios and Howe, 1982). Electron blocking at the Photosystem II complex disrupts the photosynthesis cycle and as a result is fatal (Rana, 2012). The inhibition of normal electron flow in photosystem II causes a disruption to the electron transport chain restricting the ability of plants to generate a proton-motive force that drives ATP production. Additionally, the disturbance leads to the production of excited free-radical oxygens. These excited oxygens are destructive in nature and cause membrane breakdown leading to fatal hemorrhaging within the cell (Hatzios and Howe, 1982).

Timing of Application

Timing the application of hexazinone is vital to reach maximum efficacy, especially considering the high chemical cost. Forage loss from smutgrass invasion has been estimated to cost $55 to $114 ha^{-1} in bahiagrass (Ferrell et al., 2006). Sellers & Ferrell (2011) recommend applying the herbicide treatment within 7 days of a regular rainfall event (no more than 76.2 mm) to achieve greater than 90% control. When rain exceeds 76.2 mm within a week of application, efficacy declines because of potential leaching (Sellers et al., 2018). With seasonal variability of rain events in the Coastal Plains region, it is important to apply this herbicide during late spring to early summer during the rainy season. The timing of this herbicide application is one of the main considerations to ensure efficacy.

Another parameter predicated on economic decisions for hexazinone use is smutgrass population density. Wilder et al. (2008) advise waiting to apply hexazinone when smutgrass has reached at least 20% - 35% ground coverage. Hexazinone is an expensive weed management option and any application earlier than a 20% ground coverage would have a negative economic impact for producers. To reach the full effectiveness of hexazinone, sequential spray applications in consecutive years is vital because of the nature of smutgrass' ability to withstand undesirable conditions (Mislevy et al., 1999). Sequential applications would cover misses during first application and any additional new seedlings that emerged (Rana et al., 2012).

Rate of Application

Rate of application has been heavily researched for obtaining optimal control (> 80%). Ferrel and Mullahey (2006) suggested that in order to gain 80% control of smutgrass in bahiagrass pastures consistently, an effective rate of 0.83 – 0.98 kg ha^{-1} was necessary. With further investigation, the study revealed that by increasing the rate between 1.1 – 1.7 kg a.i. ha^{-1} provided >90% control (Ferrell and Mullahey, 2006). Additional recommendations are to use a rate of 1.1 kg a.i. ha^{-1} for providing consistent and effective control of smutgrass and limit bahiagrass injury (Ferrell and Mullahey, 2006; Mislevy et al., 2002; Wilder et al., 2008). Moreover, Mislevy et al. (1999) advised that timing regarding smutgrass growth stage was not an important factor influencing hexazinone effects. More recent research, recommended applying a combination of two sequential applications no more than once a year of 0.56 kg a.i. ha^{-1} and 0.84 kg a.i. ha^{-1} for control of smutgrass up to 3 years (Rana et al., 2015). It is important to point out that application rate influence the amount of damage sustained by bahiagrass and smutgrass, thus impacting symptomology.

Efficacy and Response

Following the initial application of hexazinone symptomology responses indicates that damage can be sustained, causing temporary yellowing and burning of margins of bahiagrass (Sellers et al., 2018) that remain present between 30-40 days after treatment (DAT) (Ferrell and Mullahey, 2006). While injury has occurred, there is little concern of complete termination even at the higher recommended rate of 1.7 kg a.i. ha^{-1} because bahiagrass has recovered in approximately 30 DAT (Ferrell and Mullahey, 2006). Increases in bahiagrass densities by 2% were noted as evidence indicating a more rapid lateral spread of the cover (Ferrell and Mullahey, 2006). It is important, however, to point out that fatal forage injury is possible if the timing of application is within one year of seeding (Sellers et al., 2018). When it comes to nutritive impacts on bahiagrass, the application of hexazinone has yet to be determined and more research is required. Because hexazinone is an expensive option for weed management, monitoring economic and weed damage thresholds is essential.

Indaziflam Usage and Mode of Action

Indaziflam (Rezilon, Bayer Crop Science, Whippany, NJ), is a sprayable, soil applied, season long, pre-emergent herbicide. As a member of the alkylazine family, it was developed and classified as a cellulose biosynthesis inhibitor (CBI) (Brosnan et al., 2011). A WSSA Group 29 herbicide, indaziflam has the potential for resistance management based on its broad-acting herbicidal mode of action and may provide additional management options in combination with hexazinone (Sebastian et al., 2017). This herbicide has shown to be effective in controlling both monocotyledonous and dicotyledonous plants indicating little evidence of evolved weed resistance (Brabham et al., 2014). As a broad-spectrum herbicide that focuses heavily on controlling annual grasses, it is registered for use in grapes (*Vitis* spp.), nut trees (*Carya illinoinensis*), citrus (*Citrus*), pine trees (*Pinus*), as well as multiple perennial crops and turf grass, and more recently in pasture and hay systems (Hurdle et al., 2020; Sebastian et al., 2017).

Indaziflam performs well in aerobic soil environments with high mobility as a result of more water-soluble traits, but recent studies have indicated it showed strong adsorption potential to soil colloids because of its weak acidity (pK4 = 3.5) (Brosnan et al., 2011; Frank, 2015). Alonso et al., (2011) concluded that adsorption was also predicated on the level of soil organic matter (0.5% to 2.5%) and clay content (7% to 65%) present in the soil. There is an increased risk of injury to desired forages in sandy soils with lower levels of OM and clay, and further research is needed to see how bahiagrass responds (Jones et al., 2013). As a result of strong adsorption, leaching did not occur beyond 30 cm no matter the amount of rainfall (Frank, 2015). Because of its dependence on precipitation for mobility into the rooting zone of target plants, timing of the application is crucial.

Timing of application

Timing is critical for effective control of annual grasses and broadleaf undesirable plants. Application should occur several weeks before seedling emergence (Bayer Crop Science, 2021). Weather is also an important consideration as wind can cause undesired drift, and heavy rain events can cause off-site movement (Bayer Crop Science, 2021). Additionally, it is suggested that applications be made shortly after harvest where canopy cannot impede proper soil coverage (Bayer Crop Science, 2021). To ensure extended weed control throughout the growing season, recommendations include two applications, one in early season (green up), and one mid to late season at no more than 30 g a.i. ha^{-1} (Bayer Crop Science, 2021). The longer half-life than many other herbicides allows for more flexibility in application timing (Brosnan et al., 2011), especially when applications are dependent upon weather conditions.

Rate of application

Previous research has illustrated the effective use of indaziflam with low rates of usage (73-102 g ai ha^{-1}) in comparison to other similar acting herbicides for proper weed management on winter annual weeds (Sebastian et al., 2017). Although indaziflam has been linked to controlling both grasses and broadleaf weeds, Sebastian et al. (2017) indicated that reduced rates of application had increased activity on monocots in comparison to dicots. Rate of application should not exceed 70 g a.i. ha^{-1} in one application and 90 g a.i. ha^{-1} in a 12-month period (Bayer Crop Science, 2021). Further limitations in hay production restrict harvesting within 40 days of a 40 g a.i. ha^{-1} application, as well as reduced efficacy of the herbicide with intensive grazing closely after application (Bayer Crop Science, 2021). Additionally, hay fields and pastures should avoid applications within the first year of establishment and limit applications to no more than two per 12-month period every year after (Bayer Crop Science, 2021). Establishing and overseeding cool-season forages like Italian ryegrass (*Lolium multiflorum*) and cereal rye (*Secale cereale* L.) should be avoided as residual activity can adversely affect seedling emergence within 18 months after an application (Bayer Crop Science, 2021). There are other determinate factors, one of which is soil type, that impact efficacy and response to applications of indaziflam.

Efficacy and Response

Indaziflam's unique characteristics set itself apart from other herbicides with its lower applications rates and prolonged residual activity as a result of its persistence in the soil ($t_{1/2} = 150$) (Alonso et al., 2011). Results from Jones et al. (2013) concluded that soil type has a significant impact on efficacy and injury was sustained in turfgrass systems. Regardless of the rate of application, sandy soils increased the likelihood of bermudagrass root injury within the first 5 cm of the rooting zone (47-48% 6 weeks after treatment) compared to silty loam soils (0-17% 6 weeks after treatment) (Jones et al., 2013). However, Hurdle et al. (2020) discovered that in bahiagrass systems, above-ground stunting was not observed, but further research may be necessary to understand bahiagrass root responses to applications of indaziflam (Hurdle et al., 2020). Injury to other annual grass and broadleaf species has been documented and effective during early development at both the germination and seedling emergence stages.

As indaziflam penetrates the soil surface and infiltrates the rooting zone for plant uptake, studies have indicated that monocot and dicot root expansion from cell wall synthesis disruption is greatly reduced within the first 72 hours after application resulting in stunting also described as root clubbing (Neal, 2014; Sebastian et al., 2017). Weedy plant species such as downy brome (*Bromus tectorum*), cereal rye (*Secale cereale* L.) (monocots), and kochia (*Bassia scoparia*) (dicot) saw up to 50% reductions in root length, with monocots *seeing* in upwards of 2.9 times lower root growth (Sebastian et al., 2017). Sebastian et al. (2017) concluded that cell walls were incomplete, and gaps were discovered between cells in the roots. However, there is insignificant evidence of POST-emergence activity causing reductions in efficacy as a foliar application in bermudagrass. With similar physiology and morphology, it is assumed that bahiagrass may respond in similar ways to indaziflam as did bermudagrass, but more research is required.

Typical symptomology of this herbicide is the impact on seedlings. Symptoms include radial swelling, and phloroglucinol staining, a symptom of ectopic lignification (Brabham et al., 2014). As is the case with most CBI herbicides, cellulose production was inhibited. Furthermore, Brabham et al. (2014) illustrated indaziflam's potent efficacy as symptoms emerged on annual bluegrass (*Poa* annua) within 1 hr of application (Brabham et al., 2014). Additional symptomology includes stunted and yellowing of new growth, as well as stem swelling and girdling (Neal, 2014). These foliar injuries can be a result of negative impacts to the root structure such as root clubbing or preventing secondary roots in sandy soils (Frank, 2015). While research has investigated impacts on annual grasses and broadleaf weed species and the fate of indaziflam in a variety of environmental conditions, there is still little knowledge on how weed populations will shift as a result of applications in forage-based systems.

Weed Population Shifts

It is not uncommon to see weed populations shift in response to the introduction of new strategies. The time frame in which these introduced disturbances persist in forage systems driving population shifts depend on the intensity and frequency, and the capabilities of each plant species to respond or recover (Renne and Tracy, 2006). Such strategies as changes in the herbicidal chemistry and disturbances to the soil surface inevitably alter plant community dynamics as volunteer and undesirable species react based on species characteristics and their competitive nature (Kemp and King, 2001). Kemp and King (2001) signal the importance of management and how there are many factors that influence pastures and their desire to shift towards a more naturalized state because of the complexity based on the number of species involved. Although species differ in their resource needs for space, light, water, and nutrients, the natural fluctuation of the limiting resource in the environment increases competitive interactions between these weeds making it more difficult to predict outcomes (Kemp and King, 2001). Kemp and King (2001) point out the level of interference and competitiveness is also a result of plant species morphology and biochemistry. For example, the differences between C_3 and C_4 photosynthetic plants have variations in seasonal growth patterns (Kemp and King, 2001). The result of population shifts within forage and pasture systems is not only influenced by plant-to-plant interactions, but also external influences, for instance: grazing livestock and harvest timing.

Plant population competitiveness, abundance, and distribution are impacted by livestock influences as seen in grazing selectivity (Kemp and King, 2001). As livestock choose a more desirable forage, it allows ungrazed species to be more competitive by avoiding this vegetative impediment. It is a clear advantage as it creates more opportunities for the unharmed species to capture light, CO_2, and biochemical reactions between roots and microbiology as they reach flowering and seed dispersal stages before the grazed forage, ultimately adding to the seed bank for future generations. Additionally, forage that is wasted or impacted by trampling and manure defecation will affect their developmental progression (Kemp and King, 2001). It is also important to note that timing of harvest is another consideration that can influence population shifts. Stages of development based on growth and germination rates can alter how plant species interact (Kemp and King, 2001). Ultimately, dynamics from the direct and indirect use of management will change pasture composition and weed dynamics (Kemp and King, 2001).

Pasture and hay systems are unique in that there are a multitude of plant species at play that are directly and indirectly impacted by management decisions. It can be difficult to predict the direction and species impacted when management strategies are implemented because of the many external influences already discussed. Webster and MacDonald (2001) found that the most troublesome weeds in Georgia pastures were large crabgrass (*Digitaria sanguinalis*), horsenettle (*Solanum carolinense* L.), johnsongrass (*Sorghum halepense*), bull thistle (*Cirsium* *vulgare*) and musk thistle (*Carduus nutans*). However, regionality plays a major factor in their abundance and distribution, and more recent environmental trends may shift away from these species (Webster and MacDonald, 2001). As is the case in Florida with the increasing threat of smutgrass, it could quickly rise as a new troublesome weed in southern Georgia as it continues to encroach northward.

Summary and Objectives

Novel pest management strategies are necessary as management programs with a one-dimensional focus fail to provide proper smutgrass control. Traditionally controlling smutgrass involved large applications of fertilizer, mowing, or expensive herbicide burndown for stand renovation. Maintaining improved bahiagrass for grazing or hay has become increasingly difficult with the rising costs of fuel, herbicides, and fertilizers. Furthermore, these methods failed to provide long-lasting and acceptable control of smutgrass. Smutgrass is a hardy invasive species that can reinfest 3-4 years after initial treatment of herbicides. Therefore, this research is focused on observing the interacting effects of PRE- and POST-emergent herbicides with fertilizer applications on forage accumulation, forage nutritive value, and population shifts in bahiagrass systems. To achieve this goal, these field experiments were conducted in a preexisting bahiagrass pasture in South Georgia and will provide valuable information for developing a novel pest management plan for producers in the Southeast US.

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CHAPTER 3

EVALUATING THE INTERACTION OF HERBICIDE AND FERTILIZER APPLICATIONS ON SMUTGRASS CONTROL IN BAHIAGRASS[1]

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[1] Shay NS, Baxter LL, Basinger NT, Schwartz BM. To be submitted to *Weed Technology*

Abstract

Smutgrass (*Sporobolus indicus*) can quickly outcompete bahiagrass (*Paspalum notatum*) because of its aggressive growth, prolific seed production, and rhizomatous growth. Total renovation of bahiagrass pastures or hayfields is generally not a feasible or economically viable option for most producers. Therefore, controlling the continual spread of smutgrass will require an integrated weed management plan that incorporates multiple strategies. The objective of this study is to test the interactions of multiple IPM strategies including herbicides and fertilizers on smutgrass control in bahiagrass and determine the most efficacious and economical IPM plan for low-input bahiagrass systems. This research was conducted on a mixture of 'Tifton 9' and 'Pensacola' bahiagrass at the Alapaha Beef Station in Alapaha, GA. The study design was randomized complete block design with a three by four factorial arrangement with six replications. Fertility treatments included 50 units N ha^{-1} (ammonium nitrate, 34% N) + 56 kg K_2O ha^{-1}, 50 units N ha^{-1}, and an unfertilized control. Results show that plots receiving PRE- (PRE; Indaziflam) and POST-emergent (POST; Hexazinone) herbicides in addition to N and K_2O resulted in an improved bahiagrass stand as timely weed suppression removed competition, while fertilizer provided essential nutrients for optimum growth to fill in the gaps. A fully integrated management plan should be the most economical option for producers when compared to a complete bahiagrass renovation.

Introduction

Bahiagrass (*Paspalum notatum*) is a popular low-input forage option for livestock producers in the Coastal Plains Region of the Southeastern United States because of its low fertility and input requirements for sustained growth in sandy soils (Beaty, McCreery, and Powell, 1960). It is a reliable, warm-season perennial forage with above-average persistence in adverse climatic conditions as well as resistance to most diseases and pests (Chambliss and Sollenberger, 1991; Dias, Seller, Ferrell, Silveira, and Vendramini 2018;). Bahiagrass is well adapted to the Southern half of Georgia, outperforming other warm-season forages where extreme temperatures as well as intermittent flooding or drought can otherwise limit biomass and nutritive value. One disadvantage of bahiagrass production systems is the lack of herbicide options to control highly competitive weeds and non-native invasive species that can easily overtake the stand if left unmanaged. Mitigating performance losses to bahiagrass, such as forage accumulation and ground cover, will require effectively utilizing novel pest management strategies to deter encroachment of these opportunistic weeds.

Smutgrass (*Sporobolus* indicus) is one of the invasive, non-native weeds that has become a major pest in perennial grasslands throughout the Southeast US (Rana et al., 2012). This bunch-type, warm-season perennial grass invades around 1.6 million hectares of permanent and temporary pastures across the Southeastern United States (Wallau et al., 2010). The name is derived from the dark-colored fungus (*Drechslera ravenelii* (M.A. Curtis ex Berk.)) present on the inflorescence that closely resembles smut from a fireplace or chimney (Mislevy et al., 1999). Previous research has identified two varieties of smutgrass populations: small smutgrass (*S. indicus* (L.) R. Br. var. *indicus*) and giant smutgrass (*S. indicus* var*. pyramidalis* (P. Beauv.) Veldkamp). Small smutgrass is the dominant variety and has been found in 23 states while giant smutgrass is most predominant in Florida. Regardless of the population, smutgrass grows well in a wide array of environmental conditions, grows rapidly in vegetative and reproductive stages, continuously produces seed, and possesses discontinuous germination.

Previous research has been conducted in Florida on controlling smutgrass in bahiagrass pasture systems. Initially, viable control options were focused on isolating responses to single variables such as mowing, fertility management, or intensive rotational grazing (Ferrell & Mullahey, 2006; Kemp & King, 2001). McCaleb et al. (1963) first recommended that Dalapon herbicide (Dupont Chemical Company, Wilmington, DE) be applied at 2.27 kg a.i. ha^{-1} in 379 L of water followed by mowing to 7.62 cm starting in August every week during 13 consecutive weeks which controlled smutgrass up to 85% without serious injury to the bahiagrass. Later studies discouraged the use of mowing for smutgrass control, as it can broadcast smutgrass seeds and may not be economically feasible with rising fuel costs (Ferrell & Mullahey, 2006; Mislevy et al., 1999; Sellers & Ferrell, 2011; Sellers et al., 2020). Dalapon is also no longer recommended and was federally deregistered for use in pastures in the 1980's. Following this decision, DuPont filed for a federal label for hexazinone (Velpar L®, Bayer Crop Science, Whippany, NJ) for smutgrass control in pastures and hayfields (Mislevy et al., 1999).

The efficacy of hexazinone on smutgrass in bahiagrass and bermudagrass (*Cynodon dactylon*) has been researched thoroughly in Florida (Ferrell et al., 2006; Mislevy et al., 2002; Nolte, 2017; Sellers & Ferrell, 2011; Sellers et al., 2018; Wilder et al., 2008). Research indicates that the best timing for application is during conditions that are both warm and wet. The mode of action for hexazinone requires rainfall to allow the chemical to infiltrate the soil where it can be absorbed via root uptake, however precipitation events exceeding 76.2 mm may lead to lower rates of efficacy as well as possible soil leaching. To achieve greater than 90% control, Sellers & Ferrell (2011) recommend an application within 7 days of a rainfall event. It is also important that applications are made during the growing season when grasses are active since hexazinone requires movement into the xylem for translocation as a photosynthesis disruptor (photosystem II inhibitor) to achieve maximum herbicidal efficacy. Herbicide options for non-selective smutgrass control in bahiagrass are currently limited to hexazinone. Additionally, hexazinone presents potential challenges as an herbicide option because of cost to low-input producers as well as initial injury to bahiagrass, which could impact its competitiveness with other opportunistic weeds. In response to these disadvantages, research should explore new technologies such as Indaziflam (Rezilon®, Bayer Crop Science, Whippany, NJ). Although a common PRE-emergent herbicide in the turf industry, little is known about the use of indaziflam on smutgrass or other perennial grass weed species in bahiagrass. Previously, pendimethalin (Prowl H_2O, BASF Plant Science, Raleigh, NC) was the only recommended PRE-emergent herbicide for use in bahiagrass in Georgia, but pendimethalin had little impact on smutgrass control (Sellers et al., 2020). Rezilon® was recently registered by Bayer Crop Science for use in warm-season grass pastures and hayfields (Bayer Environmental Science, 2020). Hurdle et al., (2020) investigated the impact of indaziflam on bermudagrass forage production. The bermudagrass tolerated the indaziflam applications at the recommended rates and no crop injury was reported. However, the impact of indaziflam on bahiagrass has yet to be determined and more research will be required. With the addition of indaziflam as a new management tool in forage systems, knowledge regarding interactions with other herbicides and fertilizers is limited and will require further investigation for their combined impact on bahiagrass forage systems.

An integrated weed management plan for removing smutgrass from existing bahiagrass stands must combat rhizomatous growth, as well as the continuous and prolific seed production throughout the growing season (Mislevy et al., 2002). Isolated treatments with singular uses of herbicide or fertilizer may not be adequate for controlling smutgrass in the attempt to improve bahiagrass forage systems. Many non-targeted species could emerge unexpectedly with a broad range of responses outside the scope of targeted treatments (Kemp & King, 2001). Thus, the importance of a preemptive plan that expands the range of management in complex forage systems. Few studies have addressed the importance of fertilizing with nitrogen (N) and potassium (K) as part of an integrated weed management plan to improve herbage accumulation and increase bahiagrass vigor by giving it a competitive advantage over weed species (Beaty et al., 1974; Silveira et al., 2017; Yarborough et al., 2017). Although species differ in their resource needs for space, light, water, and nutrients, changes in these resources can increase the competition between these species (Kemp & King, 2001). Therefore, combining herbicides and fertilizer should improve productivity of bahiagrass by eliminating weed competition and increasing plant density of bahiagrass. However, there is much to learn about the interactive effects of an integrated management system. There is currently a paucity of research on how bahiagrass forage systems respond to collective herbicide and fertilizer treatments. Specifically, research should identify any synergistic or antagonistic effects of applying both PRE and POST-emergent herbicides with fertilizer applications of N and N+K to reduce smutgrass populations. Therefore, this research will investigate the interaction of herbicide and fertilizer applications on smutgrass control concerning the contemporary low-input management strategies for bahiagrass forage systems in the Coastal Plain Region of Georgia.

The objectives of this experiment were to (1) evaluate the interactive effects of herbicide and fertilizer applications for controlling smutgrass and (2) determine the most efficacious and economical IPM plan for low-input bahiagrass systems.

Materials and Methods

Description of Research Site

This research was conducted at the University of Georgia Alapaha Beef Station in Alapaha, GA, (31°35’ N, 83°35’ W; 81 m elevation) from April through October 2020-2021. The experimental site (Fig. 3.1) was located in a previously established Tifton-9 and Pensacola bahiagrass pasture with a pre-existing population of small smutgrass (location 1: average = 42%; range = 20-80% 2020; location 2: average = 27%; range = 2-100% 2021). Each location was initiated in consecutive years. The experimental areas were fenced off to exclude grazing. The research site is nearly level (<2% slope) and primarily composed of Alapaha loamy sand and Rutledge loamy sand, with an average soil pH of 5.0 (USDA, Web Soil Survey). Daily air temperatures followed 100-year historical monthly average temperatures for both 2020 and 2021. Minimum monthly average temperatures for April, July, and October representing the beginning, mid-point and the end of the growing season were 12°C, 22°C, and 16°C respectively. Maximum monthly average temperatures for April, July, and October were 25°C, 34°C, and 28°C respectively (Georgia Weather Network, 2021). Rainfall varied year to year, with precipitation following historical average rainfall of 715 mm beginning in April through October for 2020 and above average for 2021 with 1103 mm (Fig. 3.2) (Georgia Weather Network, 2021).

Experimental Design and Treatments

The experiment was arranged in a randomized complete block design with a four by three factorial arrangement and six replications. Treatments included four herbicide (factor a) and three fertilizer (factor b) combinations and totaling 12 treatment combinations. Treatment combinations were randomly assigned to plots within each replicate, for a total of 72 plots. Each 2 m x 5 m plot was surrounded by 1-m alleyways on all sides for distinction.

Herbicide treatment levels included: unsprayed control, PRE-emergent (PRE), POST-emergent (POST) and a combination of both PRE- and POST-emergent (PRE+POST). Indaziflam (PRE, Rezilon®, Bayer Crop Science, Whippany, NJ) was applied at 0.058 kg ai ha^{-1} on 7 Apr. 2020 and 15 Mar. 2021. Hexazinone (POST; Velpar L®, Bayer Crop Science, Whippany, NJ) was applied at 0.98 kg ai ha^{-1} on 7 Aug. 2020 and 30 Aug. 2021) following harvest 4. The combination (PRE+POST) herbicide treatment received both indaziflam and hexazinone applications as previously described. All herbicide treatments were applied using a tractor-mounted, 1.83-m boom sprayer with shield and TeeJet TP8003VS nozzles (TeeJet Technologies Inc., Glendale Heights, IL) calibrated to deliver 205.7 L ha^{-1}.

Ideally, the herbicide applications would have been made earlier each season. The PRE applications were delayed in Year 1 (2020) because University regulations initially prohibited any research activities following the onset of COVID-19 restrictions. The POST application should have been made in June or July, however there was insignificant precipitation forecasted to activate the hexazinone in 2020 and the plots were flooded and inaccessible in 2021 as a result, therefore application was delayed (Fig. 3.1).

Fertilizer treatment levels included: unfertilized control, nitrogen only (N) and nitrogen plus potassium (N+K). Fertilizers were hand-applied following green-up (7 Apr. 2020; 23 Apr. 2021) and following harvest 3 (12 July 2020; 16 July 2021). Each fertilizer application included 56.04 units N ha^{-1} (applied as ammonium nitrate, 34% N) (N) and 56.04 units N ha^{-1} (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O ha^{-1} (applied as muriate of potash; N+K). The fertilizer treatments were below the recommendations provided by the University of Georgia Feed and Environmental Water Laboratory in Athens, GA, but are typical of what most bahiagrass fields would receive in South Georgia (Kissel and Sonon, 2008).

Forage Sampling and Nutritive Value Analyses

Plots were harvested every 4-6 weeks from April until winter dormancy (October). Plot borders were mowed to 7.62 cm prior to each data collection. All plots were visually evaluated for bahiagrass, smutgrass, and other plant species ground cover before they were harvested to 7.62 cm with a Kubota ZD1211 mower with a 152.4-cm deck and bagger attachment (Kubota Tractor Corporation, Grapevine, TX). The collected material from each plot was weighed using a tarp and tripod before a sub-sample was collected for dry matter determination and nutritive value analysis. Post-harvest, residual forage was removed with the same mower (and to the same height) used for harvest. Sub-samples were dried in a forced air dryer at 55°C for 7 d before ground to pass through a 1-mm screen in a Thomas Model 4 Wiley Mill (Thomas Scientific, Philadelphia, PA) followed by a Foss CT-293 Cyclotec Cylcone Mill (Foss Analytics, Eden Prairie, MS) with 1-mm screen (McIntosh et al., 2022). Ground samples were scanned for nutritive value using the 2020 grass hay calibration provided by the NIRS Forage and Feed Testing Consortium (NIRSC, 2020). Samples were scanned on a Foss DS2500 near-infrared spectrometer (Metrohm USA Inc., Riverview, FL) that was standardized to the NIRSC master instrument to ensure prediction accuracy. Nutritive value data were reported with predictions fitting the allowable global H < 3.0 statistical comparison with the overall calibration population (Murray & Cowe, 2004). Total digestible nutrients were calculated using the grass equations provided in Moore and Undersander (2002) as follows:

$$\mathrm{TDN} = (\mathrm{NFC} * .98) + (\mathrm{CP} * .87) + (FA * .97 * 2.25) + NDFn * NDFDp/100) - 10$$

where NFC is non fibrous carbohydrate (% of DM) = 100 – (NDFn + CP + EE + ash), “CP” is crude protein (% of DM), FA is fatty acids (% of DM) = ether extract – 1, NDFn is nitrogen free NDF = NDF – NDFCP, otherwise estimated as NDFn = NDF*.93, and NDFDp is 22.7 + .664*NDFD, where NDFD is 48-hour in vitro NDF digestibility (% of NDF).

Statistical analyses

Data were analyzed by restricted maximum likelihood using PROC MIXED in SAS 9.4 (Littell et al., 2006). A Kenward–Rodgers adjustment was applied to correct the denominator degrees of freedom, ensuring appropriate standard errors and F statistics for each model. Multiple covariance structures were tested and the Bayesian’s Information Criterion indicated that Autoregressive (1) was the best fit. Differences in forage accumulation, nutritive value, and botanical composition were examined within harvest. Fixed effects included treatment, year, and treatment x year. Replicates were the random effect. Means were compared using the LSMEANS procedure with Tukey–Kramer adjustment ($P \leq 0.05$). Differences were considered significant at $P \leq 0.05$.

Economic analyses

An economic analysis was made with respect to market costs of the examined treatments and compared to a total bahiagrass renovation. All fertilizer prices were collected from DTN in January 2022. All herbicide prices were collected from Chemical Warehouse herbicide costs in the spring of 2022 (Chemical Warehouse, 2022; Quinn, 2022). The costs associated with each treatment were calculated by multiplying the quantities of inputs used by the market prices for the region.

Bahiagrass renovations were calculated by modifying the University of Georgia Extension, College and Agricultural and Environmental Sciences - Applied Economics, 2018 hybrid bermuda hay – non-irrigated establishment budget to reflect fertilizer rates and seed costs recommended by UGA bahiagrass management bulletin (Hancock et al., 2010). This budget included: market costs for a glyphosate burndown, 2,4-D for POST application, 'TifQuik' bahiagrass seed costs from Hancock Seed Company, fertilizer at planting and after first mowing, fuel, repairs, maintenance, labor, and interest (Hancock Seed, 2022; Lacy, Morgan, and Russell, 2016).

Results & Discussion

Forage Accumulation

Year x treatment did not interact to affect forage accumulation (FA), so data were pooled over both years ($P = 0.75$; Table 3.1). Data were analyzed within harvest to better isolate the treatment responses ($P < 0.01$) (Table 3.1). No differences in FA were reported in harvest 1 ($P = 0.15$; Table 3.2; May). This is not surprising since only PRE had been applied before this harvest and indaziflam itself should not affect FA. Plots assigned to the fertilizer treatments received the respective fertilizer following harvest 1. This generally resulted in an increase in FA of the fertilized treatments at the second harvest (June), however the increase was not always significantly different from unfertilized treatments ($P < 0.01$). Again, no differences in FA were found at harvest 3 (July) despite the previous fertilizer treatment ($P < 0.01$). It should be noted that even though the *P*-value indicated treatment differences at harvest 3, the results from the Tukey-Kramer tests did not find differences in the pairwise comparisons. The second fertilizer application was made following harvest 3, so it was not surprising that the treatments receiving N had greater FA at harvest 4 (August) than the unfertilized treatments ($P < 0.01$). The POST herbicide was applied following harvest 4 and the effects are seen in subsequent harvests. In general, FA declined in treatments including POST herbicide at harvests 5 and 6 (September – October; $P < 0.01$). However, these differences are not always different from the treatments not receiving POST. This is likely a consequence of biomass differences between bahiagrass, smutgrass, and other weeds. FA is not a sufficient metric to determine treatment effectiveness.

Overall, FA illustrated seasonal trends following low yields at the beginning of the growing season, peaking during the mid-point when daily temperatures were most extreme, and gradually declining into the fall representing a typical growth pattern for warm-season perennial forages (Beaty et al.,1960). Precipitation in the spring of both years was well above the 100-year average (Fig. 3.1). This could result in reduced herbicide and fertilizer efficacy. Plant uptake of systemic herbicides and fertilizer requires suitable soil moisture concentrations, and heavy profuse rainfall events can cause diluted soil solution (Gouy et al., 1999). Furthermore, sandy textured soils with low percentages of organic matter reduce nutrient retention because of leaching and limited cation exchange capacity. However, extensive research has been conducted in Florida on similar sandy soils to those found in the Alapaha region that illustrated bahiagrass FA increases following N applications and is less prone to seasonal variability in FA when fertilized (Blue, 1973; Volk, 1956; Yarborough et al., 2017).

Continued and sustained bahiagrass production in southern forage systems requires preemptive preparation for managing early emerging weed species. Removing invasive species has a two-fold impact on bahiagrass as opportunistic weeds can take advantage of initial herbicidal injury as well as increased disturbances to the forage canopy (Ferrell & Mullahey, 2006; Kemp & King, 2001). The PRE application of indaziflam at the beginning of the year failed to show significant differences for FA but may play a crucial role when analyzed in other compatible metrics such as shifts in weed populations. Indaziflam is well suited as a cellulose biosynthesis inhibitor (CBI) for preventing seedling emergence of both annual and perennial weed species (Brabham et al., 2014) which may not present quantifiable data regarding FA. However, previous research utilizing indaziflam as a PRE in turf systems has indicated that root injury is possible and likely in similar grasses such as bermudagrass (Jones, Brosnan, Kospell & Breeden, 2013). Jones et al. (2013), demonstrated that factors such as rooting depth, especially within the first 10 cm, as well as sandy soil types with little organic matter influence injurious effects. Although, Hurdle et al., (2020) illustrated that applications of indaziflam did not impact bermudagrass FA. Bermudagrass root systems that fall below the first 10 cm may be able to avoid herbicidal injury that would limit FA. Bahiagrass will likely have similar results as Burton (1943) reported that bahiagrass has large and deep fibrous root systems when compared to bermudagrass and other warm-season perennials. Overall, the impact of indaziflam on FA has not been shown to be substantial, especially when compared to POST application of hexazinone (Table 3.2).

The present research indicated that an application of hexazinone did reduce FA by temporarily stunting bahiagrass plants. Although bahiagrass can tolerate applications of hexazinone, it will turn slightly yellow roughly 15 to 20 days after treatment (DAT) with full recovery within 40 DAT (Sellers et al., 2020). Wilder et al., (2008) demonstrated that an inverse relationship between application rate and FA in bermudagrass was recorded 4 weeks after treatment. Cumulative FA in Tifton-85 bermudagrass by Wilder further confirms that treated bermudagrass decreased by 218 kg ha^{-1} for every 0.25 kg ha^{-1} above 0.50 kg ha^{-1} of hexazinone (Wilder et al., 2008). However, responses to treatments are species specific and bahiagrass FA may differ. Avoiding significant FA reductions would require ensuring smutgrass ground cover was at least 35% to reduce bahiagrass exposure and the risk of herbicidal injury (Wilder et al., 2008; Ferrell et al., 2006). The combination of herbicide and fertilizer can be utilized to manage smutgrass while fertilizer applications improve bahiagrass FA by enhancing vigor and vegetative development (Rana et al., 2015). Fertilizer is vital for bahiagrass recovery from initial herbicidal injury as well as giving it an advantage over other competitive weeds (Rana, 2012). This research concluded that applications involving some level of fertilizer accumulated more forage than non-fertilized treatments, supporting evidence from previous literature (Sellers et al., 2020; Rana, 2012; Wilder et al., 2008). The web of interactions that influence bahiagrass responses are complex; therefore, it is necessary to widen the focal point beyond FA to include ground cover.

Ground Cover Percentage

Year x treatment did not interact to affect smutgrass, bahiagrass, other, or dead ground cover except at harvest 4 where the interaction was a difference of magnitude ($P < 0.01$; Table 3.3). Again, the data were pooled over both years analyzed within harvest. Initial observations were recorded at harvest 0 before PRE herbicide application where no differences were reported ($P = 0.59$; Table 3.4; March). Similarly, no differences were reported for harvest 1 ($P = 0.82$; Table 3.4; April) following PRE and fertilizer application. Indaziflam has been well established as a PRE in turf where it reduces seedling emergence, and therefore it is not surprising that it did not impact preexisting smutgrass ground cover. No differences in smutgrass cover were found at harvest 2 (June) ($P = 0.84$) and harvest 3 (July) ($P = 0.12$). Despite the fertilizer application following harvest 3, harvest 4 (August) also resulted in no differences among treatments ($P = 0.28$). The POST herbicide was applied following harvest 4 and the effects were again seen in subsequent harvests (September and October). Smutgrass ground cover numerically declined for all plots that received POST herbicide compared to the unsprayed plots and most plots receiving only PRE ($P < 0.01$). Unfortunately, the large variation in the plots at the final harvest event resulted in a large standard error of the mean and this decline was not always significant among certain pairwise comparisons.

Similar trends were observed with respect to bahiagrass ground cover (Table 3.5). Treatment responses did not indicate any differences from the non-treated control for bahiagrass ground cover in harvest 0 through harvest 4 (April – August; Table 3.5; $P > 0.05$). Following POST application of hexazinone at harvest 4 (August) bahiagrass ground cover generally increased in the respective treatments for the following harvests (September and October; $P < 0.01$). Other weeds ground cover followed similar trends to bahiagrass cover from the initial observation at harvest 0 through harvest 4 (April – August; Table 3.6; $P > 0.05$). Following the application of hexazinone, the PRE+POST+N; POST+N+K; and PRE+POST+N+K reduced other weeds ground cover when compared to the non-treated control at harvest 5 ($P < 0.01$). Data could not be analyzed at harvest 6 because other weeds were not found in any of the plots.

Data for dead plant material could not be analyzed for harvests 0 through harvest 4 (April – August; Table 3.7) because none were found in any of the plots before POST application of hexazinone. However, following hexazinone treatment applications, dead plants were observed for all treatments that included some level of POST. Witnessing necrosis and terminated plants following POST application was expected (Coffman, Frank, and Potts, 1993). Observations of dead plant material did not negatively impact bahiagrass and were limited to targeted weeds. It should be noted that even though the *P*-value indicated treatment differences at harvest 5 (September) and 6 (October), the results from the Tukey-Kramer tests did not find differences in the pairwise comparisons.

When botanical composition is coupled with the results from FA, it is evident that an integrated management plan including PRE, POST, and fertilizer produces a more favorable result than the current practice (POST alone). A fully integrated management plan would help to reduce the introduction of other weedy species and provide essential nutrients for sustaining bahiagrass long-term that could not be accounted for with a singular application of hexazinone. The results of this research support previous literature on the efficacy of hexazinone as a management tool for controlling smutgrass (Hancock et al., 2010; Mislevy et al., 1999; Sellers et al., 2020). However, their research had a singular focus on POST alone or POST and fertilizer interactions. One of the many challenges faced with removing smutgrass from bahiagrass forage systems is the disturbance to the pre-existing canopy. Reduced ground cover leads to increased light penetration and accessibility to space and nutrients for many opportunistic annual and perennial weedy species. This is a well-known ecological principle among species dynamics and plant-plant interactions (Kemp & King, 2001). Integrating indaziflam can benefit bahiagrass by limiting weed competition while it grows to fill the voids left by the mature smutgrass plants. Results indicated that a PRE application of indaziflam before harvest 1 (May) did not negatively impact bahiagrass cover supporting similar research conducted by Hurdle et al. (2020) in bermudagrass. This is not surprising as morphological characteristics between bermudagrass and bahiagrass are similar. Continued research is needed to determine the impact of indaziflam on future smutgrass populations in upcoming seasons.

The benefits of fertilizer to bahiagrass have been well established. However, the lack of POST activity may permit smutgrass to outcompete bahiagrass, even when fertilizer is applied without subsequent herbicide. Consequently, a singular focus on fertilizer to increase the competitive advantage of bahiagrass over smutgrass and other weeds may not be the best approach. Vengris et al. (1953) suggested that weed species can better utilize plant nutrients and are more aggressive than most desired crop species, regardless of the stage of growth, soil fertility relationship, and seasonal weather conditions. Much of the region is prone to acidic soils (pH = 4.5-5.5) and climatic challenges coupled with a high-water table disallows forage producers from maintaining a neutral pH. It has been well established that bahiagrass grows best at a pH range of 5.5. Rana et al., (2013) concluded that a pH range that is either too high (6.5) or too low (4.5) provided a distinct competitive advantage for giant smutgrass over bahiagrass. Furthermore, Beaty et al., (1960) highlighted that the peak performance of bahiagrass is during the hottest months of the year in June and July. Holding to the advantageous characteristics of many other weedy species, smutgrass productivity is not limited by these seasonal patterns and benefits greatly as a result of declining bahiagrass later in the season. Even though bahiagrass is known as a rather aggressive warm-season perennial species, forage systems are dynamic with extreme environmental exposures and antagonistic pests competing for the same resources. As a result, continual shifts in species abundance and distribution is common-place that makes it challenging to manage.

Forage Nutritive Values

Forage samples from each harvest were subjected to NIRS analyses. No interactions between year x treatment for CP and TDN were observed, therefore, data were pooled over years ($P = 0.75$; Table 3.8). Data for CP and TDN were also analyzed within harvest. Generally, CP increased from 7.6 to 9.2 mg g^{-1} with N compared to the non-treated control supporting experimental evidence by Silveira (2017) (Table 3.9). No differences in CP concentrations were observed with K and herbicide treatments. Yarborough et al., (2017) found that bahiagrass responses to K can be affected by climatic factors, and with heavy rainfall during portions of the experimental period following application, considerable amounts of K could have been leached. Furthermore, the relatively low pH found in bahiagrass forage systems in this region (4.5-5.5) is similar to those found in Florida (5.5) where Yarborough et al., (2017) expresses the impact of this lower pH range to the potential leaching of K. Regardless of treatment combinations, there were no practical differences in TDN throughout the experimental period (Table 3.10).

The challenge for most if not all producers in the southern US is meeting the nutritive demands for cow-calf performance. As the predominant method of livestock production, additional supplementation is more than likely necessary to meet the maintenance, growth, and gestation phases as bahiagrass fails to meet the minimum requirements (NRC, 2016). The minimum daily requirement for a 545 kg lactating beef cow ranges from 8-10% CP and 55 – 65% TDN for maintenance and lactation (NRC, 2016). Even more challenging is meeting the demands of a 250 kg growing stocker with a minimum range of 12% CP and 65% TDN for growth (NRC, 2016). CP for bahiagrass did reach minimum requirements, however, variability throughout the season could limit confidence in forgoing additional supplementation. TDN failed to provide nutritive values consistent with minimum requirements reported in NRC, thus, supplementation is recommended.

Economics

Costs among the treatments ranged from US$145.00 to 610.00 ha^{-1}, whereas the estimated cost for complete bahiagrass renovation was US$1079.00 ha^{-1} (based on Lacy, Morgan, and Russell, 2016; Table 3.11). The most common practice for producers in the Southeast US is to utilize POST alone, keeping costs low at US$145.00 ha^{-1}. However, work done by Sollenberger (2019) highlights the negative impact of neglecting proper fertilization that leads to declining bahiagrass forage systems in Florida. Therefore, the addition of N is highly recommended, with an associated cost of US$415.00 ha^{-1} for POST+N. Avoiding long-term decline of bahiagrass stands will include incorporating more than just N, especially when it is considered the most common limiting nutrient in sandy soils (Blue, 1973). Yarborough et al., (2017) highlights the benefit of adding K in addition to N for increasing root mass and an important management practice for promoting persistence in extensive grazing systems. Costs for a regime that includes POST+N+K are US$515.00 ha^{-1}.

The greatest return on investment for controlling smutgrass and other advantageous weeds should include a PRE for controlling annual weed emergence, following a POST application for controlling preexisting weeds. Incorporating a full spectrum fertilizer plan that includes at a minimum N+K for boosting bahiagrass over competitive weeds increases its overall longevity. The fully integrated management plan (POST+PRE+N+K) initial estimated costs average US$610.00 ha^{-1}. Many producers will find this costly, however, when compared to the costs of complete bahiagrass renovation at US$1079.00 ha^{-1} there are significant savings that can be utilized elsewhere in the operation. Not to mention the loss of production time for reestablishment. Because of the significant expense, Sellers et al. (2020) recommend only treating fields infested with more than 50% smutgrass. Regardless, rising costs and a potentially limiting supply of both fertilizer and herbicides could negatively affect management decisions. Fortunately, data show that a range of treatment options (i.e., POST+N; US$415.00 ha^{-1}) (Table 3.11) are available for reducing smutgrass and limiting weed emergence which gives producers additional options when difficult circumstances arise.

Conclusions

The results from this study indicate that herbicide treatments with POST provide adequate control of smutgrass throughout the growing season. Previous research demonstrates that fertilizer applications provide a boost to bahiagrass giving it a competitive advantage over other weed species and increase FA linearly with increasing N application rates (Blue, 1974; Silveira et al., 2017). However, forage accumulation was primarily affected by fertilizer applications and did not adequately portray significant differences and interactions among treatments. Bahiagrass groundcover increased as a result of smutgrass reductions with the inclusion of POST applications. The benefits of fertilizer applications can provide recovery to bahiagrass injury from POST treatments as well as helping to sustain its longevity and persistence. The importance of an integrated management strategy that includes PRE, POST, and fertilizer treatments will help to mitigate risks to singular treatment exposures that could lead to future developments of resistance with herbicide applications. Additionally, rising costs of fertilizer, fuel, and herbicide will necessitate the need to provide producers in the region with financial flexibility in their management strategy. When compared to a complete bahiagrass renovation, a fully integrated management plan should be the most economical option for producers to sustain bahiagrass forage production long-term.

Future studies will determine the impact of a fully integrated management plan on sward dynamics within bahiagrass forages and the shift in species abundance and distribution as a result of smutgrass removal, which herbicide is most important for preventing the introduction of noxious weeds, as well as conduct a more thorough economic analysis. In the interim, producers should implement an integrated management plan that utilizes a timely application of indaziflam to reduce the introduction and emergence of weed species and hexazinone when pre-existing smutgrass infestations are at least 50%. This should be combined with fertilizer applications for enriching bahiagrass productivity that increases both FA and groundcover providing a competitive advantage in disturbed canopies. Future work will continue to look at preventing further smutgrass infestations utilizing this novel strategy. Research is ongoing to improve the effectiveness of herbicide and fertilizer treatments and screen new herbicide technologies for preventing the introduction of other noxious weeds. Although the need for more research is understood, the scope of this research by expanding novel management strategies will deliver agronomic and economic stability to producers for improving bahiagrass forage utilization and preventing the introduction of other weeds in the Southeastern US.

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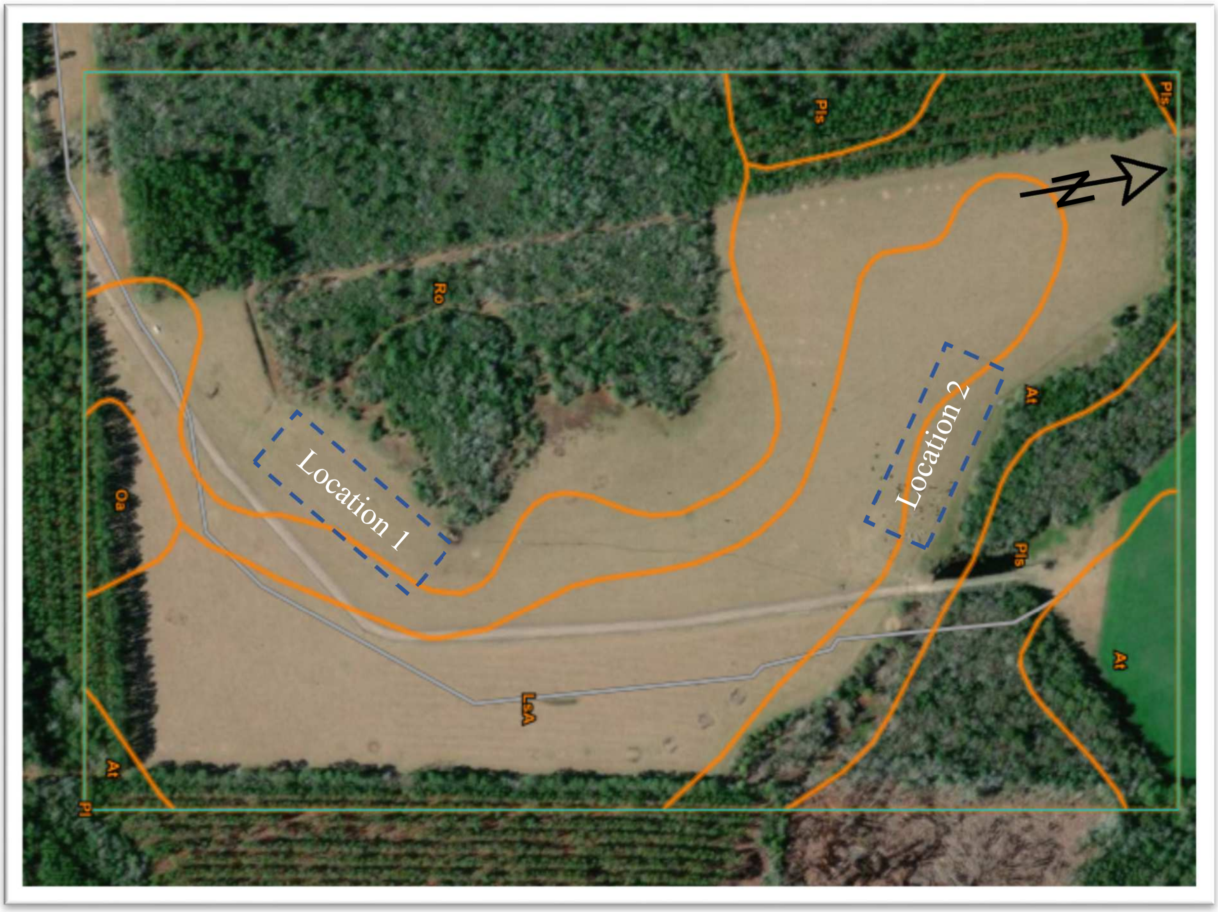

Figure 3.1. Experimental site location 1 and location 2 at the UGA Alapaha Beef Unit near Alapaha, GA (31°35’ N, 83°35’ W). Research initiated: location 1, 2020; location 2, 2021.

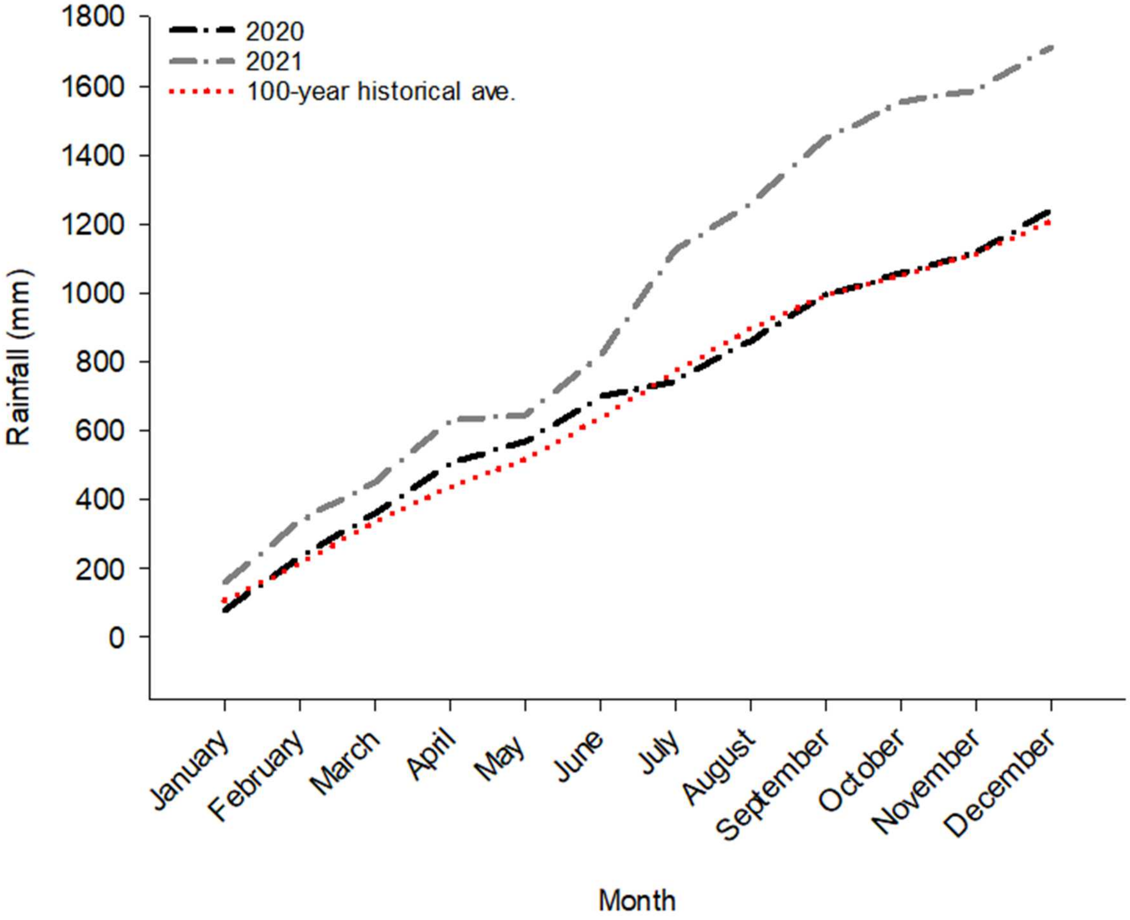

Figure 3.2. Cumulative monthly rainfall from January to December for 2020 and 2021 in Alapaha, GA. 100-year historical average and data collected from Georgia Weather Network (http://www.georgiaweather.net).

Table 3.1. ANOVA for the effects and interactions of herbicide and fertilizer treatments, harvest, and year forage accumulation FA of bahiagrass-dominant pasture (includes smutgrass, bahiagrass, other weeds) grown in Alapaha, GA in 2020 and 2021.

Effects	*F value*	*P > F*
Treatment†	8.90	<0.01
Harvest	306.41	<0.01
Harvest x treatment	3.53	<0.01
Year	214.02	<0.01
Year x treatment	0.69	0.75
Year x harvest	398.41	<0.01
Year x harvest x treatment	2.62	<0.01

† Treatment represents combinations of applied herbicides and fertilizers.

Table 3.2. Effect of treatment on forage accumulation of bahiagrass-dominant pasture (includes smutgrass, bahiagrass, other weeds) grown at the Alapaha Beef Unit near Alapaha, GA, during 2020 and 2021. Harvest periods refer to 2020 and 2021 dates, respectively, as follows: (1) 11 and 21 May, (2) 8 and 18 June, (3) 12 and 16 July, (4) 7 and 27 August, (5) 27 September and 1 October, (6) 26 October. Data are pooled across replications and years.

Treatment†	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 5	Harvest 6
	kg DM ha^{-1}					
Control	889	552 bc§	729	935 b	970 abc	380 abc
Pre	767	475 c	864	974 b	969 abc	415 ab
Post	889	541 bc	883	830 b	609 d	229 d
Pre+Post	1048	593 abc	874	984 b	717 cd	274 cd
N	1058	831 a	693	1378 a	1248 a	413 ab
Pre+N	980	685 abc	701	1442 a	1291 a	444 a
Post+N	1130	733 abc	726	1385 a	988 abc	312 bcd
Pre+Post+N	1097	705 abc	848	1312 a	828 bcd	268 d
N+K	1011	734 abc	849	1381 a	1154 ab	422 ab
Pre+N+K	1168	780 ab	826	1448 a	1269 a	455 a
Post+N+K	1095	829 a	862	1372 a	877 bcd	254 d
Pre+Post+N+K	1144	784 ab	826	1427 a	845 bcd	278 cd
SEM‡	262.84	62.53	399.85	91.37	613.79	28.10

† Pre: pre-emergent; Rezilon (0.28 kg ai ha^{-1}). Post: post-emergent; Velpar L (4.82 kg ai ha^{-1}). N: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N); N+K: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O/ha (applied as muriate of potash).

‡ SEM: standard error of the mean.

§ Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

¶ Note: *P*-value indicated treatment differences at harvest 3, although results from the Tukey-Kramer tests did not find differences in the pairwise comparisons.

Table 3.3. ANOVA for the effects and interactions of herbicide and fertilizer treatments, harvest, and year on botanical groundcover parameters of smutgrass, bahiagrass, other weeds, and dead foliage grown in Alapaha, GA in 2020 and 2021.

Effect	**Smutgrass**		**Bahiagrass**		**Other**		**Dead**	
	F-value	*P > F*	*F*-value	*P > F*	*F*-value	*P > F*	*F-value*	*P > F*
				Harvest 0				
Treatment†	0.81	0.63	0.78	0.66	1.18	0.31	-	-
Year	30.43	<0.01	22.00	<0.01	25.05	<0.01	-	-
Year x treatment	0.53	0.88	0.51	0.89	1.17	0.31	-	-
				Harvest 1				
Treatment	0.58	0.84	0.58	0.84	1.12	0.35	-	-
Year	1.47	0.23	0.08	0.79	5.12	0.03	-	-
Year x treatment	0.45	0.93	0.58	0.84	0.71	0.72	-	-
				Harvest 2				
Treatment	0.56	0.86	0.68	0.75	1.10	0.37	-	-
Year	3.28	0.07	6.60	0.01	6.38	0.01	-	-
Year x treatment	0.52	0.89	0.94	0.51	1.48	0.15	-	-
				Harvest 3				
Treatment	1.59	0.11	1.41	0.18	1.06	0.40	-	-
Year	35.42	<0.01	15.08	<0.01	105.51	<0.01	-	-
Year x treatment	1.25	0.26	1.19	0.30	1.24	0.27	-	-
				Harvest 4				
Treatment	1.55	0.12	1.81	0.06	1.59	0.11	-	-
Year	20.25	<0.01	14.78	<0.01	4.55	0.04	-	-
Year x treatment	4.09	<0.01	4.67	<0.01	1.59	0.11	-	-
				Harvest 5				
Treatment	6.74	<0.01	4.95	<0.01	3.15	<0.01	-	-
Year	0.35	0.55	2.73	0.10	1.23	0.27	-	-
Year x treatment	1.64	0.10	0.88	0.56	1.32	0.22	-	-
				Harvest 6				
Treatment	16.57	<0.01	9.17	<0.01	-	-	-	-
Year	-	-	-	-	-	-	-	-
Year x treatment	-	-	-	-	-	-	-	-

† Treatment represents combinations of applied herbicides and fertilizers.

Table 3.4. Effect of treatment on smutgrass groundcover percentage of bahiagrass-dominant pasture (includes smutgrass, bahiagrass, other weeds) grown at the Alapaha Beef Unit near Alapaha, GA, during 2020 and 2021. Harvest periods refer to 2020 and 2021 dates, respectively, as follows: (0) 7 April and 15 March, (1) 11 and 21 May, (2) 8 and 18 June, (3) 12 and 16 July, (4) 7 and 27 August, (5) 27 September and 1 October, (6) 26 October. Data are pooled across replications and years.

Treatment	Harvest 0[†]	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 5	Harvest 6
	% groundcover						
Control	42	21	27	13	20	27 ab[§]	55 a
Pre	38	27	30	9	25	32 a	51 a
Post	39	34	27	18	26	4 cd	13 bc
Pre+Post	37	29	20	20	23	12 abcd	3 c
N	32	28	25	18	35	26 ab	46 a
Pre, N	33	32	23	14	32	13 abcd	30 ab
Post, N	35	31	30	21	22	9 bcd	0 c
Pre+Post, N	30	34	29	23	17	5 cd	4 c
N+K	30	28	19	12	25	24 abc	46 a
Pre, N+K	36	35	23	22	23	27 ab	45 a
Post, N+K	26	24	29	25	23	4 cd	8 bc
Pre+Post, N+K	33	37	24	18	13	2 d	3 c
SEM[¶]	10.69	6.44	5.71	7.80	8.70	4.73	5.91

† Harvest 0 refers to initial observation.

‡ Pre: pre-emergent; Rezilon (0.28 kg ai ha^{-1}). Post: post-emergent; Velpar L (4.82 kg ai ha^{-1}). N: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N); N+K: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O/ha (applied as muriate of potash).

§ Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

¶ SEM: standard error of the mean.

Table 3.5. Effect of treatment on bahiagrass groundcover of bahiagrass-dominant pasture (includes smutgrass, bahiagrass, other weeds) grown at the Alapaha Beef Unit near Alapaha, GA, during 2020 and 2021. Harvest periods refer to 2020 and 2021 dates, respectively, as follows: (0) 7 April and 15 March, (1) 11 and 21 May, (2) 8 and 18 June, (3) 12 and 16 July, (4) 7 and 27 August, (5) 27 September and 1 October, (6) 26 October. Data are pooled across replications and years.

Treatment	Harvest 0†	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 5	Harvest 6
	% groundcover						
Control	58	65	68	84	77	68 cd§	45 b
Pre	62	62	69	88	70	64 d	49 b
Post	60	54	71	77	72	87 abc	73 ab
Pre+Post	62	63	79	78	75	81 abcd	90 a
N	65	58	69	78	60	71 bcd	54 b
Pre, N	65	60	73	83	66	86 abcd	70 ab
Post, N	64	53	65	76	75	88 abc	97 a
Pre+Post, N	69	56	66	75	81	91 ab	92 a
N+K	70	62	75	84	74	74 abcd	54 b
Pre, N+K	63	53	75	75	75	71 bcd	55 b
Post, N+K	73	60	68	73	76	93 ab	91 a
Pre+Post, N+K	65	53	73	79	86	95 a	92 a
SEM¶	9.78	7.03	6.58	6.22	8.28	5.58	7.44

† Harvest 0 refers to initial observation.

‡ Pre: pre-emergent; Rezilon (0.28 kg ai ha^{-1}). Post: post-emergent; Velpar L (4.82 kg ai ha^{-1}). N: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N); N+K: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O/ha (applied as muriate of potash).

§ Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

¶ SEM: standard error of the mean.

Table 3.6. Effect of treatment on other weeds groundcover of bahiagrass-dominant pasture (includes smutgrass, bahiagrass, other weeds) grown at the Alapaha Beef Unit near Alapaha, GA, during 2020 and 2021. Harvest periods refer to 2020 and 2021 dates, respectively, as follows: (0) 7 April and 15 March, (1) 11 and 21 May, (2) 8 and 18 June, (3) 12 and 16 July, (4) 7 and 27 August, (5) 27 September and 1 October, (6) 26 October. Data are pooled across replications and years.

Treatment	Harvest 0†	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 5	Harvest 6‡
	% groundcover						
Control	0	14	6	3	2	6 a¶	-
Pre	0	11	1	3	5	5 ab	-
Post	1	12	2	5	2	2 abc	-
Pre+Post	1	8	1	3	2	2 abc	-
N	3	14	6	4	4	3 abc	-
Pre, N	3	8	4	3	2	2 abc	-
Post, N	1	16	5	3	3	1 abc	-
Pre+Post, N	1	10	5	3	2	0 c	-
N+K	0	10	6	4	2	3 abc	-
Pre, N+K	1	13	2	3	2	2 abc	-
Post, N+K	1	15	3	3	1	1 bc	-
Pre+Post, N+K	2	10	3	3	1	1 bc	-
SEM#	1.43	3.79	2.40	2.20	1.27	1.04	-

† Harvest 0 refers to initial observation.

‡ Harvest 6 was stopped because of infinite unlikelihood.

§ Pre: pre-emergent; Rezilon (0.28 kg ai ha^{-1}). Post: post-emergent; Velpar L (4.82 kg ai ha^{-1}). N: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N); N+K: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O/ha (applied as muriate of potash).

¶ Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

SEM: standard error of the mean.

Table 3.7. Dead groundcover at the Alapaha Beef Unit near Alapaha, GA, during 2020 and 2021 that was affected by the combination of indaziflam, hexazinone, and fertilizer treatments. Harvest periods refer to 2020 and 2021 respectively, as follows: (0) 7 April and 15 March, (1) 11 and 21 May, (2) 8 and 18 June, (3) 12 and 16 July, (4) 7 and 27 August, (5) 27 September and 1 October, (6) 26 October. Standard error at alpha = 0.05.

Treatment	Harvest 0	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 5	Harvest 6
	% groundcover						
Control	-[†]	-	-	-	-	0	0
Pre	-	-	-	-	-	0	0
Post	-	-	-	-	-	14	13
Pre+Post	-	-	-	-	-	10	7
N	-	-	-	-	-	0	0
Pre, N	-	-	-	-	-	0	0
Post, N	-	-	-	-	-	3	3
Pre+Post, N	-	-	-	-	-	7	4
N+K	-	-	-	-	-	0	0
Pre, N+K	-	-	-	-	-	0	0
Post, N+K	-	-	-	-	-	5	2
Pre+Post, N+K	-	-	-	-	-	6	5
SEM[#]	-	-	-	-	-	3.89	3.62

† Dead cover not observed until POST application of hexazinone.

‡ Pre: pre-emergent; Rezilon (0.28 kg ai ha^{-1}). Post: post-emergent; Velpar L (4.82 kg ai ha^{-1}). N: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N); N+K: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O/ha (applied as muriate of potash).

SEM: standard error of the mean.

Table 3.8. ANOVA for the effects and interactions of herbicide and fertilizer treatments, and harvest on forage nutritive value parameters of bahiagrass grown in Alapaha, GA from 2020 to 2021.

	Crude Protein		Total Digestible Nutrients	
Effect	*F*-value	*P > F*	*F*-value	*P > F*
Harvest 1				
Treatment	4.15	<0.01	0.69	0.74
Year	79.58	<0.01	26.42	<0.01
Year x treatment	1.08	0.39	1.60	0.11
Harvest 2				
Treatment	2.85	<0.01	0.87	0.57
Year	0.20	0.66	27.67	<0.01
Year x treatment	0.60	0.83	0.70	0.73
Harvest 3				
Treatment	1.88	0.05	0.48	0.91
Year	1003.69	<0.01	49.25	<0.01
Year x treatment	0.78	0.66	0.83	0.61
Harvest 4				
Treatment	13.91	<0.01	1.51	0.15
Year	-[‡]	-	-	-
Year x treatment	-	-	-	-
Harvest 5				
Treatment	6.58	<0.01	2.69	<0.01
Year	46.98	<0.01	178.93	<0.01
Year x treatment	1.79	0.06	1.22	0.28
Harvest 6				
Treatment	25.81	<0.01	2.12	0.03
Year	-	-	-	-
Year x treatment	-	-	-	-

† Treatment represents combinations of applied herbicides and fertilizers.

‡ No data collected for harvest 4 or harvest 6 because flooded plots limited forage.

Table 3.9. Crude protein values at the Alapaha Beef Unit near Alapaha, GA, during 2020 and 2021 that was affected by the combination of indaziflam, hexazinone, and fertilizer treatments. Harvest periods refer to 2020 and 2021 respectively, as follows: (0) 7 April and 15 March, (1) 11 and 21 May, (2) 8 and 18 June, (3) 12 and 16 July, (4) 7 and 27 August, (5) 27 September and 1 October. Standard error at alpha = 0.05.

Treatment	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 5
	mg g^{-1}				
Control	7.6 c[‡]	9.7	7.9 ab	10.3 c	10.0 ab
Pre	7.5 c	9.3	7.8 ab	10.2 c	9.6 b
Post	7.6 bc	9.2	8.0 ab	10.8 bc	12.8 a
Pre+Post	7.6 bc	9.4	7.4 ab	9.8 c	11.7 ab
N	9.2 a	10.1	7.4 ab	12.5 a	10.4 ab
Pre, N	8.8 abc	10.2	7.4 b	12.0 ab	9.5 b
Post, N	9.1 ab	10.1	7.8 ab	12.6 a	12.0 ab
Pre+Post, N	9.2 a	10.2	7.4 b	12.8 a	12.8 a
N+K	8.9 abc	10.1	7.3 b	12.4 a	10.7 ab
Pre, N+K	9.5 a	10.1	7.5 ab	12.3 a	9.7 b
Post, N+K	9.9 a	10.1	8.4 a	13.0 a	11.8 ab
Pre+Post, N+K	9.6 a	10.0	7.4 ab	11.9 ab	11.6 ab
SEM[§]	0.38	0.34	0.24	0.35	0.66

† Pre: pre-emergent; Rezilon (0.28 kg ai ha^{-1}). Post: post-emergent; Velpar L (4.82 kg ai ha^{-1}). N: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N); N+K: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O/ha (applied as muriate of potash).

‡ Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

§ SEM: standard error of the mean.

Table 3.10. Total digestible nutrient values at the Alapaha Beef Unit near Alapaha, GA, during 2020 and 2021 that was affected by the combination of indaziflam, hexazinone, and fertilizer treatments. Harvest periods refer to 2020 and 2021 respectively, as follows: (0) 7 April and 15 March, (1) 11 and 21 May, (2) 8 and 18 June, (3) 12 and 16 July, (4) 7 and 27 August, (5) 27 September and 1 October. Standard error at alpha = 0.05.

Treatment	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 5
			mg g^{-1}		
Control	51.7 ab[‡]	50.4	52.4	51.3	47.8 ab
Pre	51.4 ab	50.7	52.0	51.4	48.0 ab
Post	51.8 ab	50.6	52.1	51.6	49.1 a
Pre+Post	51.1 b	50.7	52.1	51.4	49.3 a
N	52.1 ab	50.7	51.9	51.2	48.1 ab
Pre, N	52.4 ab	50.7	51.7	51.3	47.8 ab
Post, N	52.6 ab	50.9	52.3	51.4	48.1 ab
Pre+Post, N	52.5 ab	50.7	52.0	51.4	48.5 ab
N+K	52.8 a	51.1	52.2	51.7	48.1 ab
Pre, N+K	52.8 a	50.5	51.8	51.3	47.2 b
Post, N+K	52.6 ab	50.8	52.7	52.0	48.6 ab
Pre+Post, N+K	52.3 ab	50.5	52.1	51.3	48.1 ab
SEM[§]	0.36	0.29	0.29	0.23	0.37

[†] Pre: pre-emergent; Rezilon (0.28 kg ai ha^{-1}). Post: post-emergent; Velpar L (4.82 kg ai ha^{-1}). N: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N); N+K: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O/ha (applied as muriate of potash).

[‡] Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

[§] SEM: standard error of the mean.

Table 3.11. Market costs for selected integrated management strategies§ for controlling smutgrass in bahiagrass forage systems compared to a complete bahiagrass renovation following University of Georgia recommendations.

Treatment	U.S. $	Unit	U.S.$ ha^{-1}
Indaziflam	0.34	mL	95.00
Hexazinone	0.03	mL	145.00
Nitrogen (UAN32)†	1.02	L	270.00
Potassium (muriate of potash)†	0.90	kg	100.00
Selected integrated plans			U.S.$ ha^{-1}
POST			145.00
PRE+POST			240.00
POST+N			415.00
PRE+POST+N			510.00
POST+N+K			515.00
PRE+POST+N+K			610.00
Bahiagrass Renovation‡			
2018 hybrid bermuda hay-non-irrigated establishment			1079.00

† Fertilizer prices were collected from DTN in January 2022.

‡ Bahiagrass renovations were calculated by modifying the University of Georgia Extension, College and Agricultural and Environmental Sciences – Applied Economics, 2018 hybrid bermuda hay – non-irrigated establishment budget.

§ Market costs for integrated management strategies were selected based on smutgrass management in bahiagrass forage systems, with the addition of indaziflam for current research.

CHAPTER 4

EVALUATING SHIFTS IN SPECIES DISTRIBUTION FOLLOWING HERBICIDE AND FERTILIZER APPLICATIONS FOR SMUTGRASS CONTROL IN BAHIAGRASS[1]

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[1] Shay NS, Baxter LL, Basinger NT, Schwartz BM. To be submitted to *Weed Technology*

Abstract

Novel management strategies for controlling smutgrass (*Sporobolus indicus*) has the potential to influence sward dynamics in bahiagrass (*Paspalum notatum*) forage systems. A small plot trial was established to evaluate the effectiveness of integrated weed management strategies on potential shifts in species abundance and distribution as a result of smutgrass termination in bahiagrass grown in Alapaha, GA. A new location was defined annually in this two-year experiment. Plots were arranged in a three by four factorial arrangement with six replications per site location. Herbicide treatments included Indaziflam (PRE), Hexazinone (POST), combination of pre + post-emergent herbicides (PRE+POST), and an unsprayed control. Fertilizer treatments included 50 units N ha^{-1} (N), 50 units N ha^{-1} + 56.04 kg K2O ha^{-1} (N+K), and an unfertilized control. Eleven weed species were identified in the 13 harvests over the course of the study. Green kyllinga (*Kyllinga brevifolia*) and other common sedges emerged as the most prevalent species of the weed population, almost always present in 50% or more of the plots in both the spring and fall of each year. However, the abundance and distribution of weedy populations had no significant impact on bahiagrass ($P > 0.05$). Moreover, upon the removal of smutgrass, the introduction of other noxious weeds was not observed. Seasonal variability and uncharacteristically high precipitation that occurred in 2021 saw the inclusion of common rush (*Juncus* effusus), ladysthumb (*Polygonum persicaria*), and virginia buttonweed (*Diodia virginiana*) in the sward mixture. Even dallisgrass (*Paspalum* dilatatum) saw increases from year one to year two, although, bahiagrass remained the dominant species throughout the experimental period. Results show that a fully integrated management system including indaziflam, hexazinone and fertilizer provides sufficient control of both annual and perennial opportunistic weed species that have the potential to impact bahiagrass forage systems when managing for smutgrass.

Introduction

Bahiagrass (*Paspalum notatum*) is one of the most predominant warm-season grasses that grows in the southern Coastal Plains Region in the Southeastern United States. Bahiagrass is well suited for low-input grazing systems as it is more drought-tolerant, withstands insect pressure, requires lower fertility inputs, and better tolerates continuous grazing than other perennial forage options (Hancock et al., 2010). One of the biggest challenges in bahiagrass production is the lack of weed control options. Non-native invasive weeds can be problematic, especially perennial weeds such as smutgrass (*Sporobolus indicus*). Removal can complicate a management strategy that does not account for the possible introduction and shifts to other weedy species.

Smutgrass has become a major pest in perennial grasslands throughout the Southeast, primarily including bahiagrass pastures and hayfields (Rana et al., 2012). With dense canopies and an aggressive growth pattern smutgrass can limit the vegetative potential of both bahiagrass and other opportunistic weeds (Rana et al., 2012). Extensive research has identified the use of hexazinone (POST: Velpar L® Bayer Crop Science, Whippany, NJ) as an effective management tool for controlling smutgrass in bahiagrass (Ferrell et al., 2006; Mislevy et al., 2002; Nolte, 2017; Sellers & Ferrell, 2011; Sellers et al., 2020; Wilder et al., 2008;). One of the concerns with hexazinone is properly timing an effective application that requires adequate precipitation. If rainfall exceeds 76.3 mm or does not occur within one week of application, lack of movement into the root zone can significantly impact efficacy (Sellers & Ferrell, 2011). Consequently, it is possible to increase competition from other weed species especially during the first 30 days after application when bahiagrass is recovering from initial injury (Ferrell & Mullahey, 2006).

A timely fertilizer application following hexazinone can also accelerate bahiagrass recovery giving it a competitive advantage over other opportunistic weeds (Shay et al., 2022).

Fertilizers are often the costliest input for low-input producers, although Rana et al. (2015) reported that the combination of hexazinone and fertilizer provided more effective smutgrass termination over singular applications of hexazinone. Unfortunately, weed seed banks are dynamic in sod-based systems and many times disturbances by removing smutgrass is enough to provoke germination. Hancock et al. (2010) described various aggressive summer annual grass species that can become problematic in bahiagrass like goosegrass (*Eleusine indica*) and crowsfoot grass (*Dactyloctenium aegyptium*). There are virtually no selective, post-emergent control options for these weeds in bahiagrass-dominant forage systems that are economical for producers to use. This reinforces the need to have a fully integrated weed management plan that is both cost-effective and resilient.

Furthermore, the inadequate herbicide options may ultimately lead to herbicide resistance in weeds perennially treated with the same chemistries. The sustainability of long-term weed control plans will have to combat the potential challenge of herbicide resistance (Jabran, Mahajan, Sardana, & Chauhan, 2015). Thus, the inclusion of a pre-emergent herbicide can reduce the potential for resistance development by reducing off-target applications and permitting weed species to go to seed. Sebastian et al., (2017) stated that indaziflam (PRE: Rezilon®, Bayer Crop Science, Whippany, NJ) has a unique mode of action as a cellulose-biosynthesis-inhibitor (CBI) for resistance management. Indaziflam also provides favorable control of annual and other early germinating perennials through root and shoot growth inhibition (Sebastian et al., 2017). Shay et al. (2022) found that a fully integrated management plan that includes indaziflam and hexazinone along with a split fertilizer application reduced smutgrass while improving the vigor of bahiagrass throughout the growing season. However, disturbances to an agroecosystem following management implementation can provoke multitrophic biotic responses among varying species (Shennan, 2008). No studies have addressed sward responses to herbicide applications of hexazinone with indaziflam in bahiagrass forage systems. Kemp and King (2001) noted that competitive interactions of plant species in pastures are modified by management practices and these interactions increase in complexity as the number of species rise (Kemp & King, 2001). This explains why other authors have expressed difficulty in improving bahiagrass vigor to provide a competitive advantage over other weed species (Beaty et al., 1974; Silveira et al., 2017; Yarborough et al., 2017;). Removing smutgrass from the system shifts ecological interactions and can promote the introduction of other opportunistic annual and perennial weed species as buried seed often takes advantage of disturbed areas of bare soil and canopy gaps (Sanderson et al., 2014).

The objective of this experiment was to evaluate population shifts in species relative abundance distribution and diversity following the implementation of integrated herbicide and fertilizer management plans for controlling smutgrass in bahiagrass forage.

Materials and Methods

Description of Research Site

This research was conducted at the University of Georgia Alapaha Beef Station in Alapaha, GA, (31°35’ N, 83°35’ W; 81 m elevation) in April through October 2020-2021. The experimental site (Fig. 4.1) was located in a previously established Tifton-9 and Pensacola bahiagrass pasture with a pre-existing population of small smutgrass (location 1: average = 42%; range = 20-80% in 2020; location 2: average = 27%; range = 2-100% in 2021). Each location was initiated in consecutive years. The experimental areas were fenced off to exclude grazing. The research site is nearly level (<2% slope) and primarily composed of Alapaha loamy sand and Rutledge loamy sand, with an average soil pH range of 5.0 (USDA, Web Soil Survey). Daily air temperatures followed 100-year historical monthly average temperatures for both 2020 and 2021. Minimum monthly average temperatures for April, July, and October representing the beginning, mid-point and the end of the growing season were 12°C, 22°C, and 16°C respectively. Maximum monthly average temperatures for April, July, and October were 25°C, 34°C, and 28°C respectively (Georgia Weather Network, 2021). Rainfall varied year to year, with precipitation following historical average rainfall of 715 mm beginning in April through October for 2020 and above average for 2021 with 1103 mm (Fig. 4.2) (Georgia Weather Network, 2021).

Experimental Design and Treatments

The experiment was arranged in a randomized complete block design with a four by three factorial arrangement and six replications. Treatments included four herbicide (factor a) and three fertilizer (factor b) combinations and totaling 12 treatment combinations. Treatment combinations were randomly assigned to plots within each replicate, for a total of 72 plots. Each 2 m x 5 m plot was surrounded by 1-m alleyways on all sides for distinction.

Herbicide treatment levels included: unsprayed control, pre-emergent (PRE), post-emergent (POST) and a combination of both pre- and post-emergent (PRE+POST). Indaziflam (PRE, Rezilon®, Bayer Crop Science, Whippany, NJ) was applied at 0.058 kg ai ha^{-1} on 7 Apr. 2020 and 15 Mar. 2021. Hexazinone (POST; Velpar L®, Bayer Crop Science, Whippany, NJ) was applied at 0.98 kg ai ha^{-1} on 7 Aug. 2020 and 30 Aug. 2021) following harvest 4. The combination (PRE+POST) herbicide treatment received both indaziflam and hexazinone applications as previously described. All herbicide treatments were applied using a tractor-mounted, 1.83-m boom sprayer with shield and TeeJet TP8003VS nozzles (TeeJet Technologies Inc., Glendale Heights, IL) calibrated to deliver 205.7 L ha^{-1}.

Ideally, the herbicide applications would have been made earlier each season. The PRE applications were delayed in Year 1 (2020) because University regulations initially prohibited any research activities following the onset COVID-19 restrictions. The POST application should have been made in June or July, however there was insignificant precipitation forecasted to activate the hexazinone in 2020 and the plots were flooded and inaccessible in 2021 as a result, application was delayed (Fig. 4.2).

Fertilizer treatment levels included: unfertilized control, nitrogen only (N) and nitrogen plus potassium (N+K). Fertilizers were hand-applied following green-up (7 Apr. 2020; 23 Apr. 2021) and following harvest 3 (12 July 2020; 16 July 2021). Each fertilizer application included 56.04 units N ha^{-1} (applied as ammonium nitrate, 34% N) (N) and 56.04 units N ha^{-1} (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O ha^{-1} (applied as muriate of potash; N+K). The fertilizer treatments were below the recommendations provided by the University of Georgia Feed and Environmental Water Laboratory in Athens, GA, but are typical of most bahiagrass fields would receive in South Georgia (Kissel and Sonon, 2008).

Forage Sampling and Nutritive Value Analyses

Plots were harvested every 4-6 weeks from April until winter dormancy (October). Plot borders were mowed to 7.62 cm prior to each data collection. All plots were visually evaluated for bahiagrass, smutgrass, and other plant species groundcover before they were harvested to 7.62 cm with a Kubota ZD1211 mower with a 152.4-cm deck and bagger attachment (Kubota Tractor Corporation, Grapevine, TX). The collected material from each plot was weighed using a tarp and tripod before a sub-sample was collected for dry matter determination and nutritive value analysis. Post-harvest, residual forage was removed with the same mower (and to the same height) used for harvest. Sub-samples were dried in a forced air dryer at 55°C for 7 d before ground to pass through a 1-mm screen in a Thomas Model 4 Wiley Mill (Thomas Scientific, Philadelphia, PA) followed by a Foss CT-293 Cyclotec Cylcone Mill (Foss Analytics, Eden Prairie, MS) with 1-mm screen (McIntosh et al., 2022). Ground samples were scanned for nutritive value using the 2020 grass hay calibration provided by the NIRS Forage and Feed Testing Consortium (NIRSC, 2020). Samples were scanned on a Foss DS2500 near-infrared spectrometer (Metrohm USA Inc., Riverview, FL) that was standardized to the NIRSC master instrument to ensure prediction accuracy. Nutritive value data were reported with predictions fitting the allowable global $H < 3.0$ statistical comparison with the overall calibration population

(Murray & Cowe, 2004). Total digestible nutrients were calculated using the grass equations provided in Moore and Undersander (2002) as follows:

$$\mathrm{TDN} = (\mathrm{NFC} * .98) + (\mathrm{CP} * .87) + (FA * .97 * 2.25) + NDFn * NDFDp/100) - 10$$

where NFC is non fibrous carbohydrate (% of DM) = 100 – (NDFn + CP + EE + ash), "CP" is crude protein (% of DM), FA is fatty acids (% of DM) = ether extract – 1, NDFn is nitrogen free NDF = NDF – NDFCP, otherwise estimated as NDFn = NDF*.93, and NDFDp is 22.7 + .664*NDFD, where NDFD is 48-hour in vitro NDF digestibility (% of NDF).

Statistical analyses

Data were allocated to four observation periods before analysis: initial, the initial observation for the experimental location; after pre, includes observations made following the application of the pre-emergent herbicide but before the post-emergent herbicide; after post, includes observations made following the application of the post-emergent herbicide; and final, includes only the final observation made for the experimental location.

Data were analyzed by restricted maximum likelihood using PROC MIXED in SAS 9.4 (Littell et al., 2006). A Kenward–Rodgers adjustment was applied to correct the denominator degrees of freedom, ensuring appropriate standard errors and F statistics for each model. Multiple covariance structures were tested and the Bayesian's Information Criterion indicated that Autoregressive (1) was the best fit. Differences in botanical composition were examined within each observation period. Treatment was the fixed effect. Replicates, location, and harvest were the random effects. Means were compared using the LSMEANS procedure with Tukey–Kramer adjustment ($P \leq 0.05$). Differences were considered significant at $P \leq 0.05$.

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Results & Discussion

Impact of Integrated Management Strategies on Botanical Composition

At the time of publication, this chapter contains two years of data from location 1. This research is on-going to collect at least one more year of data from each location before publication. The final manuscript submitted for publication will reflect these changes. Data were analyzed within observation period to better isolate the treatment responses ($P < 0.01$; Tables 4.2-4.4).

Smutgrass

There were no differences among treatments in smutgrass groundcover during the first two observation periods (Table 4.2; $P = 0.50$ and $P = 0.10$, respectively). Thus, indaziflam and early season fertilizer did not appear to impact smutgrass groundcover. During the POST observation period, the effects of hexazinone were observed. All plots that received some level of POST were different than the control ($P < 0.01$; Table 4.2) supporting experimental and practical uses of hexazinone as a targeted herbicide for reducing smutgrass populations. Although there is large variation among the treatments at this time, the authors anticipate a reduction in the standard error once the second season of data are collected for location two. The final observation period showed no statistical differences among treatments (Table 4.2, $P = 0.19$). However, the agronomic implications of less than 5% smutgrass compared to more than 20 are profound for a livestock producer in a low-input system who is looking to extend his grazing days or harvest more bahiagrass forage. Likewise, the final observation only contains data from one location at this time. The authors anticipate a statistical difference to be observed at the conclusion of the 2022 harvest season.

Bahiagrass

Bahiagrass groundcover followed similar trends to smutgrass for each observation period. Again, no differences for bahiagrass groundcover were reported at the initial observation ($P = 0.50$) or following the PRE application and early fertilizer treatments ($P = 0.04$; Table 4.3).

Even though the *P*-value indicated treatment differences during the second observation period, the results from the Tukey-Kramer tests did not find differences in the pairwise comparisons. During the POST observation period the bahiagrass groundcover increased beyond the control in all plots that included some level of POST excluding POST alone (*P* <0.01; Table 4.3). This response could be indicative of either treatment synergism between herbicide and fertilizer or the injurious effects of bahiagrass without fertilizer to aid in recovery. Lastly, groundcover for bahiagrass at the final observation indicated no difference among treatments (*P* = 0.10). The same limitations exists here as discussed in the smutgrass section above. The differences among the treatments during the final two observation periods are expected to be significant (less overlap among the treatments) once more data are collected. Again, there are practical implications to the treatment differences seen at the final observation even though there are no statistical differences. For instance, there was 18% more bahiagrass in the PRE + POST + N + K treatment compared to the control at the final observation. That increase ultimately translates to more desirable forage produced to be grazed or harvested, which decreases the need for supplemental forage for livestock.

Other weeds

Differences reported for other weeds at the initial observation were negligible and thus stopped because of infinite unlikelihood (Table 4.4). Following indaziflam (PRE) and fertilizer applications at initial observation, no differences for other weeds were reported during the second observation period (*P* = 0.03; Table 4.4). Even though the *P*-value indicated treatment differences during the PRE observation period, the results from the Tukey-Kramer tests did not find differences in the pairwise comparisons once again. Neither indaziflam nor fertilizer application had a significant impact on the pre-existing weed population. This is contrary to Vengris et al., (1953) who suggests that weed species better utilize plant nutrients and are more aggressive than most desired crop species. Additionally, it is to be expected that indaziflam would have little impact on pre-existing weeds as a pre-emergent inhibiting seedling root and shoot development (Sebastian et al., 2017). During the POST observation period no differences were recorded among treatments for other weeds groundcover (*P* >0.05; Table 4.4). Unfavorable environmental conditions and the vigor of bahiagrass likely contributed more to low weed cover than treatment interactions. Lastly, groundcover for other weeds at the final observation demonstrated differences among treatments with PRE + POST + N being the only treatment difference from the non-treated control (*P* <0.01). Even though there were significant differences recorded within treatments at the final observation, other weeds were only 5% of the total plot, ultimately indicating that cover did not negatively impact bahiagrass forage utilization.

Discussion on sward dynamic implications

Smutgrass removal may induce new weed emergence

Hexazinone has played a critical role in removing smutgrass from bahiagrass forage systems as demonstrated by Shay et al. (2022). Declining smutgrass densities is likely the route cause that led to shifts in weed populations and the introduction of opportunistic annual and perennial weeds. The use of hexazinone for controlling other weeds outside of smutgrass is an indirect benefit, but producers may still require other herbicides such as 2,4-D to control broadleaf species (Hancock et al., 2010). Ideally, a pre-emergent herbicide would be used to reduce the need for additional post-emergent control options. Kaapro and Hall (2011) highlights that the chemical and physical characteristics of indaziflam make it an effective option for many annual weed species, especially grass weeds that are challenging to control selectively in bahiagrass. Fortunately, combinations of indaziflam and hexazinone did not increase the presence of other weed species in the present research (Table 4.4). However, further research is necessary to document the long-term implications of hexazinone in combination with indaziflam and fertilizer on other weed abundance and distribution. The application of fertilizer more than likely benefits all weeds present, however, the aggressive nature of bahiagrass and its extensive root system supports better nutrient utilization. As a result, fertilizer provides a boost for bahiagrass from the initial injury of hexazinone and gives it a competitive advantage over weedy species. But first, a better understanding of plant-plant interactions is required to understand new weed emergence. Forage systems are highly complex including a substantial mix of buried seed favoring this shift in abundance and distribution once vegetation and soil are disturbed (Sanderson et al., 2014).

Other weeds abundance and distribution

Eleven weed species were identified throughout the experimental period (Table 4.4). Overall, species varied depending on the time of year as weed shift dynamics followed seasonal trends throughout the growing season. Green kyllinga (*Kyllinga brevifolia*) and other common sedges emerged as the most prevalent species of the other weed population, almost always present in 50% or more of the plots in both the spring and fall of each year (Table 4.4). Dallisgrass (*Paspalum dilatatum*) was another commonly observed weed in this study, however, many have considered it a tolerable forage for livestock for both its quality and persistence in the humid Southeast (Venuto, et al., 2003). Other weed species observed throughout the experimental period can be found in Table 4.4. It is important to note that although some of these species were found in a large number of plots, they did not comprise more than 8% coverage on average. Typically, the abundance and distribution of common rush (*Juncus effusus*), ladysthumb (*Polygonum persicaria*), and virginia buttonweed (D*iodia virginiana L.*) (Table 4.5) is minimal in perennial forages in any given year. However, weather in 2021 played a critical role as above average rainfall (Fig. 4.2) more than likely influenced a shift in population dynamics to species with an affinity for wet soils. Because the study was positioned in an Alapaha sandy soil with <2% slope, common to most producers in the region, water often pooled in these areas and was a factor in influencing the dominant weed species in the system. Additionally, sedges, virginia buttonweed, elliot's lovegrass (*Eragrostis elliottii*), wandering cudweed (*Gpaphalium penysylvanicaum* Willd.), ladysthumb, and blue-eyed grass (*Sisyrinchium rosulatum*) can quickly inhabit bare soil early in the spring as a result of temperatures and a reduced photoperiod limiting early-season competition for established perennial forages like bahiagrass (Entz et al., 1995; Harvey & McNevin, 1990). (Table 4.5). The competitive distribution among species depending on the stage of development is highly variable leading to continual shifts early on in the season before bahiagrass activity accelerates with increasing temperatures. However, the results from this research showed there were no real threats of other weeds to bahiagrass groundcover (Table 4.3).

Preliminary Conclusions

The ecological symptomology as expressed by species abundance and distribution illustrates the effectiveness of a well-designed management strategy. The integrated techniques utilized in this study provide convincing evidence that indaziflam in combination with hexazinone and fertilizer is effective at manipulating sward dynamics in favor of desired forages. As nature continually pushes towards orchestrated chaos that favors a more diverse forage mixture, producers have now expanded their toolbox that consists of PRE- and POST-emergent herbicides to assist in managing undesirables that are detrimental to livestock grazing. Additional herbicidal options are welcomed when strategies are limited for optimizing bahiagrass productivity and forage utilization in order to avoid supplemental forage. Shifts in sward dynamics are undoubtedly expected as this research demonstrated that weeds emerge from a plethora of circumstantial factors outside of management implementation. What is most important is that there was no evidence of the emergence of other noxious weeds as a result of smutgrass removal. With a continued focus on noxious weeds, future studies could look at which herbicide is most effective at prevention as well as the continual observation of the impact of a fully integrated management plant on sward dynamics long-term. This fully-integrated management plan will balance risk-adverse strategies with the complexities of ecological interactions and provide sustainable methods for bahiagrass longevity in the Southeastern US.

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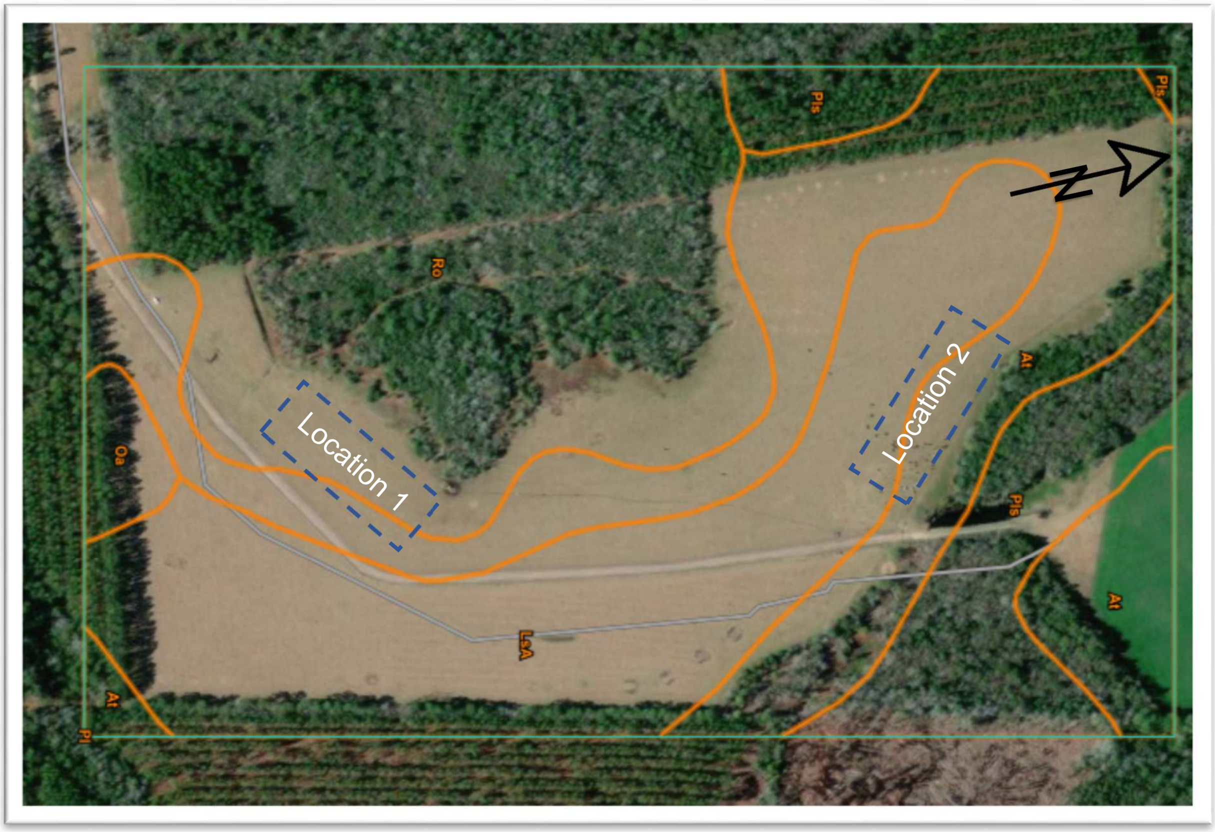

Figure 4.1. Experimental site location 1 and location 2 at the UGA Alapaha Beef Unit near Alapaha, GA (31°35’ N, 83°35’ W). Research conducted: location 1, 2020-2021; location 2, 2021.

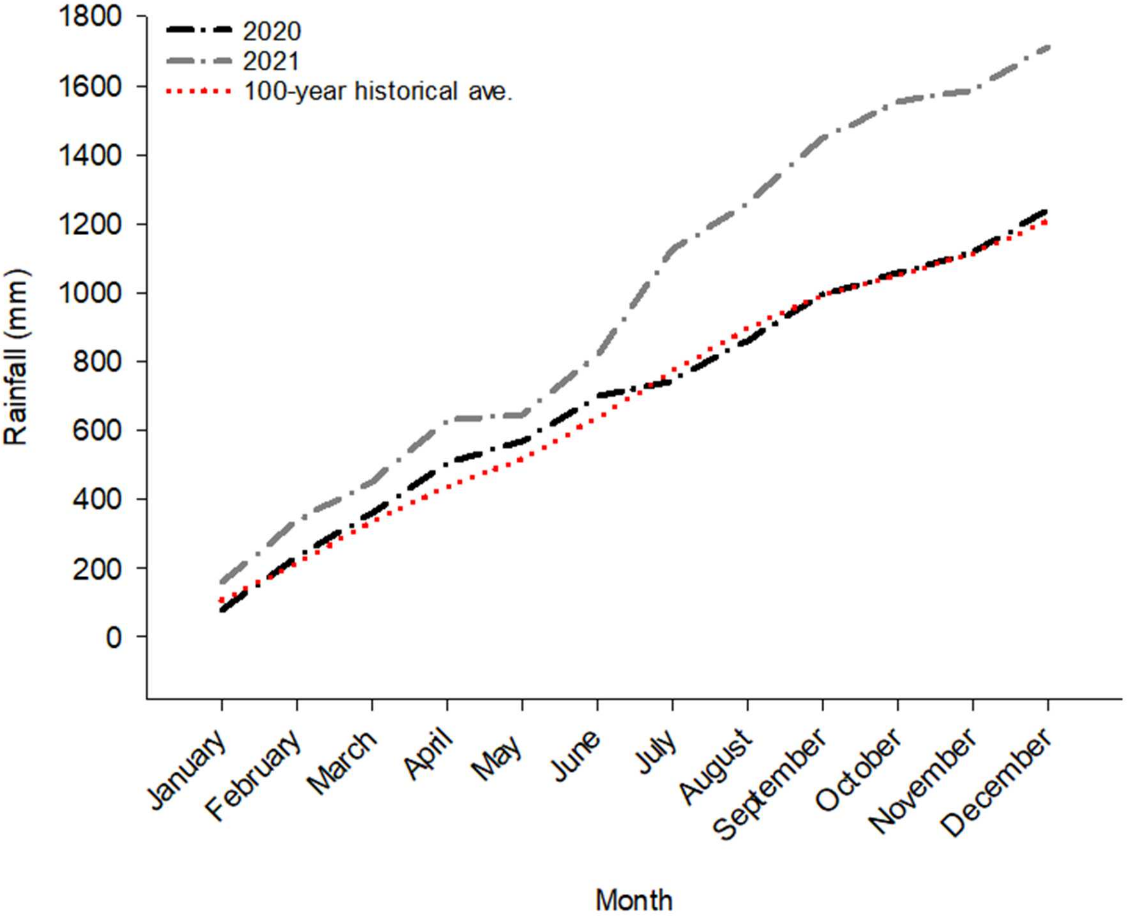

Figure 3.2. Cumulative monthly rainfall from January to December for 2020 and 2021 in Alapaha, GA. 100-year historical average and data collected from Georgia Weather Network (www.georgiaweather.net).

Table 4.1. Initial observation period and subsequent observations following PRE of indaziflam but before POST of hexazinone, following POST, and then at final harvest in Alapaha, GA, location 1.

Harvest	2020	2021
Initial observation	-	15 Mar.
PRE observation	11 May	21 May
POST observation	27 Sept.	1 Oct.
Final observation	26 Oct.	1 Oct.

† Pre: pre-emergent; Rezilon (0.28 kg ai ha^{-1}). Post: post-emergent; Velpar L (4.82 kg ai ha^{-1}). Fer: fertilizer; N: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N); N+K: nitrogen 56.04 units N/ha (applied as ammonium nitrate, 34% N) + 56.04 kg K_2O/ha (applied as muriate of potash).

Table 4.2. Effect of treatment on smutgrass groundcover in bahiagrass-dominant pasture grown at the Alapaha Beef Unit near Alapaha, GA during four observation periods at location 1.

Treatments	Initial[†]	PRE	POST	Final
	% groundcover			
Control	42	20	32 a[§]	18
Pre	48	24	30 abc	30
Post	50	36	16 bcd	7
Pre+Post	50	29	14 cd	22
N	43	33	27 abcd	20
Pre, N	38	26	25 abcd	9
Post, N	45	36	13 d	14
Pre+Post, N	37	32	15 bcd	5
N+K	38	23	26 abcd	16
Pre, N+K	40	26	30 ab	25
Post, N+K	35	30	14 bcd	7
Pre+Post, N+K	42	30	12 d	3
SEM[¶]	8.81	4.97	4.52	7.92

† Initial, observation for the experimental location; PRE, observation made following application of pre-emergent herbicide but before the post; POST, following application of post-emergent herbicide; Final, final observation for experimental location.

‡ Pre: pre-emergent; Rezilon. Post: post-emergent Velpar L. N: nitrogen (ammonium nitrate); N+K: nitrogen + potassium (K_2O).

§ Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

¶ SEM: standard error of the mean.

Table 4.3. Effect of treatment on smutgrass groundcover in bahiagrass-dominant pasture grown at the Alapaha Beef Unit near Alapaha, GA during four observation periods at location 1.

Treatments	Initial[†]	PRE	POST	Final
	% groundcover			
Control	58	75	63 c[§]	78
Pre	52	72	66 abc	67
Post	50	59	76 abc	92
Pre+Post	50	69	81 ab	76
N	57	59	68 abc	77
Pre, N	62	72	71 abc	88
Post, N	55	57	83 a	85
Pre+Post, N	63	65	80 ab	94
N+K	62	72	71 abc	81
Pre, N+K	60	72	66 bc	71
Post, N+K	65	65	82 ab	92
Pre+Post, N+K	58	68	82 ab	96
SEM[¶]	8.81	6.02	4.94	8.05

† Initial, observation for the experimental location; PRE, observation made following application of pre-emergent herbicide but before the post; POST, following application of post-emergent herbicide; Final, final observation for experimental location.

‡ Pre: pre-emergent; Rezilon. Post: post-emergent Velpar L. N: nitrogen (ammonium nitrate); N+K: nitrogen + potassium (K_2O).

§ Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

¶ SEM: standard error of the mean.

Table 4.4. Effect of treatment on other weeds groundcover in bahiagrass-dominant pasture grown at the Alapaha Beef Unit near Alapaha, GA during four observation periods at location 1.

Treatments	Initial†	PRE	POST	Final
	% groundcover			
Control	-‡	5	5	5 a¶
Pre	-	4	4	3 ab
Post	-	5	3	1 ab
Pre+Post	-	2	3	3 ab
N	-	8	4	3 ab
Pre, N	-	2	4	4 ab
Post, N	-	7	4	2 ab
Pre+Post, N	-	3	4	1 b
N+K	-	6	3	3 ab
Pre, N+K	-	2	4	4 ab
Post, N+K	-	5	3	2 ab
Pre+Post, N+K	-	3	3	1 ab
SEM#	-	2.52	2.66	0.88

† Initial observation was stopped because of infinite unlikelihood.

‡ Initial, observation for the experimental location; PRE, observation made following application of pre-emergent herbicide but before the post; POST, following application of post-emergent herbicide; Final, final observation for experimental location.

§ Pre: pre-emergent; Rezilon. Post: post-emergent Velpar L. N: nitrogen (ammonium nitrate); N+K: nitrogen + potassium (K_2O).

¶ Least square means within each harvest not sharing a common letter differ ($P \leq 0.05$).

SEM: standard error of the mean.

Table 4.5. Percent occurrence of weed species in plots from April 2020 to October 2021 at the Alapaha Beef Unit near Alapaha, GA.

Latin Binomial	Common Name	Life Cycle†	Spring 2020‡	Fall 2020	Spring 2021	Fall 2021
			range of occurrence %			
Cenchrus echinatus	Southern sandbur	A	0	0	1-10	0
Cyperus esculentus L.	Yellow nutsedge	P	>75	1-10	>75	50-75
Cyperus globulosus	Globe Sedge	P	>75	1-10	>75	50-75
Diodia virginiana L.	Virginia buttonweed	P	1-10	1-10	50-75	11-50
Eragrostis elliottii	Elliot's Lovegrass	P	0	1-10	>75	1-10
Gnaphalium penysylvanicum Willd.	Wandering cudweed	A	0	1-10	50-75	0
Juncus effusus	Common rush	P	1-10	1-10	11-50	0
Kyllinga brevifolia	Green kyllinga	P	11-50	1-10	>75	>75
Paspalum dilatatum	Dallisgrass	P	1-10	1-10	1-10	1-10
Polygonum persicaria	Ladysthumb	A	11-50	1-10	50-75	1-10
Sisyrinchium rosulatum	Blue eyed grass	A	0	1-10	>75	1-10

† A, annual; P, perennial.

‡ Spring represents harvest 1 & 2; Fall represents Harvest 5 & 6.

CHAPTER 5

FINAL CONCLUSIONS

Encroachment of smutgrass into bahiagrass forage systems throughout the Coastal Plains region of Georgia will require novel pest management strategies to mitigate agronomic and economic challenges. Livestock and hay producers will depend on these novel techniques to manage smutgrass and improve the longevity of pre-existing bahiagrass stands. Low-input perennial forage systems dominate the livestock industry in South Georgia and throughout the lower Coastal Plains. Regional environmental and abiotic constraints limit the tools available for substantial changes to many operations without significant inputs. Therefore, producers will need to explore new technologies (indaziflam) in concert with previously recommended herbicide and fertilizer treatments to maximize efficacy and enhance forage utilization. Researchers must continue to identify tools and strategies to provide economic flexibility despite current market volatility. Overall, a fully integrated management strategy that includes indaziflam, hexazinone, and fertilizer appears to be a viable option for the future of South Georgia as it can preserve bahiagrass forage systems from the invasion of noxious weed species.

Combined treatment impacts on forage accumulation

Achieving satisfactory forage production in the Southeast will most likely always require additional inputs, especially where sandy soils limits nutrient retention. One of the main objectives of this research was to control smutgrass through the interactive effects of herbicide and fertilizer and to observe any possible implications. It is not uncommon to see antagonistic interactions that lead to reduced herbicide efficacy implicating optimal performance of forage production. Producers should recognize that hexazinone has been known to impact forage accumulation (FA) and cause low-levels of injury. Observations gathered during this research demonstrated that virtually no differences existed among treatments or harmed forage accumulation. For forage producers in this region this is encouraging, as maintaining a healthy bahiagrass sward is vital for withstanding the many environmental challenges and threats from other equally advantageous pests and diseases. Empirical data over the years has also shown the significance N applications play for recovery from herbicide intolerances, as well as other factors such as increasing yields and extending the growing season. The long-term impact of a proper fertilizer program is significant for bahiagrass longevity. Continued research with a focus on the interactive effects of treatment combinations will be necessary to ensure that long-term implications do not arise from the use of indaziflam and hexazinone in conjunction with fertilizer.

Hexazinone & indaziflam herbicide treatment impacts on groundcover

With limited herbicide options in bahiagrass forage systems for managing noxious and other opportunistic weedy species, the use of hexazinone continues to be a reliable resource for smutgrass management. It is important to mention that PRE applications of indaziflam did not reduce pre-existing smutgrass or have any significant impact on other preexisting groundcovers. Overall, results from this experiment indicated that a timely application of hexazinone provides satisfactory reductions in smutgrass groundcover, some of which resulted in complete removal of both smutgrass and other weed species. This follows experimental and practical uses of hexazinone and its impact as a systemic herbicide. However, it is often difficult to apply hexazinone before an adequate rainfall event because forecasted precipitation is not delivered or poor field conditions (saturated soils) limit field accessibility. The demand by producers for a new product that has fewer requirements and challenges than hexazinone ushers in the importance of indaziflam as a new herbicide for forage systems. With the increasing threat of herbicide resistance from repeated uses, indaziflam can be used for mitigating any associated risks with future development of resistance in succeeding generations.

Indaziflam is not only unique for its low-resistance capabilities, but also for its seedling and root growth inhibition. Annual and perennial weed species that have the potential to emerge as a result of disturbed canopies following the removal of smutgrass from applications of hexazinone can be properly managed with an application of this pre-emergent. Furthermore, indaziflam is another mechanism that can aid in improvements to bahiagrass groundcover while it recovers from the initial injury of hexazinone. However, producers may be hesitant to add this new mode of action to their management program as it can negatively impact winter annuals utilized to feed their livestock until warm-season grass production resumes. The addition of another management strategy incurs more associated costs for an already limited low-input system, not to mention its unproven status as a long-term option in forage-based systems. Although utilizing indaziflam and hexazinone appears to provide favorable results for improving bahiagrass cover improving recovery and productivity will require the addition of a fertilizer program into the integrated management system.

Inclusion of fertilizer in smutgrass management plan improves bahiagrass forage systems

The importance of utilizing fertilizer as a management tool for improving bahiagrass forage systems has been well documented. This research also showed the relevance of fertilizer applications, where split applications of N and N+K resulted in numerical increases to bahiagrass groundcover, although not significantly different. Fertilization in low-input grazing systems can be a difficult decision for producers given the economic constraints and ramifications of ill-timed applications from significant rainfall events. Producers are also well acquainted with intermittent droughts in the Southeast, sometimes labelled as flash droughts. Stand persistence from a complete fertilizer program will help ensure continual forage supply for their livestock. Future work could emphasize the interactive effects of a fully integrated management plan on whole plant development include root structure, and nutrient storage, and further expand the overall impact on bahiagrass nutritive value.

Combined treatment impact on forage nutritive value

Forage nutritive values are some of the key metrics for determining overall forage quality, and the driver for optimizing animal performance. Producers depend on a good product that meets, at a minimum, the maintenance requirements of their livestock especially in the coastal plains with inadequate soil fertility. Over the experimental period, research demonstrated that nutritive values (crude protein & total digestible nutrients) did fall within the acceptable standard, although mostly for cow/calf operations, which makes up most of the southeast region. Smutgrass on occasion is utilized in a grazing program because of the similar nutritive values to bahiagrass, however it quickly produces seedheads and livestock preferentially avoid it as it matures past the firsts 2-3 weeks of new growth. Continuing to improve stand quality in low-input forage systems is challenging for many of the reasons previously discussed with economic and agronomic constraints. Because the proposed treatment combinations did not negatively impact forage nutritive value, and heavy investment into a fully integrated management plan for removing smutgrass is already being utilized, considering other options such as bahiagrass cultivar selection with enhanced quality may not be a viable option unless one is considering a complete bahiagrass renovation. Therefore, given the current limitations, the recommendation is to maximize the preexisting bahiagrass system through the suggested novel management strategies.

Recommended integrated management plan provides economic flexibility for low-input forage systems

Variability in the fertilizer and herbicide market including significant cost increases in 2022 make it challenging and can be the deciding factor for management implementation. Therefore, sustaining the long-term production and success of producers in the southeast will require a more novel approach. The benefits of an integrated management plan provide producers with the ability to selectively utilize the tools available based on their financial circumstances. Being able to add or subtract tools in the plan based on accessible funds is essential. Thus, the economic range from the basic plan of a singular use of hexazinone at a cost of US\$145.00 ha^{-1} to full integration with indaziflam, hexazinone, N+K at a cost of US\$610.00 ha^{-1} is highly beneficial. When deciding on the best management option from a financial perspective, infestation rates (> 50%) (Sellers et al., 2020) are an important parameter for the decision-making process to see an acceptable return on investment. There are other options available to producers for smutgrass management such as a complete bahiagrass renovation, however, at a cost of US\$1079.00 ha^{-1} it should be recognized as a last resort option. Additionally, it is critical to plan accordingly as renovation entails lost production time for reestablishment, and producers must make other arrangements for their livestock. Overall, when comparing a fully-integrated management plan and a complete bahiagrass renovation, the associated cost savings can be utilized elsewhere in the operation. Thus, providing flexibility through novel pest management ensures livestock and hay producers can continue to maximize animal and forage performance as a means to optimize sustainable long-term profits.

The impact of treatment combinations on shifts in plant abundance and distribution

There is an acceptable threshold for tolerating undesirable weed species that impact forage utilization. Managing for every single weed species would be a costly endeavor and not recommended as a wise return on investment. Additionally, livestock have a broad portfolio of palatable forbs and weeds that they will consume that provide nutritional value to their diet. Therefore, producers should direct their inputs to only invasive and noxious weed species. The introduction of many of these small-seeded weeds that emerged in this research was most likely the result of an application of hexazinone. Disturbances to the canopy as a result of smutgrass removal propagated the introduction of such weeds as southern sandbur (*Cenchrus echinatus*), yellow nutsedge (*Cyperus esculentus L.*), globe sedge (*Cyperus globulosus*), virginia buttonweed (*Diodia virginiana L.*), elliot’s lovegrass (*Eragrostis elliottii*), wandering cudweed (*Gnaphalium penysylvanicum* Willd.), common rush (*Juncus effusus*), green kyllinga (*Kyllinga brevifolia*), dallisgrass (*Paspalum dilatatum*), ladysthumb (*Polygonum persicaria*), and blue eyed grass (*Sisyrinchium rosulatum*). However, many of the weeds observed were not equally distributed in both years and could be the result of other external factors.

One of the many challenges for livestock and hay producers in this region is that sandy texture and < 2% grade makes it difficult to manage water. After a significant rain event, or an extended period of consistent rain, soils are often submerged. This creates a welcoming environment to many of the weeds found in 2021 when rain was well above the historical average. Such weeds as virginia buttonweed, common rush, green kyllinga, and ladysthumb prefer these wet soils. In a year with average rainfall, it is unlikely that these weeds would be an issue. Furthermore, these weeds did not pose any credible threat to bahiagrass or potential preferential grazing.

As a new technology in perennial forage systems, indaziflam provides an option to producers for reducing the introduction and emergence of many undesirables. It is also likely that indaziflam mitigated any risks of the introduction of other noxious weeds commonly found in South Georgia pastures such as foxtail (*Setaria spp.* L.). Continued research will observe potential threats and any future developments of noxious weeds. In the meantime, producers should have confidence that indaziflam with the combination of hexazinone and fertilizer will be an effective strategy for minimizing competition of other weeds and optimizing bahiagrass productivity.