INTEGRATED CONTROL OF TROPICAL SIGNALGRASS (*Urochloa subquadripara*) IN TURF

By

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To my mom

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Tropical signalgrass (TSG) has become a troublesome weed in south Florida following the removal of monosodium methane arsenate (MSMA), an effective and economical postemergence (POST) herbicide, from the turfgrass market at the end of 2012. Turfgrass managers have relied heavily upon this herbicide to control TSG, as well as many other weeds, for many years and are now searching for a comparable replacement.

In an attempt to avoid a similar situation in the future, this thesis focuses on identifying an effective integrated weed management (IWM) strategy aimed at controlling TSG in bermudagrass turf. In one study, verticutting, a cultural practice that is regularly employed on many golf courses, was combined with preemergence (PRE) and POST herbicide treatments to determine whether TSG control would be increased using this integrated approach. The POST herbicides were then evaluated to determine the most efficacious combinations. Additionally, a PRE herbicide study was conducted to demonstrate the impact of seedling recruitment on TSG reestablishment.

In this research, verticutting was found to provide limited weed control by itself. Amicarbazone demonstrated the ability to enhance other POST herbicides through

synergistic activity on TSG control with multiple modes of action. PRE herbicides proved to be a crucial component of a TSG management strategy, with indaziflam showing the greatest level of efficacy of those herbicides tested.

CHAPTER 1
INTRODUCTION

Optimal turfgrass quality is the goal of many golf course superintendents and sod farm managers. Turfgrass managers constantly deal with both biotic and abiotic stressors while attempting to maintain ideal playing conditions or grow high-quality sod. Diseases, insects, and weeds are the most common biotic agents reducing turf quality and growth while water, nutrient deficiencies and temperature extremes are important abiotic stresses (Taiz et al. 2015). All sources of stress must be considered when implementing a turf management strategy. An unhealthy plant is more susceptible to injury from diseases or insects and, in the case of turfgrass, a thinned canopy can favor unwanted weed pressure ultimately eliminating the competitive advantage that the turfgrass may have had originally. This is similar to the agronomic cropping practice of increasing plant density and decreasing the spacing between rows in order to reduce the area and resources available to weeds (Buhler 2002).

Impact of Weeds

Weeds present an enormous challenge for agriculture, as well as turfgrass production and management, as evidenced by the estimated losses in corn and soybean yields in the absence of any control measures. Soltani et al. (2016, 2017) reported that approximately 50% of corn and soybean yields in North America (valued at $27 billion and $16 billion, respectively) would be lost annually by uncontrolled weeds. In 2012, the United States Environmental Protection Agency (USEPA) estimated the world market value for herbicides and plant growth regulators (PGR) to be approximately $25 billion, accounting for nearly half of all pesticide sales in the world (Atwood and Paisley-Jones 2017). Chemical control is the most heavily relied upon method of pest management primarily because it is effective. In the turfgrass industry, it allows for selective removal of undesired plants without harming the desired species, a process that can be especially difficult when the weed is a grass species as well. Herbicide metabolism, or breakdown to non-toxic compounds, forms the basis for turfgrass selectivity compared to susceptible weeds that are less able to metabolize selective herbicides (Cole 1994).

Heavy reliance upon herbicides has led to additional problems, most notably herbicide resistance by weeds. Herbicide resistance is defined by the Weed Science Society of America (WSSA) as “the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type.” Repeated use of any herbicide may eventually select for resistance within a population of weeds. The herbicide-resistant biotypes will then pass this ability on to their progeny and the population will experience a shift towards a higher frequency of resistant plants. Although herbicide resistance in agricultural cropping systems has been occurring for several decades (Ryan 1970), Brosnan and Breeden (2013) reference several studies confirming a more recent reporting of herbicide resistance in turfgrass. These include resistant biotypes of annual bluegrass (*Poa annua* L.), goosegrass, and smooth crabgrass (*Digitaria ischaemum* (Schreb.) Schreb. Ex Muhl). Misuse of an herbicide can also affect other similar herbicides as well. Cutulle et al. (2009) reported prodiamine-resistant annual bluegrass biotypes that also displayed reduced sensitivity to pendimethalin, another preemergence (PRE) herbicide with the same mode of action.

Weed adaptability can also occur in response to nonchemical selection pressures. Barrett (1983) illustrated the consequence of overusing nonchemical control methods. For example, through the process of frequent and intensive hand-weeding in rice (*Oryza sativa* L.) fields, *Echinochloa crus-galli* (L.) Beauv. var. *oryzicola* (Vasing Ohwi) has evolved morphology traits that make it look more similar to rice than to its close weedy relative, *Echinochloa crus-galli* (L.) Beauv. var. *crus-galli*. This serves as a reminder that any control method, chemical or not, can lose efficacy due to weed adaptations especially if used improperly, repeatedly, and without integration with other forms of control.

MSMA Ban

Another negative consequence of relying heavily on a single method of control was made evident when monosodium methane-arsonate (MSMA) was banned from use on golf courses and sod farms in Florida. This herbicide was an affordable and highly effective postemergence (POST) herbicide used to control many troublesome weed species. MSMA contains an organic form of arsenic which is relatively nontoxic, less so than even aspirin when considering acute toxicity (Brosnan and Breeden 2014). Inorganic arsenic, however, is highly toxic and public concern arose around whether or not the organic arsenic from MSMA could be converted to its inorganic form in the soil and leach into groundwater or run off into surface water. In a lysimeter study under greenhouse conditions, Mahoney et al. (2015) documented that after MSMA applications to bermudagrass, a small fraction (<10%) of the herbicide was quickly converted to As(III), but after 8 weeks, more than 80% of the arsenic present in pore water was in the inorganic form As(V). However, Matteson et al. (2014) conducted year-long experiments on managed turfgrass systems under field conditions to determine the fate of arsenic after applications of MSMA. The authors demonstrated that a majority of arsenic remained in the turfgrass foliage and soils, while the concentrations of dissolved arsenic found in pore water measured at a depth of 76 cm was indistinguishable from background concentrations. They concluded that, following normal applications of MSMA, minimal leaching of arsenic into groundwater would occur, however, repeated applications could pose additional risks to the environment. Ultimately, the USEPA ruled that MSMA could no longer be sold for use on golf courses or sod farms after December 31, 2012. Turfgrass managers were left without a reliable and affordable means of controlling grass weeds such as tropical signalgrass, crabgrass, goosegrass, and dallisgrass (*Paspalum dilatatum* Poi.) and, as a result, many infestations were allowed to grow unchecked.

Weeds and Turf Quality

Turfgrass quality is dependent upon density, uniformity, and color, all of which can be disturbed by the presence of weeds. Noticeable differences in leaf blade width and color, as well as undesirable seedhead production, are some of the ways that weeds can negatively affect turfgrass aesthetics. Weeds have evolved to become excellent competitors for space and resources. Some weeds, such as goosegrass [*Eleusine indica* (L.) Gaertn.], can produce up to 140,000 seeds plant^{-1} (Chin 1979) and are well adapted for subtropical conditions such as those found in Florida (Chauhan and Johnson 2008). Tropical signalgrass (TSG), also known as smallflowered alexandergrass, two fingergrass, and two-spiked panic (Speedy 2002), is a perennial grass species that is native to Asia and Australia and is now found in Florida, Africa, and Mexico among other places (Murphy et al. 1992). Morphological characteristics include 0.75 to 1.25 cm wide leaf blades that can be up to 2 cm long and flowering stems up to 18 inches tall with two to seven “fingers” arranged off of the seedhead (Unruh et al. 2009). TSG is capable of reproducing by seed and stolons and can be found on golf courses, athletic fields, sod farms, and lawns. This weed forms dense mats on golf course fairways and in recently harvested bare areas of sod farms. Due to a lack of killing freezes in south Florida, this weed is able to grow as a perennial and increase its footprint year after year.

Integrated Weed Management

Integrated weed management (IWM) combines nonchemical control methods, such as cultural, mechanical, and biological practices, with traditional chemical control in an attempt to avoid resistance and reduce the heavy reliance upon chemicals to control weeds (Harker and O'Donovan 2013). An important aspect of a successful IWM strategy is the ease with which a method can be integrated into the farmer's (or in this case, turfgrass manager's) operations (Danyal et al. 2008).

Nonchemical Control

Cultural practices on golf courses are done to promote ideal growing conditions in an attempt to increase and/or maintain overall health, aesthetics, and playability of the turfgrass. Cultural practices routinely implemented on the golf course include top-dressing, aeration, verticutting, water management, and fertilization. These practices could all be easily integrated into an IWM strategy if they provide additional weed control at little to no additional cost. Top-dressing is usually a weekly or biweekly process of spreading sand across a putting green to smooth and firm-up the surface. Aeration involves removing small cores across the entire surface of the turf in an attempt to improve water and nutrient movement throughout the soil as well as relieve compaction that takes place from constant walking and/or driving. Verticutting is the process of chopping up stolons, which are horizontal stems that grow aboveground and take root at certain intervals forming new plants, and removing excess thatch using vertical blades that cut down into the turf. This practice promotes new growth and healthy, dense turfgrass. For densely growing weeds such as TSG and crabgrass, verticutting may eliminate apical dominance and encourage bud sprouting (Robertson et al. 1989). Apical dominance inhibits lateral bud growth, and by breaking this signaling pathway the plant will respond by sprouting buds at axillary meristems which will exhaust carbohydrate reserves stored in the shortened stolons and leave the plant more susceptible to biotic or abiotic stressors (Vengris 1962). Verticutting may also initiate weed seedling emergence by opening space in the turf canopy (Johnson 1979), a result that may also be beneficial if an herbicide application is forthcoming to target susceptible seedlings. Verticutting is done at most golf courses multiple times throughout the year, making this an ideal cultural practice to implement into an IWM strategy. If combined with an herbicide that is safe to the turfgrass, this process could aid in weed control while also encouraging turfgrass regrowth and decreasing the time required for reestablishment into the vacated areas.

Chemical Control

Chemical control methods include PRE and POST herbicides each of which have multiple modes of action that can be used in combinations to avoid selecting for herbicide-resistant weed biotypes. Current chemical control options for some difficult to control grass weeds in turf are limited, especially for POST applications. The banning of MSMA has forced some turfgrass managers to use non-selective POST herbicides such as glyphosate to eradicate weeds and, in doing so, the desired turf species as well. Teuton et al. (2004a) reported >90% TSG control in the greenhouse from early POST (2- to 8-leaf stage) applications of herbicides such as asulam, trifloxysulfuron, imazaquin, and metsulfuron. However, these results could not be duplicated in the field against mature stands of TSG, similar to what turfgrass managers are faced with after a year or two of ineffective POST herbicide applications following the banning of MSMA. More recently, Cross et al. (2016) reported excellent (>97%) TSG control 12 wk after initial treatment (WAIT) from POST fall applications of amicarbazone with rates up to 0.49 kg ai ha^{-1}. Amicarbazone proved to be a valuable tank-mix partner with numerous other herbicides, however, this may not be an economically feasible option at the rates being tested (i.e. more than $1000 per acre per treatment). Additionally, summer applications may be more advantageous than fall applications for allowing the turfgrass to recover and reestablish into the bare areas left after TSG elimination before turf growth decreases during fall and winter months. Teuton et al. (2004a) also examined PRE herbicide options for controlling this weed in sod farms. Certain treatments, such as imazapic + 2,4-D, performed extremely well (>90% TSG control) across multiple sites over two years.

POST herbicides have been the predominant tool used for TSG control on golf courses. MSMA was an affordable, effective herbicide that controlled many grass weeds in turf. Amicarbazone is a photosystem II (PSII) inhibitor that can be taken up by roots and result in chlorosis, stunting, and eventual necrosis of leaf tissue (Dayan et al. 2009). This herbicide is generally safe on cool- and warm-season turfgrasses and has activity on both broadleaf and grass weeds (Anonymous 2014). Mesotrione is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor whose symptomology includes bleaching of leaf tissue, which is a result of insufficient carotenoid production (Armel et al. 2007). Trifloxysulfuron and thiencarbazone + foramsulfuron + halosulfuron are all acetolactate synthase (ALS) inhibitors capable of being translocated to the growing regions of plants resulting in chlorosis and leaf tissue stunting (Shaner 2014). Although these POST herbicides are commonly used alone, in combination they could provide highly efficacious weed control by targeting 1) new root growth, thus affecting a plant's ability to acquire nutrients, 2) aboveground biomass and, subsequently, a plant's ability to assimilate photosynthates, and 3) meristematic regions through extensive translocation within the plant.

Vegetative propagation is a dominant method of establishment for many turfgrass weeds, however, seedling recruitment also plays an important role and must be addressed in management plans. PRE herbicides are effective tools in turfgrass weed management. They are capable of inhibiting seedling shoot and/or root growth and can affect the susceptible meristematic regions of emerging seedlings as they penetrate the soil surface (e.g. chloracetimides such as *S*-metolachlor). Some PRE herbicides, such as the dinitroanaline (DNA) compounds, are capable of root pruning and growth inhibition of mature species including turfgrass (Fishel and Coats 1993). Many PRE herbicides are applied at scheduled intervals throughout the year depending on projected germination timings of the targeted weed species such as crabgrass (Anonymous 2012). Their application may also be beneficial following the eradication of patchy weeds via a POST herbicide application. Subsequent bare patches can invite a flush of germination if weed control is timed incorrectly.

Indaziflam is a cellulose biosynthesis inhibiting herbicide used primarily PRE in turfgrass (Henry et al. 2012), but has also shown the potential to enhance POST activity of 2,4-D, fluroxypyr, and simazine (McCullough et al. 2015). Additionally, at the time of publication, Brosnan and Breeden (2013) reported that there were no known instances of cellulose biosynthesis inhibiting-resistant biotypes present in any weed populations. The authors presumed there to be a reduced likelihood of resistance developing with this mode of action due to its multiple target sites within the corresponding biosynthetic pathway, which serves to increase the value of this herbicide. *S*-metolachlor is a very long chain fatty acid (VLCFA) biosynthesis-inhibitor that primarily targets seedlings as they emerge from the soil (Shaner 2014). This results in stunted, malformed seedlings that eventually succumb to necrosis.

The present thesis evaluated verticutting along with PRE and POST herbicides in a series of studies to identify integrated strategies aimed at managing TSG in bermudagrass turf. There are currently few to no options available for controlling this weed in an effective and economical manner. In an effort to avoid developing herbicide resistance, as well as relying too heavily on a chemical control that may be taken away, the path forward should focus on an IWM approach that incorporates cultural, mechanical, biological, and/or chemical control methods.

CHAPTER 2
AN INTEGRATED APPROACH TO TROPICAL SIGNALGRASS (*Urochloa subquadripara*) CONTROL IN TURF

Summary

Tropical signalgrass (TSG) is one of the most problematic weeds found on golf courses, sports fields, and sod farms in south Florida. The recent ban of monosodium methane-arsonate (MSMA), an organic arsenical herbicide, from urban areas in Florida has left turfgrass managers searching for effective management options. In an effort to avoid relying solely on postemergence (POST) chemical control, this research examined the effect of combining a cultural practice, verticutting, along with preemergence (PRE) and POST herbicides as an integrated weed management (IWM) approach to controlling tropical signalgrass in hybrid bermudagrass. Field experiments were conducted at multiple locations over two years in south Florida to: (1) determine whether verticutting prior to herbicide applications increases TSG control and (2) identify herbicide programs that effectively control TSG. No interactions between verticutting and herbicide programs were detected, but verticutting consistently provided a slight reduction (~10%) in TSG cover. Treatments containing a PRE herbicide resulted in a significant reduction (20-50%) in TSG cover at 52 wk after initial treatment (WAIT), while some POST herbicide treatments reduced TSG cover to <20% at 52 WAIT. A study was conducted to determine which POST herbicide combinations were most efficacious in controlling TSG. Amicarbazone alone provided ≤35% TSG control at 8 and 12 WAIT, but synergistic responses were observed between amicarbazone and mesotrione, trifloxysulfuron, and thiencarbazone + foramsulfuron + halosulfuron. Two- and three-way combinations of amicarbazone with these POST herbicides resulted in >80% TSG control at 4, 8, and 12 WAIT, with some reaching 100% TSG control at 4

WAIT. Based on these data, verticutting may provide limited complementary control but certain combinations of POST herbicides exhibited excellent (>95%) TSG control.

Background

Tropical signalgrass is a perennial grass species capable of reproducing by seed and stolons and is commonly found in lawns, cultivated fields and disturbed areas (Murphy et al. 1992). Its dense, aggressive growth habit allows for quick colonization of any bare patches or areas where turfgrass density is low. This species gets its name from the angle of branching of its seedhead which resembles a “signal flag” (Murphy et al. 1992). Other common names include smallflowered alexandergrass, green summergrass, two-spiked panic, and two fingergrass (Speedy 2002). It is native to Asia and Australia (Murphy et al. 1992) and now occurs in Florida, Maryland, Hawaii, and Puerto Rico (USDA 2002).

TSG has become one of the most troublesome weeds on golf courses in south Florida. This weed thrives in tropical conditions, with seed germination (Teuton et al. 2004a) and vegetative growth being optimal around 25° C and in moist soil conditions. Frost and killing freezes are uncommon in south Florida, thus TSG has the potential to grow year-round. Monosodium methane-arsonate (MSMA), the standard for chemical control of this weed, was banned for urban uses including turfgrass in 2012, and any remaining product in storage after this time could be applied until December 31, 2013 (Brosnan et al. 2009). This has created a need to find alternative effective control tools with the ultimate goal of developing an integrated approach for managing this weed.

Prior studies have looked at herbicide use as the sole method for TSG control. For example, Teuton et al. (2004b) reported unacceptable (≤ 50%) control of mature TSG plants at 8 wk after initial treatment (WAIT) for all summer-applied postemergence

(POST) herbicides and herbicide combinations that were tested, including asulam, ethofumesate, and quinclorac. Better results were observed with bare ground preemergence (PRE) herbicide applications following burndown with glyphosate, although efficacy decreased 5 WAIT.

Integrated herbicide management utilizes PRE herbicides, POST herbicides, tank-mixes, and differing modes of action. This alone does not constitute an integrated weed management (IWM) program. Tank-mixing herbicides with different modes of action can be effective, but to truly implement an IWM approach there must also be an element of nonchemical control included (Harker and O'Donovan 2013). Danyal et al. (2008) cite the importance of accounting for cropping system design to allow for easier integration of IWM strategies into farming operations. Common cultural practices that could easily be implemented by turfgrass managers into IWM strategies include mowing, irrigation, fertilization, and cultivation.

Bergkvist et al. (2017) showed that rhizome fragmentation of quackgrass (*Elymus repens* (L.) Gould) in the early summer reduced rhizome biomass by up to 60%. In turfgrass management, verticutting is a cultural practice that uses vertical mower blades to cut down into the turf removing excess thatch and fragmenting stolons, which promotes new growth and healthy turfgrass. We hypothesized that verticutting several days before applying the herbicide will result in an increase in TSG control by weakening TSG underground reserves while favoring turf growth.

There are several POST herbicides available that have shown activity on TSG, however, they require high rates and multiple sequential applications to provide acceptable control while also potentially harming the turfgrass (McCarty and Estes

2014). Amicarbazone (AMI) is a photosystem II (PSII) inhibitor that is active in the soil and can be taken up by the roots of TSG plants recovering from foliar applied herbicides. Symptoms include chlorosis, stunting and eventual necrosis of leaf tissue (Dayan et al. 2009). This herbicide has been shown to be safe on multiple cool- and warm-season turfgrasses and is labeled for control of various broadleaf weeds as well as some grasses such as annual bluegrass (*Poa annua* L.) (Anonymous 2014). Mesotrione (MESO) is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor that causes bleaching of the leaf tissue, and subsequent necrosis, resulting from insufficient carotenoid production (Armel et al. 2007). Trifloxysulfuron (TSS) and thiencarbazone + foramsulfuron + halosulfuron (TFH) are all acetolactate synthase (ALS) inhibitors that can be extensively translocated to growing regions and result in chlorosis and stunting of leaf tissue (Shaner 2014). We hypothesized that a POST herbicide program utilizing a three-tier approach: (1) above-ground bleaching and burn-down of leaf tissue by mesotrione, (2) below-ground root uptake of amicarbazone to inhibit any new growth, and (3) systemic activity of an ALS-inhibiting herbicide to target meristematic growth, could increase TSG control while allowing the use of lower rates and fewer applications.

Although managers predominantly focus their efforts on controlling established TSG plants, we hypothesized that a PRE herbicide with strong residual properties might be necessary to effectively reduce TSG populations from one season to the next. This is true of many weed management approaches, however, little research has been done identifying the role of seedling recruitment in TSG regrowth after POST control actions.

The importance of implementing an IWM strategy and avoiding sole reliance on POST chemical control has been highlighted by the situation that now faces many turfgrass managers as they attempt to combat TSG infestations. There is a need to further explore the role that cultural practices can play as part of an integrated management program. Recent research has shown acceptable levels of TSG control using POST herbicides such as amicarbazone and thiencarbazone + foramsulfuron + halosulfuron (McCarty and Estes 2014; Cross et al. 2016). However, as was the case with MSMA, if a chemical is banned then turfgrass managers are left without any effective tools at their disposal. Therefore, the objectives of this research were to: (1) determine whether verticutting prior to herbicide applications increases TSG control and (2) identify herbicide programs that effectively control TSG.

Materials and Methods

Field experiments were conducted in 2015 and 2016 in Vero Beach, FL at Sandridge Golf Club and Pointe West Country Club to determine the effects of verticutting, PRE herbicides, and POST herbicides (Table 2-1) on TSG control. The IWM study was conducted at both sites in 2015 and one site (Sandridge) in 2016 for a total of three sites/years. The POST study was conducted at both sites in 2016. Soil type was a Myakka fine sand at both locations. Experiments were conducted in areas with rough-height (3 cm) 'Tifway 419' bermudagrass infested with TSG (>35% ground cover).

The IWM study was conducted to evaluate the benefits of integrating different tools for TSG control. For this, a split-plot factorial with four replications was used to evaluate the integration of three factors: verticutting (with and without), PRE (with indaziflam and without), and POST herbicides (AMI, MESO, TSS, TFH, and nontreated control). The main plot was verticutting and PRE and POST herbicide combinations were the subplots. Verticutting was performed 14 days before initial herbicide treatment

(DBIT) using a Toro triplex greens mower (Greensmaster Triflex Hybrid 3320, Toro, Bloomington, MN) with verticutting blade attachments. Two passes, at a depth of 2.5 cm, were made in opposite directions to increase the amount of stolon fragmentation. Two POST herbicide applications were made with a 21-d interval, and a PRE herbicide application was made with the second POST herbicide application. The POST study was conducted to identify the most effective POST herbicide combinations. This study was arranged as a randomized complete block design with four replications. Two POST herbicide applications were made with a 21-d interval.

For both studies, experimental units were 2.25 m^2 (1.5 m by 1.5 m), herbicide treatments were applied in a water carrier volume of 374 L ha^{-1}, and all applications were made with a CO_2-pressurized boom sprayer equipped with three 8002VS flat fan nozzles (TeeJet Spraying Systems Co., Wheaton, IL) on 45 cm spacing.

Visual evaluations were recorded weekly beginning 3 DBIT and ending 52 WAIT. TSG cover was evaluated visually on a 0 to 100% scale, and also using a quadrat (1 m by 1 m) with a grid to record the total number of units out of 36 that contained TSG. Weed control was evaluated visually on a 0 to 100% scale (0% = no reduction in weed population and no symptoms of injury, 100% = complete elimination of weed populations or only dead weed tissue present). Bermudagrass density was visually estimated on a 0 to 100% scale and turf color and quality were evaluated visually on a 1 to 9 index scale (1 = dead turf; 6 = acceptable turf quality/color; 9 = excellent turf quality/color) (McCarty et al. 1991). Bermudagrass injury (phytotoxicity) was visually estimated on a 0 to 100% scale (0% = no injury; 100% = complete elimination of turfgrass or only dead tissue present).

For the IWM study, nontransformed data were subjected to ANOVA using PROC GLIMMIX in SAS (SAS Institute, Cary, NC) after confirming data normality and homoscedasticity. An ANOVA was performed for each parameter by assessment date because an interaction was present between assessment date and other factors ($P<0.01$). Site by POST treatment interactions were significant ($P<0.0001$), but data was pooled due to the absence of crossover interactions. For the POST herbicide study, square root transformed grid data, arcsine transformed visual cover data, and nontransformed control data were all subjected to ANOVA by PROC GLIMMIX in SAS. To identify the presence of synergism, the Colby (1967) equation was used to calculate expected means for the herbicide combinations. Expected means were then compared to the observed means to determine whether the combinations were synergistic, antagonistic, or additive. For both studies, means were separated using Tukey's honestly significant difference (HSD) test ($\alpha = 0.05$) test.

Results and Discussion

IWM Study

Verticutting did not increase the efficacy of POST herbicide applications and interactions between these two factors were not significant ($P>0.16$). Verticutting did provide a small but consistent ($P<0.0001$) reduction in TSG visual cover through 12 WAIT (Table 2-2), however, long-term control with verticutting alone will be minimal. Busey and Johnston (2006) also demonstrated that cultural practices alone (e.g. mowing, fertilization, irrigation) may not provide acceptable, long-term results. They found that after a 3 yr period without herbicide use, most plots exhibited poor turf quality and high levels of weed pressure. The removal of photosynthetic tissue and fragmentation of stolons resulting from verticutting might reduce the amount of carbohydrate reserves each individual TSG plant can access for regrowth and recovery. At 2, 4, 8, and 12 WAIT, plots that were verticut had 39, 26, 29, and 36% TSG cover, respectively, while those that did not had 48, 34, 37, and 43% TSG cover, respectively. Therefore, verticutting reduced TSG cover on average about 8%. IWM utilizes multiple tactics, some of which may provide very little control on their own, in a complementary manner. Most importantly, these tactics must be easily integrated into the manager's existing program (Swanton et al. 2008). Verticutting results in more active growing points, potentially increasing the number of vegetative buds that are killed by herbicides with translocation and systemic activity. Although verticutting did not provide an increase in POST herbicide efficacy, future research examining this cultural practice with reduced rates of the effective POST herbicides tested in this study may prove beneficial in scenarios where verticutting is normally used.

At 52 WAIT, there was an interaction between PRE and POST herbicide ($P<0.0001$; Table 2-3). Specific combinations of PRE and POST herbicides increased long-term control considerably. For example, amicarbazone + thiencarbazone + foramsulfuron + halosulfuron treatment benefited the most from the PRE applications exhibiting 73% TSG cover without PRE and 25% with PRE. TSG seeds exhibit a dormancy mechanism that is still not well understood (Teuton et al. 2004a), but our results indicate that germination can occur during the summer and fall. Therefore, PRE herbicides should complement POST applications to prevent new seedling recruitment. Indaziflam, a cellulose biosynthesis inhibitor, is an effective PRE herbicide used in turfgrass (Henry et al. 2012) and has shown the ability to enhance POST activity of some herbicides such as 2,4-D, fluroxypyr, and simazine (McCullough et al. 2015) as well as provide PRE and early POST activity when applied alone to annual bluegrass (Brosnan et al. 2012). Although vegetative propagation of TSG seems to be the primary method of encroachment this research confirms the need for PRE herbicides in a management plan.

POST herbicide treatments reduced TSG populations at all assessment timings ($P<0.0001$; Table 2-2). Amicarbazone + mesotrione + trifloxysulfuron provided the greatest reduction in TSG cover at 4, 8, and 12 WAIT resulting in 4, 4, and 7% TSG cover, respectively (nontreated check had 61, 70, and 74 % TSG cover at those timings). Other POST herbicide treatments provided varying levels of control. The combination of amicarbazone + mesotrione + trifloxysulfuron includes three different modes of action, two of which (PSII- and HPPD-inhibitors) have been shown to produce synergistic responses in certain situations, primarily against broadleaf weeds (Abendroth et al. 2006; Hugie et al. 2008). The other mode of action, ALS-inhibition, has been shown to increase efficacy when tank-mixed with amicarbazone (Cross et al. 2016).

All POST herbicide treatments resulted in acceptable (<20%) levels of phytotoxicity to the bermudagrass turf at all assessment timings with the highest level of injury (18%) occurring in the amicarbazone + mesotrione + trifloxysulfuron treatments at 4 WAIT. Because these studies were performed on rough-height turf of lesser quality, further studies should be done to determine safety levels of these POST herbicides on well-maintained, fairway-height bermudagrass.

POST Study

POST herbicides were assessed individually and in all possible combinations to determine the most effective treatments. There was a significant ($P<0.0001$) interaction between site and treatment effects so data was analyzed separately. At Pointe West, all treatments containing only one herbicide resulted in >70% TSG cover at all assessment timings, with the exception of amicarbazone at 4 WAIT which contained 36% TSG cover (Table 2-4). Of the two-way combinations, only those containing amicarbazone resulted in <26% TSG cover at 4, 8, and 12 WAIT for both locations (Tables 2-4 and 2-5). The two-way combinations without amicarbazone resulted in >65% TSG cover at all assessment timings at Pointe West and >50% at 8 and 12 WAIT at Sandridge. Similarly, all three-way combinations containing amicarbazone greatly outperformed the treatment that did not contain amicarbazone at 4, 8, and 12 WAIT (<22% versus >60% TSG cover, respectively, at Pointe West and <10% versus >45% TSG cover, respectively, at Sandridge).

PSII-inhibitors, such as amicarbazone, have shown synergistic responses when combined with HPPD-inhibitors (Abendroth et al. 2006) and complementary responses when combined with ALS-inhibiting herbicides (Cross et al. 2016). In this study, amicarbazone displayed potential synergistic responses for TSG control when combined with HPPD- or ALS-inhibitors. Using the Colby (1967) equation, expected combination means were calculated and compared with the observed combination means to determine whether there was a synergistic response (Table 2-6). There was no interaction between site and treatment effect so data was combined. At 2 WAIT, amicarbazone and mesotrione provided 12% and 6% TSG control respectively resulting in an expected value of 17% TSG control. The observed value of the amicarbazone +

mesotrione treatment was 71% TSG control, indicating a strong likelihood of synergy. A similar trend was observed at multiple assessment dates and with various tank-mix partners.

All treatments containing amicarbazone resulted in unacceptable (>20%) levels of phytotoxicity at 4 WAIT with the four-way herbicide combination causing >70% injury to the bermudagrass turf (Table 2-7). All treatments showed full recovery by 8 WAIT. Further studies are needed to confirm these levels of injury and investigate possible methods of mitigation.

Our results demonstrated that the contribution of verticutting to an IWM strategy was considerably smaller when compared to the herbicide treatments. However, if the herbicide synergy exhibited by amicarbazone and multiple mix partners on TSG affects other weed species, amicarbazone could be a useful tool for managing difficult to control weeds and herbicide resistance. As with many weed management strategies, a PRE herbicide was shown to be a necessary component by providing longevity of control of TSG indicating that seedling recruitment is an important source of TSG population growth after POST applications. Verticutting may still provide a benefit to turfgrass managers if implemented into existing practices so as to not incur additional costs. The early summer application timing could also be beneficial in south Florida by allowing for a longer period of time for bermudagrass to reestablish into the areas that were previously covered with TSG. Future research should look at reduced rates of these combinations in conjunction with verticutting to see whether the minor effect of this cultural practice could be increased while reducing weed control cost and environmental impact.

Table 2-1. Herbicides, formulations, and rates used in the experiments.

Herbicide (abbreviation)	Formulation	Rate (g ai ha^{-1})	Trade name	Manufacturer	Location
amicarbazone (AMI)	70 WG	245[a]	Xonerate®	FMC Corporation	Philadelphia, PA
mesotrione (MESO)	4 SC	280	Tenacity®	Syngenta Crop Protection	Greensboro, NC
trifloxysulfuron (TSS)	75 WG	27.8	Monument®	Syngenta Crop Protection	Greensboro, NC
thiencarbazone + foramsulfuron + halosulfuron (TFH)[b]	60.5 WG	136	Tribute Total™	Bayer CropScience	Research Triangle Park, NC
Indaziflam (IND)	0.62 SL	32.7	Specticle® Flo	Bayer CropScience	Research Triangle Park, NC

[a] For the IWM study, AMI was applied at 147 g ai ha^{-1} when combined with other herbicides.

[b] All treatments containing TFH received methylated seed oil at 1% v/v and ammonium sulfate at 1.5 lb A^{-1}. All other treatments received a nonionic surfactant at 0.25% v/v.

Table 2-2. Effects of verticutting, preemergence (PRE) herbicide, and postemergence (POST) herbicides on tropical signalgrass (TSG) cover at 2, 4, 8, and 12 wk after initial treatment (WAIT).

	Visual				Grid[a]			
Factors	2 WAIT	4 WAIT	8 WAIT	12 WAIT	2 WAIT	4 WAIT	8 WAIT	12 WAIT
	TSG cover (%)							
Verticutting								
No	48 a[b]	34 a	37 a	43 a	86 a	69 a	67 a	72 a
Yes	39 b	26 b	29 b	36 b	72 b	53 b	53 b	56 b
PRE								
No	44	31	36	44 a	81	64	64 a	69 a
Yes	43	29	31	35 b	78	61	56 b	58 b
POST								
No	58 a	61 a	70 a	74 a	86	89 a	89 a	89 a
AMI[c]	45 b	31 b	37 b	46 b	83	72 b	69 b	75 b
AMI + TFH[d]	43 b	23 c	22 c	31 c	75	61 b	58 b	64 b
AMI + MESO[e] + TSS[f]	27 c	4 d	4 d	7 d	75	25 c	19 c	28 c
ANOVA[g]								
Verticutting	<0.0001	0.001	0.003	0.005	<0.0001	<0.0001	<0.0001	<0.0001
PRE	0.80	0.25	0.06	0.001	0.68	0.26	0.02	0.004
POST	<0.0001	<0.0001	<0.0001	<0.0001	0.06	<0.0001	<0.0001	<0.0001

[a] Assessment was taken using a 1 m^2 grid dissected into 36 identical sections. Each section was assessed for the presence of TSG and the percent of sections containing TSG was calculated.

[b] Values within columns and main factors with the same letter were not statistically different based on Tukey's HSD (α=0.05).

[c] Amicarbazone.

[d] Thiencarbazone + foramsulfuron + halosulfuron.

[e] Mesotrione.

[f] Trifloxysulfuron.

[g] There were no interactions between main factors.

Table 2-3. Interaction ($P<0.0001$) between preemergence (PRE) and postemergence (POST) herbicides on tropical signalgrass (TSG) cover at 52 wk after initial treatment (WAIT)[a].

	Visual		Grid[b]	
	PRE			
POST	No	Yes	No	Yes
	%			
No	73 ab	85 a	90 a	100 a
AMI[c]	75 a	51 b	97 a	75 a
AMI + TFH[d]	73 ab	25 c	100 a	41 b
AMI + MESO + TSS[e]	14 c	11 c	22 b	17 b

[a] Data were collected from only one site/year due to renovations at one of the golf courses in 2017 that resulted in loss of the trial site.

[b] Assessment was taken using a 1 m^2 grid dissected into 36 identical sections. Each section was assessed for the presence of TSG and the percent of sections containing TSG was calculated.

[c] Amicarbazone.

[d] Thiencarbazone + foramsulfuron + halosulfuron.

[e] Trifloxysulfuron.

Table 2-4. Postemergence (POST) tropical signalgrass (TSG) % visual cover and % of squares out of 36 occupied by tropical signalgrass (% grid) at 2, 4, 8, and 12 wk after initial treatment (WAIT) at Pointe West Country Club.

	Visual					Grid[a]				
	WAIT									
Treatment[b]	2	4	8	12	52	2	4	8	12	52
	TSG cover (%)									
Check	88 a[c]	88 a	93 a	98 a	88 a	100 a	100 a	100 a	100 a	100 a
AMI[d]	84 ab	36 b	76 abc	86 abc	85 ab	100 a	100 a	100 a	100 a	100 a
MESO[e]	76 ab	74 a	85 abc	93 ab	83 ab	97 a	99 a	100 a	100 a	100 a
TSS[f]	78 ab	79 a	86 ab	89 abc	86 a	99 a	100 a	100 a	100 a	100 a
TFH[g]	83 ab	80 a	88 ab	91 abc	81 ab	99 a	100 a	100 a	100 a	100 a
AMI+MESO	33 cd	<1 c	14 d	23 d	61 a-e	96 a	2 c	75 a	80 ab	99 a
AMI+TSS	59 abc	10 bc	14 d	14 d	69 a-d	98 a	90 a	65 ab	73 abc	99 a
AMI+TFH	54 bcd	9 bc	10 d	14 d	51 b-e	98 a	90 a	64 abc	79 ab	100 a
MESO+TSS	74 ab	68a	75 abc	70 c	84 ab	96 a	100 a	99 a	99 a	100 a
MESO+TFH	73 ab	76 a	79 abc	85 abc	86 a	99 a	100 a	100 a	100 a	100 a
TSS+TFH	74 ab	71 a	73 bc	75 bc	73 abc	100 a	100 a	100 a	100 a	100 a
AMI+MESO+TSS	31 cd	1 c	4 d	6 d	29 e	91 a	15 bc	24 cd	27 c	84 b
AMI+MESO+TFH	18 d	0 c	14 d	21 d	36 de	94 a	<1 c	73 a	95 a	94 ab
AMI+TSS+TFH	29 cd	5 bc	5 d	7 d	64 a-d	95 a	31 b	24 bcd	34 bc	99 a
MESO+TSS+TFH	79 ab	73 a	61 c	69 c	80 ab	100 a	100 a	100 a	100 a	100 a
AMI+MESO+TSS+TFH	12 d	<1 c	2 d	7 d	39 cde	83 a	<1 c	9 d	35 bc	99 a

[a] Assessment was taken using a 1 m^2 grid dissected into 36 identical sections. Each section was assessed for the presence of TSG and the percent of sections containing TSG was calculated.
[b] All treatments containing TFH received methylated seed oil at 1% v/v and ammonium sulfate at 1.5 lb A^{-1}. All other treatments received a nonionic surfactant at 0.25% v/v.
[c] Values within columns with the same letter were not statistically different based on Tukey's HSD (α=0.05).
[d] Amicarbazone
[e] Mesotrione
[f] Trifloxysulfuron
[g] Thiencarbazone + foramsulfuron + halosulfuron

Table 2-5. Postemergence (POST) tropical signalgrass (TSG) % visual cover and % of squares out of 36 occupied by tropical signalgrass (% grid) at 2, 4, 8, and 12 wk after initial treatment (WAIT) at Sandridge Golf Club.

	Visual					Grid[a]				
	WAIT									
Treatment[b]	2	4	8	12	52	2	4	8	12	52
	TSG cover (%)									
Check	58 a[c]	58 a	76 ab	79 ab	21 a	99 a	98 a	100 a	100 a	74 abc
AMI[d]	54 ab	17 abc	38 cd	43 cd	14 ab	100 a	94 a	96 a	97 a	59 abc
MESO[e]	55 ab	53 a	81 a	84 a	18 ab	97 a	98 a	100 a	100 a	72 ab
TSS[f]	56 ab	50 abc	71 ab	75 ab	9 ab	100 a	100 a	100 a	100 a	50 abc
TFH[g]	53 ab	49 abc	69 ab	71 ab	5 ab	98 a	99 a	100 a	97 a	34 abc
AMI+MESO	11 cd	<1 c	8 d	8 de	5 ab	63 ab	1 cd	29 b	32 b	18 abc
AMI+TSS	10 cd	1 bc	3 d	4 e	2 b	54 a-d	3 bcd	8 b	10 b	10 c
AMI+TFH	25 bcd	25 abc	7 d	9 de	1 b	61 abc	26 b	26 b	29 b	11 bc
MESO+TSS	58 a	56 a	65 a-c	70 abc	18 ab	100 a	100 a	99 a	99 a	76 a
MESO+TFH	54 ab	43 abc	59 abc	59 abc	14 ab	99 a	88 a	99 a	97 a	60 abc
TSS+TFH	51 ab	31 abc	51 bc	56 bc	11 ab	99 a	99 a	97 a	99 a	51 abc
AMI+MESO+TSS	4 d	<1 c	5 d	3 e	1 b	16 d	<1 d	15 b	13 b	7 c
AMI+MESO+TFH	7 d	< 1 c	8 d	6 e	<1 b	38 bcd	4 bcd	15 b	14 b	5 c
AMI+TSS+TFH	26 bcd	4 bc	5 d	6 e	2 b	98 a	22 bc	15 b	19 b	10 c
MESO+TSS+TFH	44 abc	46 abc	61 abc	60 abc	5 ab	94 a	97 a	94 a	97 a	32 abc
AMI+MESO+TSS+TFH	1 d	1 bc	4 d	5 e	2 b	17 cd	14 bcd	11 b	15 b	10 c

[a] Assessment was taken using a 1 m^2 grid dissected into 36 identical sections. Each section was assessed for the presence of TSG and the percent of sections containing TSG was calculated.
[b] All treatments containing TFH received methylated seed oil at 1% v/v and ammonium sulfate at 1.5 lb A^{-1}. All other treatments received a nonionic surfactant at 0.25% v/v.
[c] Values within columns with the same letter were not statistically different based on Tukey's HSD (α=0.05).
[d] Amicarbazone
[e] Mesotrione
[f] Trifloxysulfuron
[g] Thiencarbazone + foramsulfuron + halosulfuron

Table 2-6. Synergism between amicarbazone and multiple mix partners at 2, 4, 8, and 12 wk after initial treatment (WAIT).

			TSG control[a]		
Treatment[b]	2 WAIT	4 WAIT	8 WAIT	12 WAIT	52 WAIT[c]
			%		
AMI[d]	12	69	35	29	4
MESO[e]	6	31	4	2	3
TSS[f]	17	30	15	14	1
TFH[g]	22	30	16	13	5
AMI + MESO	71 (17)	100 (79)	85 (38)	80 (30)	30 (7)
AMI + TSS	61 (27)	93 (78)	88 (45)	87 (39)	21 (5)
AMI + TFH	59 (31)	80 (78)	88 (45)	85 (38)	44 (9)
MESO + TSS	26 (22)	34 (52)	23 (18)	20 (16)	9 (4)
MESO + TFH	15 (27)	36 (52)	28 (19)	17 (15)	5 (8)
TSS + TFH	31 (35)	48 (51)	38 (29)	33 (25)	18 (6)

[a] Numbers in parentheses represent the expected means generated using the Colby (1967) equation. If the expected is less than the actual, than the combinations resulted in a synergistic response.
[b] Treatments containing TFH received methylated seed oil at 1% v/v and ammonium sulfate at 1.5 lb A^{-1}. All other treatments received a nonionic surfactant at 0.25% v/v.
[c] Data collected at only one site.
[d] Amicarbazone.
[e] Mesotrione.
[f] Trifloxysulfuron.
[g] Thiencarbazone + foramsulfuron + halosulfuron.

Table 2-7. Turfgrass injury observed in postemergence (POST) herbicide study at 2, 4, and 8 wk after initial treatment (WAIT).

	Phytotoxicity		
Treatment[a]	2 WAIT	4 WAIT	8 WAIT
	%		
AMI[b]	0	27 def	0
MESO[c]	1	13 ef	0
TSS[d]	0	4 f	0
TFH[e]	1	3 f	0
AMI + MESO	6	60 abc	0
AMI + TSS	2	35 cde	0
AMI + TFH	0	42 bcd	0
MESO + TSS	1	2 f	0
MESO + TFH	4	8 f	0
TSS + TFH	0	3 f	0
AMI + MESO + TSS	8	64 ab	0
AMI + MESO + TFH	7	66 ab	0
AMI + TSS + TFH	6	45 bcd	0
MESO + TSS + TFH	3	22 def	0
AMI + MESO + TSS + TFH	6	74 a	0

[a] Treatments containing TFH received methylated seed oil at 1% v/v and ammonium sulfate at 1.5 lb A^{-1}. All other treatments received a nonionic surfactant at 0.25% v/v.
[b] Amicarbazone.
[c] Mesotrione.
[d] Trifloxysulfuron.
[e] Thiencarbazone + foramsulfuron + halosulfuron.

CHAPTER 3
THE IMPACT OF SEEDLING RECRUITMENT ON TROPICAL SIGNALGRASS (Urochloa subquadripara) REESTABLISHMENT IN TURF

Summary

Tropical signalgrass (TSG) has recently become one of the most difficult weeds to control on South Florida golf courses, athletic fields, and sod farms. This is partially due to the banning of monosodium methane-arsonate (MSMA), an organic arsenical herbicide that provided cost-effective postemergence (POST) control of TSG. Since this ban, TSG populations have increased considerably, but it is not known how much of the population growth is due to seedling recruitment or vegetative propagation. A field experiment was conducted in South Florida to (1) determine the impact of seedling recruitment on TSG reestablishment and (2) evaluate *S*-metolachlor and indaziflam for preemergence (PRE) TSG control. At 2, 4, and 7 wk after the PRE application, the nontreated control had 135, 538, and 581 TSG seedlings m^{-2} respectively. *S*-metolachlor provided limited TSG control compared to the nontreated control, while indaziflam provided >70% reduction in TSG seedling emergence. Based on the high levels of TSG seedling emergence observed, an effective PRE-herbicide is an important component of TSG integrated management programs.

Background

Tropical signalgrass (TSG) is a perennial grass species that is adapted to environmental conditions in Florida. The germination of this grass weed requires high soil moisture levels and an optimal temperature of 25 C with no apparent light requirements (Teuton et al. 2004a). Its common name is derived from the seedhead’s resemblance to a signal flag through its angle of branching (Murphy et al. 1992), and other common names include smallflowered alexandergrass, green summergrass, two-spiked panic, and two fingergrass (Speedy 2002). TSG can be found in intensively managed areas such as lawns, athletic fields, sod farms, and golf courses (Murphy et al. 1992).

Recently, TSG has become one of the most difficult weeds to manage on golf courses and sod farms in Florida, especially in the central and southern regions of the state. Two reasons for this distribution are first, the lack of killing freezes in this area, which would slow down the rate of TSG establishment and, second, the banning of monosodium methane arsonate (MSMA) for use in turfgrass in Florida. MSMA is an organic arsenical herbicide that had become the standard for chemical control of TSG, as well as many other weeds in turfgrass. After its banning in 2012, turfgrass managers were left without inexpensive, effective postemergence (POST) herbicides that were also safe to use on bermudagrass or St. Augustinegrass resulting in the establishment of large, dense mats of TSG in golf course roughs and fairways. TSG populations have become so problematic that some turfgrass managers have been forced to use non-selective POST herbicides such as glyphosate to eliminate this troublesome weed causing serious injury to the turfgrass.

Preemergence (PRE) herbicides, such as *S*-metolachlor and indaziflam, are useful tools for weed management programs in turfgrass. *S*-metolachlor is a very long chain fatty acid (VLCFA) biosynthesis-inhibitor, which is primarily absorbed by emerging shoots although some root absorption may also occur (Shaner 2014). Indaziflam is a cellulose biosynthesis inhibitor that can be applied PRE, resulting in weed seedling growth inhibition, or early POST with injury manifesting as root clubbing or stunted growth (Shaner 2014). These two herbicides are widely used in turfgrass in Florida, but their activity on TSG seedling emergence is unknown.

Currently, most programs aimed at TSG management are focused on control through POST herbicide applications. This weed is capable of propagating by seed and stolons, however, little research has been done to determine the extent to which seedling recruitment contributes to this plant's expansion in the field and to TSG establishment after POST control. Therefore, the objectives of this research were to: (1) determine the impact of seedling recruitment on TSG reestablishment and (2) evaluate the efficacy of *S*-metolachlor and indaziflam for PRE TSG control.

Materials and Methods

A field experiment was conducted in 2016 in Vero Beach, FL on a golf course to determine the impact of seedling recruitment on TSG reestablishment. The experiment was conducted in an area with rough-height (3 cm) 'Tifway 419' bermudagrass infested with TSG (>75% ground cover).

The study was arranged as a randomized complete block design with four replications and experimental units measuring 2.25 m^2 (1.5 m by 1.5 m). Two glyphosate (0.8 kg ae ha^{-1}, Touchdown HiTech 5 SL, Syngenta Crop Protection, Greensboro, NC) applications were made 21-d apart beginning in April to eliminate established TSG and bermudagrass, so TSG seedling emergence could be properly quantified. PRE herbicide treatments of indaziflam (0.03 kg ai ha^{-1}, Specticle FLO 0.62 SL, Bayer CropScience, Research Triangle Park, NC) or *S*-metolachlor (1.37 kg ai ha^{-1}, Pennant Magnum 7.62 EC, Syngenta Crop Protection, Greensboro, NC) were included in the second application. Diquat (4.5 kg ai ha^{-1}, Reward 2 SL, Syngenta Crop Protection, Greensboro, NC) was applied following each assessment timing to eliminate emerged seedlings. Herbicide treatments were applied in a water carrier volume of 374 L ha^{-1}, and all applications were made with a CO_2-pressurized boom sprayer equipped with three 8002VS flat fan nozzles (TeeJet Spraying Systems Co., Wheaton, IL) on 45 cm spacing.

Visual evaluations were conducted at 1, 2, 4, 7, 10, and 14 wk after PRE application (WAT). TSG seedlings and shoots from stolons were counted in a 1 m^2 area of each experimental unit and analyzed as a cumulative count over the duration of the study. Nontransformed data were subjected to ANOVA using PROC GLIMMIX in SAS (SAS Institute, Cary, NC) after confirming data normality and homoscedasticity. Means were separated using Tukey's honestly significant difference (HSD) test (α = 0.05) test.

Results and Discussion

No differences in TSG shoot regrowth were detected among treatments. This outcome was expected given glyphosate's high level of efficacy for TSG control. Cumulative TSG seedling counts were highest in the nontreated control and *S*-metolachlor, while indaziflam resulted in >70% fewer seedlings m^{-2} 14 WAT (Figure 3-1). At 4 WAT, approximately 550 seedlings m^{-2} had emerged in both the nontreated control and *S*-metolachlor plots while indaziflam resulted in nearly one-third of the seedling emergence. The prediction model generated by Teuton et al. (2005) estimates a late March or early April emergence date for TSG in Vero Beach, FL. However, in our case emergence initiated a few weeks after the prediction, and there was a noticeable peak in seedling emergence between 2 and 4 WAT, which corresponded to the end of May. This delayed emergence could be due to reductions in seed dormancy resulting from the changes in soil temperature after the elimination of TSG and bermudagrass canopies. Also, it is possible that early emerging seedlings were eliminated with the glyphosate application. By 14 WAT, there were nearly 800 seedlings m^{-2} in the *S*-metolachlor treatment.

This research confirmed the need for an effective PRE herbicide when managing TSG infestations. In situations of complete elimination of existing TSG plants, seedling recruitment will be a driving force for TSG reestablishment. The use of glyphosate or other non-selective and highly injurious herbicide programs to eliminate mats of TSG, as some turf managers have been forced to do, could allow for a situation of enhanced seedling recruitment as the desired turf species is recovering and unable to immediately reestablish into treated areas. A PRE herbicide would be important in this scenario, assuming the herbicide does not have any adverse effects on the desired species such as root-pruning or growth inhibition. Teuton et al. (2004b) demonstrated high levels of control (>90% in some instances) with metolachlor initially, however, efficacy was generally not sustained past 8 WAT. In the present study, *S*-metolachlor performed similarly to the nontreated control at each assessment timing. The contrasting results between both studies suggest that environmental factors might play an important role for *S*-metolachlor activity on TSG. Indaziflam is an effective PRE herbicide, as evidenced by the cessation in seedling emergence after 4 WAT, however, there are also some drawbacks that must be taken into consideration concerning turfgrass inhibition. Brosnan et al. (2014) demonstrated an increase in days required to reach 50% hybrid bermudagrass cover as well as a reduction in sod tensile strength after applications of indaziflam at 0.03 kg ai ha^{-1}. The authors also noted a decrease in predicted bermudagrass cover at 10 WAT with applications of indaziflam (30% cover versus 100% for the nontreated check). Jones et al. (2013) reported an 89% reduction in bermudagrass root-length density from indaziflam (35 g ai ha^{-1}) in a sandy soil with no organic matter during a greenhouse study with mini-rhizotrons.

Based on the observed emergence pattern of TSG seedlings in this research, as well as the prediction model provided by Teuton et al. (2005), turfgrass managers should make PRE herbicide applications by the middle or end of March in order to optimize their results. An additional approach could be to follow-up any TSG and/or turfgrass elimination with a POST herbicide application to target the newly emerged, and likely more susceptible, seedlings. Future research should identify selective POST herbicides that, although not highly efficacious against established TSG plants, may have increased efficacy against TSG seedlings. Amicarbazone has proven to be an effective option in combination with other POST herbicides (Cross et al. 2016). Teuton et al. (2004b) demonstrated >90% TSG control at the two- to eight-leaf stage in the greenhouse with compounds such as asulam and trifloxysulfuron, but was unable to achieve those levels of control in the field on more mature TSG plants. Also, future research should focus on additional PRE herbicides as well as the rate of reestablishment of the desired turf species into these eradicated areas to determine the most effective solution for TSG elimination followed by turfgrass reestablishment.

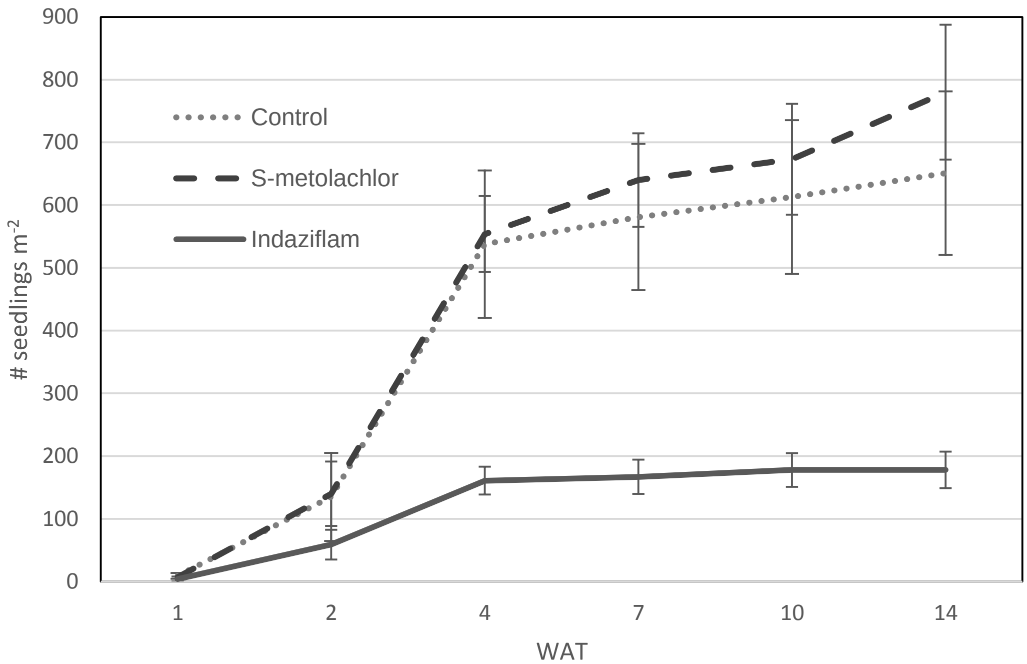

Figure 3-1. Tropical signalgrass seedling emergence over time in the nontreated control and areas treated with *S*-metolachlor and indaziflam. Weeks after treatment (WAT). Error bars correspond to standard error of the mean.

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The banning of MSMA has greatly reduced the tools available to turfgrass managers for controlling TSG and other troublesome grass weeds in Florida. MSMA provided excellent control through a unique mode of action and at an affordable price. Concerns over groundwater infiltration of highly toxic inorganic byproducts of MSMA ultimately led to its removal from the turfgrass market in Florida. Because herbicides are lost due to resistance development as well as environmental fate concerns, this research examined an integrated approach for controlling TSG in bermudagrass turf.

Verticutting, a cultural practice used extensively in turfgrass management, provided a small amount of additional TSG control by itself through 12 WAA. The process of stolon fragmentation leads to reduced carbohydrate reserves from which axillary buds are able to draw on. Verticutting would be a useful component of an IWM strategy if it is already being done by turfgrass managers as it would provide additional control without any additional cost. Future research should be aimed at identifying additional cultural practices that are already implemented by managers, such as fertilization or irrigation regimes, which may be added to an IWM strategy in an attempt to either increase TSG control or accelerate turfgrass reestablishment into the newly vacated areas.

PRE herbicides are an important component of TSG control. In a single study, cumulative TSG seedling counts reached upwards of 800 seedlings m^{-2} over a period of 14 wk with a noticeable peak in emergence at 4 wk. Failure to eliminate as much of this emergence as possible would result in a turfgrass manager being forced to start over in their attempt to control TSG. Indaziflam proved to be an effective option for controlling

TSG PRE. In this same study, the indaziflam treatment resulted in >70% reduction in TSG seedling emergence compared to the nontreated check. In the IWM study, the addition of indaziflam to one of the POST treatments resulted in nearly 50% TSG reduction at 52 WAA in comparison to the same treatment without the PRE herbicide. Future research should look at additional PRE herbicides such as oxadiazon and prodiamine to identify herbicides that are capable of providing >90% control of TSG. Much of the soils in Florida are sandy, however, there are also areas with muck or clay soils that may be found on golf courses and sod-farms. PRE, and potentially POST, herbicides may act very differently depending on the soil type that is present. Therefore, additional research is needed to determine the level of activity of indaziflam and other PRE herbicides on a variety of soils. Future research identifying methods of expediting turfgrass reestablishment should include plant growth regulators, such as trinexapac-ethyl, that encourage lateral growth which could potentially speed this process up.

Several POST herbicide combinations were identified in this research as having excellent (>90%) TSG control. The link between all of these treatments was the PSII-inhibiting compound amicarbazone, which demonstrated synergistic activity with both HPPD- and ALS-inhibitors. This ability to enhance other products could make amicarbazone a very useful component of IWM strategies. Future research should examine lower rates of amicarbazone with HPPD- and ALS-inhibiting compounds to identify effective treatments aimed at TSG (and other key weed species) control. These lower use rates would be more economically and environmentally preferable as well as provide less injury to the turfgrass.

Of utmost importance, regardless of the herbicide applied, is the POST application timing in relation to projected TSG seedling emergence. If managed incorrectly, POST herbicide applications could ultimately become an extra cost with limited to no returns in TSG control. TSG POST eradication without proper PRE herbicide applications could allow for a flush of seedling emergence that would establish in the newly vacated areas before the turfgrass is able to do so. This could be further exacerbated by POST herbicide applications that also injure the bermudagrass turf, subsequently hampering its ability to reestablish into these areas. Therefore, burndown applications of glyphosate should always be accompanied by a PRE herbicide to combat potential TSG seedling emergence which could result in reestablishment.

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BIOGRAPHICAL SKETCH

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