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Biology, Ecology, and Control of Doveweed (Murdannia nudiflora [L.] Brenan)

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BIOLOGY, ECOLOGY, AND CONTROL OF DOVEWEED (MURDANNIA NUDIFLORA [L.] BRENAN)

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by
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ABSTRACT

Doveweed (*Murdannia nudiflora* [L.] Brenan) is a summer annual in the Southeastern United States with an expanding geographic range. The light green color and texture of doveweed is problematic for turfgrass managers as it contrasts with the color and texture of desirable turfgrasses. Limited research is available concerning the biology, ecology, and herbicide control options for doveweed. Therefore, experiments were conducted to improve the understanding of how environmental conditions effect doveweed germination, how cultural practices and environmental resource availability effect doveweed growth and development, to identify pre- and postemergence herbicides with efficacy for doveweed control, and to improve the understanding of why poor control is observed with postemergence herbicides.

Doveweed germination was affected by scarification, osmotic potential and salt concentration. Mechanical abrasion of the seed coat increased germination to 84% compared to 18% in non-scarified seed. Germination was similar between osmotic potentials of 0 and -0.4 MPa and was reduced ~50% in a -0.8 MPa solution, suggesting doveweed favors a moist environment for germination. Germination was similar between NaCl concentrations of 0 and 40 mM, and reduced ~50% in a 160 mM NaCl solution, suggesting infestations can occur in moderately saline soils. Germination was not affected by nitrate concentration or pH.

Doveweed spread of established plants was between 30 and 46% less in response to low mowing after one study year; however, differences in doveweed spread were not detected after year two. The lack of mowing height effect was attributed to recruitment

of doveweed seedlings from seeds produced at the end of year one. This result suggests doveweed infestations can rapidly increase in severity if left unchecked. When grown in competition with 'Tifway' bermudagrass (*Cynodon dactylon* [L.] Pers × *C. transvaalensis* Burtt-Davy), doveweed coverage per plant was ~38% less when mown at 1.32 cm compared to mowing at 2.65 cm. In the same study, increasing nitrogen rate from 24.5 to 49 kg N ha^{-1} increased doveweed spread per plant 75%. In response to a reduced light environment (RLE), shoot production did not increase on a weight basis; however, an etiolation response was detected as internode length increased 28% in plants grown in a 30% RLE and 39% in a 50 and 70% RLE. Root production on a weight basis was between 46 and 59% less in all RLE treatments compared to full sunlight treatments. Doveweed shoot growth was significantly greater in plants maintained above 50% field capacity (FC) and plants maintained at ≥75% FC produced more root biomass than 50, 25, and 12.5% FC treatments, further suggesting doveweed suggests a moist environment for growth and development.

Sequential applications of pre- and postemergence herbicides improved doveweed control compared to single applications. Indaziflam, dimethenamid-p, and oxadiazon applied at 0.054, 1.68, and 3.36 kg ai ha^{-1}, respectively, provided ~12, 6, and 6 wk of doveweed control, respectively, when applied on May 1 in Augusta, GA. Postemergence control was greatest following sequential application of sulfentrazone + metsulfuron at 0.30 kg ai ha^{-1}, thiencarbazone + iodosulfuron + dicamba at 0.176 kg ai ha^{-1}, 2,4-D + MCPP + dicamba + carfentrazone at 0.123 kg ai ha^{-1}, or thiencarbazone + foramsulfuron + halosulfuron at 0.136 kg ai ha^{-1} 21 days apart.

Doveweed was determined to be tolerant of glyphosate applied at recommended rates. Investigation into the mechanism of tolerance determined glyphosate uptake by doveweed plants with an intact cuticle to be limited in comparison with doveweed plants with a disrupted cuticle and smooth crabgrass (*Digitaria ischaemum* [Schreb.] Schreb. Ex Muhl.).

Future research should evaluate the effect of environmental conditions and cultural practices on doveweed fecundity and determine the duration of doveweed seed viability under environmental conditions. Lastly, old and new herbicides chemistries should continue to be screened for doveweed control efficacy and further understanding of doveweed herbicide tolerance should be explored.

DEDICATION

I dedicate this dissertation to family and friends who have supported and encouraged me throughout this journey.

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I would like to acknowledge all those who helped make this dissertation possible. First I would like to thank Dr. Bert McCarty for providing me with the opportunity to grow academically, professionally, and as an independent thinker. To the rest of my committee, Dr. Bridges, Dr. McElroy, and Dr. Yelverton, thank you for sharing your expertise on reseaerch methods and interpertation of results. Your comments, critiques, and suggestions were invaluable throughout the dissertation process.

I am very appreciative of the Carolinas Golf Course Superintendents Association for funding this research. The Association's leadership in funding research initiatives and professional development for superintendents throughout the Carolinas sets this organization apart from others like it. Thank you is also in order for Mr. Greg Burelson, superintendent of Augusta Country Club, for allowing for the use of his golf course as a field research site. Mr. Burleson's cooperation and interest in this project has benefited not only my research, but also all superintendents whom this research will impact.

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CHAPTER ONE

INTRODUCTION

Doveweed (*Murdannia nudiflora* [L.] Brenan) is native to old-world tropical and subtropical lowlands. In the United States, doveweed ranges from Texas to North Carolina and exists as a summer annual (Faden 2000; Faden and Haflinger, 1982). Worldwide, doveweed is considered one of the top three major weeds in the Commelinaceae. Benghal dayflower (*Commelina benghalensis* L.), climbing dayflower (*C. diffusa* Burm. F.), and doveweed are succulent, herbaceous plants with a sprawling, creeping habit that readily root at the nodes. Benghal dayflower is reported as a weed in 25 crops in 28 countries, climbing dayflower is reported in 17 crops in 26 countries, and doveweed is reported in 16 crops in 23 countries (Holm, 1977; Wilson, 1981).

Overall, the Commelinaceae is a family of herbaceous monocots with approximately 630 species in 40 genera (Faden, 2000). Of these, eleven are known to be invasive (Burns, 2006). Several attempts have been made to divide the Commelinaceae into several subfamilies and tribes. Current classification is based on anatomy and on cytology in combination with old previous descriptions (Tomlinson, 1966; Jones and Jopling, 1972; Faden and Hunt, 1991). The family is divided into two subfamilies, the Cartonematoideae and Commelinoideae. Cartonematoideae contains a single genus, *Cartonema*, which can be distinguished from Commelinoideae species by non-succulent leaves and a lack of raphides. Species in the Commelinoideae can be identified by succulent leaves and a presence of raphide canals in between the veins of leaves (Faden and Hunt, 1991). Commelinoideae includes approximately 39 genera split into two tribes, the Tradescantieae and Commelineae. Tradescantieae and Commelineae are defined by anatomical and palynological characteristics. Tradescantieae is characterized by stomata with 2 or 4 subsidiary cells, or if 6 then the terminal pair is equal to or larger than the second lateral pair. Pollen is exine, lacks spines, mostly with a cerebroid tectum; flowers mainly actinomorphic; filament hairs (when present) moniliform (Faden and Hunt, 1991). Commelineae is characterized by stomata with 6 subsidiary cells, the terminal pair smaller than the second lateral pair. Pollen is exine, spinulose, tectum perforate; flowers actinomorphic or zygomorphic; filament hairs (when present) not usually moniliform (Faden and Hunt, 1991). Commelinoideae tribes can also be classified by chromosome size. Generally, all species having medium to large chromosomes belong to Tradescantieae and nearly all cited as having small chromosomes belong to Commelineae.

Belonging to the Commelineae, the *Murdannia* genus contains ~50 species, making it one of the largest genera in the Commelinaceae. *Murdannia spp.* can be identified from other genera in Commelinaceae by three-lobed or spear-shaped antherodes (Faden, 1998). Three *Murdannia* species are found in the United States: marsh dewflower (*M. keisak* [Hassk.] Hand.-Maz.), doveweed (*M. nudiflora* [L.] Brenan), and Asiatic dewflower (*M. spirata* [L.] G. Brückn) (Faden, 1998; Faden 2000). Floral and fruit characteristics separate doveweed from other *Murdannia spp.* in the United States. Doveweed flowers in several flowered cymes in contrast with marsh dewflower which flowers in 1-flowered cymes. Doveweed capsules contain 2 seeds per locule, and two fertile and four staminodial stamens make up the androecium. Asiatic dewflower plants can be distinguished by capsules with 3-7 seeds per locule and an androecium made up of 3 fertile and 3 staminodial stamens.

Doveweed is classified as a wetland hydrophyte, although once it is well rooted, it can live for extended periods after soil has dried out (King, 1966). It is mainly a perennial in tropical and subtropical lowlands; however, it is an annual in temperate climates such as the Southeastern United States. Doveweed is a common weed of lowland and upland rice (*Oryza spp.*) in Sri Lanka and Indonesia. It has also been reported as a weed in cocoa (*Theobroma cacao* L.) and rubber (*Hevea brasiliensis* Müll. Arg.) in Malaysia; tea (*Camellia sinensis* [L.] Kuntze) in Indonesia; pineapples (*Ananas comosus* [L.] Merr.) in Guinea, Hawaii, and the Philippines; sugarcane (*Saccharum spp.*) in Angola, Hawaii, Indonesia, Brazil, the Philippines, and Taiwan; taro (*Colocasia esculenta* [L.] Schott) in Figi and Hawaii; and corn (*Zea mays* L.), rice, sugarcane, and vegetables in Mexico (Holm et al., 1977). Doveweed has seen use as a famine vegetable in India and for poultices and animal fodder in Indonesia, Malaysia, and Africa. Livestock will eat doveweed plants; however, the plants are of too high a moisture content to be of any forage value (Holm, 1977; Wilson, 1981).

The importance of doveweed relates to its persistence in cultivated lands and to the difficulty with which it is controlled. It reproduces by both seeds and stolons and grows rapidly under irrigated conditions. The plants form dense, pure stands, which smother competing species. Doveweed can grow rapidly over desirable species, competing with them for light and nutrients (Holm et al., 1977).

As horticultural materials are shipped to distant locations for use in a landscape, chemical and cultural practices are utilized by growers which encourage the exclusion of specific species from an ecosystem, and natural processes facilitate species migration, the geographic distribution of invasive species will continue to shift. Some ecological niches will be satisfied by species that are not historically problematic in a region. Understanding the requirements of these species for germination, growth, development, and reproduction will aid growers in implementing best management practices to slow the spread and invasion of these species.

As an important weed in fine turf with an expanding geographic range, the following research provides insight into factors that affect doveweed invasibility. The scope and objectives of this dissertation will increase the understanding of the interaction between environmental conditions, management practices, and herbicide programs which favor or discourage doveweed infestations. Various environmental parameters and common cultural practices are evaluated for their effect on doveweed germination, growth, and development. Pre- and postemergence herbicide control strategies are presented for control of existing infestations in ‘Tifway’ bermudagrass turf (*Cynodon dactylon* [L.] Pers × *C. transvaalensis* Burtt-Davy). The mechanism behind tolerance of doveweed to postemergence herbicides is explored. Together, these studies will provide best management practices for minimizing doveweed invasion by improving the understanding of the interaction between doveweed, environmental conditions, cultural practices, and herbicide control programs.

CHAPTER TWO

DOVEWEED GERMINATION RESPONSE TO ENVIRONMENTAL CONDITIONS

Introduction

Understanding seed germination requirements of invasive species helps growers predict where infestations may occur and possibly manipulate environmental conditions to discourage invasion. Previous research investigated the effect of constant and alternating temperature regimes on doveweed (*Murdannia nudiflora* [L.] Brenan) germination and determined it to occur most readily when soil temperatures average between 26 and 30 C and to decline significantly in temperatures above and below this range (Wilson et al., 2006). The study was conducted in both light and dark conditions and germination was not influenced by light availability. Seedling emergence in response to soil burial depth was also evaluated. Emergence was observed from depths between 0 and 6 cm four weeks after planting although emergence declined as seed burial depth increased. The burial depth at which emergence is reduced by 50% was calculated to be ~3.2 cm (Wilson et al., 2006). Germination requirements for a closely related species, Benghal dayflower (*Commelina benghalensis* L.) are similar. Maximum seed germination in this species occurs between 30 and 35 C and emergence declines as planting depth increases (Sabila et al., 2012).

Empirical evidence suggests doveweed germination can occur in a wide range of environmental conditions. Germination typically occurs most readily in moist soils however it is not limited to these areas. Salt concentration, pH, and nitrate availability are other environmental parameters that effect germination of many weed species; however, their influence on doveweed germination is unknown. Further, the presence or absence of a dormancy mechanism within doveweed seed has not been investigated. The overall objective of this study was to evaluate the effect of physical dormancy on doveweed germination and expand the understanding of how pH, osmotic and salt stress, and nitrate availability effect doveweed germination.

Materials and Methods

Experiments were conducted between 2011 and 2014 in the Biological Research Complex at Clemson University, Clemson, South Carolina. Doveweed plants were collected in September 2010 from turfgrass sites in Augusta, GA and transplanted to containers in the Clemson University greenhouse complex in Clemson, SC for future seed collections. After harvest, seeds were sieved to remove extraneous plant material and inert matter then dried for 24 h and stored at room temperature until study initiation unless otherwise noted.

Seed Production and Viability

Number of seeds produced per plant was estimated by first counting the number of seed pods produced each week during fruit production. Ten pods of each weekly harvest were randomly selected and number of seeds within each pod counted. The average number of seeds per pod was then multiplied by the total number of pods harvested for that week. Weekly seed totals were summed across the life cycle of each plant. Seed production was estimated for 10 plants between September 18 to December 18, 2012 and again between September 6 and December 12, 2013. Seed viability was tested by first imbibing four sets of 50 seeds for 48 h between two sheets of Whatman No. 2 filter paper moistened with 10 ml of distilled water. Seeds were then bisected through the embryo and placed in a 1% tetrazolium-chloride solution (MP Biomedicals; LLC, Solon, OH). After 24 h, seeds were removed and embryo viability determined under a dissecting microscope. Percent viability was calculated as the average of viable seeds per replication divided by 50 (AOSA, 2012).

General Germination Test Protocols

Germination was evaluated by placing 50 evenly spaced seeds in a 9 cm diameter petri dish containing two sheets of Whatman No. 2 filter paper and 5 ml of distilled water or treatment solution. Dishes were sealed with parafilm to avoid moisture loss and placed in a growth chamber (Model No. PGR15; Conviron, Winnipeg, Canada) set to maintain a constant temperature of 28 C. A 12 h photo period was set to provide a photosynthetic photon flux density (PPFD) of 300 µmol m^{-2} s^{-1} using a combination of cool white fluorescent and incandescent lamps. Previous studies indicated maximum germination occurred under these conditions (Wilson, 2006). Germinated seeds were counted every 2 d for 21 d after experiment initiation. A seed was considered germinated when the radical protruded 1 mm through the seed coat. After each census, germinated seeds were removed and petri dishes were rotated to minimize growth chamber location effects. In pH, osmotic stress, salt stress, and nitrate concentration studies, seed coats were mechanically scarified by abrading seeds between two sheets of medium-grade emery cloth for 30 sec prior to study initiation to evaluate germination response to environmental parameters in the absence of physical dormancy.

Scarification

Seeds were chemically and mechanically scarified to determine if physical dormancy inhibits germination in newly harvested doveweed seed. With chemical scarification, 150 seeds were placed in each of six glass beakers with 30 ml of 1N sulfuric acid (H_2SO_4) and exposed for different lengths of time: 0, 10, 20, 30, 40, 50 and 60 min. Sulfuric acid was removed after each exposure time and seeds twice rinsed by swirling with 30 ml of distilled water for 10 seconds. Mechanical scarification treatments were imposed by abrading 150 seeds between two sheets of medium grade emery cloth for 30 seconds. Non-scarified seeds in distilled water were included as a control (Oldham, 2009).

pH

To evaluate the effect of pH on doveweed germination, buffer solutions ranging from pH 4 to 10 were prepared. A 2 mM potassium hydrogen phthalate buffer solution was adjusted to pH 4 with 1 N HCl. A 2 mM MES [2-(N-morpholino) ethanesulfonic acid] solution was adjusted to pH 5 and 6 with 1 N NaOH. A 2 mM HEPES [N-(2-hydrozymethyl) piperazine-N-(2-ethanesulfonic acid)] solution was adjusted to pH 7 and 8 with 1 N NaOH. A 2 mM tricine [N-tris(hydroxymethyl)methylglycine] solution was adjusted to pH 9 and 10 with 1 N NaOH. Unbuffered deionized water was used as a control (Chachalis and Reddy, 2000).

Osmotic and Salt Stress

Osmotic potential effect on seed germination was determined by preparing aqueous solutions of poly(ethylene glycol)-1000 (PEG) (Acros Organics, New Jersey) with osmotic potentials of 0, -0.05, -0.10, -0.20, -0.40 and -0.80 MPa by dissolving appropriate amounts of PEG in 1 L of deionized water as described by Money (1989).

The effect of salt stress on doveweed germination was evaluated by preparing sodium chloride (NaCl) solutions of 0, 10 20, 40, 80, and 160 mM in deionized water (Chachalis and Reddy, 2000; Koger et al., 2004).

Nitrate Concentration

The effect of nitrate concentration on doveweed germination was evaluated by preparing treatment solutions with nitrate concentrations of 0, 50, 100, 200, and 400 mg L^{-1}. Nitrate treatment solutions were prepared with potassium nitrate (KNO_3) in deionized water (Lowe et al., 1999).

Statistical Design

All experiments were conducted in a completely randomized design. Treatment arrangement of each experiment was a single factor design with various treatment levels. Treatments of each experiment were replicated three times, and each experiment was repeated in time. Data variance was visually inspected by plotting residuals to confirm homogeneity and normality of variance prior to analysis. Data were then subjected to ANOVA for evaluation of main effects and interaction between main effects and experimental runs. No main effect-by-run interactions were detected; therefore, data were pooled between runs for further analysis (Table 2.1). Where treatment levels were more categorical in nature, mean comparisons between treatment levels were performed using Fisher's protected LSD. All comparisons were based on $\alpha = 0.05$ significance level and analyses were conducted using JMP Pro 10 (SAS Institute Inc., Cary, NC).

Because osmotic and salt stress data were considered more continuous in nature, regression analysis was deemed most appropriate for analysis of data. Germination percentage values at different levels of osmotic potential or NaCl concentration were best fitted to a functional three-parameter sigmoid model with Prism 6 (GraphPad, La Jolla, CA). The model fitted was:

$$G = G_{max}/\{1 + e[-(X - X_{50}) / G_{rate}]\}$$

where G is the total germination percentage at osmotic potential or NaCl concentration X, G_{max} is the maximum germination percentage, X_{50} is the osmotic potential or NaCl concentration required for 50% inhibition of maximum germination and G_{rate} indicates the slope.

Table 2.1 ANOVA for the effect of environmental conditions on doveweed germination.

Source	Scarification[a]		pH[b]		Osmotic[c]		Salt[d]		Nitrate[e]	
	DF		DF		DF		DF		DF	
Treatment	7	*	6	ns[f]	4	ns	5	*	4	ns
Run	1	ns	1	ns	1	ns	1	*	1	ns
Treatment-by-Run	7	ns	6	ns	4	ns	5	ns	4	ns
Error	32		28		20		24		20	

[a] Seeds were mechanically abraded between two sheets of medium-grade emery cloth for 30 sec or soaked for 10, 20, 30, 40, 50, or 60 minutes in 1N H_2SO_4.
[b] Seeds were germinated in treatment solutions with pH 4-10.
[c] Seeds were germinated in treatment solutions with a osmotic potential of 0, -0.5, -0.10, -0.20, -0.40, or -0.80 MPa.
[d] Seeds were germinated in treatment solutions with a NaCl concentrations of 0, 10, 20, 40, 80, or 160 mM.
[e] Seeds were germinated in treatment solutions with a nitrate concentration of 0, 50, 100, 200, 400 mg L^{-1}.
* Significant at $\alpha = 0.05$ level
[f] Abbreviation: ns, not significant

Results and Discussion

Seed Characteristics and Viability

On average, doveweed produced ~2700 seeds per plant over a lifcycle. Of these, approximately 80% were viable (Table 2.2). In comparison, large crabgrass (*Digitaria sanguinalis* (L.) Scop.) and goosegrass (*Eleusine indica* (L.) Gaertn.) can produce up to 1,250,000 seeds m^{-2} and 140,000 seeds $plant^{-1}$, respectively (Chin, 1979; Johnson and Coble, 1986). Seed germination of both of these species is >75% under ideal conditions (King and Oliver, 1994; Nishimoto and McCarty, 1997). Although doveweed seed production is much lower than goosegrass and large crabgrass, viability remains >70% after four years in seeds stored at 5 C, suggesting potential for long term persistence in the soil seed bank (Table 2.2). Doveweed also has the ability to spread by stolons while the aforementioned grasses do not. Future research should determine the length of viability and persistence of doveweed seeds under field conditions.

Table 2.2. Seed production and viability of doveweed seed of various age.

Seed age	Germination	Standard Deviation
	–%–	
0 d	80	7.4
4 yr[a]	73	31.8
Seed production		
seeds plant $^{-1}$		
2687		510

[a]3 yr old seeds were stored at 5 C after harvest until viability testing.

Scarification

Chemical and mechanical scarification significantly affected doveweed germination compared to non-scarified seed (Table 2.1). Germination of non-scarified seed was approximately 18% after 3 wk. Chemical scarification, regardless of duration, reduced germination. Within chemical scarification treatments, no differences in germination were detected and ranged between 0 and 1% (Figure 2.1). Mechanical scarification improved germination compared to non-scarified and chemically scarified seeds. Thirty seconds of mechanical abrasion improved germination to ~84% from 18% in non-scarified seed which suggests an intact seed coat confers a physical dormancy that limits germination (Figure 2.1).

Dormancy is the failure of a viable seed to germinate given sufficient moisture and a suitable temperature for radicle emergence and seedling growth (Amen, 1968). Seeds with physical dormancy have impermeable testas or pericarps that prevent moisture imbibition until the seed coat is disturbed (Fenner and Thompson, 2005). In many species, dormancy allows for seed dispersal by preventing immediate and synchronous germination and prevents germination when conditions are suitable, but the probability of survival and growth of seedlings is low (Fenner and Thompson, 2005; Murdoch and Ellis, 2000). Physical dormancy can be broken by physically or chemically abrading the seed coat (Fenner and Thompson, 2005). A previous study investigated scarification of Benghal dayflower seeds by mechanical and chemical means (Budd et al., 1979; Kim et al., 1997). All scarification treatments increased Benghal dayflower germination; however, little evidence exists to support the theory that physical dormancy can be broken by chemical or mechanical abrasion in the field. If this were a viable mechanism, germination would likely occur in seasons and habitats in which seedlings could not survive, thus lowering fitness of the plant (Baskin and Baskin, 2000). In addition, the seed coat of species with physical dormancy are generally resistant to decomposition by soil microorganisms (Baskin and Baskin, 1998; Baskin and Baskin, 2000; Halloin, 1983).

Anatomically specialized water-restriction structures have evolved as part of the seed or fruit coat in some taxa with physical dormancy (Baskin and Baskin, 2000). Seeds of many Commelinaceae species have hard seed coats to protect them from environmental hazards. These species possess a small embryotega that acts as a cap-like structure over the embryo (Evans et al., 2000). Small cracks are observed during imbibition in the embryotega of Benghal dayflower, allowing for water uptake. The seed coat of this species never ruptures during germination; rather, seeds germinate by pushing the cracked embryotega aside (Goddard et al., 2009). In comparison, non-scarified doveweed seed typically requires a long imbibition period, followed by germination through the embryotega region. Although doveweed germination is not totally inhibited in absence of a physical disruption to the seed coat, investigation into the conservation of embryotega function across Commelinaceae spp. may improve the understanding of the mechanism which confers physical dormancy in doveweed and other Commelinaceae species.

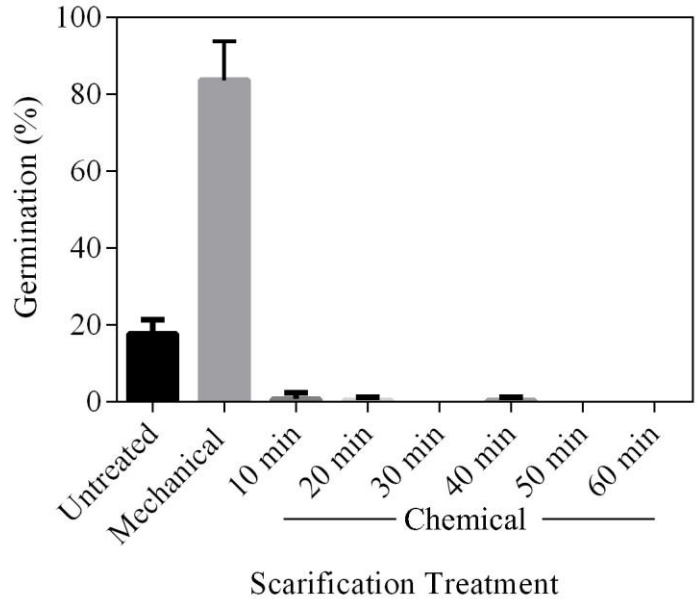

Figure 2.1. Effect of mechanical scarification for 30 sec with medium grade emery cloth and chemical scarification with 1N H_2SO_4 for various periods of time on germination of doveweed seeds incubated at 28 C in a 12-h photoperiod for 3 wk. Vertical bars represent standard error of the mean.

pH

Significant treatment effects were not detected for doveweed germination in response to pH (Table 2.1). Complete inhibition of germination was not observed at pH 4-10 and ranged between 69 and 78% (Table 2.3). Many species are documented to germinate across a wide range of pH (Jain and Singh, 1989; MacDonald et al., 1992; Singh et al., 1975; Stubbendieck, 1974). Common turfgrass weeds such as goosegrass and green kyllinga (*Kyllinga brevifolia* Rottb.) germinate over a wide pH range (Chauhan and Johnson, 2008a; Molin et al., 1997). Other species such as large crabgrass (*Digitaria sanguinalis* (L.) Scop.) and tropical signalgrass (*Urochloa subquadripara* (Trin.) R. D. Webster) are sensitive to pH values >6 (Pierce et al., 1999; Teuton et al., 2004).

These data suggest that if other germination requirements are met, soil pH should not be a limiting factor for doveweed germination. Similar germination between pH 4 and 10 supports the view that doveweed is adapted to a wide range of soil chemical conditions.

Table 2.3. Effect of pH on germination of doveweed seeds mechanically scarified for 30 sec with medium-grade emery cloth incubated at 28 C in a 12-h photoperiod for 3 wk.

pH	Germination
	–– % ––
4	78
5	77
6	71
7	71
8	75
9	69
10	71
$LSD_{0.05}$	ns[a]

[a]Abbreviation: ns, not significant (α = 0.05)

Osmotic Stress

Significant treatment effects were detected for doveweed germination in response to a range of osmotic potentials (Table 2.1). Doveweed germination was similar between osmotic potentials of 0 and -0.4 MPa and germination was reduced ~50% in -0.8 MPa treatments (Figure 2.2). This response suggests doveweed favors a moist environment for germination, confirming patterns observed in the field where germination occurs most readily in areas of perpetually high soil moisture. Doveweed is unlikely to germinate under droughty conditions but be delayed until ample moisture is available.

Similar germination patterns in response to osmotic potential have been observed in other turfgrass weed species. Green kyllinga germination is progressively reduced in water potentials between -0.1 and -0.5 MPa, with no germination occurring at -0.6 MPa (Molin et al., 1997). Germination of goosegrass is similar between 0 and -0.4 MPa, begins to decline at -0.6 MPa and is completely inhibited at -0.8 MPa (Ismail et al., 2002). Southern crabgrass (*Digitaria ciliaris* (Retz.) Koeler) germinates in osmotic potentials as low as -1.0 MPa; however, germination is reduced ~50% at -0.29 MPa (Chauhan and Johnson, 2008b). Similarly, large crabgrass germination is reduced ~50% at an osmotic potential of -0.3 MPa (King and Oliver, 1994).

Turfgrass managers frequently irrigate to supply water to turfgrass plants with rootzones limited to the top few centimeters of soil. If irrigation is applied too frequently, excessive soil moisture may encourage germination of invasive species. Doveweed germination occurs on the soil surface and up to 6 cm in depth (Wilson et al., 2006). Limiting soil moisture in the upper 6 cm of the soil profile by irrigating deeply and infrequently and improving drainage of low-lying, wet areas may be an effective means of reducing doveweed germination and subsequent invasion.

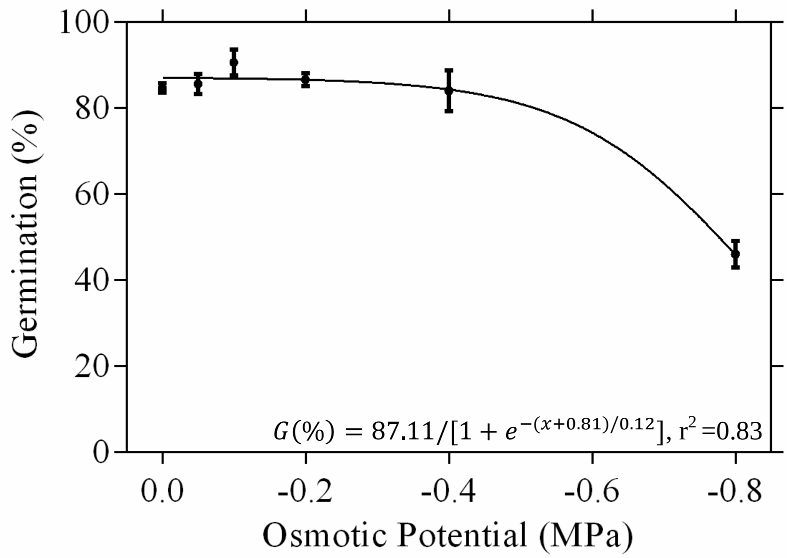

Figure 2.2. Effect of osmotic potential on germination of doveweed seeds mechanically scarified for 30 sec with medium-grade emery cloth incubated at 28 C in a 12-h photoperiod for 3 wk. The line represents a three-parameter sigmoid model fitted to the data and vertical bars represent standard error of mean.

Salt Stress

Salt stress significantly affected doveweed germination (Table 2.1). Germination was similar between NaCl concentrations of 0 and 40 mM and ranged between 81 and 85%. As NaCl concentration increased from 40 mM to 80 mM, germination decreased by 9%. Germination was further reduced at 160 mM NaCl, as germination was <50% (Figure 2.3).

In a related species, Benghal dayflower germination is reduced ~50% in a 10 mM NaCl solution and completely inhibited in a 80 mM NaCl solution (Sabila et al., 2012). In other species commonly invasive in turfgrass, goosegrass germination is >78% in up to a 50 mM NaCl solution, reduced to ~25% in a 100 mM NaCl solution, and completely inhibited by a 200 mM NaCl solution. The NaCl concentration required for 50% inhibition of goosegrass germination is ~77.5 mM (Chauhan and Johnson, 2008a). Southern crabgrass germination is reduced ~50% by a 112 mM NaCl solution although some seeds germinated in a 200 mM NaCl solution (Chauhan and Johnson, 2008b).

These data suggest doveweed infestations can occur in moderately saline soils. Infestations will lessen as soil salt concentration increases. In relation to specific turfgrass species, seashore paspalum (*Paspalum vaginatum* Sw.), bermudagrass (*Cynodon dactylon* (L.) Pers.), St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze), and Zoysiagrass (*Zoysia spp.*) are tolerant of soil salt levels in which doveweed germination begins to decline (40-80 mM or 2300-4700 ppm) (Harivandi, 2007). At the highest soil salinity level tested (160 mM or 9400 ppm) growth of these turf species would be limited with the exception of seashore paspalum. In high saline environments, competition from more salt tolerant turf species such as seashore paspalum may reduce doveweed infestation. Germination of doveweed should not be limited except for under highly saline conditions when soil salt concentration reaches >80 mM or ~4700 ppm.

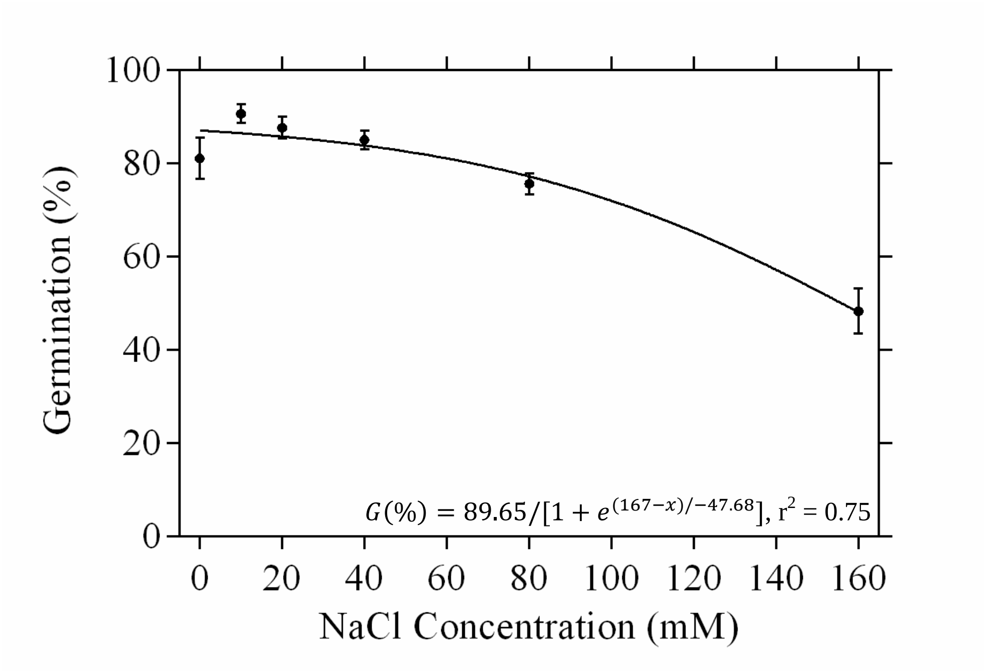

Figure 2.3. Effect of NaCl concentration on germination of seeds mechanically scarified for 30 sec with medium-grade emery cloth incubated at 28 C in a 12-h photoperiod for 3 wk. The line represents a three-parameter sigmoid model fitted to the data and vertical bars represent standard error of mean.

Nitrate

Nitrate concentration did not significantly effect doveweed germination (Table 2.1). Germination of all treatments ranged between 75 and 77% (Table 2.4). Nitrate is documented to stimulate seed germination in certain plant species. In a survey of 85 different species, germination percentage was improved in half of the species when nitrate was available (Steinbauer and Grigsby, 1957). In relation to turfgrass weeds, *Kyllinga brevifolia* Rottb., *K. squamulata* Rottb., and *K. pumila* Michx. germination is not affected by nitrate availability. However, germination of smooth and large crabgrass seedlings is improved by nitrate availability (Turner and Acker, 2014).

Use of nitrate fertilizers in turfgrass results in an expedient response in terms of shoot growth and greening. After these fertilizers solubilize in the soil, ammonium ions can be absorbed by negatively charged clay or organic matter reducing nitrogen loss through volatilization. Seed germination response to soil nitrate has generally been interpreted as a promoter of germination, only affecting seed germination once other dormancy-breaking requirements have been satisfied (Fenner and Thompson, 2005). With germination ≥75% across all treatments, germination appears to be more reliant on other environmental factors, such as water availability. Further research should evaluate seedling vigor of doveweed across a range of nitrate concentrations to identify any improvement to seedling establishment in response to nitrate availability.

Table 2.4. Effect of nitrate concentration on germination of doveweed seeds mechanically scarified for 30 sec with medium-grade emery cloth incubated at 28 C in a 12-h photoperiod for 3 wk.

Nitrate concentration	Germination
— ppm[a] —	— % —
0	77
50	77
100	75
200	76
400	76
$LSD_{0.05}$	ns

[a]Abbreviations: ppm, parts per million; ns, not significant ($\alpha = 0.05$)

Conclusions

Turf managers encourage vigorous turfgrass growth by manipulating cultural practices to create favorable growing conditions. Understanding germination requirements of invasive species improves grower ability to manipulate cultural practices to favor growth of desirable species over germination and infestation of invasive species. The data suggests doveweed germination occurs over a wide range of environmental conditions, but is reduced by low water availability and high salt stress. Irrigation should be limited to prevent excessive soil moisture and drainage should be improved to reduce water availability in low-lying areas. Use of turfgrass cultivars tolerant to droughty conditions and saline environments may reduce doveweed infestations through increased interspecies competition. Future research should evaluate the effects of similar environmental parameters on doveweed seedling vigor to better understand conditions that favor establishment of this species after seed germination.

CHAPTER THREE

DOVEWEED GROWTH RESPONSE TO ENVIRONMENTAL RESOURCE AVAILABILITY AND CULTURAL PRACTICES

Introduction

An area's susceptibility to invasion by a non-native species is a function of available environmental resources and how well they match those necessary to support plant function. Conditions such as water, nutrient, and light availability must meet basic requirements to support life (Davis et al., 2005). Change in resource availability is often explained by fluctuation in gross resource availability or resource utilization (Harrington, 1991; Davis et al., 2000). Changes in resident vegetation influencing light availability, effects of herbivory and pest outbreaks on water and nutrient use, disease incidence reducing resource utilization, variation in yearly rainfall, and eutrophication increasing nutrient availability are a few examples how resource availability is a fluid process (Harrington, 1991; Davis et al., 2000). Susceptibility of an ecosystem to invasion is neither a static nor permanent attribute. To be invasive, a species must be able to compete for available resources and enough propagules must enter the new environment to maximize use of these resources (Davis et al., 2005; Lonsdale, 1999).

In turfgrass, cultural practices interact with environmental resources and biological requirements of a species to effect species invasibility (Burns, 2004). Irrigation, mowing height, and fertilization regimes are three primary cultural practices manipulated by turfgrass managers to encourage vigorous turfgrass growth. Irrigation must be adequate to prevent wilt; however, excessive irrigation may encourage germination and establishment of invasive species. Regular mowing is necessary to prevent scalping at low mowing heights and to provide a consistent and uniform playing surface. Although some weed species are adequately controlled by mowing alone, mowing increases the amount of light that can penetrate the turf canopy to the soil surface thereby encouraging germination and establishment of other species (Black, 1975; Dernoeden et al., 1993; Lowe et al., 2000). To maintain vigorous growth, supplementary nutrients must be applied as fertilizer; however, excessive nutrient application may make available a nutrient surplus that encourages the invasion of unwanted species (Lowe et al., 2000).

Doveweed (*Murdannia nudiflora* [L.] Brenan) is rapidly expanding its geographic range by becoming a dominant colonizer of managed turf in the Southeastern United States. Doveweed can quickly invade an area by increasing its surface coverage with above ground stems that readily root at the nodes when contact is made with moist soil. A short period of time is necessary for flowering and seed production to begin after germination (~6 wk, personal observation). Rapid sexual reproduction allows for expansion into more temperate climates where it typically exists as a late-germinating summer annual. This combination of reproductive strategies makes doveweed especially difficult to control in managed turfgrass. Under favorable conditions, doveweed competes vigorously with desirable turf by forming dense, pure stands, overgrowing and outcompeting desirable turf for light and available resources. Although high soil moisture is typical of areas doveweed will first be observed, plants can persist in a wide range of soil types and moisture conditions, opportunistically growing when resources are available (Holm et al., 1977).

Previous research has not considered the effects of cultural practices common to managed turfgrass on doveweed growth and development. The goal of this research was to evaluate the effect of mowing, irrigation, nitrogen application, and light availability on doveweed growth and development. An understanding of these effects will help turf managers predict where infestation will occur and shape cultural practices to encourage vigorous turfgrass growth while discouraging doveweed invasion.

Materials and Methods

The levels of each experimental factor were selected to represent current recommendations for management of bermudagrass turf in the Southeastern United States (McCarty, 2011).

Mowing height

A field study evaluated the effect of regular mowing at various heights of cut on doveweed lateral spread, shoot width, and internode length. The study was conducted between August 15 and October 17, 2012 and repeated between July 25 and September 26, 2013. Plots were fumigated with methyl bromide at 73 kg ai ha^{-1} prior to year one study initiation. Plots were 2 × 2 m with 1 m alleys between plots. Doveweed was established by evenly spacing 50 3-to-5 leaf seedling transplants into each plot 2 wk prior to mowing. Plots were regularly mowed (2x wk^{-1}) at one of three heights, 1.9, 3.8, or 7.6

cm. A Jacobson Tri-King 1900D (Textron; Providence, Rhode Island) was used to mow 1.9 cm plots and a Toro Z-Master (The Toro Company; Bloomington, Minnesota) was used to mow 3.8 and 7.6 cm plots. An unmown control was included for comparison.

Leaf width, internode length, and percent cover were measured weekly to identify effects of mowing height on doveweed growth characteristics. Leaf width was quantified within each plot by randomly selecting and measuring the width of four mature, fully expanded leafs at their widest point. Internode length was determined by measuring the length between the second and third rooted node attached directly to the mother plant by a stem connected to the original crown. The length of four randomly selected internodes was determined per plot at each measurement date. All leaf width and internode length measurements within each plot were averaged prior to statistical analysis. Percent cover was measured within 1 d following mowing and quantified by placing a 2 × 2 m 289-square grid with 11.75 × 11.75 cm centers randomly within each plot. Grid squares containing doveweed leaf tissue were denoted as a 'hit' and counted. Lateral growth was calculated as number of hits divided by number of squares in the grid (total hit/total squares × 100).

Experimental design was a randomized complete block with three replications. Treatments were arranged in a single factor design (mowing height) with four levels. The study was repeated in sequential years and plots were re-randomized between years. Data were subjected to ANOVA for evaluation of main effects and interaction between factor levels and experimental years. Where appropriate, further mean comparisons between factor levels were performed using Fisher's protected LSD. All comparisons were based on an $\alpha = 0.05$ significance level. All analyses were conducted using JMP Pro version 10 (SAS Institute Inc.; Cary, NC).

Competition with bermudagrass

A greenhouse study was conducted to evaluate the effect of mowing height and nitrogen fertilization on competition between doveweed and 'Tifway' bermudagrass (*Cynodon dactylon* Burtt-Davy × *C. transvaalensis* L. Pers.). Mature Tifway sod was harvested on June1, 2011 and 2012 from a sod farm in Seneca, South Carolina. Sod was washed free of soil and transplanted to flats measuring 52 cm long, 37 cm wide and 8 cm deep filled with Fafard 3B potting mixture (Sun Gro Horticulture; Agawam, MA). Flats were irrigated daily for the first 10 d after planting to aid in establishment, then every 2-3 d on an as-needed basis to prevent wilt. Flats were mown with a Jacobsen Greens King 522A (Textron; Providence, Rhode Island). A rail system was constructed to facilitate uniform mower operation at 5.3 cm above the soil surface when flats were placed on the ground between the rails. For 2.65 cm treatments, a 2.65 cm thick section of plywood was placed underneath each flat prior to cutting to raise the soil surface to 2.65 cm below the mowing plane. Sod was allowed to establish for 1 wk prior to mowing height establishment then an additional 4 wk prior to sowing of doveweed seed.

Doveweed seed was sown on July 6, 2011 and 2012 by placing two doveweed seeds in 20 evenly spaced locations within each flat, totaling 40 seeds flat $^{-1}$. Prior to sowing, seeds were mechanically scarified by abrading for 30 seconds between two sheets of medium-grade emery cloth to remove any physical dormancy. Following sowing, flats were irrigated daily for 1 wk to promote doveweed germination. After this period, flats were irrigated every 2-3 d as previously described.

Nitrogen treatments were applied as urea (46-0-0) fertilizer twice monthly to total 24.5 or 49 kg N ha^{-1} mo^{-1}. Fertilizer applications were made by first grouping flats by treatment then shaking a measured amount of granular fertilizer across the group of flats in four directions to ensure even distribution across all flats. During each application, flats were randomly placed within each grouping to minimize location effects.

Lateral spread was measured by placing a 52 × 37 cm square grid with 1 cm centers over each flat, then denoting grid squares containing doveweed leaf tissue as a 'hit'. Lateral spread was calculated as number of hits divided by number of squares in the grid (total hit/total squares × 100). Lateral spread was measured weekly within 1 d following mowing. Because germination was not consistent between flats, total number of doveweed plants within each flat was counted at the end of each study year to account for any effect of fertilization and mowing on establishment.

Experimental design was a completely randomized design with three replications. A 2 × 3 factorial treatment arrangement included 2 mowing heights (2.65 and 5.3 cm) and three nitrogen rates (0, 24, and 49 kg N ha mo^{-1}). The study was repeated in sequential years. Flats were rotated weekly to minimize localized greenhouse effects. Data were subjected to ANOVA for evaluation of main and interaction effects and interaction between levels of factors and experimental years. Where appropriate, further mean comparisons between factor levels were performed using Fisher's protected LSD.

All comparisons were based on an $\alpha = 0.05$ significance level. All analyses were conducted using JMP Pro version 10 (SAS Institute Inc., Cary, NC).

Shade Tolerance

A greenhouse study was conducted to evaluate the response of doveweed to four levels of a reduced light environment (RLE): 0, 30, 50, and 70%. Light reduction of each shade cloth was determined by comparing photosynthetic photon flux (PPF) (μmol m^{-2} s^{-1}) under the shade cloths at soil level to full-irradiance PPF measurements with a LI-28663 quantum light sensor (LiCor, Inc.; Lincon, NE) $[(PPF_{full\ sun} - PPF_{under\ shade\ cloth})/PPF_{full\ sun}] \times 100$.

Reduced light environments were applied for an 8 week period beginning July 1, 2011 and ending August 31, 2011. The study was repeated beginning February 1, 2014 and ending March 31, 2014. Reduced light environments were applied continuously using neutral density, poly-fiber black shade cloth (model SC-black30, SC-black50, SC-black70; International Greenhouse Company, Danville, IL) that removed equal amounts of light across the photosynthetically active light spectrum. Individual shade cloth tent frames were 1 × 1 m and constructed with 5.3 cm diameter polyvinyl chloride (PVC) pipes. Shade cloths were attached to PVC frames with zip-ties and pulled taut to maintain shade cloths at a consistent height above the soil surface and maintain consistent surface temperature and air movement among all treatments.

Experimental units were established by sowing 20 evenly spaced seeds in a 15 cm diameter by 11 cm deep pot filled with Fafard 3B potting mixture. The seed source originated from doveweed samples collected from field-grown plants in Augusta, GA then transplanted to the Clemson University greenhouse complex for seed production and collection. After germination, plants were allowed to grow to the two-leaf stage at which point they were thinned to 5 plants per pot. Plants were allowed to continue development under full irradiance until all plants reached the 5-8 leaf stage, at which point reduced light treatments were imposed. A balanced 10-10-10 N-P_2O_5-K_2O fertilizer was applied at study initiation and 4 weeks after study initiation to provide 24.5 kg N ha^{-1} mo^{-1}.

At the end of the study, plants were harvested and washed free of soil and debris, then dried at 70 C for 48 h and weighed. Total dry biomass was partitioned into shoot and root biomass. Internode length was determined by measuring the length between the second and third node away from the mother plant on a randomly selected stem attached directly to each mother plant within each pot. Internode measurements within each pot were averaged prior to further analysis.

Experimental design was a completely randomized design with three replications. Treatments were arranged in a single factor design (shade) with 4 levels. Each treatment level replicate included three experimental units, totaling 9 observations per treatment level. Multiple experimental units were included in each replicate to reduce variation within treatment replicates. The experiment was repeated in time. Data were subjected to ANOVA for evaluation of main effects and interaction between main effects and experimental years. Where appropriate, further mean comparisons between factor levels were performed using Fisher’s protected LSD. All comparisons were based on an $\alpha =$

0.05 significance level. All analyses were conducted using JMP Pro version 10 (SAS Institute Inc., Cary, NC).

Soil Moisture

A greenhouse study was conducted to determine the effect of soil moisture on doveweed growth and development. Five soil moisture regimes were studied: 12.5, 25, 50, 75 and 100 percent field capacity (FC). Pots 15 cm in diameter and 11 cm in depth were filled with Fafard 3B potting mixture and weighed to determine pot dry weight. Pots were then sub-irrigated to saturation then allowed to drain for 6 h, then re-weighed to determine field capacity pot weight. Amount of water within the pot at field capacity was determined gravimetrically by subtracting each pot dry weight from each field capacity pot weight.

Doveweed was established by sowing 20 evenly spaced seeds into each pot. The seed source originated from doveweed samples collected from field-grown plants in Augusta, GA then transplanted to the Clemson University greenhouse complex for seed production and collection. During establishment, experimental units were irrigated daily to encourage doveweed germination. After germination, plants were allowed to grow to the two-leaf stage at which point they were thinned to 5 plants per pot. Plants were allowed to continue development under well-watered conditions until all plants reached the 5-8 leaf stage at which point soil moisture treatments were imposed on July 26, 2012 and July 15, 2013. Soil moisture levels were adjusted to initial treatment levels every 3 d on a gravimetric basis. A 10-10-10 N-P_2O_5-K_2O fertilizer was applied at study initiation and four weeks after study initiation to provide 24.5 kg N ha^{-1} 4 wk^{-1}.

Doveweed was harvested 8 wk after initiation of soil moisture treatment and washed free of soil and debris. Plants were then dried at 70 C for 48 h and weighed. Total dry biomass was partitioned into shoot and root biomass. Experimental design was a completely randomized design with three replications. Treatments were arranged in a single factor design with FC treatments serving as treatment levels. The study was repeated in sequential years. Data were subjected to ANOVA for evaluation of main effects and interaction between main effects and experimental run. Where appropriate, further mean comparisons between treatment levels were performed using Fisher's protected LSD. All comparisons were based on an $\alpha = 0.05$ significance level. All analyses were conducted using JMP Pro version 10 (SAS Institute Inc., Cary, NC).

Results and Discussion

Mowing Height

Mowing height significantly affected percent coverage, internode length, and shoot width in both study years (Table 3.1 and 3.2). A mowing height-by-year interaction effect on percent cover was only detected 9 weeks after planting (WAP) when doveweed was reaching the end of its life cycle and leaf tissue was beginning to senesce in response to seasonal weather patterns. Although a general lack of mowing height-by-year interaction occurred when weekly data were analyzed, data were not pooled to provide a picture of how quickly the severity an infestation can increase if left unchecked, regardless of mowing height. Doveweed spread typically slowed as mowing height was lowered; however, effects were more pronounced in year one than year two (Table 3.3).

Four weeks of regular mowing was necessary in year one before a significant mowing height effect could be detected (Table 3.3). At that point, doveweed spread was 30% less in plots mowed at 2 cm than plots mowed at 8 cm. Mowing at 4 cm did not reduce spread compared to mowing at 8 cm, or increase spread compared mowing at 2 cm. By the end of year one (9 WAP), doveweed spread was reduced 46% and 30% by mowing at 2 or 4 cm, respectively, compared to unmown plots and 42 and 26%, respectively, compared to plots mown at 8 cm (Table 3.3).

Overall doveweed pressure was greater throughout year two since plants were allowed to produce seed at the end of year one and plots were not fumigated prior to study initiation in year two. In response, treatment effects were less pronounced.

Although the effect of mowing height on doveweed spread in year two followed the same numerical trend as year one – no treatment-by-year interaction was detected – mowing height effects were not significant at any point throughout year two (Table 3.1). This suggests the severity of infestation can rapidly escalate over a growing season if doveweed growth is left unchecked, regardless of mowing height.

Regular mowing is necessary in managed turf to prevent excessive tissue removal during a single mowing event. Excessive tissue removal will reduce turfgrass density and impair the plants ability to regenerate leaf tissue following mowing. Tolerance of a plant species to mowing is dictated by its morphology. Poaceae *spp.* are largely tolerant to regular mowing because of intercalary meristems that regenerate leaf tissue from origins between the stem and leaf sheath. Intercalary meristems provide a competitive advantage for Poaceae *spp.* utilized for turfgrass over many invasive species by providing growth points close to ground level. In addition, several Poaceae *spp.* can rapidly colonize an area due to a prostrate above ground (stoloniferous) or below ground (rhizomatous) growth habit. As a close relative phylogeneticaly to Poaceae, some species in Commelinaceae, such as doveweed, share these morphological characteristics that are important for plant survival at low mowing heights.

Although doveweed survival was not limited by low mowing, mowing height significantly affected internode length and leaf width. In year one, internode length averaged 30 mm in plots mowed at 8 cm and 20 and 16 mm in plots mowed at 4 and 2 cm, respectively. In year two, mowing height treatment responses were generally similar; however, internode length was reduced across all treatments compared to year one possibly due to an increase in intraspecies competition resulting from seedling recruitment (Table 3.4). As internode length is shortened by low mowing, the rate at which a plant can colonize laterally is slowed. This response explains the reduction in percent coverage that resulted in treatments mowed at 2 cm. In addition, average leaf width was reduced by low-mowing, decreasing the total photosynthetic surface area of the plant (Table 3.4). Photosynthetic capacity can become a limiting growth factor at low mowing heights. Under regular mowing, a plant must manufacture enough photosynthates using limited leaf surface area to fuel normal plant function while preventing depletion of root carbohydrate reserves. Regular mowing at low heights may cause lost plant resources through mowing to exceed carbohydrate production through photosynthesis, eventually leading to exhaustion stored carbohydrates and plant death.

The effect of mowing on other weeds common to managed turfgrass has mostly been evaluated within existing turf stands. Green kyllinga (*Kyllinga brevifolia* Rottb.) spread and dry weight production doubled when mowing height decreased from 5.0 cm to 2.5 cm after 8 wk of growth (Lowe et al., 2000). Smooth crabgrass (*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.) invasion into tall fescue *(Festuca arundinacea* Schreb.) was reduced when mowing height was increased from 5.5 and 3.2 cm to 8.8 cm (Dernoeden et al., 1993). Aside from removal of meristematic tissue, regular mowing may have other effects on species establishment. For example, light is necessary for green kyllinga seed germination (Lowe, 1999). By lowering mowing height, turf canopy density and the amount of light reaching green kyllinga seed is increased, thus improving germination and increasing the severity of infestation (Lowe et al., 2000; Lowe et al., 1999). In species such as doveweed with a high soil temperature requirement for seed germination, increased light penetration may encourage warming of the soil surface and thus germination.

Mowing did not completely limit doveweed growth and development in this study; however, it effectively slowed lateral spread, indicating infestations may be less severe at reduced mowing heights. Regular mowing may also be an effective means for reducing doveweed seed production due to its decumbent growth habit during maturity. In combination with an effective herbicide control program, limiting seed production may reduce establishment from seed in subsequent seasons, lessening infestation of an area. Additional research is necessary evaluate the effect of mowing height on doveweed seed production and its long term persistence in a soil seed bank.

Table 3.1. ANOVA for the effect of mowing height on doveweed spread, July-August 2012 and 2013 in Clemson, South Carolina.

Source	DF	2 WAP[a]	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP	8 WAP	9 WAP
		2012 an 2013 Combined							
Mowing Height	3	ns	ns	*	*	*	*	*	*
Block	2	ns	ns	ns	ns	*	ns	*	*
Year	1	*	*	*	*	*	*	*	*
Mowing height-by-Year	3	ns	ns	ns	ns	ns	ns	ns	*
		2012							
Mowing Height	3	ns	ns	*	*	*	*	*	*
Block	2	ns	ns	ns	ns	ns	ns	ns	ns
		2013							
Mowing Height	3	ns	ns	ns	ns	ns	ns	ns	ns
Block	2	ns	ns	ns	ns	ns	ns	ns	ns

[a] Abbreviations: WAP, weeks after planting; ns, not significant ($\alpha = 0.05$)
*Significant at $\alpha = 0.05$ level.

Table 3.2. ANOVA for the effect of mowing height on doveweed internode length and shoot width, July-August 2012 and 2013 in Clemson, South Carolina.

Source	DF	Internode Length	DF	Shoot Width
	2012 and 2013			
Mowing Height	3	*	3	*
Block	2	ns[a]	2	ns
Year	1	*	1	*
Mowing Height-by-Year	3	*	3	ns
	2012			
Mowing Height	3	*		
Block	2	ns		
	2013			
Mowing Height	3	*		
Block	2	ns		

*Significant at α = 0.05 level

[a] Abbreviation: ns, not significant (α = 0.05)

Table 3.3. Percent doveweed cover in response to various mowing heights, July-August 2012 and 2013 in Clemson, South Carolina.

Year	Mowing height	2 WAP[a]	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP	8 WAP	9 WAP
	cm	% Cover							
2012	Unmowed	30	56	63	76	83	92	93	92
	8	26	51	63	71	74	78	84	86
	4	24	47	50	55	57	64	64	64
	2	27	42	44	46	48	52	52	50
$LSD_{0.05}$		ns	ns	13	20	21	24	23	18
2013	Unmowed	65	76	82	88	89	91	94	93
	8	60	72	83	85	86	87	90	91
	4	64	75	79	84	83	87	88	89
	2	56	68	69	74	75	75	77	79
$LSD_{0.05}$		ns	ns	ns	ns	ns	ns	ns	ns

[a] Abbreviations: WAP, weeks after planting; ns, not significant (α = 0.05)

Table 3.4. Internode length and shoot width of doveweed in response to various mowing heights, July-August 2012 and 2013 in Clemson, South Carolina.

Mowing height	Internode length	Shoot Width
cm	mm	mm
	—— 2012 ——	— 2012 and 2013 —
Unmowed	30	8.39
8	30	8.25
4	20	7.96
2	16	7.80
$LSD_{0.05}$	4	0.38
	—— 2013 ——	
Unmowed	17	
8	15	
4	15	
2	14	
$LSD_{0.05}$	1	

Competition with bermudagrass

During initial analysis of percent doveweed cover per flat, a significant mowing height-by-nitrogen rate-by-year interaction was detected. However, number of established plants in each flat was not consistent between treatment levels or years. To more accurately represent treatment effects, total doveweed coverage area within each flat was divided by the number of doveweed plants within the flat to provide average coverage per doveweed plant within each flat. Total area covered by doveweed within each flat was determined similar to the line intersect method previously described to determine percent coverage; however, each 'hit' was denoted as 1 cm^2 of surface area coverage and counted. Average plant coverage area was then analyzed for main and interaction effects and interaction between treatment levels and years. Significant mowing height and nitrogen rate effects were detected for number of plants per flat and area coverage per plant. Treatment-by-year interaction for area coverage per plant was not detected; therefore, data were pooled between years prior to further analysis (Table 3.5).

Number of established plants decreased as mowing height increased. Flats mown at 1.3 cm averaged ~8 plants $flat^{-1}$ and flats mown at 2.6 cm averaged ~3 plants per flat (Table 3.6). Although light is not a necessary for doveweed germination, high soil temperatures (>27 C) encourage rapid germination (Wilson et al., 2006). Mowing at 1.3 cm may have increased the amount of light penetrating the turf canopy relative to mowing at 2.6 cm, possibly increasing soil temperatures at a more rapid rate, stimulating doveweed germination.

Nitrogen rate did not significantly affect the number of plants established per flat (Table 3.5). Nitrogen rate treatment means ranged between 7 (0 kg N ha^{-1} mo^{-1}) and 3 (49 kg N ha^{-1} mo^{-1}) plants per flat (Table 3.6).

Area coverage of each doveweed plant increased as mowing height increased. In flats mown at 1.3 cm, doveweed averaged 14.6 cm^2 coverage per plant while doveweed averaged 23.6 cm^2 coverage per plant in flats mown at 2.6 cm (Table 3.6). This supports conclusions drawn in the mowing height study that doveweed spread is reduced in response to low mowing. Low-mowing limits the ability of doveweed to compete laterally and vertically for sunlight, water, and nutrient resources with desirable turf. Although more seeds were able to germinate and establish in low mowing height treatments, these plants were unable to establish and spread to the degree of those in taller mowing height treatments.

As nitrogen rate increased from 24.5 kg N ha^{-1} mo^{-1} to 49 kg N ha^{-1} mo^{-1}, surface area coverage per doveweed plant increased ~75% (Table 3.6). However, a difference in area coverage per doveweed plant could not be detected between plants receiving 0 and 24.5 kg N ha^{-1} mo^{-1}. Nitrogen fertilization at a rate higher than desirable turf can efficiently utilize may increase the gross availability of N for other species. Rapid growth of an invasive species may then occur, increasing its competitive ability for other resources such as sunlight. Previous studies have indicated invasive Commelinaceae spp. to have higher average performance than non-invasive congeners in a non-competitive environment (Burns, 2006). A superior ability to capitalize on resources when they are abundant does not necessarily promote the invasion of habitats where resources are limited (Burns, 2006). Fertilization should be adequate to promote turf growth while not providing excessive nutrients for growth of invasive species. Fertilization has mostly reduced the spread of other invasive species in turf by improving the competitiveness of desirable turf. Smooth crabgrass infestations are more severe when there are voids in turf density as often results from limited N application and green kyllinga density is reduced in bermudagrass turf following fertilization (Kim et al., 1997; Lowe et al., 2000).

Based on this study, doveweed invasibility can be reduced by regular mowing at heights < 2.6 cm and avoiding excessive N fertilization. In general, practices that favor establishment of a dense, healthy turf stand without making available excessive resources such as light and nitrogen will discourage doveweed invasion. Future research should focus on the effect of other nutrients on doveweed establishment and spread.

Table 3.5. ANOVA for the effect of mowing, fertilization, and competition with ‘Tifway’ bermudagrass on doveweed infestation, July-August 2012 and 2013 in Clemson, South Carolina.

Source	DF	Number of plants	Spread per plant
		——— 2012 and 2013 combined ———	
Mowing Height	1	*	*
Nitrogen	2	ns[a]	*
Year	1	ns	*
Mowing Height-by-Nitrogen	2	ns	ns
Mowing Height-by-Year	1	ns	ns
Nitrogen-by-Year	2	ns	ns
Nitrogen-by-Mowing Height-by-Year	2	*	ns

*Significant at $\alpha = 0.05$ level

[a] Abbreviation: ns, not significant ($\alpha = 0.05$)

Table 3.6. Number of doveweed plants and spread per plant in response to various mowing heights and nitrogen rates in 'Tifway' bermudagrass, July-August 2011 and 2012 in Clemson, South Carolina.

Mowing Height	Number of Plants	Spread per Plant
cm		cm^2
8	3	15
4	8	24
$LSD_{0.05}$	2	7
Nitrogen Rate		
kg N ha^{-1}		
0	7	14
24.5	5	16
49	5	28
$LSD_{0.05}$	ns[a]	9

[a] Abbreviation: ns, not significant ($\alpha = 0.05$)

Shade tolerance

A RLE level-by-year interaction was not detected for shoot weight or internode length; therefore data within these parameters were pooled between years for further analysis (Table 3.7). Growth in a RLE did not affect shoot growth on a weight basis; however, internode length was 28% longer in a 30% RLE and 39% longer in a 50 and 70% RLE in comparison with plants grown under full irradiance (Table 3.8). Internode elongation is a common RLE avoidance mechanism of plants (Gawronska et al., 1995). This response improves the ability of a plant to capture adequate sunlight for photosynthesis (Burton et al., 1959).

A RLE level-by-year interaction was detected for root weight; therefore, root weight data were analyzed separately by year (Table 3.7). Overall, root weight of plants grown in a RLE was less than plants grown in full irradiance (Table 3.8). In year one, root weight was similar between 30-70% RLE treatments and between 47 and 59% less than plants grown under full irradiance. In year two, all RLE treatments again reduced root growth compared to plants grown in full irradiance; however, 46% less root mass was measured in 70% RLE treatments than 30% RLE treatments (Table 3.8). Root growth was less across all treatments in year two than year one due to less total irradiance during the study period.

A comparison of shoot-to-root ratio suggests excessive shoot elongation in response to a RLE occurs at the cost of root growth. Analysis of shoot-to-root ratio in response to growth in a RLE indicated doveweed increased partitioning of resources to shoot growth when grown in a RLE (Table 3.8). Etiolation of stem and leaf tissue in response to environmental cues such as low light intensity and quality contribute to root carbohydrate depletion as photosynthates must be allocated to support shoot growth in reduced light environments. Light quality and intensity contribute to the limitations of a species to establish in a specific microenvironment as light levels must be adequate for carbohydrate production to exceed consumption. Continued growth in a low light environment will strain carbohydrate resources, and may eventually lead to exhaustion of carbohydrate reserves and plant death.

Physiological responses to an RLE have been observed in other species. Total dry weight, leaf dry weight, leaf area and total number of shoots and rhizomes are reduced in purple nutsedge (*Cyperus rotundus* L.) and yellow nutsedge (*Cyperus esculentus* L.) in a RLE (Patterson, 1981). In chamberbitter (*Phyllanthus urinaria* L.), plant growth was reduced by growth in >26% RLEs. Chamberbitter height was greatest in an 87% RLE, indicating a similar etiolation response to low light conditions (Wehtje et al., 1992).

In shaded areas, doveweed infestations are often observed in thin bermudagrass turf. Competition from a dense turf stand may reduce competitiveness of doveweed in shaded environments. Cultural practices in these areas should focus on promoting a dense turfgrass stand as results from this study suggest competitive fitness of doveweed is reduced when grown in a RLE.

Table 3.7. ANOVA for the effect of RLEs[a] on doveweed growth and development, July-August 2012 and 2013 in Clemson, South Carolina.

Source	DF	Shoot Weight	Root Weight	Shoot:Root Ratio	Internode Length
RLE level	3	ns	*	*	*
Block	2	ns	ns	ns	ns
Year	1	*	*	*	*
RLE level-by-Block	6	ns	ns	ns	ns
RLE level-by-Year	3	ns	*	ns	ns

[a] Abbreviations: RLE, reduced light environment; ns, not significant ($\alpha = 0.05$)

*Significant at $\alpha = 0.05$ level

Table 3.8. Effect of RLEs[a] on doveweed growth and development, July-August 2012 and 2013 in Clemson, South Carolina.

RLE level	Shoot Weight	Root Weight		Shoot:Root Ratio	Internode Length
	——— g ———				— cm —
		2012	2013		
0	1.82	0.59	0.20	5.77	18
30	1.48	0.35	0.13	6.94	23
50	1.65	0.37	0.10	7.55	25
70	1.18	0.24	0.07	9.22	25
$LSD_{0.05}$	ns	0.16	0.04	1.67	2

[a] Abbreviations: RLE, reduced light environment; ns, not significant ($\alpha = 0.05$)

Soil moisture availability

Significant treatment effects were detected for both shoot and root growth in response to soil moisture availability. A soil moisture-by-year interaction was detected for shoot growth; therefore, shoot growth data were separated by year for further mean separations. A similar interaction was not detected for root growth. Therefore, root growth data were combined between years for further analysis (Table 3.9).

Similar numerical trends in shoot production were observed in year one and year two; however, separation between treatments was more clear in year two. In year one, plants maintained at 50, 70, and 100% FC produced significantly more shoot growth on a weight basis (8.73, 10.02, and 6.9 g, respectively) than plants maintained at 25 or 12.5% FC (1.30 and 0.01 g, respectively) (Table 3.10). In 2013, increased water availability again increased shoot growth; however, shoot growth was significantly greater in 75% FC treatments than 100 and 50% FC treatments (5.96, 3.70, and 3.66 g, respectively) (Table 3.10). Extended periods of growth in soils with low aeration porosity may limit the ability of doveweed roots to adequately respire and convert photosynthates into energy for shoot growth. Comparison with an aquatic congener of doveweed such as marsh dewflower (*Murdannia keisak* (Hassk.) Hand.-Maz.) under similar environmental conditions would help to determine if a physiological difference between these species discourages doveweed shoot growth in conditions approaching soil saturation. However, ability to grow across a soil moisture gradient allows doveweed to be invasive in a wide range of soil moisture conditions. Within Commelinaceae, invasiveness of a species is in part determined by plasticity in growth characteristics in response to different environmental conditions. When compared with a non-invasive congener, doveweed produces more shoot biomass across a water gradient than *Murdannia simplex* (Vahl) Brenan (Burns, 2004). In addition, doveweed has a higher relative growth rate across a water gradient than *M. simplex*, indicating a higher potential for invasiveness under a greater diversity of conditions (Burns, 2004).

Treatments maintained at >75% FC produced more root biomass than 50, 25, and 12.5% FC treatments. Although shoot production was greater in 50% FC than 25 and 12.5% FC treatments, maintenance at 50% FC may have not provided enough water for doveweed to maximize its photosynthetic potential, resulting in a reduction in root growth.

Water requirements of a plant are dictated in part by the photosynthetic pathway of the species. Within the Commelinaceae, three separate photosynthetic pathways are documented: C3 – *Murdannia triquetra*, C4 – *Commelina communis,* and CAM – *Tripogandra multiflora* and *Callisia fragrans* (Lin et al., 1986; Martin et al., 1990; Wang, 2006). To date, the photosynthetic pathway of *M. nudiflora* has not been documented. Within the *Murdannia* genus, *M. triquetra* operates using the C_3 photosynthetic pathway. Although this does not necessarily confirm doveweed as a C_3 species, occurrence of C_3 and C_4 species within the same genus is rare. The increased growth of doveweed in response to high soil moisture levels is indicative of a C_3 species. Several *Murdannia spp.* are native to wetland habitats, indicating a likely conservation of C_3 physiology throughout the genus.

Available water is a limiting environmental parameter for the geographical distribution of a plant species. In managed turf, frequent irrigation is often necessary to supply water to turf plants with shallow root systems to prevent wilt. Frequent irrigation can locally increase the soil moisture of area, encouraging invasion of weed species otherwise not adapted to that environment. Turfgrass managers should irrigate deeply and infrequently to prevent soil moisture from remaining consistently high in the top 3 cm of soil thus discouraging doveweed germination and growth. Drought tolerant species such as bermudagrass will have a competitive advantage over doveweed under these conditions.

Table 3.9. ANOVA for the effect of various levels of soil moisture on doveweed growth and development, July-August 2012 and 2013 in Clemson, South Carolina.

Source	DF	Shoot Weight	Root Weight
Soil Moisture	4	*	*
Year	1	*	*
Soil Moisture-by-Year	4	*	ns[a]

*Significant at $\alpha = 0.05$ level

[a] Abbreviation: ns, not significant ($\alpha = 0.05$)

Table 3.10. Effect of soil moisture on doveweed growth and development, 2012 and 2013 in Clemson, South Carolina.

Soil Moisture Level	Shoot Weight		Root Weight
	2012	2013	
% Field Capacity	——— g ———		— g —
12.5	0.01	0.63	0.02
25	1.30	1.69	0.11
50	8.73	3.67	0.43
75	10.02	5.96	0.83
100	6.9	3.79	0.96
$LSD_{0.05}$	4.47	1.52	0.18

Conclusion

Doveweed is a problematic species in managed turfgrass in part because of its adaptability to a wide range of environmental conditions. This research demonstrates the ability of doveweed to grow in various levels of soil moisture and light availability, tolerate various mowing heights, and compete with other species for available nutrient resources. Doveweed control in turfgrass with cultural practices alone should not be expected; however, cultural practices can be manipulated to slow infestations. The reproductive capacity of doveweed and high germinability of its seeds increases the importance of manipulating cultural practices to favor turfgrass growth before doveweed infestations become severe.

Turf managers should limit practices that provide resources in excess of those needed for vigorous turfgrass growth. Irrigation should be applied deeply and infrequently to minimize moisture availability in the top 3 cm of soil to discourage doveweed germination and establishment. Fertilization should be applied as needed to promote turf growth and recovery from mowing, but not in excess to increase gross nutrient resources that stimulate rapid doveweed growth. Mowing alone does not control doveweed; however, low mowing will lessen spread of established plants. Implemented together, these cultural practices will limit doveweed colonization of new areas and reduce the severity of colonization in already infested areas.

Future research should evaluate the effect of other nutrients on doveweed growth and development and determine the effect of cultural practices on doveweed fecundity. A further understanding of cultural practices effects on doveweed growth and development throughout its entire life cycle will aid turf managers in formulating a holistic doveweed management plan.

CHAPTER FOUR

PRE- AND POSTEMERGENCE DOVEWEED CONTROL

Introduction

Doveweed's light green color and course texture disrupts turfgrass quality by contrasting with the color and texture of desirable turfgrass. When conditions are favorable, doveweed plants form dense, pure stands that smother competing species. Its decumbent growth habit competes both laterally and vertically for soil and light resources (Holm et al., 1977). A single plant can produce ~2700 seeds per year and stems readily root upon contact of a node with moist soil, and will do so especially when stems are broken or cut (Table 2.2) (Holm et al., 1977). The ability of doveweed to rapidly reproduce both sexually and vegetatively increases the importance of identifying effective herbicide control options. If infestations are left unchecked, doveweed plants outcompete desirable turf for available resources and leave voids in turf cover after completion of its lifecycle. Currently, research has not identified preemergence (PRE) or postemergence (POST) doveweed control options in managed turfgrass.

Based on field observation, full season PRE control is not consistently achieved by applications timed to target common summer annual grassy weeds such as crabgrass (*Digitaria spp.*) and goosegrass (*Eleusine indica* (L.) Gaertn.). End-user reports of POST control are inconsistent and control appears short-lived. In addition, inconsistent control with non-selective herbicides such as glyphosate is common. Poor control with non-selective POST herbicides is documented in other Commenliaceae species. Asiatic dayflower (*Commelina communis* L.) and Benghal dayflower (*Commelina benghalensis* L.) are not effectively controlled by glyphosate (Culpepper et al. 2004; Webster and Sosnoskie 2010). The Weed Science Society of America defines herbicide tolerance as "*the inherent ability of a species to survive and reproduce after herbicide treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant"* (Anonymous 1998). Glyphosate uptake by Benghal dayflower is impeded by a hydrocarbon rich cuticle layer that prevents diffusion of hydrophilic compounds (Monquero et al. 2004a; Monquero et al. 2004b). Being a closely related species to Benghal dayflower, investigating the effect of doveweed's cuticle layer on herbicide uptake is warranted.

Objectives of the following studies were: (1) identify selective PRE and POST doveweed control options in 'Tifway' hybrid bermudagrass (*Cynodon dactylon* [L.] Pers. × *C. transvaalensis* Burtt-Davy) turf; (2) evaluate the duration of doveweed control with various PRE application timings; (3) compare efficacy of single vs. sequential applications of PRE and POST herbicides; (4) to quantify doveweed tolerance to glyphosate; and (5) quantify glyphosate uptake in treated doveweed.

Materials and Methods

General Herbicide Control Study Protocol

Studies were conducted on a mature stand of 'Tifway' hybrid bermudagrass established in a Vaucluse loamy sand (fine-loamy, kaolinitic, thermic Fragic Kanhapludults) with a soil pH of 6.1 and 1.4% organic matter in Augusta, GA

(33°29’2.91” N, 82°0’38.22” W). Individual studies were repeated on separate plots in sequential years. Routine PRE herbicide application was not made to the study areas within 1 year of study initiation. Doveweed density within the study areas was up to 85%.

Liquid treatments were applied with a CO_2-pressurized boom sprayer calibrated to deliver 187 L ha^{-1} (20 GPA) through 8003 flat fan nozzles (Tee Jet, Spraying Systems Co.; Roswell, GA). Granular treatments were hand applied by weighing out appropriate material for each plot then distributing evenly in four directions with a shaker jar. Treatments requiring irrigation received 0.66 cm (0.25 inch) within 24 h of application and plots were irrigated thereafter as needed to prevent wilt. Plots measured 1.5 × 2 m and mown 2x wk^{-1} at 5 cm with clippings returned. Fertility was applied based on soil test recommendations and was consistent across the experimental area.

Ratings included doveweed density using a 0 to 100% scale (0 = no control, 100 = complete control) and bermudagrass turf injury using a 0 to 100% scale (0 = no injury, 100 = complete plant death). Percent doveweed control was calculated in PRE studies as reduction in density relative to the untreated within each rep:

$$\frac{\text{Untreated Plot Density} - \text{Treated Plot Density}}{\text{Untreated Plot Density}} \times 100$$

POST doveweed control was calculated as the percent control relative to initial doveweed density within each plot prior to treatment:

$$\frac{\text{Initial Plot Density} - \text{Treated Plot Density}}{\text{Initial Plot Density}} \times 100$$

Experimental design for all studies was a randomized complete block with three replications. Treatments were arranged in a two factor design with various herbicides and experimental year as treatment levels. Percent doveweed control and bermudagrass turfgrass injury data were visually inspected by plotting residuals for homogeneity and normality of variance prior to analysis. Data were then subjected to ANOVA for evaluation of main effects and interaction between main effects and experimental year. When main effect-by-year interactions were not detected, data were combined for analysis and presented over years. Where appropriate, further mean comparisons between treatments were performed using Fisher's protected LSD. All analyses were conducted using JMP Pro version 10 (SAS institute Inc., Cary, NC) and differences were based on $\alpha = 0.05$.

Preemergence Control

Two separate studies were conducted from March to September 2009-2010 and from March to September 2012-2013 to identify PRE doveweed control options with herbicides commonly used in bermudagrass turf, compare efficacy of single vs. sequential application for duration of doveweed control, and quantify the duration of doveweed control with various PRE indaziflam application timings in the Augusta, GA region. In study one PRE treatments were applied on March 12 and 16 in 2009 and 2010, respectively. Application date was selected to represent traditional preemergence herbicide application timing targeting common grassy weeds such as crabgrass and goosegrass in the Augusta, GA region. For study two, initial treatments were applied on March 18 and 13 in 2012 and 2013, respectively (PRE A), April 18 in 2012 and 2013 (PRE B) or May 1, 2012 and 2013 (PRE C). Indaziflam at 0.054 kg ai ha^{-1} was applied in mid-March and April due to its long soil half-life (>150 d) (Anonymous, 2010). Other preemergence herbicides were included in the PRE C application timing to evaluate their efficacy for season-long doveweed control when applied at this timing. When sequential applications were made, treatments were applied 6 weeks after initial treatment (WAIT) following dimethenamid-p and 12 WAIT following indaziflam. Herbicide treatments and rates are listed in Table 4.1. Environmental conditions for each application date are presented in Table 4.2. Visual doveweed density ratings were recorded 16 weeks after treatment (WAT) in study 1 and 6, 12, and 18 weeks after PRE C application in study two.

Table 4.1. PRE[a] herbicide treatment list for doveweed control in Augusta, GA, 2009-2010 and 2012-2013.

Common Name	Sample Trade Name	Rate
		----kg ai ha^{-1}---
Study 1 PRE[b]		
Dimethenamid-p	Tower	1.68
Isoxaben	Gallery	1.12
Prodiamine	Barricade	1.12
S-metolachlor	Pennant Magnum	4.27
Oxadiazon (G)	Ronstar G	3.36
Simazine	Princep	2.24
Indaziflam	Specticle	0.054
Study 2 PRE A[c]		
Indaziflam	Specticle	0.054
Study 2 PRE B		
Indaziflam	Specticle	0.054
Study 2 PRE C		
Indaziflam	Specticle	0.054
Indaziflam	Specticle	0.033
Dimethenamid-p	Tower	1.68
Oxadiazon (G)	Ronstar	3.36
Dimethenamid-p fb Dimethenamid-p 6 WAIT	Tower fb Tower	1.68 fb 1.68
Indaziflam fb Indaziflam 12 WAIT	Specticle fb Specticle	0.016 fb 0.033
Indaziflam fb Dimethenamid-p 12 WAIT	Specticle fb Specticle	0.054 fb 1.68

[a] Abbreviations: PRE, preemergence; WAIT, weeks after initial treatment; fb, followed by.

[b] Study 1 PRE treatments were March 12 and March 16 in 2009 and 2010, respectively.

[c] Study 2 PRE A treatments were March 18 in 2012 and March 14 in 2013; PRE B applications were April 18 in 2012 and 2013; PRE C applications were May 1 in 2012 and 2013.

Table 4.2. Environmental conditions for PRE[a] herbicide applications for control of doveweed in Augusta, GA during 2009-2010 and 2012-2013.

	Year							
	2009				2010			
Application timing	Application date	Air temp.[b]	Soil temp.[c]	Relative humidity	Application date	Air temp.	Soil temp.	Relative humidity
		C	C	%		C	C	%
PRE	March 12	18	21	33	March 16	15	9	50
	2012				2013			
PRE A	March 18	24	21	63	March 14	14	9	35
PRE B	April 18	18	24	50	April 18	27	22	35
PRE C	May 1	26	24	66	May 2	25	21	70
6 WA PRE C	June 14	24	26	78	6 WA PRE C	28	27	82
12 WA PRE C	July 26	29	29	50	12 WA PRE C	27	28	70

[a] Abbreviations: PRE, preemergence; WA, weeks after.
[b] Air temperature and relative humidity measured using a hand-held weather meter (Kestrel 3000, Kestrel Meters; Birmingham, MI) immediately after herbicide application
[c] Soil temperature measured at 2.54-cm depth using a hand-held analog soil thermometer immediately after herbicide application.

Postemergence Control

Studies were conducted between June and September 2009-2010 and June and September 2012-2013 to identify possible POST doveweed control options in ‘Tifway’ bermudagrass turf and to compare single vs. sequential applications.

Initial POST applications were made when the majority of plants reached the 5-8 leaf stage. POST treatments in the first study were July 2, 2009 and July 14, 2010. In study two, initial treatments were June 28, 2012 and July 18, 2013. Sequential applications were made in the second study 3 weeks after initial treatment (WAIT). Herbicide treatments and rates are listed in Table 4.3. Atmospheric and soil environmental conditions for each application timing are presented in Table 4.4. Visual ratings were recorded 2, 4, and 6 WAT in study 1 and 2, 6, and 10 WAIT in study 2.

Table 4.3. POST[a] herbicide treatment list for doveweed control in Augusta, GA, 2009-2010 and 2012-2013.

Common Name	Sample Trade Name	Rate
		kg ai ha^{-1}
Study 1 POST[b]		
Dicamba	Banvel	0.056
Bromoxynil	Buctril	0.056
Foramsulfuron	Revolver	0.043
MSMA	MSMA	0.022
Sulfentrazone + 2,4-D + MCPP + Dicamba	Surge	0.099
2,4-D + MCPP + Dicamba + Carfentrazone	Speedzone	0.123
Quinclorac + MCPP + Dicamba	Onetime	0.137
Study 2 POST[c]		
Sulfentrazone + Metsulfuron	Blindside	0.300
Thiencarbazone + Iodosulfuron + Dicamba	Celsius	0.176
2,4-D + MCPP + Dicamba + Carfentrazone	Speedzone	0.123
Thiencarbazone + Foramsulfuron + Halosulfuron	Tribute Total	0.136
Sulfentrazone + Metsulfuron - twice	Blindside fb Blindside	0.278 fb 0.185
Thiencarbazone + Iodosulfuron + Dicamba - twice	Celsius fb Celsius	0.176 fb 0.176
2,4-D + MCPP + Dicamba + Carfentrazone - twice	Speedzone fb Speedzone	0.123 fb 0.123
Thiencarbazone + Foramsulfuron + Halosulfuron - twice	Tribute total fb Tribute total	0.136 fb 0.136

[a] Abbreviations: POST, postemergence; fb, followed by.

[b] Study 1 POST treatments were July 7 and July 14 in 2009 and 2010, respectively.

[c] Study 2 Initial POST treatments were June 28 and July 18 in 2012 and 2013, respectively. Sequential POST treatments were July 19 and August 1 in 2012 and 2013, respectively.

Table 4.4. Environmental conditions for POST[a] herbicide applications for doveweed control in Augusta, GA, 2009-2010 and 2012-2013.

	Year							
	2009				2010			
Application timing	Application date	Air temp.[b]	Soil temp.[c]	Relative humidity	Application date	Air temp.	Soil temp.	Relative humidity
		C	C	%		C	C	%
POST	July 7	28	27	72	July 14	33	27	65
	2012				2013			
POST INT	June 28	31	27	41	July 18	28	28	82
3 WAIT	July 19	29	29	50	August 1	27	27	70

[a] Abbreviations: POST, postemergence; INT, intial treatment; WAIT; weeks after initial treatment.
[b] Air temperature and relative humidity measured using a hand-held weather meter (Kestrel 3000; Kestrel Meters, Birmingham, MI) immediately after herbicide application.
[c] Soil temperature measured at 2.54 cm depth using a hand-held analog soil thermometer immediately after herbicide application.

Dose Response of Doveweed to Glyphosate

Doveweed plants were prepared by first germinating seed in petri dishes containing 2 sheets of Whatman no. 2 filter paper and 5 ml of distilled water. Germinated doveweed seeds were then transplanted to 9 cm diameter × 9 cm deep pots filled with washed river sand. Plants were then placed in a growth chamber set to maintain a constant temperature of 27 C with a 12 h photoperiod providing 300 μmol m^2 sec^{-1} with fluorescent and incandescent bulbs. During this period, plants were fertilized by sub-irrigating with a hydroponic growth solution (Grow-Big Hydroponic Plant Food, FoxFarm Soil and Fertilizer Company, Arcata, California) at 1.3 ml L^{-1} (5 ml gal^{-1}) every 10 d. Plants remained in the growth solution for 24 h, then removed and allowed to drain. Between fertilizations, plants were surface irrigated to field capacity every 2 d. Doveweed plants were allowed to develop to the five- to eight-leaf stage at which point they were treated with glyphosate (Roundup ProMax, Monsanto, St. Louis, MO) at eight separate rates between 0 to 5.68 kg ae ha^{-1}. Treatments were delivered in 374 L ha^{-1} water with an air-pressurized spray chamber using a single 8003 flat-fan nozzle (TeeJet Technologies; Wheaton, IL) operating at 200 kPa. Injury ratings were expressed as percent dry weight of an untreated control 21 days after treatment (DAT) (Seefeldt et al., 1995). Data were analyzed using the nonlinear regression equation $y = C + (D - C)/(1 + 10^{x - logI_{50}})$ where *y* was shoot biomass, *x* was herbicide rate (kg ae ha^{-1}), *D* was the upper bound of *y*, *C* was the lower bound of *y*, and I_{50} was the rate of herbicide that reduced shoot biomass 50%. Treatment design was a single factor design with herbicide rates as factor levels. Treatments were completely randomized and replicated three times. The experiment was repeated in time.

Absorption of [^{14}C]-Glyphosate

Absorption of [^{14}C]-glyphosate was compared between doveweed plants with cuticle intact, doveweed plants with a disturbed cuticle, and smooth crabgrass (*Digitaria ischaemum* [Schreb.] Schreb. Ex Muhl.) plants. Doveweed plants were prepared by first germinating seed in petri dishes containing 2 sheets of Whatman no. 2 filter paper and 5 ml of distilled water. Germinated doveweed seeds and field-collected smooth crabgrass plants in the two-leaf stage were then transplanted to 9 cm diameter × 9 cm deep pots filled with washed river sand. Plants were then placed in a growth chamber set to maintain a constant temperature of 27 C with a 12 h photoperiod providing 300 µmol m^{2} sec^{-1} with fluorescent and incandescent bulbs. During this period, plants were fertilized by sub-irrigating with a hydroponic growth solution (Grow-Big Hydroponic Plant Food; FoxFarm Soil and Fertilizer Company, Arcata, California) at 1.3 ml L^{-1} (5 ml gal^{-1}) every 10 d. Plants remained in the growth solution for 24 h, then removed and allowed to drain. Between fertilizations, plants were surface irrigated to field capacity every 2 d. Once plants reached the 5-8 leaf stage, they were removed and roots washed free of potting media. Plants were then transplanted into 50 mL test tubes filled with the hydroponic solution used to subirrigate plants. Test tubes were wrapped with aluminum foil to protect against light intrusion into the growth solution.

$[^{14}C]$-glyphosate (phosphonomethyl-^{14}C; American Radiolabeled Chemicals, Inc., Saint Louis, MO) was dissolved in a commercial glyphosate formulation (Roundup ProMax; Monsanto, St. Louis, MO) and diluted with distilled water to simulate a spray solution prepared to deliver 0.87 kg ai ha^{-1} (0.71 kg ae ha^{-1}) in 374 L ha^{-1} of water with 0.20 KBq ml^{-1} $[^{14}C]$-glyphosate with no extra surfactant added. Plants were pretreated prior to application of $[^{14}C]$-glyphosate by spraying 0.71 kg ae ha^{-1} glyphosate onto foliage as described in the dose response study. Prior to pretreatment, the youngest fully expanded leaf proximal to the apical meristem on each plant was designated as the $[^{14}C]$-glyphosate treatment leaf and covered with aluminum foil to prevent glyphosate pre-treatment exposure. After pretreatment, the treatment leaf on doveweed plants designated for cuticle disruption were wiped 5 times in the acropetal direction on the adaxial side of the leaf with a 100% acetone. A micropipette was then used to deliver five 2-µl droplets of $[^{14}C]$-glyphosate solution to the treatment leaf to total 2 KBq per treatment leaf. Droplets were applied along the midrib of the adaxial leaf surface of each treatment leaf. The treated leaf of three randomly selected plants from each subset of plants was harvested at 24, 72, and 144 h after $[C^{14}]$-glyphosate treatment (HAT). At each harvest, the treated leaf was washed with 7 ml of a methanol-water solution (1:10, v/v) in a 15 ml centrifuge tube by shaking for 30 sec to remove unabsorbed $[^{14}C]$-glyphosate. A 1-ml subsample of the rinsate was mixed with 15 ml of Optiphase HiSafe 3 (PerkinElmer, Waltham, MA) scintillation cocktail, and radioactivity was quantified through scintillation spectrometry (TriCarb Liquid Scintillation Analyzer; Perkin Elmer, Waltham, MA). Radioactivity detected in the leaf wash was expressed as the percent relative to the amount applied.

Treatment arrangement was a 3 × 3 factorial design with plants (doveweed with cuticle intact, doveweed with cuticle disturbed, and smooth crabgrass) and harvest interval (24, 72, and 144 h) serving as factors. The experiment included three single plant replicates for each of the three plant treatments and harvest intervals. Experimental design was a completely randomized design. The experiment was repeated. Data were subjected to ANOVA for evaluation of main effects, interaction between main effects, and interaction between main effects and experimental run. Where appropriate, further mean comparisons were performed using Fisher's protected LSD. All comparisons were based on an $\alpha = 0.05$ significance level. Analyses were conducted using JMP Pro 10 (SAS Institute Inc.; Cary, NC).

Results and Discussion

Preemergence Control

Herbicide treatment-by-year interaction was not detected for doveweed control in either study; therefore, data were combined between years within studies for further analysis. Turfgrass injury was not observed at any rating date; therefore, data is not presented (Table 4.5).

In study 1, doveweed was not effectively controlled by any treatment 16 WAT (Table 4.6). PRE herbicides are traditionally applied between late February and mid-March in the Southeastern United States to target summer annual weeds such as crabgrass and goosegrass (McCarty, 2011). Soil temperature requirements for seed germination range between 15 and 35 C for crabgrass (King and Oliver, 1994) and between 20 and 35 C for goosegrass (Chauhan and Johnson, 2008a; Nishimoto and McCarty, 1997). Doveweed readily germinates when soil temperatures are between 25 and 30 C and germination sharply declines when soil temperatures fall below this range (Wilson et al., 2006). In the Southeastern United States, doveweed germination begins after crabgrass and goosegrass as a result of higher soil temperature requirements. Doveweed then continues to germinate throughout the remainder of summer months (i.e. June - August), creating a continuous doveweed germination pattern during this period. In this study, the time elapsed between mid-March herbicide application and doveweed germination was likely too long to provide PRE control throughout the peak doveweed germination season.

In previous research, *S*-metolachlor provided >80% Benghal dayflower control 6 WAT (Webster et al., 2006). PRE application was made closer to the peak Benghal dayflower seed germination period in comparison with PRE application timing in this study relative to peak doveweed germination. Since little doveweed control was achieved by mid-March applications, subsequent studies focused on refining herbicide timing to maximize PRE doveweed control.

In study two, significant treatment effects were detected on all rating dates (Table 4.5). Twelve weeks after PRE A, 8 weeks after PRE B, and 6 weeks after PRE C, all treatments provided >75% control (Table 4.7). Less control was observed across all treatments eighteen weeks after PRE A, 14 weeks after PRE B, and 12 weeks after PRE C (Table 4.7). Control from PRE C applied dimethenamid-p at 1.68 kg ai ha^{-1} decreased 45% and oxadiazon at 3.36 kg ai ha^{-1} decreased 33% compared to control 6 weeks after PRE C application. A sequential application of dimethenamid-p at 1.68 kg ai ha^{-1} 6 weeks after PRE C improved control by 20% compared to treatments receiving a single dimethenamid-p PRE C application. Control in single application treatments of indaziflam applied PRE A, B, or C at 0.054 kg ai ha^{-1} decreased 9 to 16% (Table 4.7).

Control continued to decline across all treatments 24 weeks after PRE A, 20 weeks after PRE B, and 18 weeks after PRE C application. PRE C applied indaziflam at 0.016 kg ai ha^{-1} fb indaziflam at 0.033 kg ai ha^{-1} 12 WAIT, and indaziflam at 0.054 kg ai ha^{-1} fb dimethenamid-p at 1.68 kg ai ha^{-1} 12 WAIT controlled doveweed >80%. All remaining treatments controlled doveweed <80%. Oxadiazon applied PRE C at 3.36 kg ai ha^{-1} controlled doveweed similar to the untreated 18 WAT. Comparison of control between PRE A, B, and C applied indaziflam at 0.054 kg ai ha^{-1} showed no statistical difference at this rating date with doveweed control between 56 and 70% (Table 4.7).

Preemergence herbicides often control numerous grassy and broadleaf weeds, but only for a period of time. Oxadiazon and pendimethalin applied at 3.4 kg ai ha^{-1} controlled smooth crabgrass >90% 10-12 weeks after treatment when applied in mid-February in Tennessee and Georgia, after which point control declined (Brosnan et al., 2011). Similarly, oxadiazon and pendimethalin applied at 3.4 kg ai ha^{-1} in early March in Guam controlled goosegrass ≥90% 10-12 wk after application, after which point control lessened (Wiecko, 2000a). Similar to these studies, PRE doveweed control can be achieved for a finite period of time after which point control is lessened. A single application of oxadiazon at 3.36 kg ai ha^{-1}, or dimethenamid-p at 1.68 kg ai ha^{-1} controlled doveweed ~6 weeks and indaziflam applied at 0.054 kg ai ha^{-1} controlled doveweed ~12 weeks when applied on May 1 in Augusta, GA (Table 4.7). While complete control was not achieved by any treatment in these studies, sequential PRE application extends PRE doveweed control compared to single applications alone. Application date did not have a significant effect on the duration of doveweed control across all experiments; however, in two of four study years, poor doveweed control was achieved by indaziflam applied in March.

Table 4.5. ANOVA for PRE[a] doveweed control for two studies in 'Tifway' bermudagrass in Augusta, GA, March-September 2009-2010 and 2012-2013.

Study 1	Doveweed Control	
Source	DF	16 WAIT
Treatment	7	ns
Block	2	ns
Year	1	ns
Treatment × Block	14	ns
Treatment × Year	7	ns
Error	16	

Study 2						
Source	DF	6 WAIT	DF	12 WAIT	DF	18 WAIT
Treatment	6	*	7	*	9	*
Block	2	ns	2	ns	2	ns
Year	1	*	1	*	1	*
Treatment × Block	12	ns	14	ns	18	ns
Treatment × Year	6	ns	7	ns	9	ns
Error	14		16		19	

[a] Abbreviation: PRE, preemergence; WAIT, weeks after initial treatment; ns, not significant ($\alpha = 0.05$).

*Significant at $\alpha = 0.05$ level.

Table 4.6. Doveweed control with select PRE[a] herbicides in 'Tifway' bermudagrass. Augusta, GA, March-September 2009-2010.

Treatment	Rate	Doveweed Control 16 WAT
	kg ai ha^{-1}	— % —
Dimethenamid-p[b]	1.68	8
Isoxaben	1.12	22
Prodiamine	1.12	25
S-metolachlor	4.27	19
Oxadiazon	3.36	28
Simazine	2.24	13
Indaziflam	0.054	24
Untreated	--	0
$LSD_{0.05}$		ns

[a] Abbreviations: PRE, preemergence; WAT, weeks after treatment; ns, not significant (α = 0.05).
[b] Applications were made March 12 in 2009 and March 16 in 2010.

Table 4.7. Doveweed control with select PRE[a] herbicides applied as single or sequential applications on various dates in ‘Tifway’ bermudagrass, Augusta, GA, March-September 2012-2013.

			Doveweed Control		
Timing	Treatment	Rate	12 WA[a] PRE A 8 WA PRE B 6 WA PRE C	18 WA PRE A 14 WA PRE B 12 WA PRE C	24 WA PRE A 20 WA PRE B 18 WA PRE C
		kg ai ha^{-1}		%	
PRE A[b]	Indaziflam	0.054	90	68	69
PRE B	Indaziflam	0.054	76	67	56
PRE C	Indaziflam	0.054	96	79	70
PRE C	Indaziflam	0.033	96	67	49
PRE C	Dimethenamid-p	1.68	83	38	28
PRE C	Oxadiazon	3.36	100	61	45
PRE C fb 6 WAIT	Dimethenamid-p fb Dimethenamid-p	1.68 fb 1.68	–	58	45
PRE C fb 12 WAIT	Indaziflam fb Indaziflam	0.016 fb 0.033	–	–	83
PRE C fb 12 WAIT	Indaziflam fb Dimethenamid-p	0.054 fb 1.68	–	–	80
	Untreated control	–	0	0	0
LSD $_{0.05}$			19	39	26

[a] Abbreviations: PRE, preemergence; WA, weeks after; fb, followed by; WAIT, weeks after initial treatment.
[b] PRE A applications were March 18 in 2012 and March 14 in 2013; PRE B applications were April 18 in 2012 and 2013; PRE C applications were May 1 in 2012 and May 2 in 2013.

Postemergence Control

Treatment-by-year interaction was not detected for percent doveweed control in study one at any rating date; therefore data were combined between years prior to further analysis (Table 4.8). In study two, treatment-by-year interaction was not detected for percent doveweed control 2 or 6 WAIT; however, treatment-by-year interaction was detected for percent doveweed control 10 WAIT. Therefore; two and six WAIT data were pooled prior to further analysis and 10 WAIT control data were separated and analyzed by year. Turfgrass injury was not significant following treatment application in either study (Table 4.8).

In study 1, significant treatment effects for POST doveweed control were detected 2 and 4 WAT although control was <60% across all treatments and rating dates (Table 4.9). MSMA controlled doveweed 54% 2 WAT, statistically superior to dicamba, bromoxynil, and foramsulfuron. All combination treatments controlled doveweed similar to MSMA 2 WAT with control ranging between 34 and 47% (Table 4.9). Four weeks after treatment, sulfentrazone + 2,4-D + MCPP + dicamba and 2,4-D + MCPP + dicamba + carfentrazone controlled doveweed 35 to 45%, significantly greater than dicamba or bromoxynil alone (Table 4.9). Further differences between treatments were not detected 6 WAT.

In study 2, all POST treatments controlled doveweed similarly (60 to 80%) 2 WAIT. Six WAIT, sulfentrazone + metsulfuron controlled doveweed 53%, significantly greater than other single application treatments (17 to 22%, Table 4.10) A sequential application of thiencarbazone + iodosulfuron + dicamba, or 2,4-D + MCPP + dicamba +

carfentrazone, and thiencarbazone + foramsulfuron + halosulfuron 3 WAIT improved control 6 WAIT from ~20% in single application treatments to between 60 and 81% (Table 4.10). Control 10 WAIT was inconsistent between years. In 2012, only sequential application of 2,4-D + MCPP + dicamba + carfentrazone controlled doveweed >90% 10 WAIT (Table 4.10). In 2013, sequential application of thiencarbazone + foramsulfuron + halosulfuron controlled doveweed 90%, while control in other treatments ranged between 40 and 50% (Table 4.10).

Differences in control 10 WAIT between 2012 and 2013 may be explained by differing weather patterns between years during the study period. Total rainfall between the initial and sequential application during the 2012 study period summed to 29.2 cm while it was 3.3 cm in 2013. Germination of doveweed seeds, and thus less control late in the growing season was likely encouraged by higher soil moisture in 2012 during the period between treatments. Overall pressure from seed germination was likely less late in the 2013 as a reflection of lower rainfall during this period.

Glyphosate controlled Benghal dayflower ~70% when applied at 0.84 kg ai ha^{-1} 3 WAT (Culpepper et al., 2004). Tank mixture of glyphosate with MSMA at 2.24 kg ai ha^{-1} or carfentrazone at 0.018 kg ai ha^{-1} improved control to ~79%. Similar to this study, 100% doveweed control was not achieved by any treatment. Sequential POST applications improved control of other species compared to single applications. Sequential application of MSMA + metribuzin at 2.2 + 1.4 kg ha^{-1} increased goosegrass control to ≥90% 14 WAIT from ≤75% control in treatments only receiving a single application (Wiecko, 2000). Purple (*Cyperus rotundus* L.) and yellow nutsedge (*Cyperus* *esculentus* L.) control 15 WAIT was improved with sequential application of sulfentrazone at 0.281 fb 0.281 kg ai ha^{-1} or halosulfuron at 0.070 fb 0.070 kg ai ha^{-1} 15 WAIT (Blum et al., 2000).

Due to doveweed's continuous germination pattern throughout the growing season, long-term control is often not achieved with a single POST application. Turf managers are recommended to apply POST herbicides sequentially on a 14-to-28 d interval to maximize POST doveweed control.

Table 4.8. ANOVA for POST[a] doveweed control in 'Tifway' bermudagrass in Augusta, GA, July-August, 2009-2010 and 2012-2013.

Study 1		——— Doveweed Control ———			Turfgrass Injury
Source	DF	2 WAT	4 WAT	6 WAT	2 WAT
Treatment	7	*	*	ns	ns
Block	2	ns	ns	ns	*
Year	1	*	*	*	*
Treatment × Block	14	ns	ns	ns	ns
Treatment × Year	7	ns	ns	ns	ns
Error	16				

Study 2		——— Doveweed Control ———			−Turfgrass Injury−	
Source	DF	2 WAIT	6 WAIT	10 WAIT	2 WAIT	6 WAIT
Treatment	8	*	*	*	ns	ns
Block	2	ns	ns	ns	ns	ns
Year	1	ns	*	*	ns	ns
Treatment × Block	16	ns	ns	ns	ns	ns
Treatment × Year	8	ns	ns	*	ns	ns
Error	18					

[a] Abbreviations: POST, postemergence WAT, weeks after treatment; WAIT, weeks after initial treatment; ns, not significant ($\alpha = 0.05$).

*Significant at $\alpha = 0.05$ level.

Table 4.9. Doveweed control with select POST[a] herbicides in 'Tifway' bermudagrass in Augusta, GA, March - September 2009-2010.

Treatment	Rate	Doveweed Control		
		2 WAT	4 WAT	6 WAT
	kg ai ha^{-1}	%		
Dicamba	0.560	13	5	0
Bromoxynil	0.560	4	5	0
Foramsulfuron	0.043	19	23	0
MSMA	0.224	54	29	11
Sulfentrazone + 2,4-D + MCPP + Dicamba	0.990	37	45	24
2,4-D + MCPP + Dicamba + Carfentrazone	0.123	48	39	14
Quinclorac + MCPP + Dicamba	0.137	34	27	8
Untreated		0	0	0
$LSD_{0.05}$		32	28	ns

[a] Abbreviations: POST, postemergence; WAT, weeks after treatment; fb, followed by; ns, not significant ($\alpha = 0.05$).

[b] Applications were March 12 in 2009 and March 16 in 2010.

Table 4.10. Doveweed control with select POST[a] herbicides in ‘Tifway’ bermudagrass. Augusta, GA, March - September 2009-2010.

		Doveweed Control			
		——— % ———			
Treatment	Rate	2 WAIT	6 WAIT	10 WAIT	
	kg ai ha^{-1}			2012	2013
Sulfentrazone + Metsulfuron	0.30	79	53	0	44
Thiencarbazone + Iodosulfuron + Dicamba	0.176	62	17	0	0
2,4-D + MCPP + Dicamba + Carfentrazone	0.123	61	22	0	17
Thiencarbazone + Foramsulfuron + Halosulfuron	0.136	70	22	0	0
Sulfentrazone + Metsulfuron - Twice	0.278 fb 0.185	-	60	0	48
Thiencarbazone + Iodosulfuron + Dicamba - Twice	0.176 fb 0.176	-	62	15	40
2,4-D + MCPP + Dicamba + Carfentrazone - Twice	0.123 fb 0.123	-	78	92	50
Thiencarbazone + Foramsulfuron + Halosulfuron - Twice	0.136 fb 0.136	-	81	25	90
Untreated		0	0	0	0
$LSD_{0.05}$		18	27	27	21

[a] Abbreviations: POST, postemergence; WAIT, weeks after initial treatment; fb, followed by.
[b] Initial applications were June 28, 2012 and July 18, 2013. Sequential applications were July 19, 2012 and August 1, 2013.

Dose Response of Doveweed to Glyphosate

Treatment-by-run interaction was not detected in dose response data; therefore data were pooled between runs prior to further analysis. Complete reduction in shoot biomass (% of the untreated) was not observed for any of the glyphosate rates tested (0 – 5.68 kg ae ha^{-1}) (Figure 4.1). The calculated I_{50} value was 0.63 kg ae ha^{-1}; however, shoot biomass was only reduced 76% at the highest rate evaluated (5.68 kg ae ha^{-1}) (Figure 4.1). The highest recommended application rate for difficult to control weeds is 1.69 kg ae ha^{-1} (Anonymous, 2009). According to these data, application at 3x the highest recommended rate will not completely reduce doveweed aboveground biomass 21 DAT, confirming the tolerance of doveweed to glyphosate. Tolerance to glyphosate has been documented in related species. Asiatic dayflower (*Commelina communis* L.) was only controlled by glyphosate applied at 13.76 kg ae ha^{-1} (Ulloa and Owen, 2009). Differences were not observed between aboveground biomass in the untreated and Asiatic dayflower plants treated with 0.84 kg ae ha^{-1}, the recommended application rate for glyphosate, confirming Asiatic dayflower tolerance to glyphosate (Anonymous, 2009; Ulloa and Owen, 2009). In a field study involving Benghal dayflower (*Commelina benghalensis* L.) glyphosate applied at 0.84 kg ai ha^{-1} provided 57% Benghal dayflower control 21 DAT. Smaller plants (<6 cm) were completely controlled, while larger plants were not (Culpepper et al., 2004).

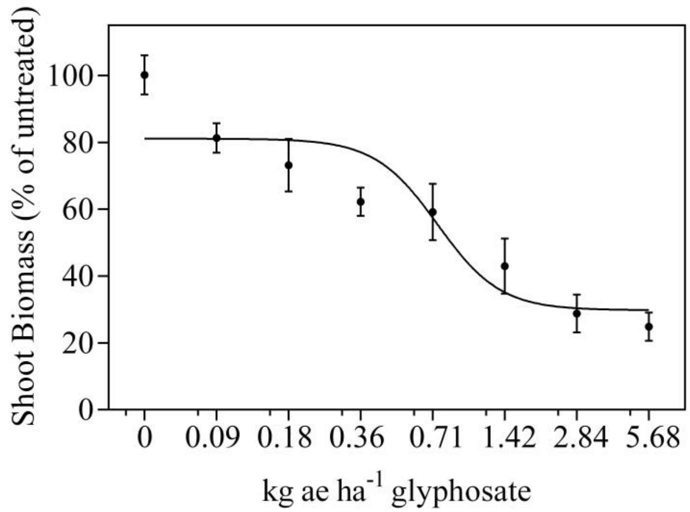

Figure 4.1. Effect of glyphosate on shoot biomass of doveweed. Vertical bars represent standard errors of the mean. Shoot biomass values were calculated as a percentage of the untreated control and analyzed using the nonlinear regression equation $y = C + (D - C)/(1 + 10^{x-logI_{50}})$ where *y* was shoot biomass, *x* was herbicide rate (kg ae ha^{-1}), *D* was the upper bound of *y*, *C* was the lower bound of *y*, and I_{50} was the rate of herbicide that reduced shoot biomass 50%. Estimates for equation parameters (C, D, I_{50}) and adjusted R^2 were 29.8, 81.1, 1.61, 0.63.

Absorption of ^{14}C-Glyphosate

Treatment-by-run interaction was not detected in glyphosate uptake data; therefore data were pooled between runs prior to further analysis (Table 4.11). Additionally, time after treatment was not significant (P = 0.512) so recovery data was pooled across treatment intervals for evaluation of plant treatment main effects. Recovery of [^{14}C]-glyphosate was 93.6% across all harvest intervals in doveweed plants with an intact cuticle. In comparison, [^{14}C]-glyphosate recovery from doveweed plants with a disrupted cuticle and crabgrass plants was 79.1 and 70.5%, respectively (Table 4.12). The lack of glyphosate uptake in doveweed plants with an intact cuticle and increased uptake in doveweed plants with a disrupted cuticle suggests herbicide tolerance is due in part to lack of cuticular penetration.

Benghal dayflower and Asiatic dayflower are species related to doveweed which have become troublesome weeds in agronomic crops because of their relative tolerance to glyphosate (Ulloa and Owen, 2009; Webster and Sosnoskie, 2010). In a study evaluating [^{14}C]-glyphosate uptake in Benghal dayflower, absorption was 66.1% after 72 hours, lower than (*Ipomoea grandifolia* [Dammer] O'Donell) and slim amaranth (*Amaranthus hybridus* L.) at 80 and 90%, respectively (Monquero et al., 2004b). Foliar absorption rates and therefore the biological efficacy of herbicide application depend largely on the type of structure found in the leaves and permeability of the target plant cuticle (Baker and Bukovac, 1971). Characterization of Benghal dayflower leaf surface composition determined the leaf cuticle was constituted of hydrocarbons (n-alkanes) and therefore relatively hydrophobic, which may inhibit penetration of hydrophilic herbicides such as glyphosate (Anonymous 2012, Monoquero et al., 2004a). Consideration of doveweed [^{14}C]-glyphosate uptake data and leaf cuticle characteristics of Benghal dayflower suggests it is likely hydrophilic herbicides, such as glyphosate, are not able to diffuse adequately across the cuticle layer to reach active sites within doveweed. Further research should investigate the leaf surface characteristics of doveweed and improve the understanding of the relationship between leaf surface characteristics of doveweed and herbicide uptake. Understanding this relationship will help to identify herbicides with potential for doveweed control based on herbicide chemical properties.

Table 4.11. ANOVA for [^{14}C]-glyphosate recovery after application to doveweed with cuticle intact, doveweed with cuticle disrupted, and crabgrass quantified at 24, 72, and 144 h after application.

Source	DF	[^{14}C]-glyphosate recovery
Plant	2	*
Harvest Interval	2	ns
Run	1	ns
Plant-by-Harvest Interval	4	ns
Plant-by-Run	2	ns
Harvest Interval-by-Run	2	ns
Error	41	

* Significant at $\alpha = 0.05$ level

[a] Abbreviation: ns, not significant

Table 4.12. Percent recovery of [^{14}C]-glyphosate after application to doveweed with cuticle intact, doveweed with cuticle disrupted, and crabgrass.[a]

Sample	Hours after treatment 24	72	144		Mean
	——————— % of applied ———————				
Doveweed (Cuticle intact)	96.9	92.4	92.2		93.8
Doveweed (Cuticle removed)	85.4	72.6	79.3		79.1
Smooth Crabgrass	75.0	68.7	63.3		69.5
				$LSD_{0.05}$	7.9

[a] Leafs were spotted with five 2-μL droplets of glyphosate corresponding to a 0.71 kg ae ha^{-1} rate with 0.20 KBq ml^{-1} radioactivity.
[b] Time after treatment not significant in ANOVA (P = 0.512) but presented to show trends in data

Conclusions

PRE and POST doveweed control options for bermudagrass turf are presented. One-hundred percent control was never achieved, regardless of treatment; however, sequential applications of PRE or POST herbicides improve control over single applications. Delaying PRE application relative to traditional spring PRE application timing improves consistency and duration of control across the growing season. Due to the long germination period of doveweed, a single PRE application rarely achieves full season control. Similarly, a single POST application provided limited control as seedling emergence continues. Sequential applications are necessary on 14 to 28 d intervals for adequate POST control over an extended period of time.

Further understanding of the interaction between leaf surface characteristics of doveweed and herbicide chemical properties will improve herbicide selection for doveweed control. Future research should continue to screen old and new chemistries, particularly lipophilic compounds that are more likely to move across doveweed's cuticle layer. In addition, turf managers should incorporate cultural practices that discourage doveweed growth and development such as reduced irrigation frequency and preventing excessive application of nutrients through fertilization into any herbicide program during formulation of a holistic doveweed management program.

CHAPTER FIVE

CONCLUSIONS

Doveweed (*Murdannia nudiflora* [L.] Brenan) is invasive in managed turfgrass in part because of its adaptability to a wide range of environmental conditions. The research presented here demonstrates the ability of doveweed to germinate in a wide range of pH, osmotic potential, and NaCl concentration solutions. It appears if adequate soil moisture is available, then adequate soil temperature (~27 C) is the ultimate limitation to doveweed germination (Wilson, 2006). Although doveweed germination was somewhat limited by NaCl concentrations ≥80 mM, this should not limit the range of doveweed expansion except for in the most saline environments.

In managed turfgrass, doveweed competes vertically and laterally with desirable species for soil and light resources. Ability to compete for these resources in a range of mowing heights indicates golf course fairways are equally susceptible to doveweed infestations as golf course roughs, or other areas maintained at taller mowing heights. Turfgrass managers should implement cultural practices that discourage doveweed growth and development. Irrigation should be applied deeply and infrequently to reduce soil moisture in the top 6 cm of soil. Fertilization should be applied to adequately support vigorous turfgrass growth; however, excessive N application may encourage doveweed growth and should be avoided.

Sequential applications of both pre- and postemergence herbicides are necessary to provide full-season doveweed control. Effectiveness of preemergence control was inconsistent when applied in March and April in Augusta, GA. Although doveweed was controlled similarly with indaziflam applied in March, April, and May in two out of four study years, little doveweed control was achieved with indaziflam applied in March of 2008 or 2009. Turf managers are recommended to delay preemergence herbicide applications relative to spring application dates which target common summer annual weeds to consistently extend preemergence doveweed control from a single preemergence herbicide application.

Sequential applications of postemergence herbicides are necessary for >4 weeks of 75% control. Because of doveweed's long germination period, postemergence herbicide application is short lived as new seedlings are recruited throughout the growing season. It is likely a tank-mixture application of a pre + postemergence herbicide is necessary for season-long doveweed control and deserves further investigation.

Tolerance of doveweed to post-emergence herbicides should be further investigated. While this research demonstrates that glyphosate uptake is limited in doveweed, uptake of herbicides with different chemical properties should be investigated. Specifically, more lipophilic herbicides should be evaluated to determine if these herbicides can move readily across doveweed's cuticle layer. Determination of doveweed's cuticle layer composition will aid in understanding why compounds such as glyphosate cannot diffuse adequately across the cuticle layer.

Until recently, doveweed was relatively localized within the Southeastern United States. The research presented here suggests doveweed has the potential to become more cosmopolitan due to its lack of environmental restrictions to growth and development. A further understanding of how environmental conditions affect the fecundity of doveweed will improve the ability to predict the adaptable range of this species. Overall, turfgrass managers should incorporate both cultural practices and herbicide control strategies to develop a holistic doveweed control program.

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