ABSTRACT

HENRY, GERALD MATTHEW. Biology, Ecology, and Control of *Paspalum* Species in Turfgrass. (Under the direction of Drs. Fred H. Yelverton and Michael G. Burton).

Paspalum species are increasing in their prevalence in managed turfgrass systems. Research evaluated herbicidal control and physiological activity of herbicides on dallisgrass (*Paspalum dilatatum* Poir.); ecological and management factors influencing the spatial distribution of *Paspalum* species, and experiments to further clarify the effect of environmental factors on the growth and reproduction of *Paspalum* species. Among many MSMA and foramsulfuron sequential application programs, MSMA (2.5 kg ai/ha) followed by (fb) foramsulfuron 2 weeks after initial treatment (WAIT) fb MSMA 3 WAIT provided the highest control (94%) of dallisgrass 1 month after initial treatment (MAIT) and control levels remained high (93%) 3 MAIT. This herbicide program provided 85% control 1 year after initial treatment (YAIT), while no other treatment provided greater than 37% control 1 YAIT. The timing of foramsulfuron application following initial MSMA application affected control of dallisgrass. Waiting 2 WAIT, rather than 1 WAIT, before applying foramsulfuron increased control of dallisgrass by 20% 1 MAIT and 19% 3 MAIT. However, the increase in control 1 YAIT was only 5% regardless of herbicide rate. Addition of a second application of MSMA following application of foramsulfuron 2 WAIT of MSMA further increased control by 10% 1 MAIT, 37% 3 MAIT, and 48% 1 YAIT. Based on studies evaluating physiological activity of foramsulfuron in dallisgrass in response to pre-application of MSMA or foramsulfuron, the observed increase in control efficacy can be attributed to increased foramsulfuron translocation. Pre-MSMA treated plants translocated 50% more ^{14}C-foramsulfuron to older leaves than pre-foramsulfuron treated plants. In evaluating the spatial distribution of dallisgrass and bahiagrass (*Paspalum notatum* Fluegge) in managed turfgrass, both species were correlated with areas of rough mowing height (6.4 cm). Although dallisgrass and bahiagrass plants were predominantly found in areas maintained at a rough height, several dallisgrass plants were observed in the fairway. A strong correlation was also observed between dallisgrass presence and soil moisture. Dallisgrass plants were predominantly located in areas of high soil moisture (> 27% volumetric soil water content). Mowing height and soil moisture experiments were conducted to confirm correlations in the absence of spatial auto correlation. When grown on soil moisture gradient tanks in the greenhouse, maximum shoot and rhizome growth of dallisgrass were observed under saturated soil conditions. Furthermore, dallisgrass survival and growth was reduced in the upper, droughtier portions of each gradient tank. Bahiagrass shoot and rhizome growth was greatest at the upper, droughtier levels of each soil moisture gradient tank when grown on sandy loam soil. Survival of bahiagrass along the soil moisture gradient was unaffected. Field experiments were conducted to observe the response of *Paspalum* spp. to different mowing heights. Bahiagrass lateral spread and rhizome production was reduced 44 to 62% and 70 to 73%, respectively, when mowed at 1.3 cm compared to a non-mowed check. Reductions in lateral spread and rhizome production were only 21 to 27% and 24 to 33%, respectively, when bahiagrass was mowed at 7.6 cm. Dallisgrass plants exhibited reductions in lateral spread of 38 to 47% compared to a non-mowed check, regardless of mowing height. Reductions in dallisgrass rhizome production were 30 to 49%, 30%, and 37 to 57% when mowed at 7.6, 5.2, and 1.3 cm, respectively.

BIOLOGY, ECOLOGY, AND CONTROL OF PASPALUM SPECIES IN TURFGRASS

by

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To my father,
Without his support and guidance,
none of this would have been possible.

“There is no friendship, no love, like that of the parent for the child.”
- Henry Ward Beecher

BIOGRAPHY

Gerald Matthew Henry was born August 31, 1975 in Manchester, NH, to Marie Annette (Rancourt) and Gerald Roger Henry. On his 3rd birthday he and his family moved to Jackson, NJ, where he attended kindergarten, elementary, middle, and high school. He graduated from Jackson Memorial High School in June, 1993. After high school, Gerald received an academic scholarship to attend Lehigh University in Bethlahem, PA. He attended Lehigh for 2 ½ years before leaving the academic arena on a brief hiatus. A summer position on the grounds maintenance staff at a local golf course triggered his return to the university setting. Gerald enrolled at Rutgers University in New Brunswick, NJ, in September 1997. He graduated 3 years later from Rutgers with a B.S. in Plant Science with a focus on turfgrass management, yet his greatest accomplishment was meeting his future wife Emily (Simmons) Henry during his undergraduate degree.

Gerald began his graduate career in the Department of Plant Biology and Pathology at Rutgers University in September 2000 under the direction of Dr. Stephen Hart, with significant guidance from Dr. James Murphy and Dr. William Meyer. Gerald's Masters project concentrated on the overseeding of bentgrass species into existing stands of annual bluegrass. After completing this degree in January 2003, he moved on to North Carolina State University to pursue his Ph.D. in turfgrass weed science under the direction of Dr. Fred Yelverton. Gerald presented his research at numerous scientific conferences, participated in several scientific society activities, and was named the North Carolina Turfgrass Council Eagle Award Scholar during his graduate degree.

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CHAPTER 1

Literature review.

Dallisgrass.

Dallisgrass (*Paspalum dilatatum* Poir.) is a warm-season perennial grass that was introduced into the United States from southern Brazil, northeastern Argentina, and Uruguay, the presumed center of origin of the species (Caponio and Quarin, 1990; Tischler and Burson, 1999). The exact date of its introduction into the United States is unknown, but the species was first collected in Louisiana in 1840 (Chase, 1929). Dallisgrass is common throughout the southern United States, north to New Jersey, west to Arizona, California, the Pacific Northwest, and Hawaii (McCarty et al. 2001; Uva et al. 1997). The grass is named for A. T. Dallis of La Grange, GA, who promoted it as a pasture grass at the beginning of the 20th century (Holt, 1956). Dallisgrass has become an important forage grass used throughout many of the warmer regions of the world, including the southeastern United States (Tischler and Burson, 1999; Burson and Watson, 1995). It is extensively used in forage programs, because it survives well under grazing and has excellent forage nutritive value (Holt, 1956). The ability of dallisgrass to tolerate grazing and adapt to a wide range of environmental factors (Robinson et al. 1998) may have led to its success and spread as a turfgrass weed.

The presence of dallisgrass negatively affects the appearance, texture, and playability of desired turfgrass species in home lawns, golf courses, and athletic fields (Turgeon, 2005; Elmore and Cudney, 2001). Its clump-forming habit and accelerated growth compared with other warm-season turfgrasses may create tripping hazards in athletic fields (Elmore and Cudney, 2001) and increase mowing frequency of desired turfgrass species. Coarser leaf texture (Elmore and Cudney, 2001; Uva et al. 1997; McCarty et al. 2001) combined with earlier spring growth initiation (Holt, 1956) and longer fall persistence (Holt, 1956; Davies and Forde, 1991) make the presence of dallisgrass in other warm-season grasses aesthetically displeasing. Additionally, the abundance of tall, unsightly seedheads (McCarty et al. 2001; Elmore and Cudney, 2001) produced from May through October often escape mowing, further decreasing playability of golf course turf and increasing maintenance requirements for their removal.

The common dallisgrass biotype is widely distributed throughout the world's temperate and warm regions and reportedly reproduces by obligate apomixis (Bashaw and Holt, 1958; Bashaw and Forbes, 1958) and rhizomes (McCarty et al. 2001; Elmore and Cudney, 2001). The species includes at least five biotypes, three ploidy levels, and different meiotic chromosome behaviors, morphologies, and methods of reproduction (Espinoza and Quarin, 2000). The five biotypes include: yellow-anthered dallisgrass (*Paspalum dilatatum* spp. *flavescens* Roseng. Arri. Et Izag.) (Bashaw and Forbes, 1958; Bashaw and Holt, 1958), prostrate dallisgrass (*P. dilatatum* var. *pauciciliatum* Parodi.) (Bashaw and Forbes, 1958; Bashaw et al. 1970), Torres, Uruguaiana (Moraes Fernandes et al.1968), and Uruguayan (Burson et al. 1991).

The center of a dallisgrass clump is often devoid of green leaves as the plant matures, and may become occupied by other turfgrasses or weeds (Elmore and Cudney, 2001). Large infestations of dallisgrass plants may begin to coalesce over time forming a near monculture (Elmore and Cudney, 2001). Dallisgrass tolerates frequent mowing, but can reach heights of 0.5 to 1.5 m when undisturbed (Uva et al. 1997).

Throughout mid-summer and into the fall, dallisgrass produces an abundance of seedheads (Uva et al. 1997). Flowers and seeds are produced on tall (up to 1.5 m) terminal stalks in a raceme that bears 3 to 5 (occasionally more) spreading or loosely ascending spike-like branches (5 to 10 cm long) (Uva et al. 1997; McCarty et al. 2001). The spikelets are ovate, 3 to 4 mm long by 2 to 2.5 mm wide, hairy, and crowded in 4 rows on the racemes (Uva et al. 1997). Spikelets are covered with silky soft hairs. Seeds are oval, shiny, and yellow to brown in color (2.5 to 3 mm long) (Uva et al. 1997; Elmore and Cudney, 2001). Seed may be spread through contact with animals, clothing, machinery, and in water. Dallisgrass seed usually germinates in the spring and summer when soil temperatures are in the range of 16 to 18 C and grow to form new clumps (Elmore and Cudney, 2001). The optimum air temperature range for dallisgrass growth is 27 to 32 C. Plants grow very rapidly when temperatures reach this range (Elmore and Cudney, 2001). Establishment of dallisgrass from seed may be difficult due to poor seed quality and slow germination (Holt, 1956; Burton, 1942; Owen, 1951). Tischler and Burson (1999) reported that germination of common dallisgrass never exceeded 38%. Bennett and Marchbanks (1969) reported that at least 30% of the spikelets of common dallisgrass shattered 14 days after anthesis. Pearson and Shah (1981) observed that only a limited number of florets on each inflorescence contain a caryopsis, and consequently low seed viability in dallisgrass may reflect a high number of sterile florets. In addition, ergot (*Claviceps paspali* Stevens and Hall) infection may further reduce numbers of germinable seed in a seed lot (Ray and Stewart 1937). Slow seedling growth after emergence is attributed to late development of the root system (Hyder et al. 1971; Frasier et al. 1984; Hsu and Nelson, 1986). Dallisgrass is also capable of spreading locally through the expansion of short, thick rhizomes (Uva et al. 1997; McCarty et al. 2001). Soil cultivation and disturbance may facilitate the spread of rhizomes over long distances as well. Dallisgrass rhizomes have short internodes that resemble concentric rings on its surface (Elmore and Cudney, 2001) and are capable of producing a single plantlet from each node.

Mature leaf blades are flat, 10 to 30 cm long by 6 to 15 mm wide, and lack hairs except for a few long hairs at the collar (Uva et al. 1997). Leaves are rolled in the bud (McCarty et al. 2001). The ligule is tall and membranous with a rounded or bluntly pointed tip (Uva et al. 1997; McCarty et al. 2001). Auricles are absent (Uva et al. 1997). Leaf sheaths lack hairs (except for a few, older leaves), are strongly compressed, with a prominent mid-vein, and may be tinged purplish red with age (Uva et al. 1997). The collar is broad, light green, smooth, often with long hairs at the edges (Uva et al. 1997). Tillers are stout and do not root at the nodes (Uva et al. 1997).

Dallisgrass is best adapted to areas receiving at least 900 mm of annual rainfall and grows well on clay or loam soils that are moist (Venuto et al. 2003; Uva et al. 1997; Elmore and Cudney, 2001). It is more common in humid and very humid sites (Burkart et al. 1990). This pattern may be explained by its tolerance of flooding conditions (Loreti et al. 1994; Rubio et al. 1995; Loreti and Oesterheld, 1996; Rubio and Lavado, 1999). Dallisgrass has been observed to undergo several physiological adaptations in response to flooding and drought. In response to flooding, an impressive (50%) reduction in root/shoot ratio has been observed (Rubio and Lavado, 1999). This change decreases the amount of respiring root tissue and facilitates oxygen diffusion to roots (Naidoo and Naidoo, 1992; Voesenek et al. 1989; Megonigal and Day, 1992; Loreti and Oesterheld, 1996). Rubio and Lavado (1999) observed that dallisgrass allocated only 30% of resources below ground in response to flooding. Leaf extension rates and tiller height were also higher in flooded dallisgrass plants (Insausti et al. 2001; Rubio et al. 1995; Loreti and Oesterheld, 1996). Increasing plant height is a flooding response that allows avoidance of leaf submergence (Laan and Blom, 1990; Van der Sman et al. 1993; Oesterheld and McNaughton, 1991). Loreti and Oesterheld (1996) observed that drought reduced plant height by 24% in three *P. dilatatum* populations. Dallisgrass was observed to produce aerotropic and adventitious roots that grow upward to oxygenated areas (Rubio et al. 1995), thus supplying oxygen to the roots (Glinski and Stepniewski, 1985; Kozlowski, 1984). Several researchers also observed an increase in root aerenchyma tissue of dallisgrass in response to flooding (Rubio et al. 1995; Loreti and Oesterheld, 1996; Vasellati et al. 2001), while others observed a reduction in response to drought (Loreti and Oesterheld, 1996; Vasellati et al. 2001). Increased aerenchyma tissue is a common adaptive response of plants to soil anoxia (Jackson and Drew, 1984; Justin and Armstrong, 1987; Jackson and Armstrong, 1999). Its low frequency in environments where water stress occurs may be explained by difficulties in seedling establishment (Cornaglia et al. 2005). Loreti and Oesterheld (1996) observed that drought reduced yield equally across three *P. dilatatum* biotypes.

Dallisgrass responds to nitrogen fertilizer and competes well with other species under high fertility. Savoy and Robinson (1990) observed that dallisgrass growth increased in response to increasing N, P, K, and S amendments in a relatively infertile soil [Ruston vfsl (Typic Paleudult)] and N and P in a relatively fertile soil [Rita muck (Hydric Fluvaquent)]. The presence of Ca and Mg amendments had no affect on dallisgrass growth in either soil (Savoy and Robinson, 1990).

Gene exchanges between tetraploid *P. dilatatum* biotypes and *P. urvillei* have been observed (Caponio and Quarin 1990). Resulting hybrids from these crosses may create morphological and physiological changes to *Paspalum* spp. that would increase the complexity of understanding their response to specific environmental constraints.

The best management practice for the control of dallisgrass may be prevention. Maintaining a healthy, vigorously growing turf may reduce the potential for dallisgrass infestation. The presence of mature dallisgrass plants in desired turfgrass species can be controlled culturally through the physical removal of plant clumps. Careful attention must be paid to the removal of all rhizome tissue within the soil, therefore negating resprouting potential. Mowing will not remove dallisgrass, but maintaining proper mowing height and frequency for desired turfgrass species may increase their competitiveness with dallisgrass, further reducing the probability of infestation. Dallisgrass is tolerant of high soil moisture and can become prevalent in saturated areas. Monitoring irrigation to provide desired turfgrass species with adequate soil moisture while minimizing over-application is critical. Aerating compacted soils and installation of drainage tiles in low areas may alleviate standing water, further increasing the competitiveness of desired turfgrass species while decreasing dallisgrass infestation.

Currently, chemical control of dallisgrass is neither efficient, nor cost effective. Typical programs include multiple applications of monosodium methanearsonate (MSMA) (Turgeon, 2005; McCarty et al. 2001), which can be phytotoxic to warm-season turfgrass, or applications of glyphosate (McCarty et al. 2001), which can be even more harmful to hybrid bermudagrass (*Cynodon transvaalensis* X *Cynodon dactylon* ‘Tifway’). Furthermore, these control methods are not entirely effective in eliminating dallisgrass from turf. Several researchers have examined the efficacy of various rates and timings of foramsulfuron and MSMA for the control of dallisgrass in bermudagrass turf. Ricker et al. (2005) observed a reduction in dallisgrass stands of 50% with sequential applications of foramsulfuron (0.05 kg ai/ha), but long term control was poor. MSMA applied at 1.8 or 1.1 kg ai/ha followed by (fb) foramsulfuron (0.05 kg ai/ha or 0.07 kg ai/ha) resulted in ≥ 85% dallisgrass control 5 weeks after initial treatment. Slightly higher dallisgrass control (> 90%) 21 to 84 days after initial treatment (DAIT) was reported by Hubbard et al. (2006) when applying MSMA at 1.8 kg ai/ha fb foramsulfuron at 0.1 kg ai/ha 7 and 28 DAIT. Effective chemical control of dallisgrass is linked to the ability of a chemical to translocate into below-ground perennial structures.

Bahiagrass.

Bahiagrass (*Paspalum notatum* Fluegge) is a warm-season perennial grass that was introduced into the United States from southern Brazil, Uruguay, northeastern Argentina, and Paraguay, the presumed center of origin of the species (Parodi, 1937). Bahiagrass is common primarily in the Gulf States, north to North Carolina, and west to Texas (McCarty et al. 2001). It is also found in the West Indies, Central America, and Hawaii (McCarty et al. 2001). Bahiagrass is widely used as a pasture, forage, roadside, and lawn grass in the southern United States (Bunnell et al. 2003; Turgeon, 2005) due to its ability to tolerate a wide range of soils and moisture conditions, low-fertility requirements, and establishment from seed (Beaty et al. 1968; Evans et al. 1961; Heath et al. 1973). The ability of bahiagrass to adapt to many environmental and edaphic conditions (Bunnell et al. 2003; Beaty et al. 1968; Evans et al. 1961) along with its abundant use as a forage may have encouraged its spread and success as a turfgrass weed.

The presence of bahiagrass negatively affects the appearance, texture, and playability of desired turfgrass species in home lawns, golf courses, and athletic fields (Hanna et al. 1989).

Its fibrous blades make it difficult to cut cleanly and often appear frayed after mowing, giving the turf a tattered appearance (Duble, 2007). Additionally, bahiagrass rapidly produces an abundance of seedheads throughout the summer and fall, many of which can become 70 to 80 cm tall within a few days (Busey, 1985). The presence of unsightly seedheads further reduces the playability of golf course turf, increases maintenance requirements for removal, and may be a sight hazard when present on roadsides (Emmons, 2000).

Bahiagrass includes two subspecific types: *P. notatum* var. *saurae* Parodi, a sexually reproducing diploid with 20 chromosomes and *P. notatum* var. *latiflorum* Doell, an apomictically reproducing tetraploid with 40 chromosomes (Turgeon, 2005). Within these subspecies, there are nine bahiagrass introductions and strains currently in the United States (Burson and Watson, 1995): ‘Common’, ‘Argentine’, ‘Paraguay’, ‘Paraguay-22’, ‘Pensacola’, ‘Tifhi-1’, ‘Tifhi-2’, ‘Wilmington’, and ‘Tifton-9’ (Chambliss, 1999). Common bahiagrass was originally introduced from Brazil into the United States by the Bureau of Plant Industry in 1913, at the Florida Agricultural Experiment Station in Gainesville (Scott, 1920). This cultivar was ‘Common’, which has a broad (> 5 mm wide) leaves and a prostrate growth habit (Hall, 1978). Pensacola bahiagrass was discovered and named by Escambia County agent Ed H. Finlayson in 1941 (Finlayson, 1941). He discovered the grass growing around the now-destroyed Perdido Wharf in Pensacola, FL. This grass was believed to have been discarded with ballast from ships when the wharf was operational (Burton, 1967). Pensacola was introduced into the U.S. in 1936 (Burton, 1967). It originated from a relatively small area of central-eastern and northeastern Argentina (Burton, 1967) and has become the most widespread bahigrass introduction used throughout the southern United States.

Bahiagrass is an aggressive, mat-forming, perennial grass with shallow, often-exposed rhizomes. The erect architecture of bahiagrass leaves combined with low shoot density create an open turf (Turgeon, 2005), making it very susceptible to competition from other species. Its prostrate and rhizomatous growth habit makes it tolerant of close and continuous shoot removal (Beaty et al. 1968). However, Blue (1976) reported a small reduction in bahiagrass rhizome weight with clipping and Beaty et al. (1970) observed that pots clipped at the soil level every six weeks yielded 50 to 70% more rhizome biomass than those clipped weekly.

Bahiagrass produces numerous seedheads from late spring through late summer (McCarty et al. 2001). Seed stalks are spike-like racemes that terminate in 2, rarely 3, rather long ascending branches (McCarty et al. 2001). Spikelets (3.0 mm long) are in two rows on lower sides with a single seed (McCarty et al. 2001; Hitchcock, 1971). Seeds are about 3 mm long, 2 mm wide, oval, and the back are very convex (Duble, 2007; Hitchcock, 1971). Seed may be spread through contact with animals, clothing, machinery, and in water. Bahiagrass grows more slowly than other warm-season turfgrasses (Busey and Myers, 1979). Germination of bahiagrass seed is slow (West and Marousky, 1989), as is the development of stands from small, weak seedlings (Williams and Webb, 1958; Beaty and Powell, 1978) that are sensitive to competition. Bahiagrass seeds shatter very readily, often before they mature (Burton, 1946). Correa (1974) reported that seed shattering was most severe 14 days after raceme exsertion. He found that 36% of the filled spikelets eventually shattered and concluded that no more than 50% of the spikelets produced could be harvested at any one time (Correa, 1974). Seed shattering may be responsible for slow germinating bahiagrass seed. Bahiagrass is also capable of spreading locally through the expansion of short, stout rhizomes that remain close to the soil surface. Soil cultivation and disturbance may facilitate long distance spread of rhizomes as well. Rhizomes are covered with persistent bases of old leaf sheaths, giving them a woody appearance (Duble, 2007). Once a rhizome is initiated, it may grow for several years, elongating through the addition of new phytomers at the terminal meristem (Sampaio et al. 1976).

Mature leaf blades are long, primarily basal, pointed at the tip, and folded at the base (Duble, 2007; Hitchcock, 1971). Leaves are smooth on both surfaces or often hairy only at the collar (Duble, 2007). The ligule is membranous, very short, and has a dense row of hairs in the back (Duble, 2007). Foliage tends to have a reddish purple tinge at the base.

Bahiagrass is well adapted to sandy soils of low fertility (Beaty and Tan, 1972; Emmons, 2000), but also responds well to fertilization (Evans et al. 1961). Bahiagrass responds to N fertilization, but yield curves generally show reduced increases at N rates above 100 lb/A (Blue and Graetz, 1977). Beaty et al. (1970) reported that rhizomes per area increased significantly as N increased from 0 to 112 kg/ha after 2 years. Sumner et al. (1990) observed that bahiagrass did not respond to P fertilization, while Ibrikci et al. (1992) reported either no response or minimal growth enhancement. Bahiagrass also has the ability to accumulate nutrients in its rhizomes at the soil surface (Chambliss and Adjei, 2006). Chambliss and Adjei (2006) estimate that the rhizomes of a mature bahiagrass plant growing in fertile soil may contain a reserve of nutrients that will last 2 to 3 years. Bahiagrass is also adapted to a wide range of soil moisture, often tolerating drought and flooding conditions (Mislevy et al. 1991; Evans et al. 1961). Bahiagrass is a very efficient forager and recovers nutrients from deeper in the soil profile than other grasses (Chambliss and Adjei, 2006). It is deep-rooted and produces an extensive root system (Heath et al. 1973; Emmons, 2000), aiding in its acquisition of soil moisture. Exposed rhizomes at the soil surface may allow for gas exchange under flooding conditions. Finally, bahiagrass has poor cold tolerance (Beard, 1973), fair shade tolerance, and poor salt tolerance (Emmons, 2000).

Probably, the best management practice for the control of bahiagrass is prevention. Maintaining a healthy, vigorously growing turf may reduce the potential for bahiagrass infestation. The mat-forming growth habit of bahiagrass makes it difficult to control by physically removing plants from stands of desired turfgrass species. Seedhead suppression has proven quite successful initially with a variety of chemicals, but long-term efficacy is difficult. In Georgia, bahiagrass seedhead suppression with glyphosate at 0.2 kg ai/ha decreased from 96 to 85% between 8 and 10 weeks after treatment (WAT) and dropped from 85 to 76% between 6 and 8 weeks following an application of trinexapac-ethyl at 0.2 kg ai/ha (Johnson, 1990). Maleic hydrazide reduced bahiagrass seedhead numbers $\geq$ 90%, but suppression decreased dramatically between 8 and 12 WAT (Nelson et al. 1993). Single applications of imazapic and imazapic + imazaquin provided 85 to 100% seedhead suppression for 12 WAT and 100% suppression for up to 16 weeks following sequential applications made 8 weeks after initial application (Baker et al. 1999).

Chemical control of bahiagrass within desired turfgrass species is neither efficient nor cost effective and appears to be cultivar dependent. Atrazine has been used for the removal of ‘Wilmington’ bahiagrass from centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.) (Johnson 1979) and ‘Pensacola’ bahiagrass from Coastal bermudagrass hayfields (Smith and Powell, 1980), but may cause extensive damage to other desired turfgrass species. Furthermore, Smith (1983) observed that ‘Pensacola’ bahiagrass was more sensitive to atrazine than ‘Wilmington’. Metsulfuron, recently registered for use in turfgrass, is labelled for the control of bahiagrass in St. Augustinegrass (*Stenotaphrum secundatum* (Walt.)

Kuntze.) and bermudagrass, but multiple applications are often necessary for adequate control (Anonymous, 2002). Inconsistent control of semi-tolerant bahiagrass cultivars with metsulfuron has recently reduced the desirability of this chemical control option in turfgrass (Bunnell et al. 2003). ‘Pensacola’ bahiagrass has been observed to be more susceptible to metsulfuron compared with ‘Argentine’ (Richburg et al. 1991; Weinbrecht and McCarty, 1993). Bunnell et al. (2003) observed that ‘Argentine’, ‘Common’, and ‘Paraguayan’ had a 4- to 5-fold increase in tolerance to metsulfuron compared with ‘Pensacola’. Postemergence control with sethoxydim (McCarty et al. 2001) or repeat applications every 5 days with MSMA/DSMA are also options (McCarty et al. 2001; Turgeon, 2005). Spot treatments with glyphosate or applications of fluazifop and fenoxaprop also provide good control of bahiagrass (McCarty et al. 2001).

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CHAPTER 2

Dallisgrass (*Paspalum dilatatum* Poir.) Control with Foramsulfuron in Bermudagrass Turf.

Abstract: Dallisgrass response to various combinations of MSMA and foramsulfuron herbicides was evaluated from 2004 through 2006 in North Carolina. Dallisgrass control declined with herbicide rates; therefore, only treatments containing the highest rates (foramsulfuron, 0.15 kg ai/ha; MSMA, 2.5 kg ai/ha) are discussed below. Foramsulfuron followed by (fb) foramsulfuron 1 WAIT gave moderate control (60%) of dallisgrass 1 MAIT, but control declined to 40% 3 MAIT. MSMA (2.5 kg ai/ha) applied three times gave good dallisgrass control (89%) 1 MAIT, but control declined to 71% 3 MAIT. Among many MSMA and foramsulfuron sequential application programs, MSMA (2.5 kg ai/ha) fb foramsulfuron 2 WAIT fb MSMA 3 WAIT provided the highest control (94%) of dallisgrass 1 MAIT and control levels remained high (93%) 3 MAIT. This herbicide program provided 85% control 1 YAIT, while no other treatment provided greater than 37% control 1 YAIT. The timing of the foramsulfuron application following the initial MSMA application affected the control of dallisgrass. Waiting 2 WAIT, rather than 1 WAIT, before applying foramsulfuron increased control of dallisgrass by 20% 1 MAIT and 19% 3 MAIT. However, the increase in control 1 YAIT was only 5% regardless of herbicide rate. The addition of a second application of MSMA following the application of foramsulfuron 2 WAIT of MSMA further increased control by 10% 1 MAIT, 37% 3 MAIT, and 48% 1 YAIT. Results from this study suggest dallisgrass may be controlled with applications of MSMA fb foramsulfuron 2 WAIT fb MSMA 3 WAIT applied during early to mid summer. The use of MSMA was required to achieve dallisgrass control, however, the relatively high level of control achieved

1 YAIT with a program including sequential applications of MSMA and foramsulfuron may help reduce the total amount of arsenical herbicides used to control dallisgrass infestations over time.

Nomenclature: foramsulfuron, 2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-4-(formylamino)-*N*,*N*-dimethylbenzamide; MSMA, monosodium methanearsonate; metribuzin, 4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one; hybrid bermudagrass, *Cynodon transvaalensis* X *Cynodon dactylon* ‘Tifway’; dallisgrass *Paspalum dilatatum* Poir. #[1] PASDI.

Additional index words: turfgrass, golf course, alternatives to MSMA.

Abbreviations: WAIT, weeks after initial treatment; MAIT, month after initial treatment; YAIT, year after initial treatment; fb, followed by; postemergence, POST; acetolactate synthase, ALS; methylated seed oil, MSO; urea ammonium nitrate, UAN.

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[1] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th St., Lawrence, KS 66044-8897.

INTRODUCTION

Dallisgrass (*Paspalum dilatatum* Poir.) is a rhizomatous perennial warm-season grass that commonly infests managed turfgrass systems. Typically dallisgrass is used as a forage or roadside grass, but its ability to adapt to a wide range of environmental factors may have led to its success and spread as a turfgrass weed. Spatial distribution research recently conducted to examine the response of dallisgrass to several edaphic and topographic features present on golf course fairways and roughs showed strong correlations between volumetric soil moisture and species presence (Henry et al. 2006a). Several controlled environment experiments showed that dallisgrass can tolerate high soil moisture content (Henry et al. 2006b, Rubio and Lavado 1999, Loreti and Oesterheld 1996, Rubio et al. 1995). Furthermore, dallisgrass exhibits tolerance of close mowing and can persist at mowing heights typical of golf course fairways and roughs (Henry et al. 2004). Finally, unlike other warm-season perennial grasses, dallisgrass continues active growth later into fall months (Davies and Forde 1991), further complicating its control.

Currently, chemical control of dallisgrass is neither efficient, nor cost effective. Typical programs include multiple applications of monosodium methanearsonate (MSMA), which can be phytotoxic to warm-season turfgrass, or applications of glyphosate, which can be even more harmful to hybrid bermudagrass (*Cynodon transvaalensis* X *Cynodon dactylon* ‘Tifway’). Furthermore, these control methods are not entirely effective in eliminating dallisgrass from turf.

The sulfonylurea herbicide foramsulfuron was registered in 2003 by the U.S. Environmental Protection Agency for use in turfgrass. It exerts its herbicidal activity by inhibiting acetolactate synthase (ALS), a key enzyme in the biosynthesis of branched-chain amino acids (Ashton and Monaco 1991). Foramsulfuron is labelled for the post-emergence (POST) control of several cool-season grasses, goosegrass, and henbit present within warm-season turf. Busey (2004) reported effective control (>85%) of goosegrass (*Eleusine indica* (L.) Gaertn.) with two applications of foramsulfuron plus metribuzin at 0.210 kg/ha. Complete control of Kentucky bluegrass was achieved in 2 of 4 locations with sequential applications of foramsulfuron at 0.03 kg/ha (McCullough et al. 2006). Foramsulfuron can be applied to warm-season turf with minimal phytotoxic affects. McElroy et al. (2005) observed that foramsulfuron did not injure or reduce bermudagrass cover of four recently sown bermudagrass cultivars. Although foramsulfuron is labeled for the control of cool-season grasses, preliminary analysis showed it as a potential alternative to MSMA and glyphosate for the control of dallisgrass.

Although alternatives to MSMA have already been identified for control of goosegrass (Busey 2004), there are no known herbicide alternatives for the efficient selective POST control of mature crabgrass, dallisgrass, and tropical signalgrass in bermudagrass turf. Therefore, the objective of our research was to evaluate foramsulfuron alone and in combination with MSMA for POST control of dallisgrass in bermudagrass turf as an alternative to the currently recommended three MSMA applications each year.

MATERIALS AND METHODS

Field experiments were initiated during the summer of 2004 and 2005 at Hidden Valley Golf Course in Willow Springs, NC, and in 2004 at Garner Country Club in Raleigh, NC. Research was performed on established dallisgrass infestations present in a common bermudagrass rough that was cut to a height of 5.0 cm. Plots measured 1.2 x 3.0 m and were arranged in a randomized complete block design, with four replications of treatments. Each plot was assessed at the time of initial herbicide application for percent dallisgrass cover. Initial canopy cover of dallisgrass within each plot was recorded for control estimation and ranged from 50 – 90%. All experimental areas were mowed once weekly. There was no rain or irrigation during the 24 hour period after any treatments were applied.

Twenty two herbicide treatments or application regimes and a nontreated control were included in all experiments. Herbicide treatments were initiated on June 10, 2004 and June 12, 2005, and consisted of MSMA[2] (2.5 kg ai/ha) followed by (fb) foramsulfuron[3] (0.05, 0.09, 0.11, or 0.15 kg ai/ha) 1 week after initial treatment (WAIT), MSMA (2.5 kg ai/ha) fb foramsulfuron (0.05, 0.09, 0.11, or 0.15 kg ai/ha) 2 WAIT, MSMA (2.5 kg ai/ha) fb foramsulfuron (0.05, 0.09, 0.11, or 0.15 kg ai/ha) 2 WAIT fb MSMA (2.5 kg ai/ha) 3 WAIT, MSMA (2.5 kg ai/ha) fb MSMA (2.5 kg ai/ha) 1 WAIT, MSMA (2.5 kg ai/ha) fb MSMA (2.5 kg ai/ha) 1 WAIT fb MSMA (2.5 kg ai/ha) 2 WAIT, foramsulfuron (0.05, 0.09, 0.11, or 0.15 kg ai/ha) fb foramsulfuron (0.05, 0.09, 0.11, or 0.15 kg ai/ha), foramsulfuron (0.11 kg ai/ha) fb MSMA (1.25 kg ai/ha) 1 WAIT, MSMA (1.25 kg ai/ha) fb foramsulfuron (0.11 kg ai/ha) 1 WAIT, metribuzin[4] (0.4 kg ai/ha) fb foramsulfuron (0.11 kg ai/ha) 1 WAIT, MSMA

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[2] MSMA 6 Plus, Platte Chemical Company, P.O. Box 667, Greeley, CO 80632-0667.

[3] Revolver 0.19 SC, Bayer Environmental Science, 2 T. W. Alexander Dr., Research Triangle Park, NC 27709.

[4] Sencor 75 DF, Bayer Crop Science LP, P.O. Box 12014, 2 T. W. Alexander Dr., Research Triangle Park, NC
27709.

(1.25 kg ai/ha) fb MSMA (1.25 kg ai/ha) 1 WAIT. A non-ionic surfactant[5] was included in all MSMA applications. Treatments were applied using a CO_2 pressurized backpack sprayer equipped with XR8004VS Teejet[6] nozzle tips and calibrated to deliver 304 L/ha at 290 kPa.

Data collected included percent bermudagrass phytotoxicity and percent dallisgrass control based on visual estimates. Bermudagrass phytotoxicity was rated at 1, 2, and 4 WAIT, on a scale of 0 (no visual phytotoxic symptoms) to 100% (complete turfgrass necrosis). Dallisgrass control was rated at 1 and 3 months after initial treatment (MAIT) and 1 year after initial treatment (YAIT) on a scale of 0 (no dallisgrass control) to 100% (complete dallisgrass removal). Visual estimates of percent phytotoxicity and percent control were arc-sin square root transformed prior to analysis. Transformation did not improve variance homogeneity; therefore, nontransformed data were used in analysis and presentation. There were no significant year or location interactions, so data were combined and ANOVA was performed. Means were separated using Fisher's protected LSD test at $P = 0.05$. MSMA fb foramsulfuron 1 WAIT, MSMA fb foramsulfuron 2 WAIT, and MSMA fb foramsulfuron 2 WAIT fb MSMA 3 WAIT treatments were averaged across foramsulfuron rates (0.05, 0.09, 0.11, and 0.15 kg/ha) and evaluated by a separate ANOVA in order to compare foramsulfuron timings following MSMA application (1 or 2 WAIT) and the addition of a sequential MSMA application.

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[5] X-77, a mixture of alkylarylpolyoxyethylene glycols, free fatty acids, and isopropanol. Valent USA Corp., 1333 North California Blvd., Walnut Creek, CA 94596-8025.

[6] Teejet flat-fan extended range spray tips. Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60189.

RESULTS AND DISCUSSION

All treatments containing the active ingredient MSMA injured bermudagrass 1 WAIT, however, no other treatments injured bermudagrass significantly (data not shown). Bermudagrass phytotoxicity ratings never exceeded 15% at any rating date, and all bermudagrass recovered within 14 d of herbicide application (data not shown). Ricker et al. (2005) reported bermudagrass injury with MSMA 1 WAIT, but the bermudagrass recovered to acceptable levels 3 WAIT. Hubbard et al. (2006) reported slightly higher injury (< 30%) with MSMA and foramsulfuron treatments during an 84 day rating period.

Herbicide treatment main effects were observed for dallisgrass visual control (Table 1). Dallisgrass control declined with herbicide rates; therefore, only treatments containing the highest rates (foramsulfuron, 0.15 kg ai/ha; MSMA, 2.5 kg ai/ha) are discussed below. At 1 MAIT, MSMA fb foramsulfuron 2 WAIT, MSMA fb foramsulfuron 2 WAIT fb MSMA 3 WAIT, and three sequential applications of MSMA controlled dallisgrass ≥ 85% (Table 1). Two months later (3 MAIT), MSMA fb foramsulfuron 2 WAIT fb MSMA 3 WAIT gave dallisgrass control of 93%, while control with three sequential applications of MSMA declined to 71% and MSMA fb foramsulfuron 2 WAIT declined to 64%. MSMA fb foramsulfuron 1 WAIT, foramsulfuron fb foramsulfuron 1 WAIT, and two sequential applications of MSMA provided moderate control (≥ 60%) 1 MAIT, but control declined to ≤ 52% 3 MAIT. All other treatments provided ≤ 55% control 1 MAIT and their control declined to ≤ 31% 3 MAIT. Similar results were observed in VA with sequential applications of foramsulfuron at 0.05 kg/ha during the summer controlling dallisgrass 50% (Ricker et al. 2005). Ricker et al. (2005) also observed 85% control 5 WAIT with applications of MSMA fb foramsulfuron 1 WAIT, which gave similar control to our MSMA fb foramsulfuron 2

WAIT treatment. Slightly higher dallisgrass control (> 90% 21 to 84 days after initial treatment) was reported by Hubbard et al. (2006) when applying MSMA at 1.8 kg/ha fb foramsulfuron at 0.1 kg/ha during the summer.

Although initial dallisgrass injury was observed in all treatments, effective long-term control was difficult to achieve. Only MSMA fb foramsulfuron 2 WAIT fb MSMA 3 WAIT provided 85% control of dallisgrass 1 YAIT. MSMA fb foramsulfuron 2 WAIT and three sequential applications of MSMA gave only 37% control 1 YAIT. MSMA fb foramsulfuron 1 WAIT and two applications of MSMA provided ≤ 30% control 1 YAIT, while control with foramsulfuron fb foramsulfuron 1 WAIT was only 5% 1 YAIT. Ricker et al. (2005) also reported poor long-term control with sequential applications of foramsulfuron. All other treatments in this experiment provided unacceptably low levels of control 1 YAIT.

Foramsulfuron application timing and the use of a second MSMA application were identified as important dallisgrass control program components. Waiting 2 WAIT of MSMA, rather then 1 WAIT, before applying foramsulfuron increased control of dallisgrass by 20% 1 MAIT and 19% 3 MAIT. However, the increase in control 1 YAIT was only 5% regardless of foramsulfuron rate (Table 2). The addition of a second application of MSMA following the application of foramsulfuron 2 WAIT of MSMA further increased control by 10% 1 MAIT, 37% 3 MAIT, and 48% 1 YAIT (Table 2). The reason for the increased efficiency resulting from the additional MSMA application in the MSMA fb foramsulfuron 2 WAIT fb MSMA 3 WAIT program 1 YAIT is unknown, and begs the examination of the absorption, translocation, and metabolism of foramsulfuron by dallisgrass previously exposed to MSMA.

The difficulty of dallisgrass control may be linked to its perennial structure. Dallisgrass produces an abundance of rhizomes used to store carbohydrates for emergence and growth in subsequent years. Effective dallisgrass control is limited by the ability of the applied herbicides to be absorbed and translocated to kill the perennial structures. Studies on corn and other grass weed species provide some insight into that magnitude of herbicide uptake, movement, and the role of adjuvants. Although 75% of ^{14}C-foramsulfuron was absorbed by two corn hybrids 24 hours after application, less than 1 and 3% of the ^{14}C-foramsulfuron was translocated to plant portions above and below the treated leaf, respectively (Bunting et al. 2004b). The phytotoxicity and absorption of foramsulfuron was reported to increase with the addition of various adjuvants to the spray solution (Bunting et al. 2004a).

The long-term (as assessed by the 1 YAIT visual control estimates) efficacy of the MSMA fb foramsulfuron 2 WAIT fb MSMA 3 WAIT program is a strong incentive for its adoption in place of the three MSMA treatments applied in a traditional MSMA-dallisgrass control program. Although MSMA is still a required component of the new management program, the much higher long-term efficacy of the MSMA fb foramsulfuron fb MSMA program could result in a more permanent reduction in the number and frequency of MSMA applications, because the program more often results in dallisgrass death. The traditional MSMA-dallisgrass control program resulted in weed suppression, but was not often fatal (Table 1). Although effective long-term control was not achieved in our experiment with sequential applications of foramsulfuron alone, further research is needed to evaluate the effectiveness of alternate timings, tank mixes, herbicide programs, and use of adjuvants involving this herbicide.

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Table 1. Control of dallisgrass in bermudagrass 1 MAIT, 3 MAIT, and 1 YAIT[a].

Treatment[b]	rate	1 MAIT	3 MAIT	1 YAIT
	Kg/ha	- - - - - - - -	% Control	- - - - - - - -
MSMA[c] fb foram 1WAIT	2.5 + 0.05	57	24	19
MSMA fb foram 1WAIT	2.5 + 0.09	59	30	21
MSMA fb foram 1WAIT	2.5 + 0.11	66	40	24
MSMA fb foram 1WAIT	2.5 + 0.15	66	33	30
MSMA fb foram 2WAIT	2.5 + 0.05	75	35	20
MSMA fb foram 2WAIT	2.5 + 0.09	81	50	25
MSMA fb foram 2WAIT	2.5 + 0.11	86	54	35
MSMA fb foram 2WAIT	2.5 + 0.15	85	64	37
MSMA fb foram 2WAIT fb MSMA 3WAIT	2.5 + 0.05 + 2.5	90	84	71
MSMA fb foram 2WAIT fb MSMA 3WAIT	2.5 + 0.09 + 2.5	92	87	70
MSMA fb foram 2WAIT fb MSMA 3WAIT	2.5 + 0.11 + 2.5	90	90	79
MSMA fb foram 2WAIT fb MSMA 3WAIT	2.5 + 0.15 + 2.5	94	93	85
MSMA fb MSMA 1WAIT	2.5	68	52	23
MSMA fb MSMA 1WAIT fb MSMA 2WAIT	2.5	89	71	37
Foram fb foram 1WAIT	0.05	40	19	0
Foram fb foram 1WAIT	0.09	42	19	2
Foram fb foram 1WAIT	0.11	59	24	2
Foram fb foram 1WAIT	0.15	60	40	5
Foram fb MSMA 1WAIT	0.11 + 1.25	54	31	15
MSMA fb foram 1WAIT	1.25 + 0.11	55	28	0
Metribuzin fb foram 1WAIT	0.4 + 0.11	48	17	1
MSMA fb MSMA 1WAIT	1.25	49	22	14
Nontreated	——	0	0	0
LSD (P = 0.05)	——	7	8	3

Table 1. (Continued)

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[a] Data were pooled over locations and experimental years.

[b] Single or sequential applications were made with each application within a treatment receiving the same herbicide rate. Foram = foramsulfuron.

[c] MSMA was applied with a non-ionic surfactant at 0.25% v/v.

Table 2. Control of dallisgrass in bermudagrass 1 MAIT, 3 MAIT, and 1 YAIT.

Treatment[a]	1 MAIT	3 MAIT	1 YAIT
	- - - - - - - - -	% Control	- - - - - - - - -
MSMA fb foram 1WAIT	62	32	24
MSMA fb foram 2WAIT	82	51	29
MSMA fb foram 2WAIT fb MSMA 3WAIT	92	88	77
LSD (P = 0.05)	3	5	3

[a] Treatments were averaged across foramsulfuron rates to examine the effect of foramsulfuron application timing and the addition of a second MSMA application.

CHAPTER 3

Absorption, translocation, and metabolism of foramsulfuron in dallisgrass (*Paspalum dilatatum*).

Abstract: Several field studies have observed increased foramsulfuron efficacy for the control of dallisgrass when foramsulfuron is applied after MSMA. Therefore, laboratory studies were conducted to examine the effect of pre applications of MSMA and foramsulfuron on the absorption, translocation, and metabolism of ^{14}C-foramsulfuron when foliar applied to mature dallisgrass. A non-pre-application treatment was used as a control. After 48 h, plants that received either pre-treatment absorbed 70% of the herbicide, while absorption of non-pre-treated plants was 55%. Percent of applied radioactivity detected after 48 h in the treated leaf was approximately 60% regardless of pre-treatment. Translocation above (younger tissue) and below (older tissue) the treated leaf was 0.65 and 0.62% for control plants, respectively. Pre-treated plants exhibited a 2.12 to 2.33% translocation of applied radioactivity above the treated leaf. Translocation below the treated leaf was 1.55% for the pre-foramsulfuron treated plants and 2.34% for the pre-MSMA treated plants. No apparent metabolism of the parent ^{14}C-foramsulfuron was observed in the leaf tissue of dallisgrass, regardless of treatment. These data indicate that the increase in translocation of foramsulfuron to older tissue of the pre-MSMA treated plants may explain the increase in control efficacy observed in the field when comparing it to the pre-foramsulfuron treated dallisgrass plants.

Nomenclature: foramsulfuron, MSMA; dallisgrass, *Paspalum dilatatum* Poir. #[1] PASDI.

Additional index words: turfgrass, golf course, MSMA, dallisgrass, thin-layer chromatography, sulfonylurea.

Abbreviations: YAIT, years after initial treatment; MSMA, monosodium methanearsonate; fb, followed by; DAIT, days after initial treatment; LSS, liquid scintillation spectrometry; ANOVA, analysis of variance; TLC, thin-layer chromatography.

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[1] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th St., Lawrence, KS 66044-8897.

INTRODUCTION

Dallisgrass (*Paspalum dilatatum* Poir.) is one of the most troublesome perennial weed species invading managed turfgrass systems in North Carolina. Dallisgrass has long been used in pastures as a forage and on roadsides for erosion control, but its ability to grow and reproduce in a wide range of environments may have contributed to its success and spread as a turfgrass weed. Growth of persistent rhizomes and the production of seeds on numerous tall divided spikes throughout the growing season lend to its spread (McCarty et al. 2001). The presence of dallisgrass negatively affects the appearance, texture, and playability of desired turfgrass species in home lawns, golf courses, and athletic fields (Turgeon 2005).

Currently, chemical control of dallisgrass is neither efficient, nor cost effective. Typical programs include multiple applications of monosodium methanearsonate (MSMA) (Turgeon 2005), which can be phytotoxic to warm-season turfgrass, or applications of glyphosate, which can be even more harmful to hybrid bermudagrass (*Cynodon transvaalensis* X *Cynodon dactylon* 'Tifway'). Furthermore, these control methods are not entirely effective in eliminating dallisgrass from turf.

The sulfonylurea herbicide foramsulfuron was approved for registration in 2003 by the U.S. Environmental Protection Agency for use in turfgrass. Foramsulfuron is labelled for the post-emergence control of several cool-season grasses, goosegrass, and henbit present within warm-season turf. Busey (2004) reported effective control (>85%) of goosegrass (*Eleusine indica* (L.) Gaertn.) with two applications of foramsulfuron plus metribuzin at 0.21 kg ai/ha. Complete control of Kentucky bluegrass was achieved in 2 of 4 locations with sequential applications of foramsulfuron at 0.03 kg ai/ha (McCullough et al. 2006). Foramsulfuron can be applied to warm-season turf with minimal phytotoxic affects. McElroy et al. (2005)

observed no injury or reduction in bermudagrass cover of four recently sown bermudagrass cultivars after foramsulfuron application. Although foramsulfuron is labeled for the control of cool-season grasses, preliminary analysis showed it as a potential alternative to MSMA and glyphosate for the control of dallisgrass.

Several researchers have examined the efficacy of various rates and timings of foramsulfuron and MSMA for the control of dallisgrass in bermudagrass turf. Henry et al. (2007) observed 5% control of dallisgrass 1 year after initial treatment (YAIT) following sequential applications of foramsulfuron (0.15 kg ai/ha) one week apart. Control increased to 30 to 37% when the initial foramsulfuron application was replaced with an application of MSMA (2.5 kg ai/ha). Ricker et al. (2005) observed a reduction in dallisgrass stands of 50% with sequential applications of foramsulfuron (0.05 kg ai/ha), but long-term control was poor. MSMA applied at 1.8 or 1.1 kg ai/ha followed by (fb) foramsulfuron (0.05 kg ai/ha or 0.07 kg ai/ha) resulted in ≥ 85% dallisgrass control 5 weeks after initial treatment. Slightly higher dallisgrass control (> 90%) 21 to 84 days after initial treatment (DAIT) was reported by Hubbard et al. (2006) when applying MSMA at 1.8 kg ai/ha fb foramsulfuron at 0.1 kg ai/ha 7 and 28 DAIT.

The difficulty of dallisgrass control may be linked to its perennial structure. Dallisgrass produces an abundance of rhizomes, which increases the population, and will emerge and grow in subsequent years. Effective dallisgrass control is provided by foliar applied herbicides that translocate to perennial structures, eventually leading to their death. Studies on corn (*Zea Mays* L.) may provide some insight into the characteristics of foramsulfuron absorption and translocation. Although 75% of ^{14}C-foramsulfuron was absorbed by two corn hybrids 24 h after application, < 1 and 3% of the ^{14}C-foramsulfuron was translocated to plant portions above and below the treated leaf, respectively (Bunting et al. 2004). Metabolism of almost 80% of the parent compound was reported 24 h after treatment in both corn hybrids (Bunting et al. 2004). Observed increases in dallisgrass control efficacy when MSMA is applied before foramsulfuron may be a result of an increase in translocation or altered metabolism of the compound in response to the prior presence of MSMA.

Reasons for differential tolerance of dallisgrass to MSMA and foramsulfuron have not yet been investigated. Likewise, physiological behavior of foramsulfuron in dallisgrass or other perennial grasses has not been reported. Therefore, our objective is to examine the effect of pre-applications of MSMA or foramsulfuron on the absorption, translocation, and metabolism of foramsulfuron in mature dallisgrass plants.

MATERIALS AND METHODS

Plant Culture

Dallisgrass plants were propagated, from previously collected field populations [Lake Wheeler Research Station, Raleigh, NC (35.7 N, -78.7 W)], in greenhouse conditions to evaluate the physiological activity of foramsulfuron. Greenhouse temperatures were 32/22 ± 3 C day/night. Natural lighting was supplemented with artificial light at 600 μmol $m^{-2} \cdot s^{-1}$ photosynthetic photon flux to provide a 14 h photoperiod. The soil medium was a mixture of 50 to 60% horticultural grade Vermiculite, Canadian sphagnum peat moss, horticultural grade Perlite, Dolomitic limestone, and a wetting agent[2]. Plastic pots with a surface area of 182 cm^2 were filled to capacity with soil medium. A 2.5 cm rhizome section of dallisgrass

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[2] Sun Gro Metro Mix 200 Series, Sun Gro Horticulture Distribution Inc., 15831 N.E. 8th St., Suite 100, Bellevue, WA 98008.

from greenhouse stock plants was planted at a 2 cm depth in each pot. Each rhizome section contained several adventitious roots and a 5 cm above-ground shoot. An excess number of pots were planted in order to select a uniform population for experimentation. Plants were irrigated twice daily with an overhead misting irrigation system and fertilized biweekly with a general-purpose fertilizer with micronutrients[3]. Plants were grown to maturity to simulate the approximate size of plants sprayed in the field. After 8 weeks of growth, plants were divided evenly into three groups. One group was treated with foramsulfuron at 0.11 kg ai/ha. A second group was treated with MSMA at 1.25 kg ai/ha plus 0.25% v/v non-ionic surfactant[4]. Group three did not receive an herbicide application. Reduced rates were used in this research to account for enhanced herbicidal activity due to greenhouse growing conditions. Herbicide applications were made using an enclosed-cabinet, track sprayer[5] calibrated to deliver 304 L/ha through an XR8002VS nozzle tip[6] at an operating pressure of 172 kPa. Plants were returned to the greenhouse where overhead irrigation was avoided for the next 24 h. Two weeks after initial application, a shoot from each plant was selected and a

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[3] Peter's 20-20-20 Professional Plant Food. Spectrum Group, Division of United Industries Corporation, P.O. Box 15842, St. Louis, MO 63114-0842.

[4] X-77®, a mixture of alkylarylpolyoxyethylene glycols, free fatty acids, and isopropanol. Valent USA Corp., 1333 North California Blvd., Walnut Creek, CA 94596-8025.

[5] Research Track Sprayer, DeVries Manufacturing Corp., 28081 870th Ave., Hollandale, MN 56045.

[6] TeeJet extended range flat fan tips, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60188.

portion of a center-ranking leaf was covered with tin foil. Foramsulfuron was applied at 0.11 kg ai/ha to all plants with the same enclosed-cabinet, track sprayer.

Absorption and Translocation

Technical grade [pyrimidine-2-^{14}C]-foramsulfuron (Figure 1) with 4.51 MBq·mg^{-1} and 97.1% radioactive purity was used in this experiment. The radioactive solution was a combination of 10 µl of 830 Bq·µl^{-1} radioactivity of ^{14}C-foramsulfuron and the spray solution (0.11 kg ai/ha foramsulfuron). Ten 1- µl droplets[7] of radioactive foramsulfuron solution were placed on the adaxial surface of each previously covered leaf. The droplets were placed laterally between the leaf margin and midrib, midway between the base and the tip.

Plants were excavated from the soil at 2, 4, 8, 24, and 48 h after treatment and divided into treated leaf, above the treated leaf (younger leaves), below the treated leaf (older leaves), and the rest of the plant. Below the treated leaf portions contained the immediate rhizome of the shoot. The rest of the plant was the largest portion and consisted of other shoots, rhizomes, and roots. Five plants (replications) were also spotted with the radiolabeled foramsulfuron solution and harvested immediately to test the efficiency of the leaf wash technique. Foliar absorption of ^{14}C-foramsulfuron was quantified by excising the treated leaf and rinsing it in 10 ml of a 50:50 methanol–water solution for 45 s to remove unabsorbed ^{14}C-foramsulfuron. Aliquots (1-ml) of the leaf wash were added to 15 ml scintillation cocktail[8] and radioactivity was quantified by liquid scintillation spectrometry (LSS)[9]. Plant

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[7] Hamilton® Microliter Pipetter No. 705, Hamilton Co., 4970 Energy Way, Reno, NV 89502.

[8] Ultima Gold®, High flash-point LSC-cocktail, PerkinElmer Life and Analytical Sciences, 549 Albany St., Boston, MA 02118-2512.

parts were stored at -10 C until further analysis. All plant parts were weighed prior to processing. Translocation was determined by grinding plant parts with a mortar and pestle, and subjecting them to extraction filtration under vacuum. Extract (1 ml) was added to 15 ml scintillation cocktail and radioactivity was quantified through LSS. Remaining filter paper[10] was combusted in a biological sample oxidizer[11] using a mixture of carbon dioxide absorbent (10-ml) and scintillation fluid (10-ml) to trap evolved $^{14}CO_2$. All samples were then quantified by LSS.

Data were subjected to analysis of variance (ANOVA) (P = 0.05) with sums of squares partitioned to reflect a split-split plot treatment structure. Harvest interval (0, 2, 4, 8, 24, and 48 h) were considered main plots, pre-application treatments were considered subplots, and the four portions of quantified radioactivity (wash, treated leaf, above the treated leaf, and below the treated leaf) were considered sub-subplots. Log transformation improved homogeneity of variance based on visual inspection of plotted residuals; therefore, data were transformed before ANOVA. The 0 harvest interval was only used in the herbicide absorption analysis. When a significant harvest interval interaction was detected, sample means were fit with the appropriate regression equation to explain the relationship of measured responses over time. Where appropriate, means were separated using Fisher's

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[9] Packard TRI-CARB 2100TR Liquid Scintillation Spectrometer, Packard Instrument Company, 2200 Warrenville Road, Downers Grove, IL 60515.

[10] Whatman® Filter Paper 55 mm, Whatman International Ltd., Whatman Holst Leonards Road Allington Maidstone, Kent ME160LS, U.K.

[11] Model OX-500 Biological Material Oxidizer, R. J. Harvey Instrument Corp., 123 Patterson Street, Hillsdale, NJ 07642.

Protected LSD ($P = 0.05$). Since data transformation did not change mean rank, mean separation tests were performed on non-transformed data for clarity and ease of presentation.

Metabolism

The remaining filtrate from the translocation portion of the research was evaporated to dryness with nitrogen gas. All samples were re-eluted with 1 ml of methanol, sonicated for 30 s, and stored at -10 C until further analysis. Extraction samples (50 µl) were spotted on 20- by 20-cm silica gel thin-layer chromatography[12] (TLC) plates and developed to an 18-cm solvent front. The developing solvent consisted of ethyl acetate-isopropanol-water-ammonium hydroxide 30:50:15:5 v/v/v/v mixture. Plates were partitioned into 1-cm lanes, and a lane was spaced between each spotted lane to prevent contamination. A standard of 5 µl of ^{14}C-foramsulfuron was spotted on the center lane of each plate. Eight additional lanes on each plate were spotted with extracted plant samples, and comparisons were made with the standard to determine the length of travel of the parent compound.

Plates were air-dried after development, and radioactive positions, quantities, and corresponding R_f values were determined by scanning TLC plates with a radiochromatogram[13]. Radioactive peaks were integrated using Win-Scan software[14], with smoothing set to 13-point cubic and background excluded from peak area calculation. Peaks

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[12] Whatman® K6F Silica Gel 60A thin-layer chromatography plates, Whatman Inc., 9 Bridewell Place, Clifton, NJ 07013.

[13] Bioscan System 200 Imaging Scanner, Bioscan, 4590 MacAuthor Boulevard NW, Washington, D.C. 20007.

[14] Lablogic® Win-Scan Radio TLC Version 2.2(5) 32-bit, Bioscan, 4590 MacArthur Blvd. NW, Washington, D.C. 20007.

below 1% of total radioactivity were rejected. Parent herbicide was identified by comparing R_f values from the corresponding standard. Data consisted of the percentage parent herbicide. Statistical procedures were similar to the absorption and translocation portion of the study.

RESULTS AND DISCUSSION

Absorption and Translocation

Run by treatment interactions were non-significant ($P > 0.05$) so data were pooled across experimental runs. Plant absorption of ^{14}C-foramsulfuron followed a logarithmic trend regardless of treatment (Figure 2). Most of the ^{14}C-foramsulfuron was absorbed by 24 h regardless of treatment. An accumulation of 54, 69, and 68% was observed after 48 h for the non-pre, pre-foramsulfuron, and pre-MSMA treated plants, respectively. A 14 to 15% increase in absorption was observed in pre-treated dallisgrass plants compared to non-pre-treated plants. Hook and Glenn (1983) observed an increase in absorption (36, 57, and 50%) of acifluorfen when plants received a mefluidide application 3, 5, or 7 days before ^{14}C-acifluorfen application, respectively. Foramsulfuron absorption observations in our research are similar to previously reported studies concerning foramsulfuron absorption. Bunting et al. (2004) observed 65 to 70% absorption of ^{14}C-foramsulfuron in two hybrid corn varieties after 24 h. Similar trends have also been observed with the absorption of other sulfonylurea herbicides such as nicosulfuron and primisulfuron (Gallaher et al. 1999), halosulfuron and trifloxysulfuron (McElroy et al. 2004), and rimsulfuron (Ackley et al. 1999). Observations in absorption in our research may partially explain differential control of dallisgrass with respect to the two pre-treatments.

The main effects and interactions for treatment and harvest timings were non-significant ($P > 0.05$) for translocation of ^{14}C-foramsulfuron. The treatment by plant partitioning interaction was significant for translocation of ^{14}C-foramsulfuron; therefore, data are presented as the percentage of ^{14}C-foramsulfuron recovered from the leaf wash and plant parts pooled over harvest timings (Table 1). A greater percentage of ^{14}C-foramsulfuron was recovered in the initial leaf wash of the non-pre-treated plants than the pre-treated plants. Consequently, greater percentages of ^{14}C-foramsulfuron were recovered in the treated leaf, above the treated leaf, and below the treated leaf portions of the pre-treated plants. The greatest amount of radioactivity was recovered in the treated leaf (45.6, 59.7, and 60.3%) of the non-pre-treated, pre-foramsulfuron, and pre-MSMA treatments, respectively. Total translocation away from the treated leaf was minimal, regardless of treatment, and was no greater than 3%. Bunting et al. (2004) observed translocation of 0.7 to 1.5% away from the treated leaf of two hybrid corn varieties after 24 h. More translocation in our research was observed in pre-treated plants than non-pre-treated plants. Translocation above the treated leaf was 2.12 and 2.33% for pre-foramsulfuron and pre-MSMA treated plants, respectively, while only 0.65% translocated in non-pre-treated plants. Hook and Glen (1983) observed that translocation of ^{14}C-acifluorfen in common cocklebur (*Xanthium pensylvanicum* Wallr.) increased, with 1.3 or 1.6% of the amount applied found above or below the treated leaf, respectively, with acifluorfen alone and 4.6 or 4.3%, respectively, when mefluidide was applied 7 days earlier. Movement of ^{14}C-foramsulfuron below the treated leaf in our research was statistically different among all treatments. Translocation below the treated leaf was 0.62, 1.55, and 2.34% for non-pre-treated, pre-foramsulfuron, and pre-MSMA treated plants, respectively. Greater herbicide movement to the meristematic regions of the plant can contribute to greater herbicidal activity, because acetolactate synthase is most active in developing tissue. However, in our research, it is not clear why the treatment with the greatest efficacy in the field (pre-MSMA) has significantly more radioactivity translocated below the treated leaf after 48 h than the pre-foramsulfuron treated plants.

Metabolism

Results of the metabolism portion of the study are presented in Figure 3. No apparent metabolism of the parent compound foramsulfuron was observed in the leaf tissue of dallisgrass plants regardless of treatment. The level of radioactivity for the TLC chromatogram was lower for non-pre-treated plants than either pre-treatment due to a higher percentage of absorption of ^{14}C-foramsulfuron into and movement out of the treated leaf (as discussed in the absorption and translocation results). For each treatment, only one peak with an R_f value of 0.59 was detected. The R_f value for this peak matched that of the standard ^{14}C-foramsulfuron.

Metabolism work conducted by Bunting et al. (2004) detected three metabolites of ^{14}C-foramsulfuron using TLC techniques. Less than 50% of the parent ^{14}C-foramsulfuron remained in both corn hybrids after 4 h, and less than 20% remained after 24 h. Askew and Wilcut (2002) observed three metabolites of ^{14}C-trifloxysulfuron in cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogaea* L.), jimsonweed (*Datura stramonium* L.), and sicklepod (*Senna obtusifolia* (L.) Irwin and Barnaby). McElroy et al. (2004) observed 23 and 39% metabolism of ^{14}C-halosulfuron and ^{14}C-trifloxysulfuron, respectively, when absorbed by green kyllinga (*Kyllinga brevifolia* Rottb.) and false-green kyllinga (*Kyllinga gracillima* L.). Similar to our findings, Zawierucha and Penner (2000) observed no metabolism of ^{14}C-quinclorac by *Digitaria sanguinalis* L. or *Eleusine indica* L. after an 80-h exposure time using reversed-phase high-performance liquid chromatography. Hook and Glenn (1984) observed that metabolism of ^{14}C-acifuorfen was reduced in ivyleaf morningglory (*Ipomoea hederacea* (L.) Jacq.) and velvetleaf (*Abutilon theophrasti* Medic.) with 3-, 5-, and 7-day pre-treatments with mefluidide. Accompanying this slower metabolism was a decrease in the metabolite(s) that remain at the origin (metabolite A) of the TLC plate with 3-, 5-, and 7-day sequential treatments in ivyleaf morningglory and 5- and 7-day sequential treatments in velvetleaf.

In the dallisgrass study there were no differences observed in foramsulfuron metabolism between non-pre-treated and pre-treated treatments; therefore, this phenomenon may not be able to explain results observed in our research. Sequential applications of foramsulfuron have been observed to provide < 5% control of dallisgrass 1 YAIT (Henry et al. 2007). Consequently, since there was no apparent metabolism in the leaf tissue of the ^{14}C-foramsulfuron by dallisgrass in any treatment, we suggest there must be another factor or group of factors that convey differences in efficacy with respect to pre-treatment.

Results of this research suggest that MSMA may enhance the activity of foramsulfuron on dallisgrass by increasing translocation away from the treated leaf. Henry et al. (2007) reported a 25 to 32% increase in dallisgrass control when MSMA was applied 1 or 2 weeks before foramsulfuron compared to sequential applications of foramsulfuron alone. This may correspond to an increase in translocation of foramsulfuron to older leaf tissue after MSMA application (Table 1). It is conceivable that MSMA could be applied in bermudagrass turf at specific intervals prior to application of foramsulfuron to increase the control of dallisgrass, while causing no greater injury to bermudagrass.

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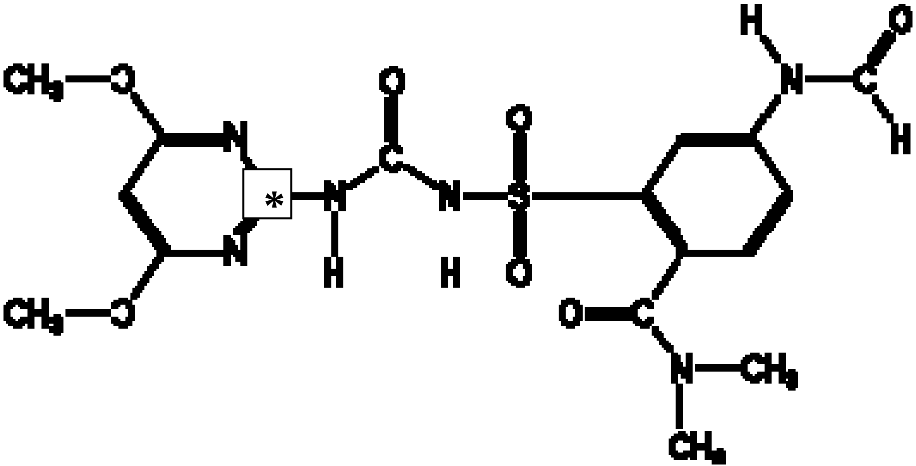

Figure 1. Structure of foramsulfuron. * Denotes the position of ^{14}C.

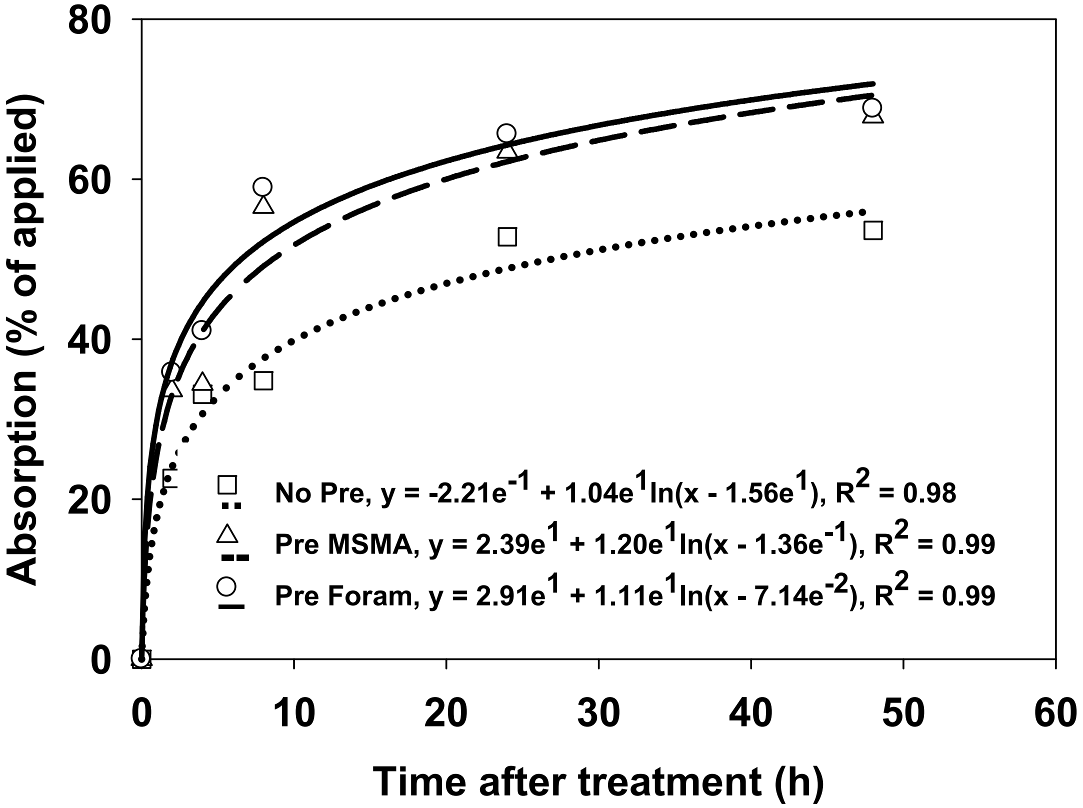

Figure 2. Percent absorption of [pyrimidine-2-^{14}C]-foramsulfuron by dallisgrass after pre-treatment over time, averaged over trials.

Table 1. Percentage of ^{14}C-foramsulfuron applied by dallisgrass recovered in the partitioned plant parts, averaged over harvest intervals 2 to 48 h.[a]

Treatment	Wash	Treated leaf	Above treated leaf	Below treated leaf
	---------------------------- % of recovered ----------------------------			
No pre	46.4	45.6	0.65	0.62
Pre foram[b]	31.2	59.7	2.12	1.55
Pre MSMA	32.2	60.3	2.33	2.34
LSD[c]	10.9	3.8	0.43	0.36

[a] Data reflects the percent of the total ^{14}C-foramsulfuron herbicide recovered. Fisher's LSD (P = 0.05) was not conducted between plant parts of a given treatment, because of unequal variances between the partitioned plant parts.

[b] Abbreviations: foram, foramsulfuron.

[c] Fisher's Protected LSD conducted at P = 0.05.

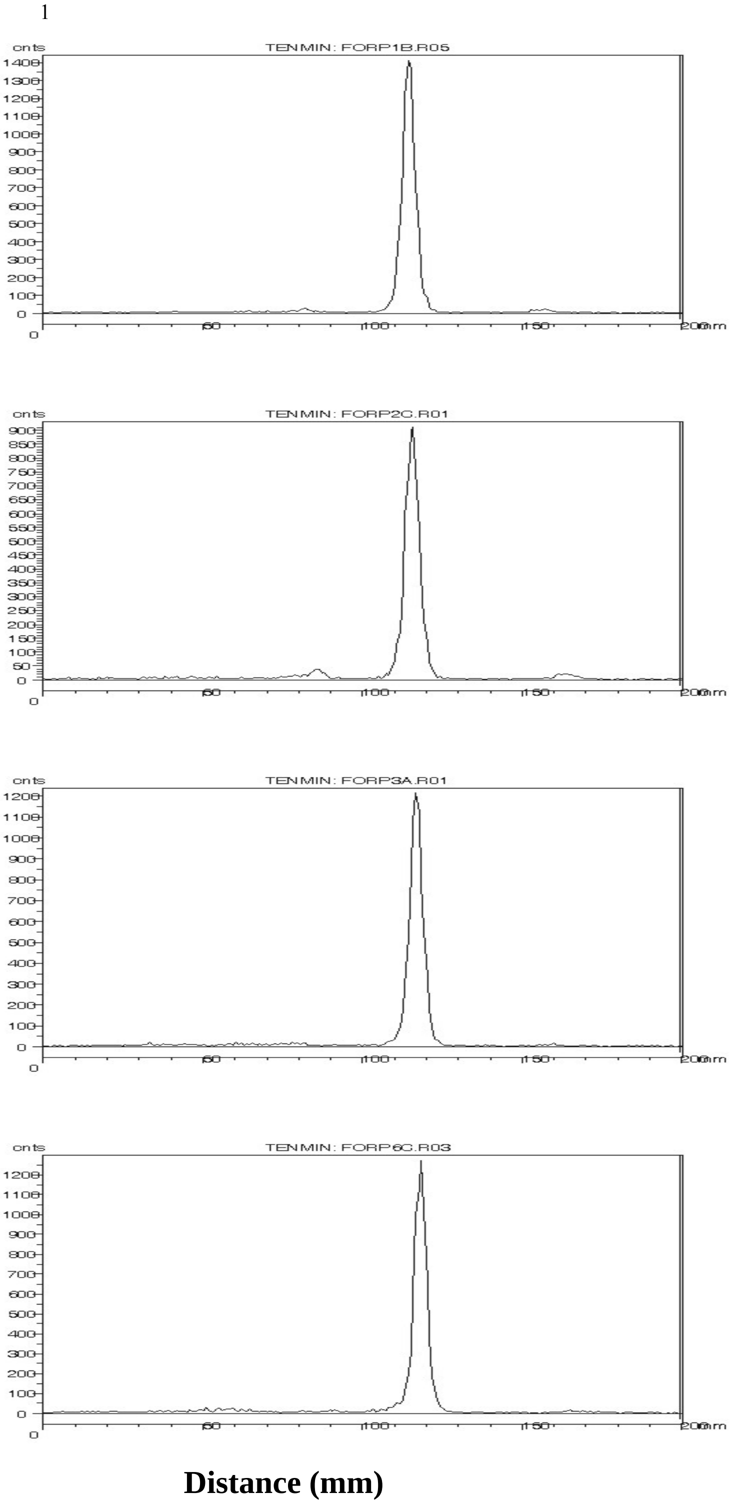

Figure 3. TLC of ^{14}C- foramsulfuron standard (A) vs. non-pre-treated (B), pre-foramsulfuron (C), and pre-MSMA treatments (D) after 48 h of exposure.

[1] radioactivity (counts·min^{-1}).

CHAPTER 4

Heterogeneous Distribution of Weedy *Paspalum* Species and Edaphic Factors in Turfgrass.

Abstract: Dallisgrass (*Paspalum dilatatum* Poir.) and bahiagrass (*Paspalum notatum* Fluegge) are two of the most troublesome weed species in managed turfgrass. These rhizomatous, perennial grass species affect appearance, texture, and playability of turf in home lawns, golf courses, and athletic fields. The severity and prevalence of these problem species, as well as the difficulty of achieving control with herbicide management alone, invite the examination of their realized niches for clues to improved management tactics. The distribution of these species was evaluated in both fairways and roughs of three holes on each of two golf courses in North Carolina. Golf courses were selected based on the presence of both weed species. Individual plants were mapped using a high-precision global positioning system (GPS) unit. This unit was also used to delineate between the rough and fairway height of cut as well as obtain elevation characteristics of each hole. Soil moisture and soil compaction estimates were obtained by sampling on a 9-m grid. Environmental characteristics used for chi-square analysis consisted of mowing height, soil compaction, soil moisture, and elevation. Data were subjected to chi-square analysis in order to determine if the extant distribution of *Paspalum* spp. differed from an expected random distribution across all environmental factors. Bahiagrass growth and distribution was more affected by mowing height than dallisgrass. Bahiagrass was predominantly distributed in the rough, while dallisgrass occurred at both mowing heights. Similar responses were observed for both species with regards to soil compaction. Higher plant density for both species was observed

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in moderately compacted soil (40 to 60 N). Bahiagrass distribution was not affected by soil moisture. Dallisgrass density was lower in areas with low volumetric soil water content (< 27%). Although different from an expected uniform distribution on all 6 holes, the elevation with the highest *Paspalum* spp. density varied across holes. Results suggest that it may be possible to disadvantage *Paspalum* spp. in competitive interactions with desirable species by altering landscape attributes and cultural practices. Substrate selection during construction, aeration, and mowing height may help create a landscape that discourages *Paspalum* spp. infestation.

Nomenclature: dallisgrass, *Paspalum dilatatum* Poir. # PASDI[1]; bahiagrass, *Paspalum notatum* Fluegge. # PASNO; hybrid bermudagrass, *Cynodon transvaalensis* X *Cynodon dactylon* ‘Tifway 419’; common bermudagrass, *Cynodon dactylon* (L.) Pers.

Additional index words: realized niche, turfgrass management, weed science, GPS, spatial distribution, soil moisture, soil compaction, mowing height, elevation.

Abbreviations: GPS, global positioning system.

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[1] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th St., Lawrence, KS 66044-8897.

INTRODUCTION

The perception of weed management changed from a systems approach to a reliance on chemical weed control soon after the introduction of herbicides (Mortensen et al. 2000). Unfortunately, the onset of the “herbicide era” has yet to yield the eradication of a single weed species, while several new troublesome weed species have increased in number (Altieri 1991). Growing public concern and increasing occurrence of herbicide resistance has fueled the interest of several countries to propose herbicide use reductions. Knowledge of the interaction between weeds, their management tactics, and the environment they exist in would better equip us for their control than over reliance on chemical control options (Mortensen et al. 1998a; Mortensen et al. 2000).

The development of integrated weed management strategies for managed ecosystems centers around habitat delineation of weed species (Cardina et al. 1997). The manipulation of environmental factors to improve crop growth conditions may be feasible through the correct identification of optimal environmental factors for weed growth and those unsuitable for desired crop growth, while further reducing the amount of herbicide inputs (Johnson et al. 1997; Mortensen et al. 1998b). This is especially true for perennial weeds in natural ecosystems or reduced tillage systems, where plowing and cultivation are not management options.

Landscape attributes and weed species presence are spatially variable (Cardina et al. 1997; Johnson et al. 1995, 1996; Marshall 1988; Thornton et al. 1990). In contrast, weed control tactics are often selected and implemented based on average field conditions. Investigating the spatial association of weed populations with edaphic and topographic features has the potential to benefit growers by reducing both input costs and the unneeded application of control tactics.

The introduction of new equipment and computer software used in georeferencing and managing data has made the study of spatial distribution of weeds with respect to their environment much easier (Dieleman and Mortensen 1999; Prather and Callihan 1993). A global positioning system (GPS) can be a valuable instrument for monitoring the spread and establishment of perennial weeds over time and may provide researchers with information about the effect of current management practices on specific perennial weeds (Webster and Cardina 1997).

Several agronomic studies have examined the impact of cultural practices on the environment and the subsequent impact that the environment has on weed species distribution. Medlin et al. (2001) determined that sicklepod [*Senna obtusifolia* (L.) Irwin and Barnaby] infestation in agricultural fields was best predicted by organic matter content, phosphorus, potassium, and magnesium concentrations in the soil. Correlations between the presence of several broadleaf weeds with increased soil organic matter and lower topography were observed by Burton et al. (2004, 2005) and Dieleman et al. (2000). Andreasen et al. (1991) correlated increasing common lambsquarter (*Chenopodium album* L.) populations with decreasing soil phosphorous and increasing common chickweed [*Stellaria media* (L.) Vill.] with increasing soil potassium.

To date, little information exists on the spatial dynamics of perennial turfgrass weeds. McElroy et al. (2005) correlated the presence of green kyllinga (*Kyllinga brevifolia* Rottb.) and false-green kyllinga (*Kyllinga gracillima* L.) on golf course fairways with increasing volumetric soil water content. Snaydon (1962) correlated increased white clover (*Trifolium* *repens* L.) density present in *Festuca* spp. – *Agrostis* spp. grass swards with soil pH, calcium, and phosphorus.

In North Carolina, dallisgrass (*Paspalum dilatatum* Poir.) and bahiagrass (*Paspalum notatum* Fluegge), are two of the most prevalent and difficult to control weed species in turfgrass. They are both rhizomatous, perennial grass species that readily invade golf course fairways and roughs. Few post emergence herbicide options exist for the effective, economical control of these weeds (Henry et al. 2007; Hubbard et al. 2006; Ricker et al. 2005). These species are widely distributed throughout the state and anecdote suggests both tolerate droughty, sandy soils and moist, clayey soils. However, no known studies have examined the distribution of these species with respect to soil/environmental conditions or landscape features in managed turfgrass environments. Therefore, the objective of our research is to characterize the spatial distribution of naturally occurring populations of dallisgrass and bahiagrass and examine possible associations with mowing height, soil penetration resistance, volumetric soil water content, and elevation.

MATERIALS AND METHODS

Ecological surveys were conducted on three golf course holes (rough and fairway) in the fall of 2004 at Hidden Valley Golf Club, Willow Springs, NC, and 2005 at Riverwood Golf Club, Clayton, NC. Golf courses were selected based on the presence of naturally occurring populations of dallisgrass and bahiagrass. The fairways and roughs of both golf courses are comprised of hybrid bermudagrass (*Cynodon transvaalensis* X *Cynodon dactylon* 'Tifway 419') mowed to a height of 1.3 and 6.4 cm, respectively, and at a frequency of twice and once weekly, respectively. Fairways and roughs were supplied with supplemental irigation on a need basis to promote vigorous and healthy turf. The soil types present at Hidden Valley G. C. and Riverwood G. C. were a Wagram loamy sand (Loamy, kaolinitic, thermic Arenic Kandiudults) and a Norfolk loamy sand (Fine-loamy, kaolinitic, thermic Typic Kandiudults), respectively.

A real-time kinematic GPS unit[1] was used to delineate mowing height (fairway vs. rough), georeference *Paspalum* spp., and obtain elevation characteristics of each golf course hole. A differentially-corrected GPS unit[2] in combination with Farm Site Mate 7.13 software, was used to superimpose a 9-m grid over each fairway and rough in order to sample for volumetric soil water content (soil moisture) and penetration resistance (soil compaction). The antenna was mounted just above the sensor, to obtain sub-meter accuracy. Volumetric soil water content samples were recorded 3 days after an irrigation or rainfall event and were measured with a theta probe[3] [measures percent volumetric soil water content in the top 10 cm of the soil profile (+/- 1%)]. Soil penetration resistance samples were recorded 3 days after an irrigation or rainfall event and were measured with a penetrometer[4] (estimates penetration resistance to a maximum depth of 12 cm in the soil profile). Two samples of each measurement were obtained at every reference location to ensure consistent instrument readings.

Categorical ranges were created for each landscape characteristic using Jenk's Natural Breaks Method with ArcMap software[5]. Data from the 9-m grid sampling were interpolated using the Kriging method to create raster maps of each landscape characteristic for each golf course hole. A spherical semi-variogram model with a variable radius type set to 12 was

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[1] CMT Z33 Dual-Frequency GPS, CMT Inc., Corvallis, OR.
[2] Trimble AgGPS 132, Trimble, Sunnyvale, CA.
[3] TH2O Theta Probe, Delta-T Devices, Ltd., Cambridge, England.
[4] Lang penetrometer, Lang Penetrometer Inc., Gulf Shores, AL.
[5] ArcMap 8.1 software, ESRI, Redlands, CA.

performed by the Kriging method. Kriging uses prior knowledge about the spatial distribution of a variable to predict values of said variable at unobserved points (Figure 1). The number of each *Paspalum* species was determined in every categorical range of each landscape characteristic.

Data were subjected to chi-square analysis. Chi-square analysis is calculated by finding the difference between each observed and expected frequency for each possible outcome, squaring them, dividing each by the expected frequency, and taking the sum of the results:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

where:

O_i = an observed frequency

E_i = an expected frequency

Chi-square analysis was used to test for goodness of fit to an expected, random distribution with respect to each landscape characteristic for each *Paspalum* spp. for each golf course hole (Table 1). A test of goodness of fit establishes whether or not an observed frequency distribution differs from an expected, random distribution. Chi-square analysis was used to test the associations between categorical data at $P < 0.05$. Preferred environments (categorical ranges) were reported for each species whose distribution differed from the expected distribution with respect to each landscape characteristic tested.

RESULTS AND DISCUSSION

Mowing height

Spatial distribution of both *Paspalum* spp. on all six golf course holes was affected by mowing height ($P \leq 0.001$) (Table 2). Large patches of bahiagrass plants were observed in the rough of all holes, while few plants were recorded in the fairway. Henry et al. (2007) observed that bahiagrass lateral spread and rhizome production was reduced 44 to 62% and 70 to 73%, respectively, when mowed at 1.3 cm when compared to a non-mowed check. Lateral spread and rhizome production reductions were only 21 to 27% and 24 to 33%, respectively, when bahiagrass was mowed at 7.6 cm. Reductions in bahiagrass lateral spread and rhizome production in response to low mowing may be attributed to its morphology. Bahaigrass plants produce shallow, often-exposed rhizomes at the soil surface (McCarty et al. 2001). The increased frequency associated with close mowing and subsequent wear common to golf course fairways may cause extensive damage to bahiagrass rhizomes. The erect architecture of bahiagrass leaves and low shoot density create an open turf (Turgeon 2005), making it very susceptible to competition from other turf and weed species. Therefore, when mowed at a low height of cut, reductions in lateral spread and rhizome production combined with competition from close-mowing tolerant species like hybrid bermudagrass may create a habitat unsuitable for bahiagrass growth.

Dallisgrass plants were predominantly found in the rough, but many plants were also observed in the fairway. Plants in the fairway were typically smaller in diameter than those observed in the rough (visual assessment, data not shown). Henry et al. (2007) reported reductions in dallisgrass lateral spread of 38 to 47% when compared to a non-mowed check, regardless of mowing height (7.6, 5.2, or 1.3 cm). Reductions in dallisgrass rhizome production were 30 to 49, 30, and 37 to 57% when mowed at 7.6, 5.2, and 1.3 cm, respectively. Similar reductions in dallisgrass lateral spread and rhizome production in response to all mowing heights may be attributed to its morphology. Dallisgrass plants produce rhizomes deep beneath the soil surface. The protection of the soil may reduce potential damage due to low and frequent mowing, and wear. Although dallisgrass plants were tolerant to close mowing, its bunch-type growth habit and direct competition with bermudagrass may make it difficult to spread throughout the fairway.

Penetration resistance (soil compaction)

Soil compaction was identified as a factor apparently affecting spatial distribution of both *Paspalum* spp. on all six golf course holes ($P \leq 0.001$) (Table 2). Bahiagrass and dallisgrass were observed predominantly in areas with penetration resistance readings of 45 to 64 N. This range of soil compaction is considered moderate and areas of this magnitude consistently had dense, healthy bermudagrass turf cover.

Plant stress caused by soil compaction is often considered an indirect stress. Heavy and frequent traffic can alter the structure of the soil in a way that influences the aeration and moisture characteristics of the soil profile. Soil compaction can cause several physiological and morphological responses in plants including reduced shoot and root growth, reduced nutrient and water uptake, and reduced tolerance to heat and drought stress (Turgeon 2005).

Valoras et al. (1966) observed a reduction in top growth of common bermudagrass from 0.83 g dry weight to 0.40 g when grown in compacted soil conditions. Thurman and Pokorny (1969) also observed reductions in shoot growth of bermudagrass subjected to compaction. Letey et al. (1966) observed a reduction in root length of plants grown in compacted soils when compared to plants grown in non-compacted soils. Although bermudagrass morphology is negatively affected by soil compaction, the dense, aggressive growth habit of bermudagrass may enable it to tolerate compaction better than dallisgrass and bahiagrass. Carrow et al. (2001) observed higher turf coverage for *Cynodon* spp. subjected to soil compaction and turfgrass wear than *Paspalum vaginatum*, a turf-type grass in the same genus as dallisgrass and bahiagrass.

Volumetric soil water content (soil moisture)

Soil moisture was identified as a factor apparently affecting spatial distribution of bahiagrass on one hole ($P < 0.05$) and not on the other five (Table 2). The small bahiagrass sample size (73) associated with the one hole may have affected the resulting chi-square analysis. Van Wychen et al. (2004) observed increasing wild oat (*Avena fatua* L.) growth and seed production regardless of field-scale heterogeneity of soil water use with or without competition from spring wheat (*Triticum aestivum* L.). Henry et al. (2006) suggested a possible correlation between bahiagrass competitive success (against bermudagrass) and low soil moisture content. Bahiagrass shoot and rhizome growth was greatest at the upper, droughtier levels of each soil moisture gradient tank when grown on sandy loam soil, regardless of whether grown in monoculture or in competition with hybrid bermudagrass ($P < 0.0001$). Survival of bahiagrass was unaffected by the soil moisture gradient regardless of soil type or whether grown in monoculture or in competition with hybrid bermudagrass ($P < 0.0001$). The morphology of bermudagrass may provide insight into its ability to tolerate a wide range of soil moisture levels. Bahiagrass produces an extensive amount of adventitious roots that extend deep within the soil profile (Turgeon 2005). A deep root system may allow bahiagrass to access soil moisture resources that would be difficult for other species to acquire. As previously mentioned, bahiagrass produces an abundance of shallow, often-exposed rhizomes at the soil surface (McCarty et al. 2001). The extension of rhizomes above the soil surface may allow for gas exchange in the presence of saturated soil conditions. Hybrid bermudagrass survival was greatly reduced in the droughtier portions of each gradient tank (Henry et al. 2006). Huang et al. (1997) reported a reduction in root growth of common bermudagrass (*Cynodon dactylon* (L.) Pers.) when the upper 20- and 40-cm layers of the soil profile were dried. Root dry weight of common bermudagrass only partially recovered to control levels after rewatering. Reductions in root growth and recovery during and after drought conditions may make bermudagrass less competitive against bahiagrass.

Dallisgrass spatial distribution was affected by soil moisture level on all six golf course holes ($P \leq 0.001$) (Table 2). Dallisgrass was predominantly observed in areas that had percent volumetric water content > 27%. McElroy et al. (2004) reported that both green and false-green kyllinga were correlated with volumetric water levels greater than field capacity at five golf course locations. Henry et al (2006) suggested a possible correlation between dallisgrass success in competition with hybrid bermudagrass and high soil moisture content. Maximum rhizome and shoot production was observed on the lower, more saturated portions of each soil moisture gradient tank regardless of soil type. Dallisgrass survival was reduced in the upper, droughtier portions. Rubio et al. (1995) and Rubio and Lavado (1999) observed a slight promotion of growth in *P. dilatatum* plants when exposed to flooding, while Loreti and Oesterheld (1996) only observed an increase in biomass accumulation in one of three biotypes they examined. They observed that drought reduced yield equally across three *P. dilatatum* biotypes. The tolerance of dallisgrass to high soil moisture may be described by its growth characteristics and anatomical changes in response to flooding. Leaf extension rates and tiller height were also higher in flooded *P. dilatatum* plants (Insausti et al. 2001; Rubio et al. 1995; Loreti and Oesterheld 1996). Increasing plant height is a flooding response that allows avoidance of leaf submergence (Laan and Blom 1990; Van der Sman et al. 1993; Oesterheld and McNaughton 1991). *P. dilatatum* was observed to produce aerotropic and adventitious roots that grow upward to oxygenated areas (Rubio et al. 1995), thus supplying oxygen to the roots (Glinski and Stepniewski 1985; Kozlowski 1984). Several researchers also observed an increase in root aerenchyma tissue of *P. dilatatum* in response to flooding (Rubio et al. 1995; Loreti and Oesterheld 1996; Vasellati et al. 2001). Increased aerenchyma tissue is a common adaptive response of plants to soil anoxia (Jackson and Drew 1984; Justin and Armstrong 1987; Jackson and Armstrong 1999). Scifries and Mutz (1975) reported that longtom (*Paspalum lividum* Torr.) initially stabilized areas as free-standing water withdrew, followed by common bermudagrass following extended fresh water inundation for several years in a coastal rangeland. The presence of common bermudagrass immediately following the removal of free-standing water may confirm its ability to tolerate saturated soil environments. Therefore, in the presence of saturated soil conditions, dallisgrass and hybrid bermudagrass may remain competitive with one another.

Elevation

Although different from an expected uniform distribution on all six holes, the elevation with the highest *Paspalum* spp. density varied across holes. Van Wychen (2004) reported that elevation correlated with existing wild oat patches in individual fields, but wasn’t consistent with wild oat patches in all three fields. Elevation leads to edaphic heterogeneity along elevation gradients by influencing spatial patterning of edaphic variables (Beckett and Webster 1971; Brubaker et al. 1993; Day et al. 1987; Miller et al. 1988). McElroy et al. (2004) hypothesized that the influence of elevation on edaphic variables led to a lack of significant correlations. The effect of elevation on edaphic variables was significant at all site locations, but results varied across sites.

Chi-square analysis is limited by its inability to examine interactions between edaphic variables with respect to species distribution. Therefore, ignoring obvious relationships between elevation, soil moisture, soil compaction, and mowing height may have complicated our attempts to associate edaphic variables with the presence of dallisgrass and bahiagrass. However, our results suggest that high mowing height is a major contributor to dallisgrass and bahiagrass proliferation and is probably related to decreased turfgrass competitiveness. Therefore, the most conceivable integrated weed management strategy for dallisgrass and bahiagrass would be to decrease the mowing height in the rough to discourage *Paspalum* spp. growth and encourage the competitiveness of bermudagrass. Based on our results, this may not be as effective for dallisgrass management. More frequent mowing in the rough may also reduce seedhead production and further improve long term management of these weeds. High soil moisture may also lead to increased infestation of *Paspalum* spp. and is probably related to decreased turfgrass growth. Thus, the most plausible management strategy for dallisgrass and bahiagrass would be to maintain adequate soil moisture but avoid over irrigation. Installation of subsurface drainage may reduce standing water in frequently inundated areas and further improve long-term control of these weeds. Low soil moisture may lead to increased infestation of bahiagrass and is probably related to decreased turfgrass growth or plant death. Maintaining adequate soil moisture, applying wetting agents, and amending the soil to increase water holding capacity may aid in the control of bahiagrass in situations of low soil moisture

Weed spatial distribution and habitat suitability will differ for other species. Extrapolating correlative results between environmental factors and weed species distribution should be done with great caution, especially for weeds with a wide geographic range. The effects of fecundity, seed dispersal, management, and habitat need to be considered when predicting weed population distributions across turfgrass environments. More importantly, potential influence of edaphic conditions on weed management along elevation gradients should be considered high priority by golf course designers in order to avoid potential edaphic heterogeneity (such as drainage and soil compaction) and aid in the reduction of suitable habitats for weed invasion.

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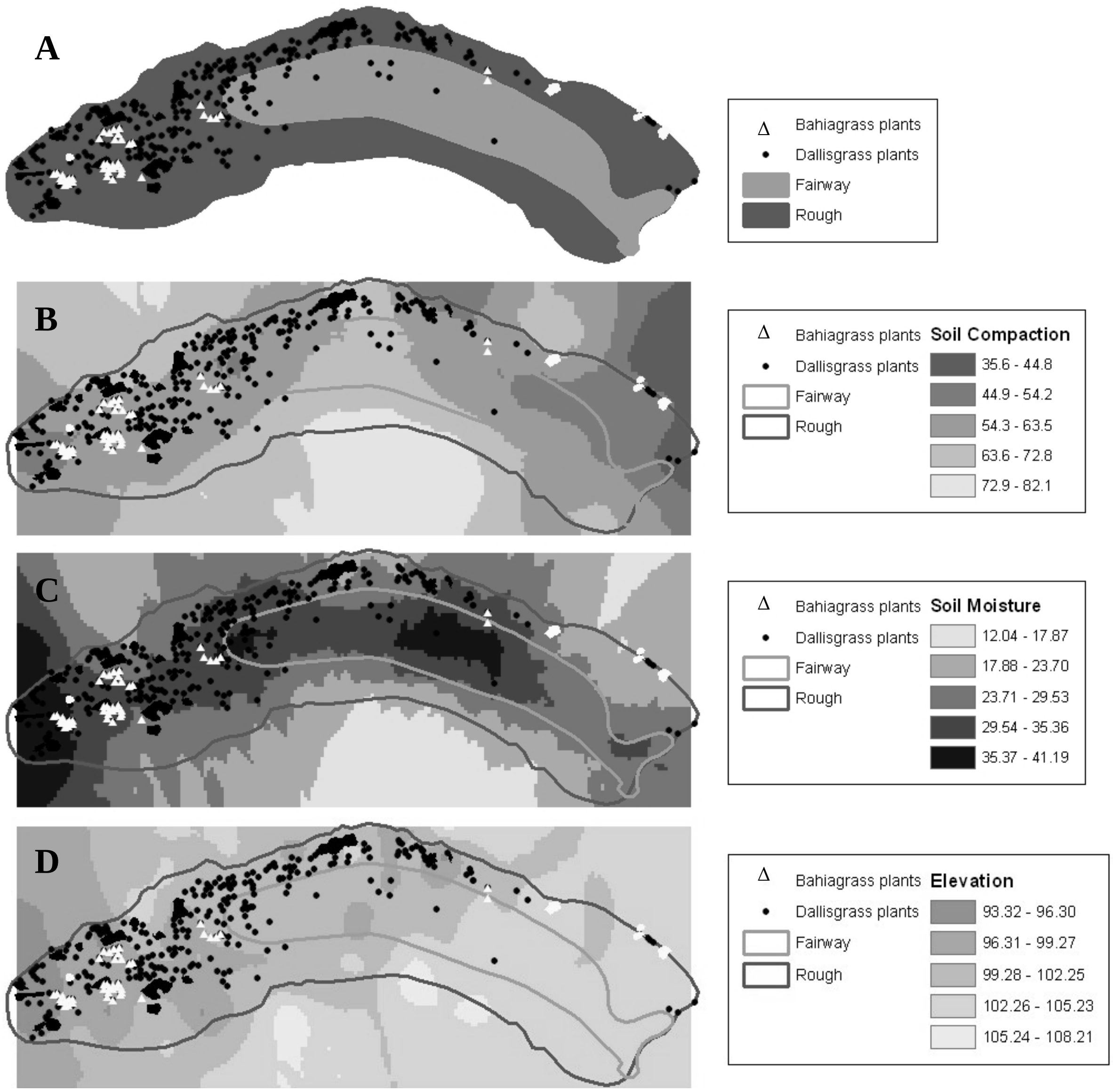

Figure 1. Distribution of dallisgrass and bahiagrass on hole 14, Hidden Valley Golf Course, Willow Springs, NC, with respect to: A. Mowing height; B. Soil compaction; C. Soil moisture; D. Elevation.

Table 1. Chi-square analysis of dallisgrass frequency with respect to soil compaction for hole 14, Hidden Valley Golf Club, Willow Springs, NC.

	-----------------------------Soil Compaction (N) †-----------------------------				
Dallisgrass	35.6 – 44.8 ‡	44.9 – 54.2	54.3 – 63.5	63.6 – 72.8	72.9 – 82.1
---present---					
Observed	25	70	145	43	0
Expected	56.6	56.6	56.6	56.6	56.6
---absent---					
Observed	258	213	138	240	283
Expected	226.4	226.4	226.4	226.4	226.4

† N = Newtons.

‡ Ranges were determined using Jenk’s Natural Breaks Method.

Table 2. Chi-square analysis of dallisgrass and bahiagrass spatial distribution with respect to landscape factors on six golf course holes in North Carolina.

Variable	Range of N † Across Holes	Total N Across Holes	df	P-value	Apparent Optimal Environment
---bahiagrass---					
Mowing height	(73 – 224)	928	1	all ≤ 0.001	Rough
Soil compaction	(73 – 224)	928	4	all ≤ 0.001	45 to 64 N
Soil moisture	(73 – 224)	928	4	P ≤ 0.05, 5 NS ‡	Unaffected
Elevation	(73 – 224)	928	4	all ≤ 0.001	Volatile §
---dallisgrass---					
Mowing height	(278 – 1043)	2481	1	all ≤ 0.001	Rough
Soil compaction	(278 – 1043)	2481	4	all ≤ 0.001	45 to 64 N
Soil moisture	(278 – 1043)	2481	4	all ≤ 0.001	%VWC > 27% *
Elevation	(278 – 1043)	2481	4	all ≤ 0.001	Volatile

† N is number of observations.

‡ Soil moisture was significant at the P ≤ 0.05 level on one hole and not significant on the other five holes.

§ Although chi-square analysis indicated distributions that were significantly different from expected distributions in all cases, the pattern of distribution across elevation differed among holes and was not predictable.

* %VWC is percent volumetric water content.

CHAPTER 5

Effect of Mowing on Lateral Spread and Rhizome Growth of Troublesome *Paspalum* Species.

Abstract: The effect of mowing regime on lateral spread and rhizome growth of *Paspalum dilatatum* Poir. (dallisgrass) and *Paspalum notatum* Fluegge (bahiagrass) was determined in field studies conducted in 2003 and 2004 in North Carolina over five month periods. Treatments were selected to simulate mowing regimes common to intensively managed common bermudagrass turfgrass and included mowing at 1.3, 5.2, and 7.6 cm at frequencies of three, two, and two times per week, respectively. A non-mowed check was included for comparison. Lateral spread of dallisgrass was reduced 38 to 47% regardless of mowing regime when compared to the non-mowed check. Rhizome fresh weight of dallisgrass was reduced 49% in 2003 and 30% in 2004 when mowed at the 7.6-cm regime after five months, while the 5.2-cm mowing regime caused a similar reduction in rhizome fresh weight of 31%. Rhizome fresh weight of dallisgrass was most negatively affected by the 1.3-cm regime, which caused reductions of 57% in 2003 and 37% in 2004. Lateral spread of bahiagrass was more strongly affected by mowing height and frequency than dallisgrass, with reductions of 21 to 27%, 40%, and 44 to 62% when mowed at 7.6, 5.2, and 1.3-cm regimes, respectively. Rhizome fresh weight of bahiagrass was reduced 24 to 33%, 55%, and 70 to 73% when mowed at 7.6, 5.2, and 1.3 cm, respectively. These results suggest that areas mowed at a golf course rough height may be more conducive to bahiagrass spread, while dallisgrass may tolerate areas mowed at a fairway height. Mowing at the shorter heights examined in this study clearly reduced the potential of *Paspalum* spp. vegetative spread and may help to explain observed distributions of *Paspalum* spp. infestations in bermudagrass turfgrass.

Nomenclature: common bermudagrass, *Cynodon dactylon* (L.) Pers.; dallisgrass, *Paspalum dilatatum* Poir. #[1] PASDI; bahiagrass, *Paspalum notatum* Fluegge # PASNO.

Additional index words: turfgrass, golf course, biology, rhizome production, dallisgrass, bahiagrass.

Abbreviations: SRS, Sandhills Research Station; LWRS, Lake Wheeler Research Station; MAIT, months after initial treatment; ANOVA, analysis of variance; PAR, photosynthetically active radiation.

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[1] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th St., Lawrence, KS 66044-8897.

INTRODUCTION

Dallisgrass (*Paspalum dilatatum* Poir.) and bahiagrass (*Paspalum notatum* Fluegge) (hereafter referred to as *Paspalum* spp. when discussed collectively) are perennial warm-season grasses that readily invade managed turfgrass systems in North Carolina. Infestations may spread through the growth of persistent rhizomes and the production of seeds on numerous tall divided spikes from May through October. The presence of either *Paspalum* spp. in desired turfgrass negatively affects the appearance, texture, and playability of golf courses, athletic fields, and home lawns.

Paspalum spp. have long been used in pastures, forages, and roadsides, but their ability to grow and reproduce in a wide range of environments contributes to their success and spread as turfgrass weeds. For example, several controlled environment experiments showed that *P. dilatatum* tolerates high soil moisture content (Henry et al. 2006b, Rubio et al. 1995, Rubio and Lavado 1999, Loreti and Oesterheld 1996), while *P. notatum* tolerates low (Henry et al. 2006b, Miller and McCarty 2001) and high (Henry et al. 2006b) soil moisture content. Spatial distribution research recently conducted on golf course fairways and roughs showed strong correlations between volumetric soil moisture and mowing height with *Paspalum* spp. presence (Henry et al. 2006a).

Currently, chemical control of *Paspalum* spp. is neither efficient, nor cost effective. Typical programs for the control of *P. dilatatum* include multiple applications of monosodium methanearsonate (MSMA), which can be phytotoxic to warm-season turfgrass, or applications of glyphosate, which can be even more harmful to bermudagrass (*Cynodon dactylon* (L.) Pers.). Experiments with various timings and combinations of foramsulfuron and MSMA have recently been conducted for the control of *P. dilatatum* with varied success

(Warren et al. 2006, Henry et al. 2007, Ricker et al. 2005). Atrazine has been used for the removal of *P. notatum* from centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.), but may cause extensive damage to other desired turfgrass species (Johnson 1979). Metsulfuron, recently registered for use in turfgrass, is labelled for the control of *P. notatum* in St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze.) and bermudagrass, but multiple applications are often necessary for adequate control. Inconsistent control of semi-tolerant *P. notatum* cultivars with metsulfuron has further reduced the desirability of this chemical control option in turfgrass (Bunnell et al. 2003). Alternatives to help in the management of these species are needed.

Cultural management of weeds in turfgrass may help reduce weed encroachment while alleviating heavy dependence on herbicidal control. Mowing height and frequency may have differential effects on weeds and desired turfgrass species. Typically, it is expected that mowing at higher heights or too infrequently may increase weed infestations, while short mowing heights impose stress that may weaken desired turfgrass species and results in an environment that is more susceptible to invasion by more well-adapted weeds. However, some have recommended maintaining cool-season turfgrass such as tall fescue at 7.6 to 10.2 cm to prevent weed encroachment and reduce stress in the summer in North Carolina. Smooth crabgrass (*Digitaria ischaemum* (Schreb.) Muhl.) infestations in cool-season turfgrasses have been observed to increase at lower mowing heights in Chewings fescue {*Festuca rubra* var. *commutate* Gaudin [= *F. rubra* subsp. *fallax* (Thuill.) Nyman]} (Jagschitz and Edbon 1985); and tall fescue (*Festuca arundinacea* Schreb.) (Dernoeden et al. 1993). Annual bluegrass (*Poa annua* L.) infestation increased from 9 to 34% as mowing height of perennial ryegrass (*Lolium perenne* L.) dropped from 7.5 to 1.25 cm (Adams 1980).

Percent annual bluegrass cover increased from 8.6 to 30.8% as mowing height of carpetgrass {*Axonopus affinis* Chase [= *A. fissifolius* (Raddi) Kuhlm.]} was reduced from 7.6 to 3.8 cm (Bush et al. 2000). Purple nutsedge (*Cyperus rotundus* L.) exhibited a 45 to 90% reduction in rhizome length, 38 to 82% reduction in tuber number, and 7 to 19% reduction in tuber size when mowed at 1.3 and 3.8 cm in the absence of turfgrass competition when compared to the non-mowed plants (Summerlin et al. 2000). Mowing at 1.3 cm reduced shoot number and plant spread of green kyllinga (*Kyllinga brevifolia* Rottb.) by 52 and 32 %, respectively, while mowing at 3.8 cm resulted in reductions of 0 and 13 %, respectively (Summerlin et al. 2000). In contrast, Lowe et al. (2000) observed an increase in green kyllinga infestation in competition with bermudagrass by a factor of 2 to 5 when the mowing height was reduced from 5.0 to 2.5 cm. Although close mowing may discourage the presence of some weeds, it may be even more harmful to desired turfgrass species, ultimately giving weeds a competitive edge. Possible benefits of timely mowing include the reduction of mature seeds in the seedbank (Williams 1984; Henskens 1998) and the depletion of stored reserves of perennial weed structures (Stoll et al. 1998). For this reason, when selecting a proper mowing height considerations must be made for both desired turfgrass and weed species present.

Little published research has examined the effect of mowing height and frequency common to managed turfgrass on *Paspalum* spp. growth. Therefore, the objective of this study was to evaluate the lateral spread and rhizome biomass accumulation responses of *P. dilatatum* and *P. notatum* to mowing heights and frequencies common to intensely managed bermudagrass fairways and roughs.

MATERIALS AND METHODS

Experiments were conducted in 2003 and 2004 at the Sandhills Research Station (SRS) in Jackson Springs, NC and in 2004 at the Lake Wheeler Research Station (LWRS) in Raleigh, NC on a Wakulla Sand (sandy, siliceous, thermic, Psammentic Hapludults) and an Appling fine sandy loam (fine, kaolinitic, thermic, Typic Kanhapludults), respectively. *P. dilatatum* and *P. notatum* plants were removed from naturally occurring populations present in the rough of several holes at Hidden Valley Golf Course in Willow Springs, NC (35.6 N, 78.8 W). A 10.2 cm cup cutter centered over each plant was used to remove the above-ground biomass and coinciding rhizomes together as a plug. Plants were transplanted to the study site into bare-ground by removing a core of soil and replacing it with a plant plug. Plants were transplanted at SRS on 5/29/2003 and 5/26/2004; and at LWRS on 6/3/2004. Fertilizer (5N-2.2P-0K) was applied to each study area at time of transplant at a rate of N of 37 $kg \cdot ha^{-1}$. Monthly applications of fertilizer (16N-1.7P-6.6K) were made throughout the duration of the study at a rate of N of 30 $kg \cdot ha^{-1}$.

In 2003, treatments consisted of two mowing regimes: 1.3 cm mowed three times per week and 7.6 cm mowed two times per week. In 2004, treatments consisted of three mowing regimes: 1.3 cm mowed three times per week, 5.2 cm mowed two times per week, and 7.6 cm mowed two times per week. Each mowing height and frequency was selected to simulate bermudagrass management on golf course fairways and roughs. A non-mowed check was included for comparison purposes. Treatments were in a factorial arrangement – two *Paspalum* spp. by three or four management treatments – in a split plot experimental design with four replications. Main plot factors were mowing heights and the non-mowed check. Subplot factors were *Paspalum* spp. Each experimental unit (subplot) measured 1.8 x 1.5 m and contained six plugs arranged in a 0.5 m grid. Mowing height in the 1.3 cm treatment was reduced gradually during the week before study initiation. Studies were initiated at SRS on 6/20/2003 and 6/18/2004; and at LWRS on 6/25/2004. Plants cut to 1.3 cm were mowed with a walk-behind reel mower[2], while plants cut to 5.2 or 7.6 cm were mowed with a walk-behind rotary mower[3]. Irrigation was supplied as a supplement to rainfall at a rate of 3.0 to 4.0 $cm \cdot wk^{-1}$. Plots were maintained weed free by hand weeding and through applications of glyphosate[4] (0.28 $kg \cdot ha^{-1}$) with a hand-held wiper with a paint roller-type head.

Plant diameters were taken at the beginning of each study and were recorded monthly through November. Two diameter measurements were taken perpendicular to each other (the first measurement was taken in the largest diameter) and averaged to obtain the reported diameter of a plant at each sampling time. Monthly diameter measurements were converted to % diameter increase by comparison to initial diameters. Plants were excavated five months after initial treatment (MAIT) in both years. At SRS plants were harvested on 11/15/2003 and 11/17/2004, while plants at LWRS were harvested on 11/20/2004. After harvest, above-ground biomass was removed from each sample and rhizome fresh weights were obtained for each of the six plants within a given plot. Data from the six plugs were averaged to give estimates for each experimental unit.

Differences in number of mowing treatments would not permit combining data from 2003 and 2004. No significant location by run interactions were observed, so data were pooled for

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[2] Toro Walk-Behind Greensmaster 1000, The Toro Company, Bloomington, MN 55420.

[3] John Deere mower model 14SB, Revels Tractor and Supply Co., Fuquay Varina, NC 27536.

[4] Glyphosate, Round-up Pro Dry, Monsanto Company, St. Louis, MO 63167.

locations in 2004 and subjected to analysis of variance[5] (ANOVA) by year, using error partitioning appropriate to a split plot analysis. Means were separated using Fisher's protected LSD test at P = 0.05.

RESULTS AND DISCUSSION

Paspalum notatum

The lateral growth of *P. notatum* plants subjected to mowing was reduced immediately when compared to the non-mowed check in both years (Figure 1). Differences in lateral spread among mowing regimes were apparent 1 MAIT in 2003 and 2 MAIT in 2004. Lateral spread of the non-mowed checks increased 210 and 240% in diameter when compared to the initial diameters at the start of each study in 2003 and 2004, respectively. Reduction in lateral spread was most severe in the 1.3-cm mowing regime. At the conclusion of the experiment, *P. notatum* lateral spread in the 1.3-cm regime was reduced 44 and 62% in 2003 and 2004, respectively, when compared to the non-mowed check. Lateral spread in the 5.2-cm regime was reduced 40% in 2004 when compared to the non-mowed check. Lateral spread in the 7.6-cm regime was reduced 21 and 27 % in 2003 and 2004, respectively, when compared to the non-mowed check.

All treatment regimes reduced *P. notatum* final rhizome fresh weight (Table 1). The 7.6-cm mowing regime reduced rhizome production 33 and 24% in 2003 and 2004, respectively. Reducing the mowing height to 5.2 cm decreased rhizome production 55% in 2004. Mowing

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[5] SAS, Statistical Analysis Systems, 2003, Release 9.1, Statistical Analysis Systems Institute, Cary, NC 27513.

at 1.3 cm three times per week further decreased rhizome production by 70% in 2003 and 73% in 2004.

Paspalum dilatatum

The lateral growth of *P. dilatatum* plants subjected to mowing was also reduced immediately when compared to the non-mowed check in both years (Figure 2). At the conclusion of each study, however, *P. dilatatum* plants subjected to different mowing regimes were similar in terms of % increase in diameter. Lateral spread of the non-mowed checks increased 130 and 150% in diameter when compared to the initial diameters at the start of each study in 2003 and 2004, respectively. In 2003, mowed *P. dilatatum* plants exhibited a 38 to 39% reduction in lateral spread when compared to the check regardless of mowing regime. In 2004, mowed plants exhibited a 42 to 47% reduction in lateral spread when compared to the check regardless of mowing regime.

All treatment regimes reduced total rhizome fresh weight harvested from *P. dilatatum* at the end of each study (Table 2). The 7.6-cm mowing regime reduced rhizome production 49% in 2003, but this effect was less in 2004, where production was only reduced by 30%. A similar decrease in rhizome production was observed when the mowing height was reduced to 5.2 cm in 2004. Mowing at 1.3 cm three times per week further reduced rhizome production by 57% in 2003 and 37% in 2004, when compared to the non-mowed check.

The overall growth of the two *Paspalum* spp. evaluated was greater in 2004 at LWRS than SRS (data not shown). This may be attributed to differences in edaphic characteristics associated with the different soil types at each research station. SRS has a well drained sandy soil type that may have reduced soil nutrient and moisture retention, while LWRS has a well-drained sandy loam soil type with higher cation exchange and water holding capacities.

Differences in growth from year to year were also observed which may be attributed to air temperature, soil temperature, and photosynthetically active radiation (PAR) conditions prior to and after transplant. In 2003, average daily temperature, soil temperature at 7.6 cm, and PAR in the last two weeks of May (prior to transplant) were 6 to 8 C lower, 6 to 7 C lower, and 73 to 328 $\mu mol \cdot m^{-2} \cdot s^{-1}$ lower than in 2004, respectively. The lower temperatures and PAR in 2003 may have resulted in the transplantation of plant plugs that were growing less vigorously than those transplanted in 2004. This may have allowed plants transplanted in 2004 to grow and mature quicker in the beginning of the study, thus giving them an advantage throughout the duration of the study and leading to an increase in there size at the end of the experiment.

Results of this study suggest that the low mowing height and frequent shoot removal of the 1.3-cm mowing regime common to golf course fairways significantly reduced the spread and rhizome production of *P. notatum*. Although the 5.2 and 7.6-cm mowing regimes also caused reductions, *P. notatum* was better able to withstand these mowing regimes common to golf course roughs. Summerlin et al. (2000) observed similar results when comparing the effect of mowing height on several problematic sedge species. A greater reduction in plant spread was observed in false green kyllinga when mowed at 1.3 cm than 3.8 cm. On the contrary, Lowe et al. (2000) observed that green kyllinga growth increased in response to mowing at 2.5 cm compared with a 5.0 cm height when grown in competition with hybrid bermudagrass (*Cynodon transvaalensis* X *Cynodon dactylon* 'Tifway'). The differential response of *P. notatum* to the various mowing heights employed in this experiment may explain the predominant presence of this species on turfgrass maintained at higher mowing heights. Henry et al. (2006a) observed the presence of *P. notatum* primarily in the rough (6.4

to 7.6 cm height of cut) of two golf courses, which is similar to the 7.6-cm mowing regime used in the present study. The inability of *P. notatum* to withstand frequent low mowing might be explained by its morphology. *P. notatum* is a warm-season perennial grass that expands through the growth and spread of rhizomes at the surface of the soil. Frequent close mowing and traffic typical of a golf course fairway may damage *P. notatum*'s shallow rhizomes, reducing its ability to grow under these conditions. A reduction in rhizome production for a perennial grass weed that relies predominantly on vegetative propagation for spread and survival may prove detrimental over time.

On the contrary, a similar reduction in *P. dilatatum* rhizome growth and lateral spread was observed for all three mowing heights and frequencies examined in our research. However, additional control options may be necessary in order to effectively reduce *P. dilatatum* populations. Although growth was reduced when frequently mowed, *P. dilatatum* still exhibited lateral spread and rhizome growth under mowing regimes commonly used in intensively managed bermudagrass turfgrass. Kikuyugrass (*Pennisetum clandestinum* Hochst ex Chiov.) aboveground dry weight and root dry weight was also reduced in response to close mowing, but mowing alone did not effectively control it (Wilen and Holt 1996). Voigt et al. (2001) observed that significantly more *Digitaria* spp. infested tall fescue plots maintained at 2.5 cm than plots maintained at 5.1 and 7.6 cm. The similar response of *P. dilatatum* to mowing heights typical of golf course fairways and roughs may explain the widespread presence of these species on intensively maintained turfgrass areas. The ability of *P. dilatatum* to withstand frequent low mowing may also be explained by its morphology. *P. dilatatum* is a warm-season perennial grass that expands through the growth and spread of rhizomes deep within the soil. Such protection may allow *P. dilatatum* to withstand frequent close mowing and traffic associated with its presence on golf course fairways.

Several factors pertinent to proper turfgrass management practices were not accounted for in the methods employed in our research. The amount of observed lateral spread and rhizome production in the non-mowed checks throughout the length of each study is not likely to occur in managed turfgrass environments, because turfgrass communities found in golf courses, athletic fields, and home lawns are mowed frequently. *Paspalum* spp. were grown on bare-ground without the presence of a competing desired turfgrass species. Experimental units were also maintained weed-free through cultural and chemical practices. If hybrid bermudagrass had been present to introduce competition, lateral spread and rhizome growth may have been further reduced, because bermudagrass varieties are bred to form dense canopies under frequent, low mowing conditions. However, the growth exhibited by *P. dilatatum* in this experiment combined with previous observations on control difficulties, suggest that this species can thrive and reproduce rapidly under common mowing conditions present on both fairways and roughs. The inability of *P. notatum* to tolerate the close mowing regimes we applied suggests that its expansion may be dramatically reduced in fairways with effective cultural practices.

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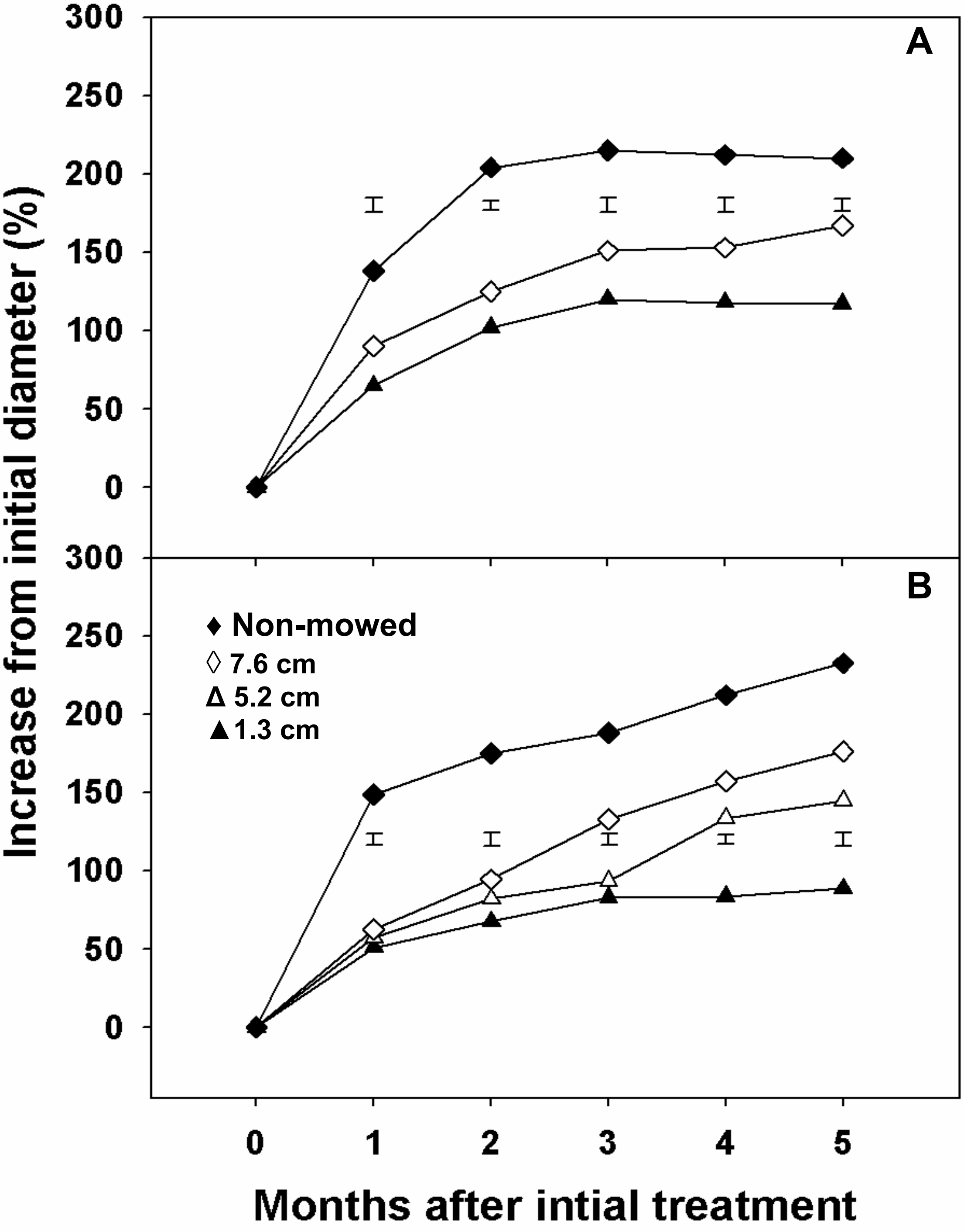

Figure 1. Effect of mowing on *Paspalum notatum* lateral spread in 2003 (A) and 2004 (B). Vertical bars represent least significant differences of treatment means presented by month.

Table 1. Effect of mowing on *Paspalum notatum* rhizome production in 2003 and 2004[a].

Mowing height (cm)	Rhizome fresh weight (g) 2003 [b]	2004 [b]
1.3	89 c	91 d
5.2	--	152 c
7.6	200 b	256 b
Non-mowed	300 a	335 a

[a] The experiment was conducted at one site in 2003. Data for two sites were combined in 2004.

[b] Means within the same parameter and year followed by the same letter are not significantly different according to Fisher's Protected LSD test at P = 0.05.

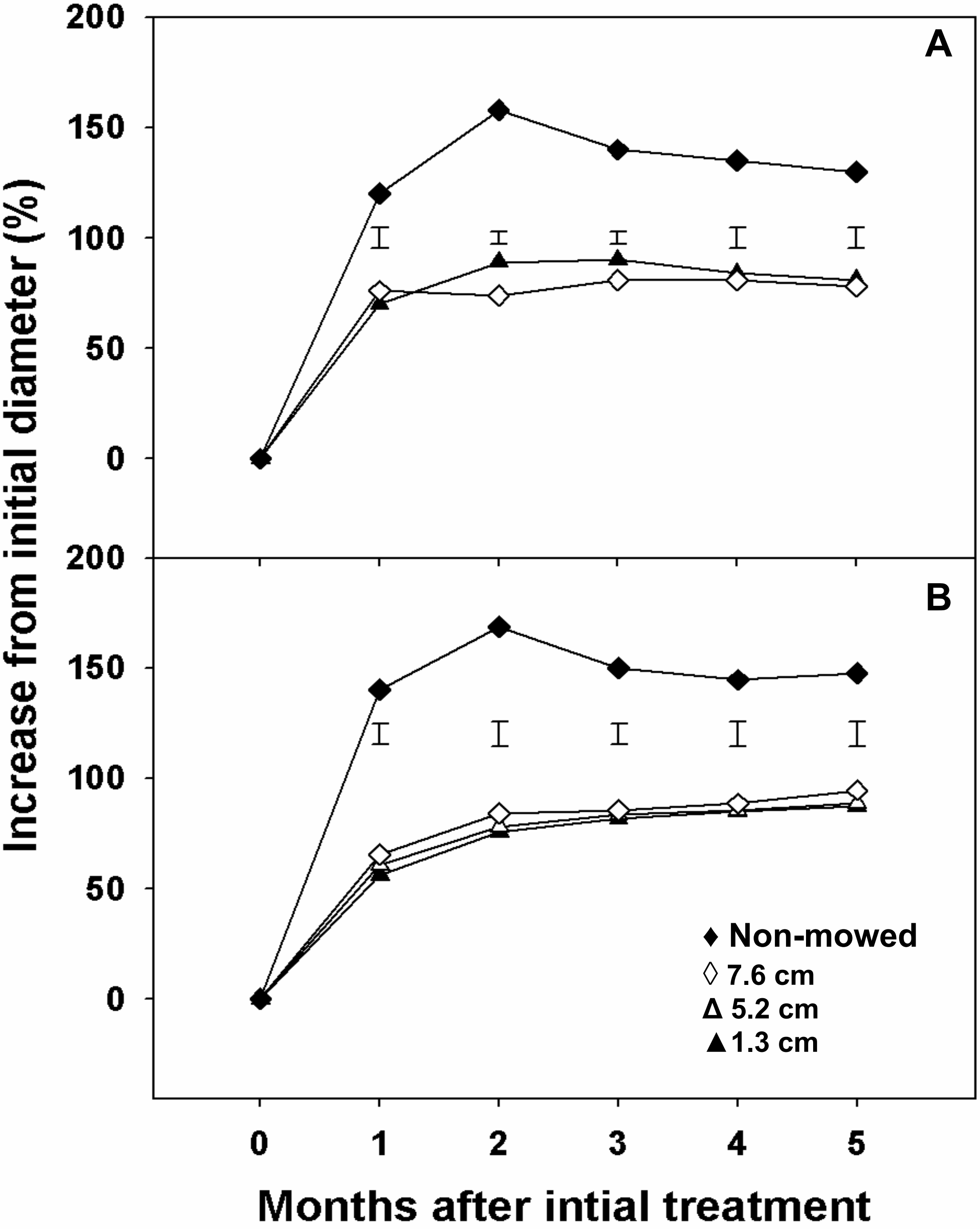

Figure 2. Effect of mowing on *Paspalum dilatatum* lateral spread in 2003 (A) and 2004 (B). Vertical bars represent least significant differences of treatment means presented by month.

Table 2. Effect of mowing on *Paspalum dilatatum* rhizome formation in 2003 and 2004[a].

	Rhizome fresh weight (g)	
Mowing height (cm)	2003 [b]	2004 [b]
1.3	35 b	67 b
5.2	___	73 b
7.6	42 b	74 b
Non-mowed	82 a	106 a

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[a] The experiment was conducted at one site in 2003. Data for two sites were combined in 2004.

[b] Means within the same parameter and year followed by the same letter are not significantly different according to Fisher's Protected LSD test at P = 0.05.

CHAPTER 6

Asymmetric Responses of *Paspalum* Species to a Soil Moisture Gradient.

Abtract: Employing a novel technique first used in a manuscript published in this journal in 1966 refutes anecdotes suggesting that *Paspalum dilatatum* and *Paspalum notatum* are both drought and flood tolerant. Growth and survival responses of *Paspalum* spp. along a soil moisture gradient were assessed when grown as monocultures or in competition with *Cynodon transvaalensis* X *Cynodon dactylon* ‘Tifway 419’ in sand or sandy loam soil by employing several water table depth gradient tanks. Shoot and rhizome growth of *P. dilatatum* was greatest at the more saturated levels of each gradient tank regardless of soil type or competition. Percent survival of *P. dilatatum* decreased to a low of 50% as depth to water table increased when grown as a monoculture and 12.5% when grown in competition with *C. dactylon*. Percent survival of *P. notatum* was 100% regardless of water table depth, soil type, or competition. Shoot and rhizome growth of *P. notatum* was greatest as depth to water table increased when grown in sandy loam soil. The opposite trend was observed when grown in sandy soil. Results suggest that *P. dilatatum* may be more competitive with *C. dactylon* when volumetric soil moisture is high, while *P. notatum* may be more competitive when volumetric soil moisture is low.

Nomenclature: dallisgrass, *Paspalum dilatatum* Poir. #[1] PASDI; bahiagrass, *Paspalum notatum* Fluegge. # PASNO; hybrid bermudagrass, *Cynodon transvaalensis* X *Cynodon dactylon* 'Tifway 419'.

Additional index words: soil moisture, water table depth, competitive interactions.

Abbreviations: comp, competition.

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[1] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th St., Lawrence, KS 66044-8897.

INTRODUCTION

Plant interactions can differ across landscapes as a consequence of heterogeneous soil moisture distribution resulting from differences in soil type, management practices, topography, and plant community composition and density. Large local fluctuations in volumetric soil water content may result in a species composition that is tolerant to extreme soil moisture stress (i.e. flooding or drought). The onset of flooding and drought conditions may elucidate similar wilting responses in plants sensitive to extreme soil moisture stress (Kozlowski 1984). However, further examination into the potential selective pressures exerted on plant communities and the physiological effects of these two factors, reveals several striking differences. Drought tolerant plants may avoid detrimental effects brought on by drought through the development of physiological mechanisms such as osmotic adjustment, reduced leaf area, increased leaf thickness, increased root:shoot ratio, and a prostrate growth habit (Coughenour 1985; Pugnaire et al. 1993). In contrast, mechanisms of flood tolerance in plants may include increased plant height, aboveground adventitious rooting, reduced root:shoot ratio, increased root and sheath aerenchymatic tissue, and stomatal closure (Blom et al. 1990; Davy et al. 1990; Jackson and Drew 1984; Blom and Voesenek).

Paspalum dilatatum Poir. (dallisgrass) and *Paspalum notatum* Fluegge (bahiagrass) have long been used in pastures, forages, and roadsides, but their ability to adapt to a wide range of environmental factors may have led to their success and spread as weeds. Spatial distribution research recently conducted to examine the response of *P. dilatatum* and *P. notatum* to several edaphic and topographic features present within areas of frequently mowed *Cynodon transvaalensis* X *Cynodon dactylon* ‘Tifway 419’ (hybrid bermudagrass) showed strong correlations between volumetric soil moisture and *Paspalum* spp. presence (Henry et al. 2006).

Studies that investigate the response of weed species to soil moisture have been conducted with a variety of experimental approaches, each of which has its limitations. Pot studies based on frequency or volume of watering, or irrigation triggered by sensors (e.g. gypsum blocks) have been employed for many years. However, pot studies have been criticized for problems associated with rooting depth and volume, and unnatural soil moisture profile and root distribution. Plaut et al. (1996) reported unnatural root distribution upon examination of the effect of drip irrigation and partial wetting of the upper soil profile on the growth of cotton plants in plastic cylinders. Roots of the cotton plants grew uniformly with depth as a result of the restricted volume of the cylinders. Root restriction can mimic the effect of soil moisture stress even when there is sufficient soil moisture for normal plant growth (Krizek et al. 1985). A classic study that employed an approach that reduces these shortcomings was conducted by Mueller-Dombois and Sims (1966). This approach requires a fairly large amount of space to house water table depth gradient tanks that allow for natural capillary action (soil water) as well as surface irrigation to simulate rainfall. Water table depth is regulated by a standpipe while capillary rise keeps the low end of the tank near field capacity. Plants growing at higher elevations are subjected to progressively lower soil moisture levels and greater depth to the water table. Our research employs this novel technique with replication over time. The construction of several smaller gradient tanks allowed the examination of each *Paspalum* spp. grown as a monoculture or in competition with *C. transvaalensis* X *C. dactylon* ‘Tifway 419’ in different soil types. *C. transvaalensis* X *C. dactylon* is a useful standard for comparing competitive outcomes across studies because of its uniform genotype, aggressive growth habit, and predominant use in managed turfgrass environments.

The objective of our research was to assess the tolerance of *P. dilatatum* and *P. notatum* to various levels of soil moisture in terms of shoot and rhizome biomass accumulation and survival when grown as monocultures or in competition with *C. transvaalensis* X *C. dactylon* in sand or sandy loam soil.

MATERIALS AND METHODS

Six water table depth gradient tanks were constructed (see Mueller-Dombois and Sims 1966; Mueller-Dombois 1965) in a greenhouse in Raleigh, NC (35° 47' N, 78° 39' W). Each tank was steeply sloped and had a volume of nearly 4 m^3. The tanks measured 2.4 m long, 1.2 m wide, and were 0.3 m high at one end and 1.8 m high at the other end (Figure 1A). Tanks were oriented to face south and contained either [Wakulla sand (sandy, siliceous, thermic, Psammentic Hapludults) or Appling fine sandy loam (fine, kaolinitic, thermic, Typic Kanhapludults)] and species composition (either a *Paspalum* spp. monoculture or in competition with *C. transvaalensis* X *C. dactylon*). Tanks were paired by soil type and species competition. Species composition was randomly assigned to a pair of tanks prior to transplant. Each tank was lined with a double layer of 3 mil plastic and had 10 cm base of pea gravel to provide a uniform substrate for water movement. In tanks containing sandy loam soil, the pea gravel was covered with 3 cm of coarse sand to reduce soil movement into the pea gravel. Tanks were then filled with steamed soil or sand. A valve at the high end of the tank regulated water inflow, while a standpipe at the low end of the tank regulated the water table height. Tank surfaces were divided into 9 levels ranging in depth to water table of

27 cm (level 1) to 150 cm (level 9). Soil moisture measurements were taken at time of final harvest by probing the soil profile at each level and measuring percent volumetric water content with a theta probe[2]. The capillary fringe of each soil type was determined from these measurements (Figure 1B). Soil moisture near the surface changed gradually from level 1 to level 9 in each tank regardless of soil type.

Replication of this experiment was accomplished by performing two runs. *C. transvaalensis* X *C. dactylon* sod was transplanted into two tanks on August 13, 2004 and May 27, 2005. Rhizomes of *P. dilatatum* and *P. notatum* were collected from naturally occurring populations and transplanted in monoculture or in competition with *C. transvaalensis* X *C. dactylon* on September 11, 2004 and June 28, 2005. Rhizomes of similar length (approximately 2 cm) and morphology (approximately 3-leaf stage) were planted perpendicular to the slope (moisture gradient) to allow examination of growth characteristics at several moisture levels. Plants were spaced approximately 15 cm from each other or the adjacent edge of the tank. A 5 cm circular plug was removed from tanks containing *C. transvaalensis* X *C. dactylon* that coincided with transplant locations for each *Paspalum* spp. along the moisture gradient. *Paspalum* spp. were transplanted in the center of each plug. A slow release fertilizer (15 N-10 P_2O_5-20 K_2O) was applied at transplant and twice more during establishment. Surface irrigation provided through an aerial misting system was employed for approximately 12 weeks during *Paspalum* spp. establishment to give a greater opportunity for uniform recruitment (stopped on December 17, 2004 and September 21, 2005) and occasionally as needed throughout the experiment to prevent permanent wilting. Tap water was used for both surface irrigation and ground water. Natural light was

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[2] TH2O Theta Probe, Delta-T Devices Ltd., 128 Low Road, Cambridge, CB5 OEJ, England.

supplemented with artificial light at 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ photosynthetic photon flux in a 12-h day to approximate summer light intensity and photoperiod. All gradient tanks were mowed using sheep shears once a week to a height of 6.3 cm. Rhizomes and shoots were harvested at the end of each run (February 17, 2005 and November 18, 2005). Rhizomes were carefully removed from the soil and were stripped of all adventitious roots before being weighed. Aboveground tissue was removed at the soil surface for *P. dilatatum* and at the rhizome surface for *P. notatum*. Dead and living tissues were combined in fresh weights to account for mortality differences between species and gradient levels.

Resulting data were tested for homogeneity of variance by plotting residuals. An arc-sin square root transformation did not improve homogeneity, so non-transformed data were used in analysis and presentation for clarity. An analysis of variance was conducted using the General Linear Models procedure of SAS[3], and sums of squares were partitioned to evaluate the effect of species, soil type, competition, soil moisture, and greenhouse trials using error partitioning appropriate to a split-split plot analysis (Table 1). *Paspalum* spp. were considered main plots; soil type and competition were considered subplots; and soil moisture level was considered the sub-sub plot in the analysis. Study repetition was considered a random variable, and main effects and interactions were tested by the appropriate mean square associated with the random variable. Lowest order curves giving high R^2 values were fit to the data for comparisons of *Paspalum* spp. across soil moisture levels.

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[3] SAS Institute Inc. 2003, SAS Procedures Guide, Version 9.1, SAS Campus Dr., Cary, NC 27513.

RESULTS AND DISCUSSION

Rhizome and shoot fresh weights along with percent survival ratings were recorded for both species two months after soil moisture treatments were initiated. These measurements were recorded for each soil type, competition treatment, and soil moisture level. Although plants were mowed weekly, each grass exhibited a specific growth habit: *P. dilatatum* grew as a bunch-type grass, while *P. notatum* was more aggressive and spread out laterally in several directions. *P. dilatatum* plants were robust and dark green from levels 1 to 7 and slightly stunted in levels 8 and 9 when grown on sandy loam soil regardless of competition ($P < 0.05$) (Table 1). However, when grown on sandy soil, plants at level 4 and above were stunted and discolored regardless of competition ($P < 0.05$). *P. notatum* plants expressed vigorous growth at all levels regardless of soil type and competition, but when grown on sandy soil, plants above level 3 were markedly smaller in size and exhibited less lateral growth ($P < 0.05$). In the competition tanks, *C. dactylon* survival began to decrease at level 4 and above regardless of soil type (data not shown). *P. notatum* survival was unaffected regardless of simulated environmental conditions (Fig. 2A, 3A, 4A, and 5A) ($P < 0.0001$). *P. dilatatum* survival decreased at level 3 regardless of soil type when grown in competition (Fig. 4A and 5A) ($P = 0.001$), while survival began to decrease at level 4 regardless of soil type when grown as a monoculture (Fig. 2A and 3A) ($P = 0.0001$).

The total rhizome fresh weight produced on the loamy sand soil was about 80% greater than that produced on the sandy soil (data not shown) ($P < 0.0001$). The total rhizome fresh weight produced when plants were grown as monocultures was about 13 times greater than when grown in competition with *C. dactylon* (data not shown) ($P < 0.0001$). Maximum rhizome fresh weight for *P. dilatatum* occurred at levels 1 to 3 regardless of soil type or competition treatment (Fig. 2B, 3B, 4B, and 5B) ($P < 0.0001$). Maximum rhizome fresh weight for *P. notatum* occurred at levels 6 to 8 and 4 to 9 when grown as a monoculture and in competition in sandy loam soil, respectively (Fig. 2B and 4B) (P , 0.0001). When grown as a monoculture in sandy soil, *P. notatum* exhibited maximum rhizome fresh weight at levels 1 to 2 (Fig. 3B), but exhibited a more linear response to the soil moisture treatments when grown in competition (Fig. 5B) ($P < 0.0001$).

The total shoot fresh weight produced on the sandy loam soil was about 16% greater than that produced on the sandy soil (data not shown) ($P < 0.0001$). The total shoot fresh weight produced when plants were grown as monocultures was about 15 times greater than when grown in competition with *C. dactylon* (data not shown) ($P < 0.0001$). Maximum shoot fresh weight for *P. dilatatum* occurred at levels 1 to 6 and 1 to 5 when grown as a monoculture and in competition in sandy loam soil, respectively (Fig. 2C and 4C) ($P < 0.0001$). Maximum shoot fresh weight for *P. notatum* occurred at levels 6 to 8 and 4 to 9 when grown as a monoculture and in competition in sandy loam soil, respectively (Fig. 2C and 4C) ($P < 0.0001$). When grown as monocultures in sandy soil, both species exhibited maximum shoot fresh weights at levels 1 to 3 (Fig. 2C) ($P < 0.0001$). The maximum shoot fresh weight for *P. dilatatum* when grown in competition in sandy soil occurred at levels 1 to 3, while *P. notatum* exhibited a more linear response to the soil moisture treatments (Fig. 4C) ($P < 0.0001$).

Mueller-Dombois and Sims (1966) observed differences in mortality of three grass species grown alone or in competition with one another in sand or loamy sand soil. On both substrates *Calamagrostis canadensis* (Michx.) suffered the greatest mortality as soil moisture became more limiting, followed by *Andropogon gerardi* Vitman and *Koeleria cristata* (L.).

Our findings suggest a possible correlation between *P. dilatatum* success and high soil moisture content. This may further indicate an adaptation by *P. dilatatum* to wet, poorly drained soils on which it is commonly found in the field. The growth patterns of *P. notatum* in our study were different with respect to the two soil types, but similar with respect to competition. *P. notatum* shoot and rhizome growth was greatest at the upper, droughtier levels of each gradient tank when grown on sandy loam soil, regardless of competition ($P < 0.0001$). *P. notatum* may be more tolerant of drought conditions than *P. dilatatum* due to the presence of smaller leaf blades, greater production of rhizomes and adventitious roots, or other mechanisms. When grown on sandy soil, however, *P. notatum* growth was greatest on the lower, more saturated levels of each gradient tank ($P < 0.0001$). Even though supplemental nutrients were supplied to plants throughout establishment, lack of additional nutrient applications during the experiment may have contributed to the reduced growth of *P. notatum* in sandy soil. *P. notatum* survival was not affected by any soil moisture level regardless of soil type or competition ($P < 0.0001$). *P. notatum* may be more competitive with *C. dactylon* than *P. dilatatum* due to enhanced rhizome production and lateral spread during the growing season. Although these findings do not show a direct correlation between *P. notatum* success and low soil moisture content, they do indicate tolerance of dry, sandy soils on which it is commonly found in the field.

Several researchers have examined the growth characteristics and anatomical changes of *P. dilatatum* in response to flooding, drought, or both (Rubio and Lavado 1999; Vasellati et al. 2001; Loreti and Oesterheld 1996; Rubio et al. 1995; Insausti et al. 2001). Rubio et al. (1995) and Rubio and Lavado (1999) observed a slight promotion of growth in *P. dilatatum* plants when exposed to flooding, while Loreti and Oesterheld (1996) only observed an increase in biomass accumulation in one of three biotypes they examined. Although our plants were not subjected to submerged conditions, *P. dilatatum* did exhibit the greatest growth response when grown at the highest soil moisture level. Loreti and Oesterheld (1996) observed that drought reduced yield equally across three *P. dilatatum* biotypes. *P. dilatatum* exhibited reduced shoot and rhizome growth and decreased survival when subjected to low soil moisture in our research ($P < 0.0001$).

P. dilatatum has been observed to undergo several physiological adaptations in response to flooding and drought. In response to flooding, an impressive reduction in root/shoot ratio has been observed (Rubio et al. 1995; Rubio and Lavado 1999). This change decreases the amount of respiring root tissue and facilitates oxygen diffusion to roots (Naidoo and Naidoo 1992; Voesenek et al. 1989; Megonigal and Day 1992; Loreti and Oesterheld 1996). Rubio and Lavado (1999) observed that *P. dilatatum* allocated only 30% of resources below ground in response to flooding. Leaf extension rates and tiller height were also higher in flooded *P. dilatatum* plants (Insausti et al. 2001; Rubio et al. 1995; Loreti and Oesterheld 1996). Although plants in our study were mowed weekly, it was observed that more biomass was removed from *P. dilatatum* plants subjected to higher soil moisture levels than those in droughtier portions of the gradient tank throughout the length of the experiment. Increasing plant height is a flooding response that allows avoidance of leaf submergence (Laan and Blom 1990; Van der Sman et al. 1993; Oesterheld and McNaughton 1991). Loreti and Oesterheld (1996) observed that drought reduced plant height by 24% in 3 *P. dilatatum* populations. *P. dilatatum* subjected to low soil moisture in our research rarely grew above the maintained mowing height of 6.3 cm. *P. dilatatum* was observed to produce aerotropic and adventitious roots that grow upward to oxygenated areas (Rubio et al. 1995), thus supplying oxygen to the roots (Glinski and Stepniewski 1985; Kozlowski 1984). Several researchers also observed an increase in root aerenchyma tissue of *P. dilatatum* in response to flooding (Rubio et al. 1995; Loreti and Oesterheld 1996; Vasellati et al. 2001), while others observed a reduction in response to drought (Loreti and Oesterheld 1996: Vasellati et al. 2001). Increased aerenchyma tissue is a common adaptive response of plants to soil anoxia (Jackson and Drew 1984; Justin and Armstrong 1987; Jackson and Armstrong 1999). Minimal published research exists that investigates the physiological response of *P. notatum* to flooding and drought conditions. Although these plants are similar, our research has shown that both respond differently to soil moisture stress. Therefore, developmental responses of *P. notatum* to soil moisture stress may be quite different than *P. dilatatum*. Further research on this subject may be warranted.

Intrinsic differences between naturally occurring *P. dilatatum* biotypes may result in diverse responses to fluctuating soil moisture in field and controlled environment experiments. Clearly, the responses to soil moisture in one biotype of *P. dilatatum* cannot be generalized to the whole species. Gene exchanges between tetraploid *P. dilatatum* biotypes and *P. urvillei* have been observed (Caponio and Quarin 1990). Resulting hybrids from these crosses may create morphological and physiological changes to *Paspalum* spp. that would increase the complexity of understanding their response to specific environmental constraints. Therefore, additional research with several *P. dilatatum* and *P. notatum* biotypes may be necessary to further define the response of these species to different soil moisture levels.

The implementation of water table depth gradient tanks in our research allowed examination of the effect of various soil moisture levels on *Paspalum* spp. growth without the usual constraints observed in research employing pots. The large volume of soil (4m^3) in each gradient tank helped reduce the potential for root restriction, thus allowing for lengthier study duration. The water table provided an even distribution of soil moisture throughout the gradient tank profile. However, position across soil moisture row did affect the level of competition imposed on each plant. Plants growing along the edge of each tank did not have the same competition for resources as plants growing in the center of the tank. Therefore, eight plants present across each row of the soil moisture profile represented replications to compensate for in-row variation.

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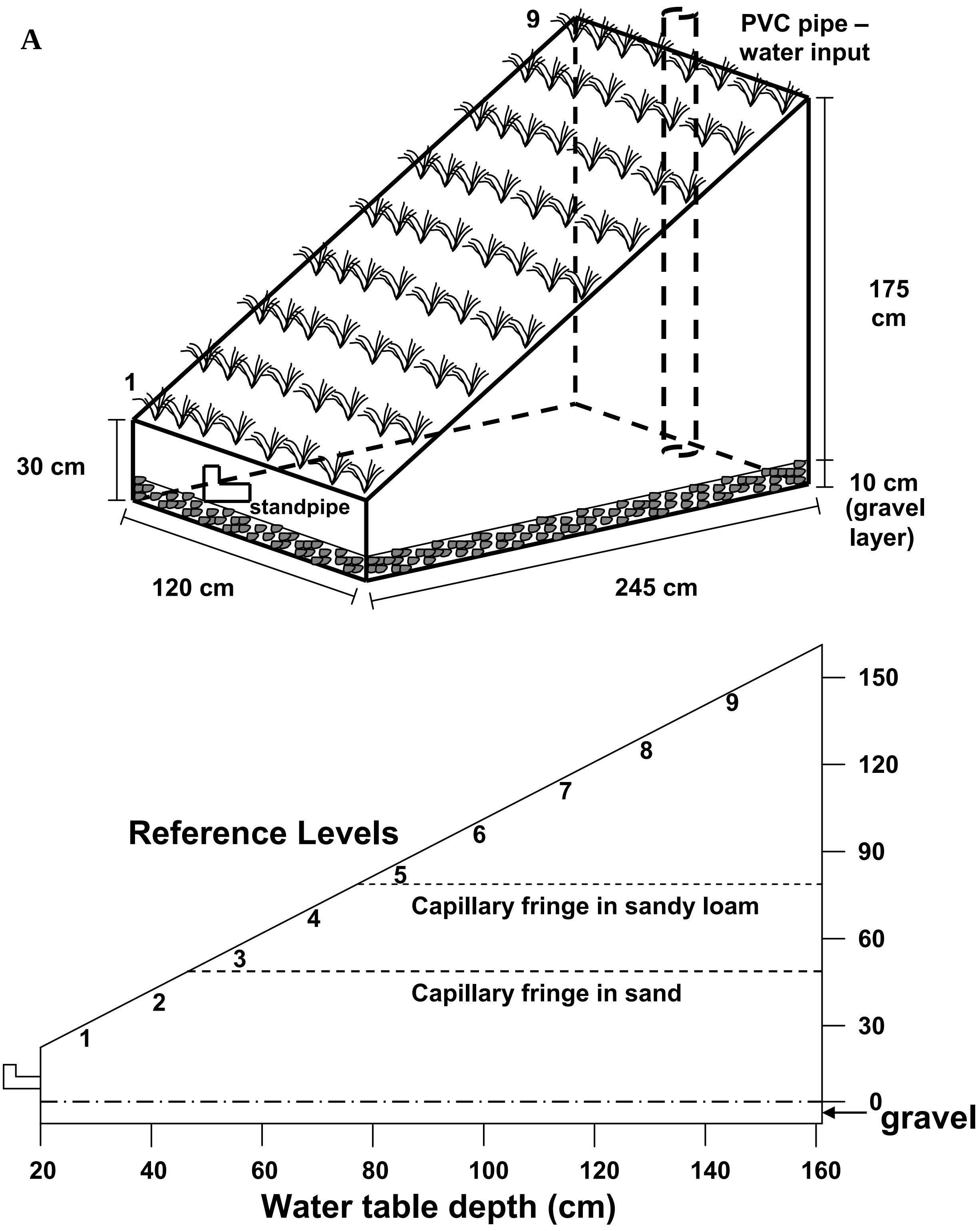

Figure 1. A. Schematic of water table depth gradient box construction. B. Length section through a tank showing capillary fringe of sand and sandy loam soils.

Table 1. ANOVA results for split-split plot analysis of the data.

		------------------------ P-values------------------------		
Source	df	Rhizome Weight	Shoot Weight	Survival
Species	1	P < 0.0001	P = 0.0959	P < 0.0001
Comp[a]	1	P < 0.0001	P < 0.0001	P < 0.0001
Species*Comp	1	P < 0.0001	P = 0.4508	P < 0.0001
Soil Type	1	P < 0.0001	P < 0.0001	P = 0.0410
Species*Soil Type	1	P < 0.0001	P < 0.0001	P = 0.0410
Comp*Soil Type	1	P < 0.0001	P < 0.0001	P = 0.6781
Species*Comp*Soil Type	1	P < 0.0001	P < 0.0001	P = 0.6781
Level	8	P < 0.0001	P < 0.0001	P < 0.0001
Species*Level	8	P < 0.0001	P < 0.0001	P < 0.0001
Comp*Level	8	P < 0.0001	P < 0.0001	P = 0.0001
Species*Comp*Level	8	P < 0.0001	P < 0.0001	P = 0.0001
Soil Type*Level	8	P < 0.0001	P < 0.0001	P = 0.0488
Species*Soil Type*Level	8	P < 0.0001	P < 0.0001	P = 0.0488
Comp*Soil Type*Level	8	P < 0.0001	P < 0.0001	P = 0.1952
Species*Comp*Soil Type*Level	8	P < 0.0001	P < 0.0001	P = 0.1952

a Abbreviation: Comp = competition.

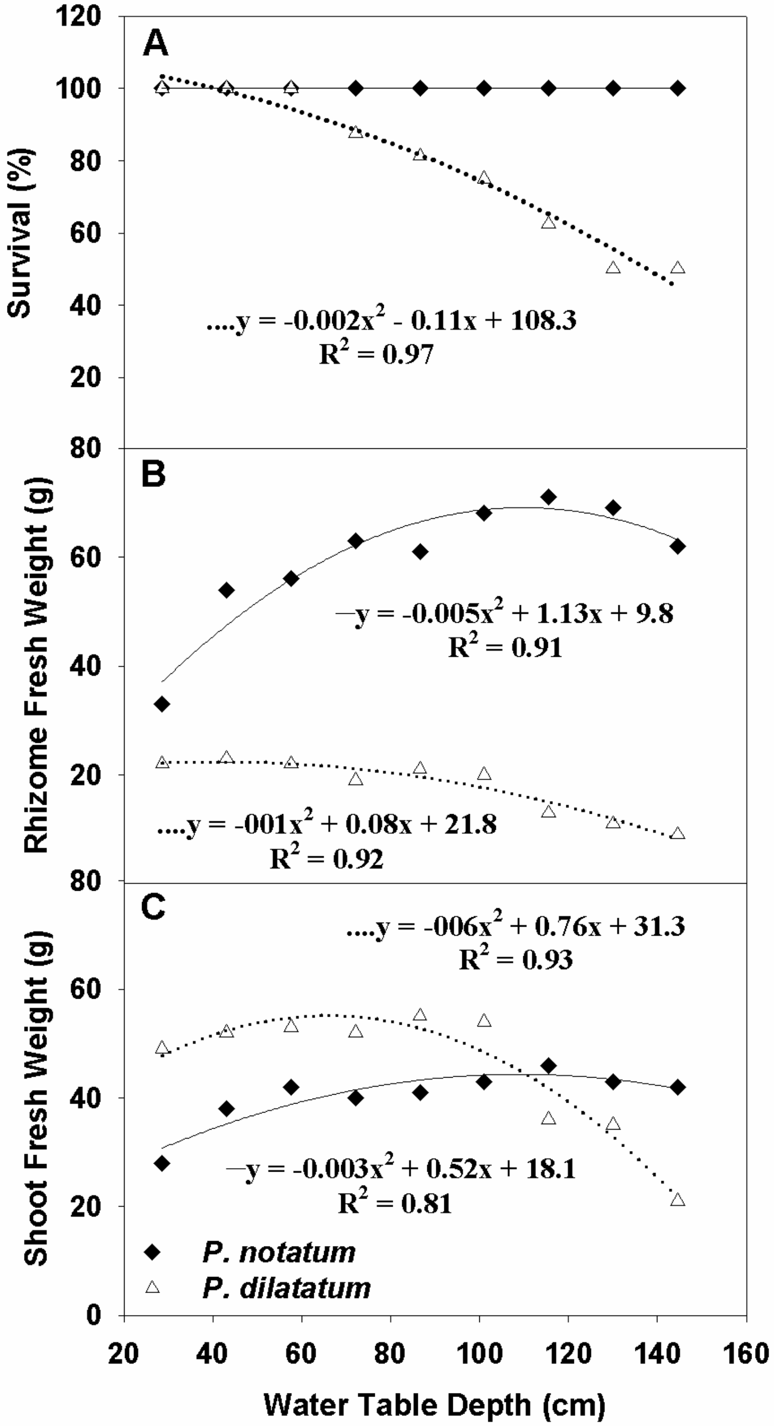

Figure 2. A. Percent survival of *Paspalum* spp. grown as monocultures in sandy loam soil. B. Rhizome weight of *Paspalum* spp. grown as monocultures in sandy loam soil. C. Shoot weight of *Paspalum* spp. grown as monocultures in sandy loam soil.

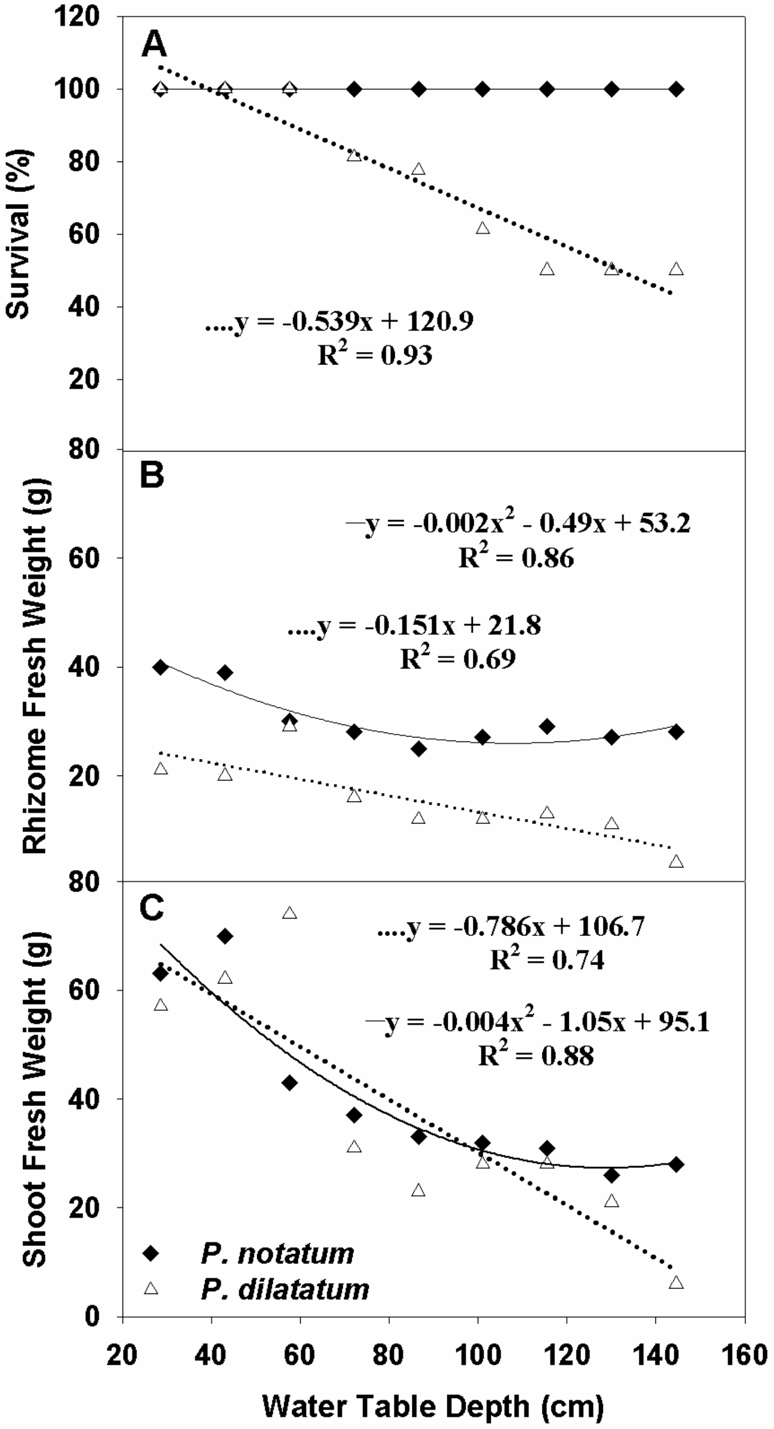

Figure 3. A. Percent survival of *Paspalum* spp. grown as monocultures in sand. B. Rhizome weight of *Paspalum* spp. grown as monocultures in sand. C. Shoot weight of *Paspalum* spp. grown as monocultures in sandy soil.

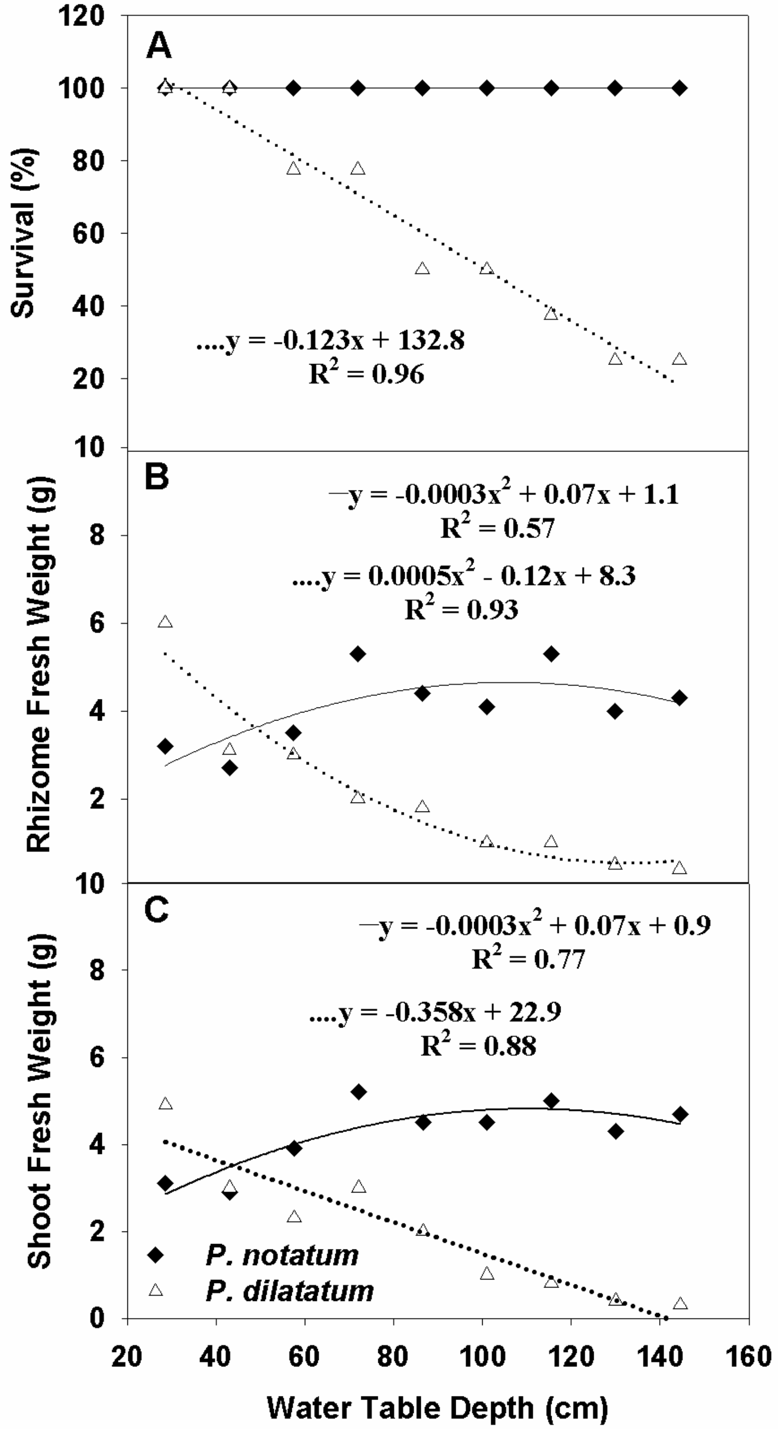

Figure 4. A. Percent survival of *Paspalum* spp. grown in competition in sandy loam soil. B. Rhizome weight of *Paspalum* spp. grown in competition in sandy loam soil. C. Shoot weight of *Paspalum* spp. grown in competition in sandy loam soil.

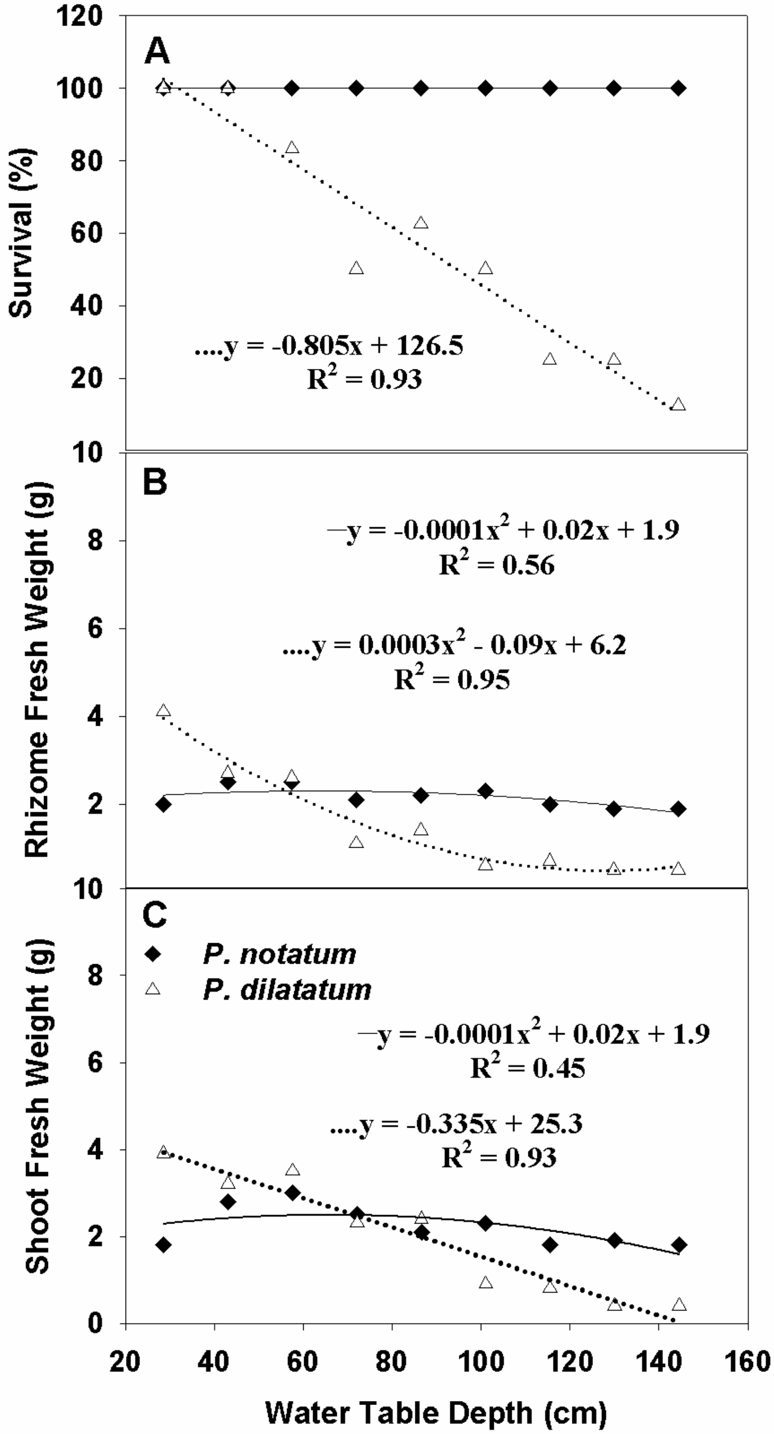

Figure 5. A. Percent survival of *Paspalum* spp. grown in competition in sand. B. Rhizome weight of *Paspalum* spp. grown in competition in sand. C. Shoot weight of *Paspalum* spp. grown in competition in sand.