ALUMINUM TOLERANCES OF TEN WARM-SEASON TURFGRASSES

Christian Michael Baldwin, H. Liu*, L.B. McCarty, W.L. Bauerle, and J.E. Toler

ABSTRACT

Acid soils are abundant in tropical and subtropical regions and account for approximately 40 percent of arable land in the world. Next to oxygen and silicon, aluminum (Al) is the third most abundant element in soils and is the main toxic factor for plant growth in acidic soils. Therefore, two glasshouse studies were conducted to determine the influence of Al on root and shoot mass and nutrient uptake of ten warm- season turfgrass species. Turfgrasses selected included 'Pensacola' bahiagrass (*Paspalum notatum* Flugge.), buffalograss (*Buchloe dactyloides* [Nutt] Engelm.), 'Isle' seashore paspalum (*Paspalum vaginatum* Swartz.), centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.), common carpetgrass (*Axonopus affinis* Chase.), 'Princess 77' dactylon bermudagrass (*Cynodon dactylon* var. *dactylon*), 'Meyer' Japanese lawngrass (*Zoysia japonica* Steud.), manilagrass (*Zoysia matrella* (L.) Merr.), 'Raleigh' St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze.), and 'TifEagle' hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. *x C. transvaalensis* Burtt-Davy). In study I, Al was applied at 240, 480, and 720 µm and phosphorus (P) was applied at 0.425 kg ha^{-1} day^{-1}, while in study II, Al was applied at 480, 960, and 1440 µm and P application levels were reduced to 0.0425 kg ha^{-1} day^{-1}. Root and shoot samples were separated, dried, and weighed at the conclusion of both studies and tissue samples were analyzed for nutrients (N, P, K, Ca) and Al concentrations. Japanese lawngrass, manilagrass, and centipedegrass experienced the least root growth reductions as Al increased. These species increased 1%, 24%, and 23% in relative root growth at 480 µm of Al. At the same concentration, St. Augustinegrass and seashore paspalum decreased relative root growth by 31% and 30%. As Al increased to 1440 µm, all species, except for carpetgrass (15% increase) and manilagrass (30% increase), exhibited a reduction in relative root growth. Significant differences were reported for relative P recovery. Japanese lawngrass increased relative root P recovery (5%) and manilagrass minimized relative root P recovery (15%), while buffalograss and bahiagrass decreased relative root P recovery by 72% and 35%, respectively.

Keywords

aluminum resistance, bahiagrass, buffalograss, bermudagrass, centipedegrass, zoysiagrass, carpetgrass, seashore paspalum, St. Augustinegrass, roots, shoots, phosphorus, potassium, calcium

INTRODUCTION

Aluminum (Al) toxicity has been identified as a major problem in acidic soils for more than 80 years (Hartwell and Pember, 1918) and is a major factor in reducing productivity as most plants are sensitive to soil micromolar Al concentrations (Kinraide, 1991). Approximately 40% of arable land in the world is acidic including southern and transitional zones of the United States, where warm-season turfgrasses are grown (Kochian et al., 2004). Generally, Al toxicity is closely associated with low soil pH (<5.0) where such soils release Al for uptake and therefore, adversely affect plant growth. Lastly, soils may become Al saturated by agricultural, manufacturing, mining, and waste disposal practices (Foy et al., 1978; Kochian, 1995).

When exposed to Al, plant growth is negatively affected because Al affects plant root tip cell division and cell elongation (Clarkson, 1965). Ryan et al. (1993a) demonstrated the terminal ~5 mm of wheat (*Triticum aestivum* L. Thell) root required Al exposure for root elongation to be affected. If the entire root, except the root cap, was exposed to the same Al concentration, the root would continue normal elongation.

Turfgrasses exposed to acidic soils experience nutrient deficiencies (P, K, Ca, and Mg), reduced root and shoot growth, and decreased stress tolerance (Marschner, 1991). The effects of nutrient uptake, especially P and Ca, for cool-season turfgrasses and wheat cultivars have been reported in several studies (Huang et al., 1991; Ryan et al., 1993b; Foy and Murray, 1998; Rengel and Robinson, 1998). In addition, genetic differences in

Christian Michael Baldwin, H. Liu, L.B. McCarty, W.L. Bauerle, Department of Horticulture, Clemson University, Clemson, SC, 29630, USA . J.E. Toler, Department of Applied Economics and Statistics, Clemson University, Clemson, SC, 29630, USA. *Corresponding author: haibol@clemson.edu

tolerance of many cool-season grasses to excess Al have been reported (Rengel and Robinson, 1989; Liu et al., 1995, 1996; Foy and Murray, 1998). However, few studies have been conducted on the Al tolerance of warm-season turfgrasses. Two studies investigated intra-specific variations within bermudagrass. In the first, Liu (2005) reported differences in seeded bermudagrass cultivars to Al tolerance. In the second, Wu et al. (1981) reported different Al tolerances of four vegetative-propagated bermudagrass cultivars. Therefore, the objectives of this study were to determine if genetic differences in Al tolerance exist among selected warm-season turfgrasses and how nutrient concentrations in root and shoot tissue are affected when exposed to micromolar Al concentrations.

MATERIALS AND METHODS

Two glasshouse studies were conducted at Clemson University, Clemson, SC, in 2003. In study I (March 12, 2003 – April 19, 2003), glasshouse conditions averaged 23.4 °C/18.7 °C day/night temperature and 69% relative humidity. Study II (August 25, 2003 – October 6, 2003) glasshouse conditions had average day/night temperature of 25.6 °C/18.2 °C and 68% relative humidity. Environmental conditions (temperature and humidity) were maintained by an automated computer recording system (Argus Controls, Whiterock, British Columbia V4B 3Y9).

Study I: Low to moderate Al exposure

Study I was designed to determine the aluminum tolerances of 10 warm-season species and consisted of three Al treatments at 240, 480, and 720 µm at pH of 4.0 and two controls (0 µm of Al) at pH 4.0 and 6.5 replicated three times. The experiment began on March 12, 2003 and lasted six weeks. Treatments were arranged in a randomized complete block design with three replications. Pot dimensions were 15 cm in diameter and 12 cm in height with 8 holes (1.01 cm) at the bottom to allow for drainage. In each pot, 30 single meristem shoots from two-year old well-rooted sprigs were planted in 100% sand obtained from Golf Agronomics, Fl, USA (Table 1) with roots and shoots clipped to ensure similar length.

All turfgrasses were fertilized daily (50 ml to 100 ml) using a modified ½ strength Hoagland's nutrient solution (Hoagland and Arnon, 1956). Aluminum was added to the solution as $Al_2(SO_4)_3 18H_2O$ and was adjusted to pH of 4.0 (+/-0.1) using 6 M HCl or 0.1 M NaOH and P levels were 0.425 kg ha^{-1} day^{-1}. Deionised distilled water was used to make all solutions.

Table 1. Physical properties of sand used in studies I and II.

	Very Coarse	Coarse	Medium	Fine	Very Fine
Particle Size (mm)	1.00 - 2.00	0.5 - 1.0	0.25 - 0.50	0.10 - 0.15	0.05 - 0.15
Particle Size Distribution	<10%	-	>60%	-	<5%

Study II: Moderate to high Al exposure

Study II was designed to determine the aluminum tolerances of 10 warm-season species by increasing Al to 480, 960, and 1440 µm and reducing P concentrations to 0.0425 kg ha^{-1} day^{-1}. The experiment was initiated on August 25, 2003. Study II consisted of five treatments with each species of grass replicated three times including two controls (0 µm of Al) at pH 4.0 and 6.5. Treatments were arranged in a randomized complete block design and the same 10 species were selected as in study I. Unless otherwise stated, materials and experiment duration were identical to study I.

Data collection

Relative values were used for all data collected due to the inherent variability among turfgrasses selected. Dry weight of shoots and roots were measured in both studies and used to calculate relative root and shoot mass. Also, relative nutrient recovery was determined. Roots were extracted from the soil and thoroughly washed until all soil was removed. Once clean, roots were clipped from the base of the shoot tissue. All relative values were based on the control pH of 4.0 and calculated as the relative root mass [RRM = (root mass with Al / root mass without Al) x 100], relative shoot mass [RSM = (shoot mass with Al / shoot mass without Al) x 100], relative nutrient recovery [RNR = (nutrient concentration with Al / nutrient concentration without Al) x 100], and relative total biomass [RTB = (root and shoot mass with Al / root and shoot mass without Al) x 100].

Fresh weight of roots and shoots were collected and placed in an oven at 80.0 °C and dried for 48 hours. Once dried, samples were weighed for root and shoot mass. Roots, shoots, and soil samples were analyzed by the Clemson University soil testing laboratory for P, K, Ca, Mg, S, Cl, Zn, Cu, Mn, Fe, Al, and B.

Nutrient Analyses

Tissue was digested using a nitric acid (HNO_3) + 30% peroxide (H_2O_2) in a wet ash procedure. Plant material (0.50 g) was weighed and placed into a 100 ml digestion tube with 5 ml of HNO_3. Each digestion tube was heated at 125°C for one hour. Once tubes were heated and allowed to cool, 3 ml of 30% H_2O_2 was placed in each sample and heated at 200 °C or until samples dried. Plant tissue was then removed from the digestion tubes by adding 10 ml of 1:10 HNO_3 and diluted in 50 ml of deionized water and shaken vigorously. An Inductively Coupled Plasma (ICP) autosampler (61E, Thermo Jarrell-Ash, Franklin, MA) was used to determine nutrient concentrations (Ca, K, P, and Al).

Table 2. Significance of variances for relative root mass (RRM), relative shoot mass (RSM), relative total biomass (RTB), relative shoot aluminum concentration (S-Al), relative root aluminum concentration (R-Al), relative root phosphorus concentration (R-P), relative root potassium concentration (R-K), relative root calcium concentration (R-Ca), relative shoot phosphorus concentration (S-P), relative shoot potassium concentration (S-K), and relative shoot calcium concentration (S-Ca) affected by aluminum 240, 480, and 720 mm, study I, and aluminum 480, 960, and 1440 mm, study II.

		Study I										
Source	df	RRM	RSM	RTB	S-Al	R-Al	R-P	R-K	R-Ca	S-P	S-K	S-Ca
Turf	9	***		****	****	****	****	****	****	***	***	****
Trt	2	**	***	****	****	*	****			****	***	
Turf X Trt	18											
		Study II										
Source	df	RRM	RSM	RTB	S-Al	R-Al	R-P	R-K	R-Ca	S-P	S-K	S-Ca
Turf	9	****	****	****	***	***	***	****	****	**	***	
Trt	2	**		***	****	****	****	*	****	***		**
Turf X Trt	18		*									

* Indicates significance at $P \leq 0.10$ ** Indicates significance at $P \leq 0.05$

*** Indicates significance at $P \leq 0.01$ **** Indicates significance at $P \leq 0.001$

Data Analysis

All statistical computations were conducted using analysis of variance (ANOVA) within the Statistical Analysis System (SAS Institute, 1999). Means were separated by the Fisher's Least Significant Difference (LSD) test. An alpha of 0.05 was used for relative shoot and root mass and for all Al and nutrient analyses of soil and plant tissue.

RESULTS AND DISCUSSION

Relative Growth Parameters

No differences were found in study I for relative root mass (RRM) or relative shoot mass (RSM). In study II, Japanese lawngrass exhibited 23% increase in RRM at 960 µm of Al, but as Al increased to 1440 µm, a 21% decrease in rooting occurred. Carpetgrass and manilagrass produced greater RRM (15% and 30%) at 1440 µm of Al compared to the other eight selected species. Buffalograss,

Table 3: Relative root, shoot, and total biomass based on control pH 4.0 of ten warm-season species affected by aluminum at 480, 960, and 1440 µm, study II.

	Relative Root Mass, %			Relative Shoot Mass, %			Relative Total Biomass, %		
Species	480	960	1440	480	960	1440	480	960	1440
SP§	0.70c†	0.71	0.57c	0.88abc	0.65	0.54d	0.88bc	0.66bc	0.54c
Carp	0.99abc	1.00	1.15ab	0.87abc	0.90	1.31a	0.88b	0.79bc	1.08a
JL	1.01abc	1.23	0.79bc	0.84bc	0.93	0.74cd	0.83bc	0.98b	0.74bc
Man	1.24a	1.03	1.30a	1.03ab	1.04	0.97b	1.23a	1.37a	0.98ab
Bah	0.82c	0.94	0.71c	0.80bc	0.67	0.71cd	0.80bc	0.69bc	0.67c
DB	0.86bc	0.79	0.77c	0.69bc	0.59	0.62cd	0.74bc	0.65bc	0.62c
Buff	0.88abc	0.67	0.45c	0.55c	0.67	0.67cd	0.60c	0.59c	0.56c
Cent	1.23ab	1.16	0.66c	1.18a	0.94	0.72cd	1.18a	0.98bc	0.71c
Aug	0.69c	0.63	0.50c	0.92ab	0.80	0.83bc	0.89b	0.78bc	0.78abc
HB	0.77c	0.66	0.73c	0.72bc	0.71	0.66cd	0.74bc	0.74bc	0.67c
LSD	0.38	ns	0.36	0.34	ns	0.24	0.27	0.38	0.30
p-value	0.05‡	0.17	0.01	0.05	0.34	0.01	0.01	0.01	0.02

†Values within a column followed by the same letter are not significantly different at $p \leq 0.05$ by protected LSD.

‡Significance at the probability level $p \leq 0.05$.

§SP=seashore paspalum, Carp=common carpetgrass, JL=Japanese lawngrass, Man=manilagrass, Bah=bahiagrass, DB=dactylon bermudagrass, Buff=buffalograss, Cent=centipedegrass, Aug=St. Augustinegrass, HB=hybrid bermudagrass.

Table 4: Distribution (g kg^{-1})of aluminum in shoots and roots of ten warm-season species affected by aluminum at 240, 480, and 720 µm, study I.

	Shoots			Roots		
Species	240	480	720	240	480	720
SP§	0.148	0.136	0.180	0.810ab†	0.896ab	0.953a
Carp	0.353	0.487	0.580	0.326c	0.262d	0.386c
JL	0.210	0.272	0.378	0.855a	0.449bcd	0.683abc
Man	0.213	0.269	0.374	0.354c	0.413d	0.434bc
Bah	0.138	0.155	0.249	0.235c	0.374d	0.375c
DB	0.097	0.123	0.191	0.829ab	0.936a	0.935a
Buff	0.186	0.295	0.405	0.891a	0.892ab	0.993a
Cent	0.143	0.258	0.370	0.306c	0.385d	0.540abc
Aug	0.096	0.145	0.274	0.735ab	0.780abc	0.880ab
HB	0.120	0.178	0.252	0.463bc	0.566bcd	0.829abc
LSD	ns	ns	ns	0.37	0.33	0.46
p-value	0.09	0.39	0.15	0.02‡	0.01	0.04

†Values within a column followed by the same letter are not significantly different at $p \leq 0.05$ by protected LSD.

‡Significance at the probability level $p \leq 0.05$.

§SP=seashore paspalum, Carp=common carpetgrass, JL=Japanese lawngrass, Man=manilagrass, Bah=bahiagrass, DB=dactylon bermudagrass, Buff=buffalograss, Cent=centipedegrass, Aug=St. Augustinegrass, HB=hybrid bermudagrass.

seashore paspalum, bahiagrass, and St. Augustinegrass, however, consistently performed poorly, showing a 55%, 43%, 29%, and 50% decrease in RRM at 1440 µm of Al, respectively (Table 3). All species had decreased relative shoot mass (RSM) at 1440 µm of Al, except carpetgrass (31% increase) (Table 3). Increased root and shoot growth due to exposure of Al has been previously reported. Rengel and Robinson (1989) observed two annual ryegrass (*Lolium multiflorum* Lam.) cultivars ('Marshall' and 'Gulf') to have increased root and shoot growth at lower Al concentrations (<74µm). Liu et al. (1995) reported enhanced root and shoot growth in Kentucky bluegrass (*Poa pratensis* L.) cultivars when exposed to 320 µm of Al.

Aluminum Distribution

Generally, Al is absorbed through root tissue (Kochian et al., 2004) and translocated slowly to shoots. In study I, with the exception of carpetgrass, all species reported higher levels of Al in roots than in shoots (Table 4). This is consistent with Rengel and Robinson's (1989) observation in annual ryegrass cultivars, where the transport of Al from roots to shoots was slow, as most Al remained in root tissue.

Study II had similar results as study I, with most species translocating less Al to shoot tissue at Al concentrations of 480 and 960 µm (Data not shown). Foy and Murray (1998) reported low shoot Al concentrations in Kentucky bluegrass cultivars compared to the root tissue.

Relative Nutrient Recovery

Under high Al stress in studies I and II, relative concentrations of P and Ca were significantly reduced in the root tissues (Tables 5 and 6). Krizek and Foy (1988) found a similar response when they investigated two barley (*Hordeum vulgare* L.) cultivars ('Kearney' and 'Dayton') and noted Al stress decreased root tissue mineral concentrations of P, Ca, and Mg.

All treatments influenced P recovery in root tissue in study I (Table 5). At 720 µm of Al, Japanese lawngrass increased relative root P recovery 5%, while manilagrass minimized relative root P loss (15%). However, a 35%, 72%, and 44% decrease in relative root P concentration occurred for bahiagrass, buffalograss, and hybrid bermudagrass (Table 5). Study I results agree with Foy and Murray's (1998) observations where P concentrations in shoots and roots of tall fescue (*Festuca arundinacea* Schreb.) cultivars decrease when exposed to Al treatments.

In study II, relative root P concentrations was unaffected by Al levels. This was probably due to drastic reductions in P levels for all treatments. However, most species had reduced relative root P concentration as Al treatments increased, which were similar to the results in study I (Table 5).

Table 5: Relative phosphorus (%) recovery in shoot and root tissue based on pH 4.0 of ten warm-season species affected by aluminum at 240, 480, and 720 µm, study I and 480, 960, and 1440 µm, study II.

	Study I						Study II					
	Roots			Shoots			Roots			Shoots		
Species	240	480	720	240	480	720	480	960	1440	480	960	1440
SP§	0.94bc†	0.81ab	0.60bc	0.77	0.80	0.46	0.71	0.57	0.54	0.69	0.50	0.61
Carp	0.87bc	0.78ab	0.55bc	1.54	1.11	0.95	1.17	0.66	0.66	0.85	0.67	0.63
JL	1.56a	0.56bc	1.05a	1.02	0.94	1.00	0.99	0.72	0.65	0.89	0.59	0.71
Man	0.77bc	0.52bc	0.85ab	0.95	0.73	0.61	0.74	0.57	0.47	0.62	0.54	0.54
Bah	0.82bc	0.66bc	0.65bc	0.84	0.57	0.56	1.26	0.87	0.85	0.93	0.67	0.68
DB	1.09ab	0.79ab	0.71ab	0.95	0.76	0.70	0.90	0.87	0.77	0.76	0.54	0.54
Buff	0.51c	0.35c	0.28c	1.21	0.92	0.69	0.79	0.57	0.60	0.86	0.82	0.74
Cent	0.81bc	0.81ab	0.67b	0.91	0.73	0.57	0.66	0.47	0.47	0.66	0.48	0.48
Aug	1.12ab	1.03a	0.75ab	0.86	0.69	0.63	0.91	0.55	0.64	1.12	0.71	0.62
HB	0.48c	0.34c	0.56bc	0.84	0.71	0.74	0.71	0.43	0.43	0.81	0.38	0.52
LSD	0.51	0.37	0.37	ns	ns	ns	ns	ns	ns	ns	ns	ns
p-value	0.01‡	0.01	0.04	0.64	0.44	0.43	0.43	0.30	0.66	0.64	0.07	0.26

Table 6: Relative calcium recovery (%) recovery in shoot and root tissue based on pH 4.0 of ten warm-season species affected by aluminum at 240, 480, and 720 µm, study I and 480, 960, and 1440 µm, study II.

	Study I						Study II					
	Roots			Shoots			Roots			Shoots		
Species	240	480	720	240	480	720	480	960	1440	480	960	1440
SP§	0.90	0.82	0.57bc†	0.90	0.98	0.71	0.40	0.41e	0.33d	0.85	0.75	0.75
Carp	0.89	0.76	0.76ab	1.20	1.11	1.02	0.79	0.72abcde	0.62abcd	1.05	0.99	0.75
JL	1.16	0.82	0.77ab	1.21	1.07	1.07	1.16	1.06a	0.87a	1.02	0.86	0.70
Man	1.04	0.94	0.81ab	0.97	1.06	0.92	1.15	0.65bcde	0.39cd	1.19	0.80	0.89
Bah	0.66	0.74	0.88a	1.01	0.89	0.87	1.10	1.00ab	0.75abc	1.02	1.00	0.78
DB	1.15	0.99	0.84a	0.95	0.95	0.91	1.17	1.06a	0.81ab	0.86	0.75	0.72
Buff	1.05	0.97	0.88a	0.95	1.08	0.74	1.30	0.98abc	0.82ab	0.85	0.95	0.95
Cent	1.02	0.88	0.86a	0.97	0.91	0.89	0.97	0.61cde	0.33d	0.81	0.77	0.95
Aug	1.13	0.87	0.71ab	0.65	0.59	0.69	1.02	0.93abcd	0.86ab	1.18	1.05	0.87
HB	0.50	0.59	0.40c	0.92	0.80	0.79	1.03	0.58de	0.52bcd	1.11	0.97	0.82
LSD	ns	ns	0.24	ns	ns	ns	ns	0.38	0.42	ns	ns	ns
p-value	0.08	0.44	0.01‡	0.07	0.06	0.07	0.06	0.01	0.05	0.81	0.79	0.90

†Values within a column followed by the same letter are not significantly different at $p \leq 0.05$ by protected LSD.

‡Significance at the probability level $p \leq 0.05$.

§SP=seashore paspalum, Carp=common carpetgrass, JL=Japanese lawngrass, Man=manilagrass, Bah=bahiagrass, DB=dactylon bermudagrass, Buff=buffalograss, Cent=centipedegrass, Aug=St. Augustinegrass, HB=hybrid bermudagrass.

Regardless of species, relative root and shoot Ca concentrations were reduced as Al increased in both studies (Table 6). This is consistent with observations reported by Krizek and Foy (1988).

No definitive trends for K recovery in shoot or root tissues occurred in studies I or II (Table 7). Alva and Edwards (1990) reported higher K concentrations in shoot tissue as Al increased in lupin (*Lupinus angustifolius* L.) cultivars. However, Rengel and Robinson (1989) noted K uptake decreased as Al increased in annual ryegrass cultivars.

CONCLUSIONS

Japanese lawngrass, manilagrass, and carpetgrass are relatively tolerant of Al levels. In study II, carpetgrass and manilagrass were the only warm-season turfgrass species that produced superior rooting at 1440 µm of Al with an increase of 15% and 30%, respectively. Species that performed poorly included seashore paspalum,

Table 7: Relative potassium recovery (%) recovery in shoot and root tissue based on pH 4.0 of ten warm-season species affected by aluminum at 240, 480, and 720 µm, study I and 480, 960, and 1440 µm, study II.

	Study I						Study II					
	Roots			Shoots			Roots			Shoots		
Species	240	480	720	240	480	720	480	960	1440	480	960	1440
SP§	1.19	1.07a†	1.28a	1.00	1.09	0.76	0.94	0.81	0.96	0.86	0.65de	0.80
Carp	0.99	1.21a	1.33a	1.27	1.03	1.01	1.12	0.94	1.02	1.06	1.01ab	0.95
JL	0.75	0.52de	0.70bcd	1.10	1.05	0.98	1.20	0.61	0.89	1.06	0.93abc	0.83
Man	0.90	0.79abc	0.81abcd	1.02	0.91	0.85	0.89	0.69	0.70	0.92	0.83abcde	0.98
Bah	0.93	0.92ab	0.85abcd	0.93	0.90	0.87	1.06	1.19	1.37	0.95	0.87abcd	0.91
DB	1.19	1.07a	1.09abc	0.90	0.96	0.88	0.86	0.68	0.73	0.82	0.77abcd	0.78
Buff	0.83	0.57bc	0.65cd	1.37	1.18	1.00	1.40	1.30	0.75	1.02	1.05a	1.01
Cent	0.85	0.84abc	0.55d	0.94	0.91	0.74	0.80	0.70	0.73	0.95	0.78bcde	0.97
Aug	1.29	1.09a	1.22ab	1.08	1.10	1.02	1.09	1.03	0.96	0.86	0.75cde	0.79
HB	0.63	0.48c	1.00abcd	1.09	0.95	0.91	0.85	0.89	0.82	0.95	0.61e	0.68
LSD	ns	0.43	0.52	ns	ns	ns	ns	ns	ns	ns	0.24	ns
p-value	0.06	0.01‡	0.04	0.44	0.83	0.54	0.24	0.08	0.08	0.85	0.01	0.43

†Values within a column followed by the same letter are not significantly different at $p \leq 0.05$ by protected LSD.

‡Significance at the probability level $p \leq 0.05$.

§SP=seashore paspalum, Carp=common carpetgrass, JL=Japanese lawngrass, Man=manilagrass, Bah=bahiagrass, DB=dactylon bermudagrass, Buff=buffalograss, Cent=centipedegrass, Aug=St. Augustinegrass, HB=hybrid bermudagrass.

bahiagrass, and buffalograss with 46%, 33% to 44% decreases, respectively, in relative total biomass (RTB) at 1440 µm of Al. Al impacted nutrient recovery in most turfgrass species. In both studies, as Al increased, relative Ca recovery generally decreased in root and shoot tissues. K levels, however, were unaffected by Al at any treatment level.

In study I, nine of the ten species contained more Al in root tissue than in shoot tissue. Since Al is absorbed by root tissue, this may indicate Al does not readily translocate from roots to shoots in the grasses selected. At higher Al solution concentrations, increased Al concentrations in shoots were noted in half of the species.

In these glasshouse studies, zoysiagrass and carpetgrass performed well when exposed to acid media. Future research could investigate these two species at the cultivar level to further understand their mechanisms of Al tolerance. Also, additional Al experiments should include field studies. This may be difficult due to various environmental conditions affecting the desired soil Al concentrations. Finally, screening new cultivars from the National Turfgrass Evaluation Program (NTEP) for their Al tolerance may prove beneficial.

REFERENCES

Alva, A.K., and D.G. Edwards. 1990. Response of lupin cultivars to concentration of calcium and activity of aluminum in dilute nutrient solutions. J. Plant Nutr. 13:57-76.

Clarkson, D.T. 1965. The effect of aluminum and some other trivalent metal cations on cell division in the root apices of *Allium cepa*. Ann. Bot. 29:309-325.

Foy, C.D., R.L. Chaney, and M.C. White. 1978. The physiology of metal toxicity in plants. Ann. Rev. Plant Physio. 29:511-566.

Foy, C.D., and J.J. Murray. 1998a. Responses of Kentucky bluegrass cultivars to excess aluminum in nutrient solutions. J. Plant Nutr. 21:1967-1983.

Foy, C.D., and J.J. Murray. 1998b. Developing aluminum-tolerant tall fescue for acid soils. J. Plant Nutr. 21:1301-1325.

Hartwell, B.L. and F. R. Pember. 1918. The presence of aluminum as a reason for the difference in the effect of so-called acid soils on barley and rye. Soil Sci. 6:259-279.

Hoagland, D. R., and D. I. Arnon. 1956. The water-culture methods for growing plants without soil. California Agr. Experiment Sta. Circular 347pp.

Huang, J.W., J.E. Shaff, D.L. Grunes, and L.V. Kochian. 1991. Aluminum effects of calcium fluxes at the root apex of aluminum-tolerant and aluminum-sensitive wheat cultivars. J. Plant Physiol. 98:230-237.

Kinraide, T.B. 1991. Identity of the rhizotoxic aluminum species. Plant Soil 134:167-178.

Kochian, L.V. 1995. Cellular mechanisms of aluminum toxicity and resistance in plants. Ann. Rev. Plant Physio. 46:237-260.

Kochian, L.V., O.A. Hoekenga, and M.A. Pineros. 2004. How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorus efficiency. Annu. Rev. Plant. Biol. 55:459-493.

Krizek, D.T., and C.D. Foy. 1988. Mineral element concentrations of two barley cultivars in relation to water deficit and aluminum toxicity. J. Plant Nutr. 11:369-386.

Liu, H. 2005. Aluminum toxicity of seeded bermudagrass cultivars. HortScience 40(1):221-223

Liu, H., J. R. Heckman, and J. A. Murphy. 1995. Screening Kentucky bluegrass for aluminum tolerance. J. Plant Nutr. 18:1797-1814.

Liu, H., J. R. Heckman, and J. A. Murphy. 1996. Screening fine fescues for aluminum tolerance. J. Plant Nutr. 19:677-688.

Marschner, H. 1991. Mechanisms of adaptations of plants to acid soils. Plant Soil 134:1-20.

Rengel, Z., and D.L. Robinson. 1989. Aluminum effects on growth and macronutrient uptake by annual ryegrass. Agron. J. 81:208-215.

Ryan, R.R., J.M. DiTomaso, and L.V. Kochian. 1993a. Aluminum toxicity in roots: An investigation of spatial sensitivity and the role of the root cap. J. Exp. Bot. 44:437-446.

Ryan, R.R., J.M. DiTomaso, and L.V. Kochian. 1993b. Al^{3+} - Ca^{2+} interactions in a aluminum rhizotoxicty. I. Inhibition of root growth is not caused by reduction in calcium uptake. Planta 192:192-198.

SAS Institute Inc. 1999. SAS Version 8.0. SAS Inst., Cary, NC.

Wu, L., D.R. Huff, and J.M. Johnson. 1981. Metal tolerance of bermudagrass cultivars. p.35-40. *In* R.W. Sheard (ed.) Proc. Int. Turfgrass Res. Conf., 4th, University of Guelph. Ontario, Canada.19-23 July 1981. Int Turfgrass Soc and Ontario Agric. College, Univ. of Guelph, Guelph, Ontario, Canada.