Evaluation of Aluminum Tolerance and Nutrient Uptake of 50 Centipedegrass Accessions and Cultivars

Jun Yan
Department of Horticulture, Nanjing Agricultural University, Nanjing 210095, P.R. China

Jingbo Chen, Tingting Zhang, and Jianxiu Liu
Institute of Botany, Jiangsu Province, Chinese Academy of Science, Nanjing 210014, P.R. China

Haibo Liu
Department of Horticulture, Clemson University, 253 Poole Agriculture Center, P.O. Box 340375, Clemson, SC 29634-0375

Additional index words. aluminum toxicity, acid soils, turfgrass, turfgrass nutrition, Al resistance, calcium, potassium, phosphorus, magnesium

Abstract. Centipedegrass [Eremochloa ophiuroides (Munro) Hack] is a native grass of China, and information on soil adaptation ranges, including acid soils, among centipedegrass cultivars is limited. Therefore, objectives of this study were 1) to conduct a preliminary evaluation of relative aluminum tolerance of 48 centipedegrass accessions plus a cultivar, TifBlair, and a common centipedegrass under aluminum (Al) stress (0 and 1500 μM Al) by using a solution culture method; and 2) to determine Al effects on nutrient uptake between resistant-group and sensitive-group accessions among the 50 accessions and cultivars. Differences were found among accessions and cultivars, and the CV of relative root weight, relative shoot weight, and relative total weight were 39.9%, 32.9%, and 33.6%, respectively. After growing 28 days in an acid subsoil, the resistant-group accessions showed much better growth than the sensitive-group accessions. The Al concentrations in roots and shoots of the two groups of accessions were increased under Al treatment, but most absorbed Al remained in roots with greater Al absorption among the sensitive group compared with the resistant group. The concentrations of phosphorus (P), magnesium (Mg), calcium (Ca), and potassium (K) in the two groups were reduced under Al stress with reductions of 59.3%, 54.8%, 47.9%, and 41.3% in shoots and reductions of 8.70%, 52.5%, 43.2%, and 34.4% in roots, respectively. Under Al stress, differences in P, Mg, and Ca concentrations were found between the two groups; however, differences were not found for K. The resistant-group accessions maintained higher concentrations of Mg and Ca than the sensitive group.

Soil acidity is a major problem in establishment and maintenance of turfgrass in many areas of the world (Foy and Murray, 1978). Aluminum (Al) toxicity has been identified as a major problem for crop production in acidic soils since 1918 (Hartwell and Pember, 1918). At soil pH 5.0 or less, toxic forms of Al become soluble in the soil solution, inhibiting root growth and function and thus affecting plant growth (Kochian et al., 2005). Negative effects of Al on uptake of calcium (Ca), magnesium (Mg), and phosphorus (P) have been demonstrated in plant species, including maize (Zea mays L.) (Keljens, 1995), sorghum (Sorghum bicolor L.) (Tan and Keljens, 1990), and rice (Oryza sativa L.) (Jan, 1991). Marschner (1991) and others (Foy and Murray, 1978) demonstrated that grasses in acidic soils suffered from P, potassium (K), Ca, and Mg deficiencies; inhibition of growth; and poor environmental stress tolerance. The negative effects of Al on plant growth and nutrient uptake for cool-season turfgrasses have been reported in several studies (Foy and Murray, 1998a, 1998b; Liu et al., 1995, 1996, 1997; Rengel and Robinson, 1989). However, few studies have examined the Al tolerance of warm-season turfgrasses (Baldwin et al., 2005; Duncan and Shuman, 1993; Liu, 2005).

Centipedegrass is a warm-season perennial grass originating from south to central China (Hanna, 1995; Hanna and Liu, 2003). Centipedegrass is often referred to as a low-maintenance turfgrass because of its lower maintenance requirement and fertility input. It has excellent heat and moderate shade tolerance and is relatively unsusceptible to diseases and insects. It has a naturally light green color and grows well on a wide range of soil types (Hanna, 1995; Hanna and Liu, 2003; James and Hanna, 1994). The centipedegrass accessions collector of this study, Dr. Jianxiu Liu, has found that centipedegrass is well adapted to acid soils, but it also can live in slightly neutral soils and coastal areas with soil pH greater than 7. Johnson and Carrow (1992) found that centipedegrass growth was better in pH 6.7 than in pH 5.1 when the soil was poorly fertilized. Baldwin et al. (2005) reported the Al effect on growth and nutrient uptake of 10 warm-season turfgrass species, including centipedegrass, and found that growth and nutrient absorption of most turfgrasses were inhibited when Al concentrations were greater than 640 μM. Among the 10 warm-season turfgrasses studied, carpetgrass (Axonopus affinis Chase) was the most Al-resistant species and centipedegrass exhibited moderate Al resistance. However, a lack of information remains about Al tolerance among centipedegrass accessions or cultivars to demonstrate the genetic diversity in acid soil adaptation. Therefore, the objectives of this study were 1) to conduct a preliminary evaluation of relative aluminum tolerance of 48 centipedegrass accessions plus TifBlair centipedegrass and a common centipedegrass from the United States by using a culture solution method; and 2) to determine Al effects on nutrient uptake between resistant-group and sensitive-group accessions among the 50 accessions and cultivars screened.

Materials and Methods

Aluminum solution screening experiment. A total of 48 representative native accessions collected from 13 provinces in the Yangtze River Valley in China (Fig. 1) plus TifBlair centipedegrass and a common centipedegrass developed in the United States were used in this experiment. All accessions were collected by Dr. Jianxiu Liu from 1998 to 2001 and cultured at the Turfgrass Plots of Nanjing Botanical Garden Mem. Sun Yat-Set. The experiments were conducted under greenhouse conditions in Nanjing Botanical Garden Mem. Sun Yat-Set, Nanjing, Jiangsu Province, China. The greenhouse was maintained at 33 to 37 ºC during the day and 25 to 28 ºC at night with 90% natural sunlight and a relative humidity range of 48% to 69% during the study.

To have enough young seedlings for the experiments and a uniformity control, a pre-experimental culture was conducted. Pieces of stolons with only one bud with similar length between 5 to 6 cm were used. In each 250-mL plastic cup (6.5 cm in diameter, 9.5 cm in height) filled with quartz grits with multiple pinholes at the bottom, four similar pieces of the previously described stolons were planted. A total of 100 pieces of stolons of each accession or cultivar were planted into 25 cups, and then the cups were suspended on a foam rack, which had 54 holes cut and held as many as 54 cups. The foam racks with cups were placed on top of large containers filled with 40 L modified half-strength Hoagland nutrient solution (Hoagland and Arnon, 1956) with the following nutrient concentrations (in mM): 2.5 Ca(NO3)2, 2.5 KNO3, 1 MgSO4, and 0.5 NH4H2PO4; and (in
mM): 46 boron (B), 0.3 copper (Cu), 0.1 molybdenum (Mo), 9.2 manganese (Mn), 0.8 zinc (Zn), and 50 iron (Fe)–EDTA aerated continuously by using an aerating pump and was changed weekly. All plant materials were pre-experimentally cultured for 2 weeks under the greenhouse conditions described.

After 2 weeks of pre-experimental culture, similar shoot and root size plants (four to five fully open leaves and 5 to 6 cm root) were transplanted into new cups of similar sizes and materials filled in as described earlier for the preliminary solution screening experiment. Three similar individual plants of each accession or cultivar were transplanted into one cup. To avoid and minimize possible contaminations of root exudates between different accessions or cultivars (Ma et al., 1997), three cups of the same accession or cultivar were suspended on one foam board cut with three holes, which was put on the top of a 2.5-L pot (17 cm in diameter, 15 cm in height) filled with 2 L culture solution with the following nutrient concentrations (in mM): 1.25 Ca(NO₃)₂, 1.25 KNO₃, 0.5 MgSO₄, and 0.025 NH₄H₂PO₄; and (in μM): 46 B, 0.3 Cu, 0.1 Mo, 9.2 Mn, 0.8 Zn, and 28 Fe-EDTA. An AI concentration of 1500 μM used for this study was determined based on findings by Baldwin et al. (2005) on 10 warm-season turfgrasses using a 1440 μM AI solution culture for 1 month with relative root mass and relative shoot mass reductions of 34% and 28%, respectively, for centipede-grass. As a result of the large number of centipede-grass accessions used in this study, which were distributed among areas from 19°01’ to 35°01’ north latitude in China (Liu and He, 1998) plus two U.S. centipede-grasses, only a control and 1500 μM Al (AlCl₃·6H₂O) were used. The pH of nutrient solutions of both concentrations was adjusted daily to 4.0 ± 0.2 (HCl or NaOH) and measured by using a portable pH meter (JENCO 6010; INC Technical Incorporated, Cincinnati, OH). All solutions were aerated continuously by using an aerating pump and solutions were changed every 3 d. All the nutrient solution was prepared with DD H₂O and the duration of treatment lasted 28 d. All the screened accessions and cultivars were arranged as a randomized complete block design with three replications.

An acid soil culture experiment with 10 selected accessions. The 10 accessions used for evaluation difference in nutrition uptake were planted in acid subsoil for confirming the results by culture solution method in the greenhouse mentioned. The acid subsoil, collected from Red Soil Ecological Experiment Station of Chinese Academy of Sciences, has a pH of 4.5 (ratio of soil to water is 1:1 and KCl-extractable Al is 11.6 cmol kg⁻¹), 0.27% organic matter, 0.056% total nitrogen, 5.41 mg kg⁻¹ available P, and 54.41 mg kg⁻¹ available K. The acid subsoil was air-dried and put into the pot (16 cm in diameter, 12 cm in height), and each pot contained 1000 g acid subsoil. The acid subsoil was treated with CaCO₃ to adjust its pH to 5.8 and used as a control. Fertilization with NH₄NO₃ and KH₂PO₄ added N, P, and K at 100, 109, and 137 mg kg⁻¹ of the soil, respectively, for both limed and nonlimed soils. The 10 accession stolons with one bud on each piece of stolon were uniformly planted in each pot. Each accession was repeated in three pots. After 1 week of growth, six stolon pieces with the similar size and appearance were retained in each pot and grown for 28 d.

The relative dry shoot mass (RSW), relative dry root mass (RRW), and relative dry total biomass (RTW) in acid subsoil were obtained and calculated in the same method as in culture solution method mentioned.
Previously taking one pot as a replication. All pots were arranged in a randomized complete block design with three replications.

Date collection and analyses. After 28 d of Al treatment, roots and shoots were separated and washed with deionized water to remove any residual soil or nutrients and then oven-dried at 80 °C for 48 h and weighed. The dried roots and shoots were used for nutrient uptake analyses by determining the individual nutrient concentrations. The RSW, RRW, and RTW were calculated using the following formulas, respectively: (dry root or shoot mass in one cup with Al/dry root or shoot mass in one cup without Al) × 100% (dry root + shoot mass in one cup with Al/dry root + shoot in one cup without Al) × 100%. All relative values were based on the controls.

Values of the relative growth parameters (RSM, RRM, RTM) were submitted to analysis of variance procedures and parameters. Means were separated using Duncan’s multiple range test (α = 0.05). As a result of the difficulty in handling all 50 accessions and cultivars for nutrient uptake analyses, only five most Al-resistant and five most Al-sensitive accessions were artificially chosen for comparing differences in plant uptake of Al, P, Mg, Ca, and K when exposed to Al based on the list provided in Table 1. For individual nutrient concentration analyses, the dry shoots and roots of the chosen accessions were ground. From the ground material, 0.2 g was weighed and placed into a 100-mL tube and digested with 5 mL 87% HNO₃ + 13% HClO₄ for 12 h, and then the digestion tubes were heated in a sequential procedure (80 °C 40 min, 100 °C 60 min, 120 °C 80 min, 140 °C 100 min, 160 °C 120 min, and 180 °C until the samples were totally dried). The samples were then removed from the digestion tube by adding 50 mL 5% HNO₃ and shaken vigorously. The concentrations of P, Mg, Ca, and Al of the sample solutions were analyzed by ICP-AES (Zhao et al., 1994). The relative concentrations of P, Mg, Ca, K, and Al were calculated using the

| Accession | Collecting site | Longitude | Relative root mass (%) | Relative shoot mass (%) | Relative total biomass (%) |
|-----------|----------------|-----------|------------------------|-------------------------|---------------------------|
| E041      | Lingchuan Guangxi | 107°17'   | 78.5 a                  | 80.5 a                  |
| E014      | Nanchang Jiangxi | 107°01'   | 97.2 b                  | 72.3 ab                 |
| E036      | Longli Guizhou  | 107°05'   | 93.7 b                  | 62.5 a-f                |
| E072      | Guilin Guangxi  | 107°06'   | 97.2 b                  | 67.4 a-e                |
| E016      | Huaihua Hunan   | 110°03'   | 97.2 b                  | 68.8 a-d                |
| E077      | Fuzhou Fujian   | 109°06'   | 97.2 b                  | 97.2 abc                |
| E180      | Zhongjiaju Hunan| 110°12'   | 79.6 def                | 65.5 a-f                |
| E137      | Ganzhi Hanzhi  | 119°30'   | 79.3 def                | 50.4 d-k                |
| E111      | Boluo Guangdong| 106°37'   | 77.8 d-g                | 53.4 b-h                |
| E131      | Yiyang Hunan   | 122°7'    | 74.9 e-h                | 59.0 b-h                |
| E035      | Chuxian Anhui  | 118°20'   | 72.1 f-k                | 53.9 d-j                |
| E071      | Liuzhou Guangxi| 109°26'   | 71.2 f-1                | 52.3 d-j                |
| E039      | Lushan Jiangxi | 116°00'   | 71.0 f-1                | 57.8 b-i                |
| E142      | ‘TriBlair’     | —         | 69.0 f-m                | 52.6 b-i                |
| E137      | Qionglai Sichuan| 103°41'   | 68.9 F-m                | 53.7 d-j                |
| E062      | Fuyun Guangdong| 113°15'   | 68.5 f-m                | 52.2 d-j                |
| E079      | Shien Hubei    | 109°22'   | 67.9 g-m                | 52.6 d-j                |
| E154      | Common         | —         | 67.7 g-m                | 52.3 d-j                |
| E084      | Anshun Guizhou | 105°54'   | 67.4 g-m                | 51.7 d-j                |
| E013      | Yongtai Fujian | 119°06'   | 67.3 g-n                | 52.5 d-j                |
| E022      | Wuji Jiangsu   | 120°20’   | 66.1 h-o                | 48.8 d-k                |
| E126      | Changsha Hunan | 112°49’   | 65.6 h-p                | 51.3 d-k                |
| E074      | Yongzhou Hunan | 111°37’   | 65.3 h-p                | 55.7 b-j                |
| E064      | Yinghong Hunan | 113°30’   | 64.3 h-p                | 47.8 d-k                |
| E030      | Ningguo Anhui | 119°00’   | 63.8 h-p                | 50.8 d-k                |
| E189      | Guangde Anhui | 119°32’   | 63.3 i-q                | 48.9 d-k                |
| E152      | Luoshan Henan  | 114°33’   | 62.9 j-q                | 49.0 d-k                |
| E007      | Yichang Hubei  | 118°20’   | 62.1 k-q                | 48.2 e-k                |
| E033      | Xuzhou Anhui   | 118°20’   | 62.1 k-q                | 42.9 g-k                |
| E051      | Yixing Jiangsu | 119°49’   | 59.8 l-r                | 47.8 e-k                |
| E151      | Xinyang Henan  | 114°04’   | 59.5 l-r                | 46.8 F-k                |
| E121      | Chuzhou Anhui  | 118°06’   | 59.0 m-r                | 47.5 e-k                |
| E090      | Nanshan Park Chongqing| 106°33’ | 58.3 m-s                | 44.1 e-i                |
| E021      | Hangzhou Zhejiang| 119°54’  | 57.7 m-t                | 46.5 F-k                |
| E092-1    | Yubei Chongqing| 106°33’   | 56.0 n-t                | 45.7 F-k                |
| E185      | Fuyang Zhejiang| 119°54’   | 55.6 o-t                | 45.7 F-k                |
| E142      | Huoqiu Jiangsu | 116°06’   | 54.6 p-t                | 38.3 j-k                |
| E107      | Queshan Henan  | 113°59’   | 52.4 q-u                | 44.9 d-i                |
| E143      | Gushi Henan    | 115°37’   | 49.8 r-u                | 45.1 d-i                |
| E016      | Jinhua Zhejiang| 119°32’   | 49.6 r-u                | 43.3 e-i                |
| E109      | Xuyu Jiangsu  | 118°46’   | 49.1 r-v                | 43.7 g-k                |
| E136      | Lianyungang Jiangsu| 119°21’  | 47.8 r-v                | 41.3 g-k                |
| E080      | Qianjiang Hubei| 112°48’   | 36.7 r-g                | 40.7 g-k                |
| E146      | Suzhou Jiangsu| 120°34’   | 46.7 s-w                | 37.6 j-k                |
| E027      | Lianyungang Jiangsu| 119°12’  | 43.6 u-w                | 36.6 k                |
| E184      | Putsun Zhejiang| 122°30’   | 42.2 u-w                | 42.3 g-k                |
| E089      | Xinjin Sichuan | 103°48’   | 38.6 v-w                | 39.0 h-k                |
| E006      | Nanjing Jiangsu| 118°52’   | 36.6 w                   | 31.5 k                |
|          |                | —         | 36.6–107.7              | 0.531–80.5              |
|          |                | —         | 39.0 (%)                | 32.9 (%)                |
|          |                | —         | 0.2 (%)                  | 3.2 (%)                |
|          |                | —         | 20.3**                   | 2.63**                 |

Values within a column followed by the same letter are not different at the 5% level of probability based on Duncan’s multiple range test. **P < 0.05 significant difference; *P < 0.01 significant difference; NS = no significant difference.

HortScience Vol. 44(3) June 2009 859
Table 2. Relative root mass, shoot mass, total biomass of five resistant accessions and five sensitive accessions grown in acid subsoil for 28 d.

| Accession | Relative root mass (%) | Relative shoot mass (%) | Relative total biomass (%) |
|-----------|------------------------|-------------------------|---------------------------|
| E041      | 82.0 c*                | 85.5 ef                 | 84.4 e                    |
| E014      | 77.5 bc                | 80.5 ef                 | 79.8 de                   |
| E136      | 66.4 b                 | 86.3 f                  | 79.2 de                   |
| E072      | 67.8 b                 | 67.9 cd                 | 67.9 c                    |
| E076      | 68.7 b                 | 74.0 de                 | 72.3 cd                   |
| E046      | 47.9 a                 | 49.6 ab                 | 49.0 ab                   |
| E027      | 45.4 a                 | 62.0 c                  | 56.4 b                    |
| E184      | 45.6 a                 | 48.5 ab                 | 47.7 ab                   |
| E089      | 51.1 a                 | 56.8 bc                 | 54.9 b                    |
| E006      | 41.4 a                 | 44.1 a                  | 43.5 a                    |
| F value   | 17.13**                | 17.74**                 | 22.69**                   |

*Values within a column followed by the same letter are not different at the 5% level of probability based on Duncan’s multiple range test.

**P < 0.05 significant difference; ***P < 0.01 significant difference; NS = no significant difference.

Table 3. The phosphorus (P), magnesium (Mg), calcium (Ca), and potassium (K) concentrations (RT/control %) and aluminum (Al) concentration (RT/control) of resistant-group and sensitive-group accessions affected by Al at 1500 μM in culture solutions for 28 d.

| Accession | Shoot P | Root P | Shoot Mg | Root Mg | Shoot Ca | Root Ca | Shoot K | Root K |
|-----------|---------|--------|----------|---------|----------|---------|---------|--------|
| E041(T)² | 1.27 a  | 6.98 a | 55.3 b   | 86.4    | 51.8 cd  | 58.4    | 63.3 c  | 71.0 c  |
| E014(T)  | 1.48 ab | 7.55 ab| 52.4 b   | 92.1    | 55.5 d   | 51.7    | 60.5 c  | 63.2 bc |
| E136(T)  | 1.39 ab | 7.62 ab| 50.0 b   | 98.9    | 48.9 bcd | 49.5    | 56.2 de | 60.6 abc|
| E072(T)  | 1.30 ab | 9.12 bc| 52.8 b   | 86.9    | 50.5 cd  | 50.8    | 60.8 e  | 66.6 bc |
| E076(T)  | 1.56 bc | 8.07 ab| 49.5 b   | 93.3    | 47.9 bcd | 48.5    | 56.9 de | 55.2 ab |
| E006(S)  | 2.06 c  | 15.18 d| 27.7 a   | 89.0    | 36.7 c   | 39.6    | 41.1 ab | 52.1 ab |
| E089(S)  | 2.09 c  | 14.98 d| 28.4 a   | 92.0    | 38.4 ab  | 41.0    | 39.3 a  | 50.8 ab |
| E184(S)  | 1.74 cd | 13.69 cd| 31.8 a   | 95.6    | 41.5 abc | 44.0    | 44.6 abc| 52.0 ab |
| E027(S)  | 1.82 cde| 14.04 cd| 29.5 a   | 92.8    | 39.1 ab  | 49.9    | 47.1 bc | 45.4 a  |
| E046(S)  | 1.85 de | 12.39 c| 30.1 a   | 95.4    | 41.2 abc | 41.7    | 50.6 cd | 51.7 ab |
| Mean     | 1.65    | 10.96  | 40.7     | 91.3    | 45.2    | 47.5    | 52.1    | 56.8    |
| F value  | 12.78** | 40.37**| 18.15**  | NS      | 3.68**   | NS      | 13.93** | 2.78**  |

²T = resistant group; S = sensitive group.

³Values within a column followed by the same letter are not different at the 5% level of probability based on Duncan’s multiple range test.

**P < 0.05 significant difference; ***P < 0.01 significant difference; NS = no significant difference.
in P of 59.3% in shoots and 8.7% in roots was observed. The P concentration of the resistant group was significantly higher than the sensitive group (Table 3). The results indicate that there was less influence of P concentration in the resistant group compared with the sensitive group. Also, there was less influence of P in roots compared with shoots after Al treatment. Baldwin et al. (2005) reported that Al stress reduced both shoot and root P concentrations of centipedegrass and the results of this study also confirmed that conclusion. It was reported that formation of P–Al complexes caused a reduction in root influx of P and transportation to shoots, consequently decreasing P accumulation in plant (Pfeffer et al., 1986). So, the assumption is that the formation of P–Al complexes might occur in both resistant-group and sensitive-group accession roots. However, the higher P concentrations (RT/control %) of the resistant group might be explained by mechanisms that ameliorate Al toxicity and reduce the formation of P–Al complexes, consequently increasing the transport of P to shoots and improving use of P in roots. Organic acid and phenolic compounds can form complex Al compounds resulting in reduced Al toxicity (Kochian et al., 2005), but higher P concentrations (RT/control %) of the sensitive group were found as well and this could be the result of the formation of complex P–Al compounds. However, additional experiments are needed to further explore P and Al relationships among centipedegrass and other turfgrass species.

There was a remarkable negative effect of Al on Mg, Ca, and K concentrations in shoots and roots in the two groups with an average reduction of 54.8%, 47.9%, and 41.3% in shoots and 52.5%, 43.2%, and 34.4% in roots, respectively (Table 3). When plants are exposed to Al, Mg and Ca uptake has been significantly inhibited (Marschner, 1995). Rengel and Robinson (1989) reported that Al-resistant annual ryegrass (Lolium multiflorum Lam.) cultivars could maintain greater uptake of Ca and Mg than sensitive ryegrass cultivars. Eduardo and Willem (2005) observed the same phenomenon in maize. Our study agreed with these findings. There were some controversies about the Al effect on K. Gassmann and Schroeder (1994) reported that Al inhibited plant uptake of K and decreased K concentrations in shoots and roots, because Al was considered a cation channel inhibitor and could subsequently result in the deficiency of K in shoots. However, Rengel and Robinson (1989) found that the K concentrations increased after a lower dosage of Al stress treatment with annual ryegrass.

Further research is needed to evaluate centipedegrass accessions on acid soils, including turf quality, drought stress, low temperature stress, and other environmental stresses. It is also meaningful to study Al tolerance mechanisms of resistant-group accessions such as P and Al relationships, the function of root secretions, and intracellular resistance mechanisms. Furthermore, to improve overall turf quality and morphological characteristics such as leaf width, plant height, recuperative ability, and pest resistance among centipedegrass accessions and cultivars, the Al-resistant group should be evaluated under field conditions to identify potential for further enhancement of this economically important turfgrass species.

**Literature Cited**

Baldwin, C.M., H. Liu, L.B. McCarty, W.B. Bauere, and J.E. Toler. 2005. Aluminum tolerance of warm-season turfgrasses. Int. Turfgrass Soc. Res. J. 10:811–817.

Duncan, R.R. and L.M. Shuman. 1993. Acid soil stress response of zoysiagrass. Intl. Turfgrass Soc. Res. J. 7:805–811.

Eduardo, D.M. and G.K. Willem. 2005. Long-term effects of aluminum exposure on nutrient uptake by maize phenotypes differing in aluminum resistance. J. Plant Nutr. 28:323–333.

Foy, C.D. and J.J. Murray. 1978. Differential tolerance of turfgrass cultivars to an acid soil high in exchangeable aluminum. Agron. J. 70:769–774.

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.

Gassmann, W. and J.I. Schroeder. 1994. Inward-rectifying K+ channels in root hair of wheat. A mechanism for aluminum sensitive low-affinity K+ uptake and membrane potential control. Plant Physiol. 105:1399–1408.

Hanna, W.W. 1995. Centipedegrass diversity and vulnerability. Crop Sci. 35:323–334.

Hanna, W.W., J. Dobson, R.R. Duncan, and D. Thompson. 1997. Registration of ‘TifBlair’ Centipedegrass. Crop Sci. 37:1017.

Hanna, W.W. and J. Liu. 2003. Centipedegrass. p. 287–293. In: Casler, M.D. and R.R. Duncan (eds.), Turfgrass biology, genetics, and breeding. John Wiley & Sons, Inc., Hoboken, NJ.

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 soil 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. p. 347.

James, E.H. and W.W. Hanna. 1994. Drought resistance in centipedegrass cultivars. HortScience 29:1528–1531.

Jan, F. 1991. Aluminum effects on growth, nutrient net uptake and transport in 3 rice (Oryza sativa L.) cultivars with different sensitivity to aluminum. Physiol. Plant. 83:441–448.

Johnson, B.J. and R.N. Carrow. 1992. Influence of soil pH and fertility programs on centipedegrass. Agron. J. 84:21–26.

Keltjens, W.G. 1995. Magnesium uptake by Al-stressed maize plants with special emphasis on cation interactions at root exchange sites. Plant Soil 171:141–146.

Kochian, L.V., M.A. Piñeros, and O.A. Hoekenga. 2005. The physiology, genetics and molecular biology of plant aluminum resistance and toxicity. Plant Soil 274:175–195.

Liu, H. 2005. Aluminum resistance among seeded bermudagrasses. HortScience 40:221–223.

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.

Liu, H., J.R. Heckman, and J.A. Murphy. 1997. Greenhouse screening of turfgrasses for aluminum tolerance. Int. Turfgrass Soc. Res. J. 8:719–728.

Liu, J.Y.L. and S. He. 1998. Species diversity of Chinese warm-season turfgrasses and the characteristic of geography distribution. Acta Agrestia Sinca. 6:45–52.

Ma, J.F., S.J. Zheng, S.F. Li, K. Takeda, and H. Matsumoto. 1997. A rapid hydropenic screening for aluminum tolerance in barley. Plant Soil 191:133–137.

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

Marschner, H. 1995. Mineral nutrition of higher plants. 2nd Ed. Academic Press, New York, NY.

Pfeffer, P.E., S.I. Tu, W.V. Gerasimowicz, and J.R. Cavanaugh. 1986. In vivo 31P NMR studies of corn root tissue and its uptake of toxic metal. Plant Physiol. 80:77–84.

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

SPOOL.0 Software in Medical Statistics. 2003. Guangdong Provincial Center for Disease Control and Prevention, Guangzhou, Guangdong, China.

Tan, K. and W.G. Keltjens. 1990. Effects of aluminum on growth, nutrient uptake, proton efflux and phosphorus assimilation of aluminum-tolerant and aluminum-sensitive sorghum (Sorghum bicolor) phenotypes, p. 397–401. In: van Beusichem, M.L. (ed.). Plant nutrition: Physiology and applications. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Xiong, Y. and L. Kui. 1987. Chinese soil science Press, Beijing, China. p. 34–35 (in Chinese).

Zhao, F.J., S.P. McGrath, and A.R. Croslan. 1994. Chinese soil science. Science Press, Beijing, China. p. 34–35 (in Chinese).