Evaluation of Aluminum Resistance among *Zoysia* Willd. Accessions from China

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Abstract. Aluminum ion (Al^{3+}) toxicity is a major factor limiting plant production on acid soils. Species of zoysiagrass (*Zoysia* Willd.) are grown for lawn, turf, and soil conservation, especially in temperate zones. Herein, 46 zoysiagrass accessions obtained from eight provinces in China were evaluated for Al resistance using small-scale liquid culture. Each accession was grown in triplicate in nutrient solutions with $1500 \mu\text{M AlCl}_3 \cdot 6\text{H}_2\text{O}$ (experimental) or without exposure to Al (control). The mean dry weights of the roots, shoots, and total bodies of the accessions relative to those of the nontreated controls were calculated after 60 days, and showed considerable diversity. Overall, the cv for the shoot, root, and total weights of the Al-treated accessions relative to the nontreated controls were 45.78%, 56.67%, and 42.84%, respectively. A cluster analysis based on Al resistance and subordinate function values revealed that 12 of the 46 zoysiagrass accessions (26.09%) were resistant to Al, 9 (19.57%) were moderately resistant, and 25 (54.35%) were sensitive to Al stress. These 46 zoysiagrass accessions from China have great potential for horticultural breeding and development, and for research into mechanisms that underlie Al resistance.

Soil acidification is normally a slow process, and acidic or acid soils are natural in humid tropical, subtropical, and temperate regions. However, the acidification of soil may be aggravated unnaturally by acid rain due to industrial emissions, or applications of acid fertilizers, and it is estimated that worldwide 40% of cultivated land is now acidic. In China, areas with acid soil are widely distributed across 14 provinces, primarily in the south. The total area affected is about 2.03 million square hectometer, comprising 21% of domestic farmland (Ying et al., 2006). Acid soils made toxic by heavy metals such as Al inhibit the growth of pasture and crops. Although Al is the third most abundant element in the earth's crust (after oxygen and silicon), its form in the soil is dependent on soil potential of hydrogen (pH). As soil becomes acidic, particularly when the pH is below 5.5, Al (mainly as free Al ions, or Al^{3+}) and some micronutrients become more soluble and toxic to plants. Concurrently, most of the nutrients required by plants are less available

(Kochian et al., 2005). Thus, in acid soils Al toxicity is a primary inhibitor of plant growth (Armiger et al., 1968), plants exhibit signs of nutrient deficiencies, and they are also less able to withstand stress (Marschner, 1991).

In agricultural practice, the two main approaches to improve plant growth in acid soils have been soil conditioning and breeding Al-resistant plant lines. Regarding soil conditioning, chemicals such as lime and other ameliorants are applied to neutralize the soil (i.e., increase the pH) and therefore decrease the solubility of Al^{3+} . However, lime affects only the soil surface and long-term application changes the soil's structure and other features. Soil ameliorants are effective only for the short term, are expensive, and their improper application decreases the solubility of other micronutrients such as zinc and iron and leads to over-decomposition of soil organics, to the detriment of the ecological environment. In terms of environmental conservation and protection, using plant germplasm resources for bioremediation of the soil (i.e., phytoremediation) is preferable to adding further chemicals to raise the soil's pH. The primary goal of phytoremediation on agricultural land is to return the soil's ecology to one that can support crop production. Remedial plant species should have Al resistance and high biomass. Zoysiagrass (*Zoysia* Willd., family Poaceae) is a perennial turfgrass that is mainly grown in temperate and humid tropical and subtropical regions (Guo et al., 2012). Its resistances to drought, cold, and salinity have made it popular all over the world for lawn and turf, and for soil conservation (Guo et al., 2012, 2014). There are 11 identified *Zoysia* species, five of which are distributed in China (*Z. japonica*, *Z. matrella*, *Z. tenuifolia*, *Z. sinica*, and *Z. macrostachya*) (Guo et al., 2014). In tropical southern China, soil acidification is an acute problem in pasture production and lawn conservation (Murray and Foy, 1978). The selection and breeding of

Fig. 1. A map showing the collection sites for the 46 *Zoysia* Willd. accessions from China.

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Al-resistant zoysiagrass accessions could improve pasture production and lawn quality in these areas of acid soils.

Although studies on Al resistance in plants have included crops such as *Zea mays* (Garzón et al., 2011; Keltjens, 1995; Maron et al., 2013), *Sorghum bicolor* (Sivaguru et al., 2013), *Oryza sativa* (Chen et al., 2012; Jan, 1991; Tsutsui et al., 2012), and *Triticum aestivum* (Delhaize et al., 1993; Garcia-Oliveira et al., 2013; Raman et al., 2010; Zhou et al., 2013), little progress has been made in grass species (Arroyave et al., 2013; Baldwin et al., 2005; Campbell et al., 1994; Duncan and Shuman, 1993; Ezaki et al., 2013; Gould et al., 2014; Liu, 2005; Yan et al., 2009). It has been suggested that differences in Al resistance among grass species or varieties is linked to genetic variations. Thus, the characterization of Al resistance in zoysiagrass and screening for Al-resistant accessions may enable grass breeders to improve and remediate acid soils. In this study, 46 zoysiagrass accessions from eight provinces in China were evaluated for Al resistance using small-scale liquid cultivation. The information we provide herein is fundamental to the selection of Al-resistant lines, as well as investigations into the resistance mechanisms of zoysiagrass.

Materials and Methods

Plant material

Forty-six native *Zoysia* Willd. accessions, which contained 1 *Z. sinica* Hance., 7 *Z. matrella* (Linn.) Merr., and 38 *Z. japonica* Steud., were collected from eight provinces in China from 2004 to 2008, ranging from tropical Hainan Island to the temperate climatic region around Shandong, between 18° N and 37° N latitudes and between 109° E and 122° E longitudes (Fig. 1; Table 1). Each accession was originally collected from grassland, roadside, or seaside, and was cultured in one 20-cm diameter pots in the greenhouse under uniform conditions at the Tropical Crops Genetic Resources Institute, Chinese Academy of Tropical Agricultural Sciences, Danzhou, Hainan Province, China (19°98' N, 110°32' E; elevation 176 m).

Plant growth

To ensure enough young seedlings for the experiments and a uniformity control, stolons of only one bud from each of the 46 zoysiagrass accessions were cut and cultivated in bags. In early July 2013, stolons at identical developmental stages were selected and cut into similar fragments (one node) and planted in 250-mL plastic cups (diameter 6.5 cm, height 9.5 cm, with six drilled holes at the bottom) filled with silica sand. Each accession was planted in six cups (three cups for treatments in one container, three cups for control in another container), and each cup held three sprig fragments.

Plants were grown by small-scale liquid cultivation. The plastic cups (200 mL, 6.5 cm in diameter, 7.5 cm in height) hung in foam plate each with three cups of a single accession, floating in a big container (45.0 cm in

length, 32.0 cm in width, and 16.0 cm in height) filled with 10 L half-strength Hoagland nutrient solution that was aerated continuously by an aerating pump and changed every 3 d (Yan et al., 2009). All accessions were cultured for 2 weeks under greenhouse conditions before the experiments began. The greenhouse was maintained at 32 °C to 38 °C during the day, 24 °C to 30.5 °C at night, with 90% natural sunlight and a relative humidity range of 40% to 75% during the study.

Al treatment

After 2 weeks, plants were treated with Al ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$) at concentrations of 0 (control) or 1500 μM (treatment) (Liu, 2005; Yan et al., 2009). The treatment period lasted 60 d. The pH of the nutrient solutions was adjusted to 4.0 ± 0.2 using HCl or NaOH, as appropriate, measured with a portable pH meter. All

nutrient solutions were aerated continuously with an aerating pump and solutions were changed every 3 d. The volume of the solution was maintained by replenishing water on a daily basis. Figure 2 showed the experimental design.

Data acquisition and statistical analyses

Measurement of root and shoot dry weight. At the end of the treatment period (60 d), the shoots and roots were separated and rinsed three times with deionized water. The plant materials were kept at 105 °C for 15 min and then dried at 75 °C for 48 h. The dried material was weighed on a scale. For each individual growth cup, the relative dry weights of plants (shoot, root, or total) in the Al-treated groups were calculated as a percentage of the average dry weight of the corresponding nontreated control plant parts. Specifically, the relative shoot weight (RSW),

Table 1. Geographical origins of 46 zoysiagrass accessions investigated in the present study.

Accession	Species	Origin	Accessions	Species	Origin
Z02	<i>Z. sinica</i>	Nanjing, Jiangsu	Z29	<i>Z. japonica</i>	Lianyungang, Jiangsu
Z03	<i>Z. japonica</i>	Lianyungang, Jiangsu	Z30	<i>Z. japonica</i>	Qingdao, Shandong
Z04	<i>Z. japonica</i>	Qingdao, Shandong	Z31	<i>Z. japonica</i>	Wuhe, Anhui
Z05	<i>Z. japonica</i>	Rongcheng, Shandong	Z32	<i>Z. japonica</i>	Jinshan, Shanghai
Z06	<i>Z. japonica</i>	Xianju, Zhejiang	Z33	<i>Z. japonica</i>	Kaihua, Zhejiang
Z07	<i>Z. japonica</i>	Lianyungang, Jiangsu	Z34	<i>Z. japonica</i>	Qingdao, Shandong
Z08	<i>Z. japonica</i>	Weifang, Shandong	Z35	<i>Z. matrella</i>	Tong'an, Fujian
Z09	<i>Z. japonica</i>	Longyou, Zhejiang	Z36	<i>Z. matrella</i>	Zhangpu, Fujian
Z10	<i>Z. japonica</i>	Yantai, Shandong	Z37	<i>Z. japonica</i>	Feidong, Anhui
Z13	<i>Z. japonica</i>	Dongying, Shandong	Z38	<i>Z. japonica</i>	Weihai, Shandong
Z14	<i>Z. japonica</i>	Tai'an, Shandong	Z39	<i>Z. japonica</i>	Nantong, Jiangsu
Z15	<i>Z. japonica</i>	Yantai, Shandong	Z40	<i>Z. japonica</i>	Weifang, Shandong
Z16	<i>Z. japonica</i>	Bengbu, Anhui	Z41	<i>Z. japonica</i>	Nanjing, Jiangsu
Z18	<i>Z. japonica</i>	Quzhou, Zhejiang	Z42	<i>Z. japonica</i>	Qingdao, Shandong
Z19	<i>Z. japonica</i>	Linyi, Shandong	Z43	<i>Z. japonica</i>	Rongcheng, Shandong
Z21	<i>Z. japonica</i>	Xiangshan, Zhejiang	Z44	<i>Z. japonica</i>	Yantai, Shandong
Z22	<i>Z. japonica</i>	Kaihua, Zhejiang	Z45	<i>Z. japonica</i>	Qingdao, Shandong
Z23	<i>Z. japonica</i>	Nanjing, Jiangsu	Z46	<i>Z. matrella</i>	Wenchang, Hainan
Z24	<i>Z. japonica</i>	Yantai, Shandong	Z47	<i>Z. matrella</i>	Wenchang, Hainan
Z25	<i>Z. japonica</i>	Qingdao, Shandong	Z48	<i>Z. matrella</i>	Lingshui, Hainan
Z26	<i>Z. japonica</i>	Nanjing, Jiangsu	Z49	<i>Z. matrella</i>	Lingshui, Hainan
Z27	<i>Z. japonica</i>	Feidong, Anhui	Z50	<i>Z. matrella</i>	Wanning, Hainan
Z28	<i>Z. japonica</i>	Yantai, Shandong	Z51	<i>Z. japonica</i>	Meizhou, Guangdong

Fig. 2. A picture of greenhouse showing the experimental design.

relative root weight (RRW), and relative total weight (RTW) were calculated.

Subordinate function value of Al resistance. The Al resistance of each zoysiagrass accession *i* was ranked by the subordinate function value for Al resistance (*F*): $F_i = (X_{ij} - X_{\min}) / (X_{\max} - X_{\min})$, where X_{ij} is the average value of feature *j* of accession *i*, and $X_{\min}$ and $X_{\max}$ are the minimum and maximum values, respectively, of feature *j* of accession *i*. The average *F* value of each accession *i* was defined as the average F_i of all features (Wang et al., 2013). The data were compiled using Microsoft Excel and analyzed using the Statistical Analysis System (SAS) Software. Values of the relative growth parameters (RSW, RRW, and RTW) were submitted to analysis of variance procedures and parameters. Means

were separated using Duncan's multiple range test ($\alpha = 0.05$) using the SAS program. Cluster analysis based on the relative growth parameters (RSW, RRW, and RTW) using the Euclidean distance was performed according to hierarchical clustering analysis of the SAS program.

Results

Effect of Al treatment on vegetative growth in 46 zoysiagrass accessions. After the 60-d experimental period, comparisons were conducted of the root, shoot, or total weights of the treated 46 zoysiagrass accessions, relative to the weights of the corresponding nontreated controls (RRW, RSW, and RTW, respectively; Table 2). Relative

root weight varied the most, from 5.80% to 470.87%, with a cv of 56.67%. This indicates that great diversity exists among the accessions with regard to Al resistance. Relative shoot weight ranged from 28.87% to 222.87%, and RTW from 31.88% to 214.09% (cvs = 45.78% and 42.84%, respectively).

Cluster analysis. The 46 accessions were classified into four groups (I–IV) after a hierarchical clustering analysis of the RSW, RSW, and RTW data (Euclidean distance = 0.85; Fig. 3). Group I comprised two accessions (Z41 and Z23) consisting of 4.35% of all evaluated materials. The mean *F* value for Al resistance was 0.6778 (0.5543–0.8012), indicating that the Al resistance of Group I was above average. Group II included six

Table 2. Effect of aluminum treatment on vegetative growth and *F* value in 46 *Zoysia* Willd. accessions.

Accession	Relative shoot wt (%)	Relative root wt (%)	Relative total wt (%)	Subordinate function value	Resistance level
Z02	79.59 bcde	154.63 bcdefgh	86.03 bcdef	0.1656	5
Z03	52.03 de	237.14 abcdefgh	63.64 def	0.4933	4
Z04	57.19 de	135.00 cdefgh	61.93 def	0.1666	5
Z05	45.34 e	137.44 cdefgh	53.90 ef	0.2841	5
Z06	67.11 de	78.23 efgh	67.46 cdef	0.4401	4
Z07	105.07 abcde	117.89 cdefgh	105.69 abcdef	0.1296	5
Z08	69.09 de	359.36 abc	83.75 bcdef	0.3127	5
Z09	65.83 de	83.32 efgh	66.34 def	0.6726	3
Z10	146.17 abcde	286.18 abcdefg	160.47 abcde	0.7193	3
Z13	91.88 bcde	110.20 cdefgh	93.08 abcdef	0.3572	4
Z14	71.07 de	168.63 bcdefgh	78.77 bcdef	0.1201	5
Z15	67.91 de	54.25 fgh	66.52 def	0.1821	5
Z16	104.06 abcde	115.00 cdefgh	105.76 abcdef	0.1962	5
Z18	59.82 de	79.22 efgh	61.55 def	0.5040	3
Z19	52.34 de	152.94 bcdefgh	60.39 def	0.2016	5
Z21	136.92 abcde	248.33 abcdefgh	142.56 abcdef	0.5479	3
Z22	65.99 de	175.46 bcdefgh	74.71 bcdef	0.2215	5
Z23	199.73 ab	185.42 bcdefgh	197.07 ab	0.5543	3
Z24	77.19 bcde	172.44 bcdefgh	87.05 bcdef	0.2573	5
Z25	196.96 abc	312.79 abcdef	214.09 a	0.6917	3
Z26	146.11 abcde	214.93 bcdefgh	152.92 abcdef	0.7271	3
Z27	108.94 abcde	104.61 cdefgh	108.63 abcdef	0.4068	4
Z28	100.82 bcde	201.30 bcdefgh	110.66 abcdef	0.3136	5
Z29	74.92 cde	106.07 cdefgh	76.71 bcdef	0.3112	5
Z30	139.00 abcde	144.44 bcdefgh	138.21 abcdef	0.9530	1
Z31	78.70 bcde	226.23 abcdefgh	90.72 abcdef	0.4154	4
Z32	91.23 bcde	98.74 defgh	92.39 abcdef	0.1997	5
Z33	63.34 de	324.22 abcde	77.32 bcdef	0.2989	5
Z34	28.87 e	87.20 defgh	31.88 f	0.0932	5
Z35	105.26 abcde	157.25 bcdefgh	110.25 abcdef	0.2157	5
Z36	101.65 bcde	167.68 bcdefgh	106.36 abcdef	0.5129	3
Z37	113.91 abcde	394.93 ab	140.59 abcdef	0.6206	3
Z38	90.52bcde	132.77 cdefgh	93.95 abcdef	0.1942	5
Z39	38.76 e	125.88 cdefgh	44.93 ef	0.3650	4
Z40	90.76 bcde	126.64 cdefgh	92.16 abcdef	0.2774	5
Z41	222.87 a	95.53 defgh	194.66 abc	0.8012	2
Z42	88.98 bcde	287.18 abcdefg	105.29 abcdef	0.4426	4
Z43	173.16 abcd	344.57 abcd	186.48 abcd	0.9726	1
Z44	79.71 bcde	65.16 fgh	74.00 bcdef	0.0353	5
Z45	75.00 cde	272.08 abcdefg	87.58 bcdef	0.4108	4
Z46	46.30 e	34.08 gh	45.15 ef	0.0713	5
Z47	71.53 de	470.87 a	95.27 abcdef	0.3238	5
Z48	108.74 abcde	5.80 h	57.27 ef	0.0016	5
Z49	114.61 abcde	151.21 bcdefgh	117.79 abcdef	0.1821	5
Z50	88.06 bcde	182.38 bcdefgh	94.05 abcdef	0.3465	5
Z51	52.94 de	290.47 abcdefg	64.58 def	0.4669	4
Maximum	222.87	470.87	214.09	0.9726	
Minimum	28.87	5.80	31.88	0.0016	
Mean	93.61	177.74	98.26	0.3734	
SE	42.85	100.73	42.09	0.2328	
cv (%)	45.78	56.67	42.84	62.33	
<i>F</i> value	1.48 ^{ns}	1.91 ^{**}	1.38 ^{ns}		

Values within a column followed by the different letters are significantly different at 5% level of probability based on Duncan's multiple range test.

^{ns}, *, ^{**}Nonsignificant or significant at $P < 0.05$ or 0.01 , respectively.

Fig. 3. Cluster dendrogram of the 46 *Zoysia* Willd. accessions from China, based on their aluminum resistance.

accessions (Z43, Z25, Z30, Z26, Z21, and Z10), comprising 13.04% of all the plant materials. The mean F was 0.7689 (0.5479–0.9726) indicating high Al resistance. Accessions Z43 and Z30 ($F = 0.9726$ and 0.9530, respectively) were the most Al resistant.

Group III included two accessions (Z37 and Z47) comprising 4.35% of all evaluated materials. This group has moderate Al resistance [$F = 0.4722$ (0.3238–0.6206)].

The 36 accessions in Group IV account for 78.26% of all accessions. These were further stratified into three subgroups (IVa, IVb, and IVc), with a Euclidean distance of 0.70. Subgroup IVa consists of seven accessions, with below-average Al resistance [$F = 0.4058$ (0.2989–0.4933)]. Subgroup IVb holds only one accession, and the F value indicates sensitivity to Al (Z48; $F = 0.0016$). Subgroup IVc includes 28 accessions, and resistance to Al is weak [$F = 0.2651$ (0.0353–0.6726)].

Ranking on Al resistance in zoysiagrass accessions. Based on the results of the cluster analysis and the subordinate function values, the 46 accessions were ranked into five levels of Al resistance: level 1 very highly resistant ($F \geq 0.9$); level 2, highly resistant ($0.75 \leq F < 0.9$); level 3, moderately resistant ($0.50 \leq F < 0.75$); level 4, neutral resistance ($0.35 \leq F < 0.50$); and level 5, sensitive to Al ($F < 0.35$). Among the evaluated 46 zoysiagrass accessions, 12 (26.09%) accessions belong to

Al-resistant ranked within levels 1–3, 9 (19.57%) accessions belong to neutral resistance ranked within level 4, and 25 (54.34%) accessions belong to Al-sensitive ranked within level 5.

Discussion

Although Al resistance has been intensively studied in crops, germplasm resources or resistance mechanisms related to Al stress in zoysiagrass have not been explored. Thus, screening for Al-resistant accessions is necessary to provide fundamental information toward the genetic breeding of zoysiagrass. In general, soil or liquid culture is used to screen for Al-resistant accessions. In soil culture, plant materials are grown on acid soil with high Al content, Al resistance is assessed based on shoot growth and biomass, and the method simulates agricultural practice. However, soil is a complex matrix with many variables, it is difficult to control and compare treatments, and soil culture is time consuming and tedious. Therefore, liquid culture is more commonly used to screen for Al-resistant lines. In liquid culture, Al is added to the culture solution, and the growth of roots and shoots is evaluated and ranked for Al resistance. In large-scale liquid culture, the plant materials to be compared can be grown in the same culture container to maintain consistent growth conditions.

Although convenient and efficient, liquid culture also has disadvantages. Plants in the same container can be influenced by complex biochemical reactions. For example, organic acids, phosphoric acid, and colloids may be secreted by Al-resistant plants under treatment, or pH elevation can occur in the rhizosphere. To prevent such problems, small-scale liquid culture (in vitro culture) has been used for Al resistance screening. Aluminum toxicity in plants is caused by an interaction between Al^{3+} and the root tip, which inhibits root development. Therefore, reduced root growth is the most obvious sign of Al toxicity and is used when assessing Al resistance. In *Eremochloa ophiuroides*, changes in the growth of aerial parts (e.g., relative height and shoot dry weight) and the RRW have also been evaluated as indicators of Al toxicity (Yan et al., 2009). In the present study, we used RRW, RSW, and RTW to comprehensively evaluate Al resistance in the 46 zoysiagrass accessions. Because changes in a single feature in response to Al stress may not be consistent for the same plant material, determining resistance based on only one feature is not reliable. Subordinate function analysis method based on multi-index measurement provides a way of comprehensive evaluation of material properties, and can overcome the shortage of only a few indicators to evaluate and make the result more objective and accurate. In the present study, the subordinate function values were calculated based on RRW, RSW, and RTW values; the greater the average subordinate function values, the stronger the resistance to Al. So there were 12 accessions (26.09%) that belong to Al resistant with F values ranging from 0.5040 to 0.9726, 9 accessions (19.57%) that belong to neutral resistance with F values ranging from 0.3572 to 0.4933, and 25 (54.34%) accessions that belong to Al sensitive with F values ranging from 0.0016 to 0.3465. In previous research, the average subordinate function values (F) for seedling height, leaf age, root dry weight, and shoot dry weight were used to evaluate the Al resistance in 51 soybean accessions from Huang-Huai-Hai and the middle and lower reaches of the Yangtze River (Liu and Gai, 2004).

In plants, Al is absorbed mainly by roots and accumulates more in the root tip than in mature regions. Although high Al concentrations are toxic in plants, it has also been reported that in the annual grass *Lolium multiflorum* varieties Marshall and Gulf grown in nutrient solutions, the growth of root and shoot were promoted by Al at concentrations lower than 74 μM (Rengel and Robinson, 1989). Promoted growth in the shoot and root were also observed in *Poa pratensis* when Al concentrations in the nutrient solution were lower than 320 μM (Liu et al., 1995). In our present study, relative root growth was promoted by treatment of 1500 μM Al in most of the zoysiagrass accessions (Table 1), indicating greater Al resistance in zoysiagrass than the abovementioned grass species.

In this study, we evaluated the Al resistance of 46 zoysiagrass accessions using small-scale liquid culture. Based on the results of the cluster analysis and ranking, the Al resistance of these accessions from China ranged from virtually none to very high. This indicates the diversity of zoysiagrass in China and its potential for horticultural breeding and development. Zoysiagrass accessions with high Al resistance were screened. These provide materials for further investigation on Al toxicity in zoysiagrass, and bioremediation of Al-rich acid soil in southern China.

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