Root Development and Profile Characteristics of Bermudagrass and Zoysiagrass

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Abstract. Irrigation for commercial and residential turf is becoming limiting, and water scarcity is one of the long-term challenges facing the turfgrass industry. Potential root development and profile characteristics of turfgrass provide important information regarding their drought resistance mechanisms and developing drought-resistant cultivars. The objective of this study was to determine the potential root development and root profile characteristics of two bermudagrass species and two zoysiagrass species using experimental lines and commercial cultivars. The species evaluated in the study were: African bermudagrass (*Cynodon transvaalensis* Burtt-Davy), common bermudagrass (CB) [*Cynodon dactylon* (L.) Pers. var. *dactylon*], *Zoysia japonica* (ZJ) (Steud), and *Zoysia matrella* (ZM) L. Plants were grown outdoors in clear acrylic tubes encased in poly vinyl chloride (PVC) sleeves. The experimental design was randomized complete block design with four replications. Rates of root depth development (RRDD) during the first 30 days were obtained. Root length density (RLD) in four different horizons (0–30, 30–60, 60–90, and 90–120 cm) was determined 60 days after planting. Specific root length (SRL, $\text{m}\cdot\text{g}^{-1}$) was also calculated dividing total root length by total root dry weight (RDW). The root depth in four turfgrass species increased linearly during the first 30 days after planting. Common bermudagrass (CB) had high RRDD and uniform RLD in different horizons, while ZM accumulated the majority of its roots in the upper 30 cm. *Z. matrella* had higher RLD than CB in the upper 30 cm. African bermudagrass had higher SRL than CB. There was limited variation within the two African bermudagrass genotypes studied except at the lowest horizon (90–120 cm). Two genotypes in CB and ZJ, respectively, including ‘UF182’ (ZJ), which consistently ranked in the top statistical group for RRDD, and RLD for every horizon, and ‘UFCD347’ (CB) demonstrated greater RLDs in the lower horizons in comparison with the commercial cultivars.

Water scarcity is one of the major long-term problems that the turf industry faces worldwide, and the use of water on commercial and residential turf is increasingly regulated at national and regional levels. Both chronic shortages of water that occur in arid and semiarid zones (Eriyagama et al., 2009) and occasional extended droughts in humid regions (Carrow, 1996b) can increase the need to irrigate turf and pose challenges to maintain acceptable turfgrass quality. Drought avoidance refers to the plant’s ability to increase water uptake by developing a deep, extensive, and viable root system; and to reduce water loss through stomatal control (Huang, 2008; Huang et al., 1997a, 1997b).

Determining genetic potential in various root traits that are associated with drought mechanisms is an important screening process for developing turfgrasses with good drought response. Root length density (RLD, cm root cm^{-3} soil), has been widely used to quantify the extensiveness of the roots (Carrow, 1996a; Miller and McCarty, 1998), and is generally positively correlated with the rate of water uptake under well-watered conditions (Huang, 2000). Variations of RLD in a limited number of turfgrass species including cool-season and warm-season grasses have been documented. For example, Qian et al. (1997) reported that total root length in a 120-cm profile of ‘Mustang’ tall fescue (*Festuca arundinaceae* Schreb) was three times greater than ‘Meyer’ zoysiagrass (ZJ), ‘Midlawn’ hybrid bermudagrass [*C. dactylon* (L.) Pers. var. *dactylon*], and ‘Prairie’ buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.] when grown in a greenhouse in

calcin clay. This study was in accordance with Carrow (1996b), who documented similar results when comparing RLD between zoysiagrass and tall fescue.

However, high RLD alone does not translate to good performance during drought. In fact, high RLD in the surface soil would result in faster depletion of water and early onset of drought stress (Su et al., 2008). Profile characteristics of roots and associated drought avoidance mechanisms have been reported in several studies (Burton et al., 1954; Carrow, 1996b; Qian et al., 1997; Sheffer et al., 1987). Carrow (1996b), reported that high RLD close to the soil surface (3–10 cm) was related to greater leaf firing, while high RLD in the 20–60-cm horizon was associated with less leaf firing and wilting in tall fescue cultivars during drought.

The rate of root depth development (RRDD, cm/d) has been used as a potential criterion for selecting drought-resistant plants (Hamblin and Tennant, 1987). Root penetration of warm-season grasses (Burton et al., 1954) and rooting depth of 25 zoysiagrass cultivars (Marcum et al., 1995) were found to be correlated with drought response. Plants with rapid root extension were expected to develop deep roots, and the narrow-sense heritability of root extension in creeping bentgrass (*Agrostis stolonifera* L.) was high when grown in flexible root tubes (Lehman and Engelke, 1991). Acuña et al. (2010) developed a screening technique to evaluate bahiagrass (*Paspalum notatum* Flüggé) germplasm for RRDD, and a linear increase of root depth was reported. This technique can be potentially used to screen other turfgrass species for their root development.

Rooting patterns under well-watered conditions may not translate to rooting patterns under drought (Huang, 1999); however, the ability to develop deep and extensive root systems under well-watered conditions may ensure access to moisture deeper in the soil profile at the onset of drought. Correlations have been documented between rooting characteristics under well-watered conditions and survival under deficit irrigation in zoysiagrass (Marcum et al., 1995).

Common bermudagrass and zoysiagrass are widely used as warm-season turfgrass species in the southern United States for landscapes and sport fields (Trenholm et al., 2000; Unruh et al., 2013). African bermudagrass, indigenous to the Transvaal region of South Africa (De Wet and Harlan, 1971), has been used for turf (Juska and Hanson, 1964) and as a parent to produce interspecific bermudagrass hybrids (Burton, 1991; Kenworthy et al., 2006). There is no available information related to rooting traits in African bermudagrass.

The objectives of this study were to 1) determine RRDD and root profile characteristics of two bermudagrass species and two zoysiagrass species, 2) identify genotypes with great RRDD and high RLD in the lower profile. Both experimental lines and

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commercial cultivars were included in the study.

Materials and Methods

Location, materials, and experimental design. The study was conducted in Gainesville, FL (29°39'5''N/82°19'30''W), at the Plant Physiology and Breeding Laboratory facilities of the University of Florida (UF) Agronomy Department. Seventeen genotypes and cultivars were evaluated from the following species (Table 1): African bermudagrass (AB), CB, ZJ, and ZM. The genotypes used in the study trace to germplasm from the UF, Texas A&M University (DALZ), Germplasm Resources Information Network (PI) and commercial cultivars. The study was conducted twice, initiated 1 July 2009 and 1 June 2010. Temperature and daily average photosynthetically active radiation (PAR) during the study are provided in Fig. 1.

Procedures were a modification of those described by Acuña et al. (2010). Plants were grown outdoors in clear acrylic tubes with a depth of 122 cm by 6.4 cm diameter. Tubes were filled with an 80:20, USGA sand:peat, mix and set inside of 7.6-cm diameter white PVC pipes. Plugs (5 cm diameter) of each genotype taken from field plots or greenhouse trays, washed free of soil and roots removed below the crowns, were planted into the tubes. The experiment was arranged in a randomized complete block design with four replications. One week after planting, plants were fertilized with a 10–10–10 Scotts (Marysville, OH) granular fertilizer at a rate of 48 kg·ha⁻¹. Nitrogen (N) sources were urea (7.9%) and ammoniacal N (2.1%). Plants were subsequently fertilized weekly with

a water-soluble fertilizer (36–0–6; Miracle-Gro, Marysville, OH), at a rate of 5 kg·ha⁻¹ (1.8 kg N/ha per application) with N sources being urea (33.2%) and ammoniacal nitrogen (2.8%). Grasses were trimmed every week at a height of 6.3 cm. The tubes were irrigated every 2 d to maintain field capacity (when rainfall was inadequate), and placed at an angle of 75° to the ground to facilitate the visibility of the roots along the wall of the clear tubes for data measurements (Su et al., 2008).

Measurements. Root depth measurements, based on the single deepest visible root, were initiated the first week after planting and subsequently recorded three times per week. Rate of root depth development (RRDD, cm/d) was determined from the linear increase in the depth of the deepest root as a function of time in the first 30 d (Acuña et al., 2010). Sixty days after planting the root/soil cores were harvested from the tubes. For harvesting, the tubes were fully watered to keep the column of soil wet for easier removal of the intact soil/root samples. Roots were separated by cutting the roots from the base of the crown and rhizomes. The roots were then sectioned into 30-cm horizons: horizon A (1–30 cm), horizon B (30–60 cm), horizon C (60–90 cm), and horizon d (90–120 cm). Roots were washed to remove soil on a 1-mm mesh screen, digitally scanned and analyzed using WinRHIZO (Québec, Canada) software to determine root length (cm) and RLD (cm root cm⁻³ soil) by considering the diameter of the tubes and the length of each horizon. Subsequently, RDW was obtained after drying at 60 °C for 72 h. Specific root length (m·g⁻¹), which represents the amount of absorptive root tissue produced

per unit of mass invested, was calculated by dividing the total RLD by the total RDW.

Statistical analysis. All the data were analyzed using proc glimmix in SAS software (SAS Institute Inc., Cary, NC). There was no significant interaction between year and species for root depth, RLD and its distribution, RDW distribution, and SRL. Therefore, data from the two trials were pooled. Least square means were estimated and tested for significant differences at the 0.05 level of probability. Due to the rapid growth of roots in bermudagrass, a linear regression between days after planting and root depth over the first 30 d was fit using proc reg in SAS. RRDD (cm/d), the slope of the regression, indicated the increase in root depth overtime.

Results

Rate of root depth development. Regression analysis between days after planting and root depth showed that species and genotypes within species differed for RRDD as indicated by their respective slopes (Figs. 2 and 3). Common bermudagrass had higher RRDD (4.02 cm/d, Fig. 2) than other species. African bermudagrass (3.46 cm/d) and ZJ (3.32 cm/d) had similar RRDD, whereas ZM exhibited the lowest RRDD (2.50 cm/d). Rate of root depth development ranged from 2.35 to 4.38 cm/d for all genotypes and cultivars (Fig. 3). Differences for RRDD were found within CB, ZJ, and ZM but not AB. For genotypic comparison, 'UFCD295' had higher RRDD than the other CB genotypes except for 'Celebration' and 'UFCD12'. Genotypes 'DALZ5269-24', 'JaMur', and UF182 demonstrated higher RRDD than 'DALZ4360' and 'Empire'. Within ZM, 'PristineFlora' had higher RRDD than other entries.

RLD and root distribution. Turfgrass species varied for RLD and root distributions within different horizons of the soil profile (Fig. 4). African bermudagrass and ZJ did not differ in their total RLD and RLDs in all horizons (Fig. 4A). At 1–30 cm, zoysiagrass species (ZJ and ZM) had higher RLD than CB (Fig. 4A). But RLDs of CB were the highest at 30–120-cm horizon. Common bermudagrass had greater total RLD than AB and ZM. *Zoysia japonica* had higher RLD than ZM only at 90–120-cm horizon.

The percentages of roots distributed within each horizon to the total root length (Fig. 4B) indicate differing root distribution abilities among these turfgrass species. Common bermudagrass had the most uniform root distribution between the four horizons in comparison with ZM, which distributed ≈80% of total root length in the top two horizons (1–60 cm).

For genotypic comparisons within a species, no differences were found for AB genotypes in 0–30 and 30–60-cm horizons and total RLD (Table 2). Genotype 'UFCT42' AB had higher RLDs in the lower horizons (60–120 cm) than 'UFCT33'. Within CB, differences were found in lower

Table 1. Genotypes and cultivars from four turfgrass species in the study.

Species	Genotype	Species	Genotype
African bermudagrass	UFCT33	<i>Zoysia japonica</i>	DALZ4360
African bermudagrass	UFCT42	<i>Z. japonica</i>	DALZ5269–24
Common bermudagrass	289922	<i>Z. japonica</i>	Empire ^z
Common bermudagrass	Celebration ^z	<i>Z. japonica</i>	JaMur ^z
Common bermudagrass	UFCD12	<i>Zoysia matrella</i>	UF336
Common bermudagrass	UFCD295	<i>Z. matrella</i>	UF374
Common bermudagrass	UFCD347	<i>Z. matrella</i>	PristineFlora ^z
Common bermudagrass	UFCD481	<i>Z. matrella</i>	Zeon ^z
<i>Z. japonica</i>	UF182		

^zCommercial cultivar.

Fig. 1. (A) Temperature (°C) and (B) daily average PAR (μmol·m⁻²·s⁻¹) when the two trials were conducted in 2009 and 2010. Error bars represented standard error.

Fig. 2. Rate of root depth development (RRDD) of four turfgrass species during the first month grown in acrylic tubes in 2009 and 2010. (A) Regression between date of planting and root depth for each turfgrass species; data points were averaged across replications, cultivars, and years. (B) Slope of the regression for each species. Error bars represented standard error and vertical bars followed by the same letter are not different at 0.05 *P* value. AB = African bermudagrass (*n* = 160); CB = common bermudagrass (*n* = 480); ZJ = *Zoysia japonica* (*n* = 400); ZM = *Zoysia matrella* (*n* = 320).

Fig. 3. The confidence intervals (at 0.05 *P* level) of the rate of root depth development (RRDD, cm/d) for genotypic comparison within four turfgrass species. AB = African bermudagrass; CB = common bermudagrass; ZJ = *Zoysia japonica*; ZM = *Zoysia matrella*. Genotypes or cultivars with nonoverlapping bars were significant different.

horizons (30–120 cm) and total RLD where UFCD347 remained among the best performing genotypes. UFCD295 and UFCD12 were both similar to UFCD347 in horizons B (30–60 cm) and C (60–90 cm). Celebration was lower in RLDs in lower horizons and total RLD compared with UFCD347.

Within ZJ, the experimental line UF182 and commercial cultivars JaMur and Empire were in the top statistical grouping for Total RLD. DALZ5269-24 had less favorable horizon RLD values and total RLD, but was

similar to Empire. DALZ4360 consistently had the lowest RLD in each horizon. For ZM, differences were found only in the upper horizon (1–30 cm) where ‘Zeon’ had higher RLD than PristineFlora and ‘UF336’.

Genotypic differences among the soil profiles were also found for the distribution of RLD (Table 2). UFCT42 AB distributed more RLD in its deeper horizons (60–120 cm) than UFCT33. UFCD347 and UFCD12 had less of their RLD in the 1–30 cm horizon, but greater distribution in the 60–120 cm

horizons. ‘UFCD481’ was opposite compared with the two previous genotypes. Celebration and UFCD347 were not different for RLD distribution in their deeper horizons. DALZ4360 ZJ distributed more RLD in its upper horizon (1–30 cm) than its lower horizon (90–120 cm) in comparison with other ZJ genotypes. *Z. matrella* genotypes did not differ in distribution of RLD.

RDW distribution and SRL. In accordance with RLD distribution, CB distributed less RDW in its uppermost horizon (1–30 cm) and

Fig. 4. (A) Root length density (RLD, cm root cm⁻³ soil) and (B) root distribution (%) of RLD in four horizons of four turfgrass species in 2009 and 2010. Lower case letters indicate differences among species within a given horizon. Upper case letters indicate differences among species for total RLD. AB = African bermudagrass; CB = common bermudagrass; ZJ = *Zoysia japonica*; ZM = *Zoysia matrella*.

Table 2. Root length density (RLD) and distribution in different horizons of 17 genotypes within 4 species grown in acrylic tubes in 2009 and 2010.

		RLD					Distribution in RLD			
		1–30 cm	30–60 cm	60–90 cm	90–120 cm	Total	1–30 cm	30–60 cm	60–90 cm	90–120 cm
Species	Genotype	cm root cm ⁻³ soil					%			
AB ^a	UFCT33	3.26 ^a	1.75	0.91 b	0.54 b	1.62	53.97 a	26.33	12.99 b	6.70 b
AB	UFCT42	2.77	2.37	1.63 a	1.01 a	1.94	38.79 b	30.50	19.12 a	11.59 a
CB	289922	2.59	1.99 c	1.58 bc	1.72 c	1.97 cd	34.54 a	25.93 b	19.80 ab	19.73 ab
CB	Celebration	2.51	2.42 bc	1.51 bc	1.60 cd	2.01 cd	31.62 ab	29.31 ab	18.78 ab	20.29 a
CB	UFCD12	2.39	2.68 ab	2.25 a	2.39 ab	2.43 b	25.91 b	27.37 ab	23.11 a	23.62 a
CB	UFCD295	2.66	2.70 ab	2.05 ab	1.77 bc	2.30 bc	31.00 ab	29.48 ab	21.99 ab	17.53 ab
CB	UFCD347	2.78	3.09 a	2.55 a	2.77 a	2.80 a	24.95 b	28.17 ab	22.66 a	24.22 a
CB	UFCD481	2.53	2.25 bc	1.31 c	1.02 d	1.78 d	37.71 a	31.75 a	17.34 b	13.20 b
ZJ	DALZ4360	3.37	1.77 b	0.82 b	0.31 b	1.57 c	55.06 a	27.96	12.48	4.50 b
ZJ	DALZ5269–24	3.03	1.81 b	1.19 ab	1.38 a	1.85 bc	42.46 b	24.13	16.42	16.99 a
ZJ	Empire	3.51	2.34 ab	1.49 a	1.56 a	2.23 ab	40.42 b	26.53	16.33	16.73 a
ZJ	JaMur	3.39	2.50 a	1.54 a	1.42 a	2.21 ab	39.88 b	28.95	16.75	14.43 a
ZJ	UF182	3.38	2.64 a	1.57 a	1.62 a	2.30 a	37.45 b	29.16	17.24	16.15 a
ZM	PristineFlora	3.08 b	2.01	1.20	0.38	1.67	48.06	30.17	16.66	5.11
ZM	UF336	3.13 b	1.88	0.93	0.35	1.57	51.76	30.25	12.97	5.03
ZM	UF374	3.63 ab	2.10	1.23	0.58	1.89	51.05	27.49	14.86	6.60
ZM	Zeon	3.85 a	2.11	0.79	0.41	1.79	54.52	29.52	10.64	5.33

^aAB = African bermudagrass; CB = common bermudagrass; ZJ = *Zoysia japonica*; ZM = *Zoysia matrella*.

^bMeans followed by the same letter (or without letter) are not different within each species at 0.05 *P* level.

more in its lower horizons (60–120 cm) than other species (Fig. 5A). No differences in RDW distribution were found among AB, ZJ, and ZM. Moreover, AB had larger SRL than other species, and CB had smaller SRL than ZJ (Fig. 5B).

African bermudagrass genotypes exhibited similar RDW distribution and SRL (Table 3). For CB, UFCD12 and UFCD347 distributed more RDW in their lower horizons (31–120 cm) and less in their uppermost horizon (1–30 cm) compared with other genotypes. ‘289922’ had larger SRL than UFCD12, UFCD347, and UFCD481.

DALZ4360 ZJ distributed more RDW in its upper horizon (1–30 cm) and less lower in the profile (60–120 cm) compared with Empire, which exhibited an opposite trend. Empire had larger SRL than other ZJ genotypes. Fewer differences were found within ZM genotypes for their RDW distribution

and SRL except that Zeon distributed more RDW in horizon B (30–60 cm) than others.

Discussion

Species comparison. A linear increase in rooting depth of bermudagrass and zoysiagrass was observed during the first 30 d after planting. Compared with other’s evaluations of RRDD, the values obtained in this study were generally higher (Acuña et al., 2010; Engelke et al., 1991; Huang, 1999). This was likely due to the outdoor environment with a high level of irradiance and the method of planting in the present study compared with greenhouse conditions and germinating from seeds in other studies. Nevertheless, the results agreed with previous studies reporting that CB had higher RRDD than ZM (Engelke et al., 1991; Sinclair et al., 2011). Higher RRDD could be associated with faster growth

of aboveground tissues. Common bermudagrass has demonstrated faster lateral stolon growth rates vs. zoysiagrass under well-watered conditions and after exposure to moderate drought (Steinke et al., 2013). Higher RRDD could be a desirable trait in the consideration of selecting drought-resistant genotypes. Huang (1999) suggested that the superior drought resistance in Prairie buffalograss compared with Meyer zoysiagrass was partly attributed to its greater RRDD. Turfgrass with a greater RRDD acquires access to deeper soil moisture, which may reduce the amount of supplemental irrigation required to maintain acceptable turfgrass quality as shown in Qian and Engelke’s (1999) study.

In addition to differences in RRDD, RLD and its distribution in the soil profile was different. Common bermudagrass, distributed ≈20% of its total root length in

Fig. 5. (A) Root distribution (%) in root dry weight in four horizons and (B) specific root length (m g^{-1}) of four turfgrass species in 2009 and 2010. Lower case letters indicate differences among species within a given horizon. AB = African bermudagrass; CB = common bermudagrass; ZJ = *Zoysia japonica*; ZM = *Zoysia matrella*.

Table 3. Distribution in root dry weight and specific root length (SRL) in different soil horizons of 17 genotypes within 4 species grown in acrylic tubes of 2009 and 2010.

Species	Genotype	Distribution in root dry wt				SRL m g^{-1}
		1–30 cm	30–60 cm	60–90 cm	90–120 cm	
AB ²	UFCT33	78.99	13.92	4.89	2.21	79.92
AB	UFCT42	75.83	14.35	6.38	3.45	62.08
CB	289922	67.72 ab ³	16.81 ab	8.84 bc	6.63 bc	54.54 a
CB	Celebration	72.65 a	14.89 b	7.35 bc	5.11 c	42.25 ab
CB	UFCD12	59.20 bc	20.82 a	10.20 ab	9.78 ab	39.12 b
CB	UFCD295	68.64 a	17.26 ab	8.64 bc	5.47 c	45.81 ab
CB	UFCD347	55.67 c	20.81 a	12.50 a	11.02 a	39.86 b
CB	UFCD481	73.66 a	15.86 ab	6.69 c	3.79 c	37.27 b
ZJ	DALZ4360	82.07 a	12.99 b	3.93 b	1.01 b	50.54 b
ZJ	DALZ5269–24	73.46 ab	13.22 b	7.37 ab	5.95 a	49.71 b
ZJ	Empire	66.14 b	18.27 a	8.76 a	6.83 a	64.85 a
ZJ	JaMur	72.16 b	16.55 ab	6.66 ab	4.63 ab	51.16 b
ZJ	UF182	67.47 b	18.81 a	7.18 ab	6.54 a	42.11 b
ZM	PristineFlora	79.20	14.34 b	5.21	1.25	46.56
ZM	UF336	77.97	14.97 b	5.48	1.58	49.21
ZM	UF374	76.88	14.82 b	6.47	1.84	50.32
ZM	Zeon	74.94	18.39 a	4.98	1.69	49.60

²AB = African bermudagrass; CB = common bermudagrass; ZJ = *Zoysia japonica*; ZM = *Zoysia matrella*.

³Means followed by the same letter (or without letter) are not different within each species at 0.05 *P* level.

horizon D (90–120 cm). In contrast, for ZM, the respective value was 5.5%. Thus, ZM accumulated the majority of its roots in the upper soil profile (1–30 cm), and this would likely lead to rapid water depletion and result in early onset of water stress. This contrasting difference may explain why CB generally shows better turf growth and performance under drought than ZM (Carrow, 1996b; Qian et al., 1997). Not only did ZM have the greatest percentage of total RLD within 1–30 cm, but it also had greater RLD at this depth compared with other species. This is likely a disadvantage for ZM during periodic droughts. Improvement of root depth distribution in species like ZM, especially from 60 to 120 cm horizon, could result in gains at delaying drought stress. However, this goal may be difficult to accomplish due to lack of genetic variation of RLD in the lower profile in our study. The comparison of RDW

distribution between CB and ZM was similar to RLD distribution. However, SRL was not different between CB and ZM. Specific root length is negatively correlated with root thickness or tissue density (Eissenstat, 1992). The prominent difference in SRL was found between CB and AB, indicating that AB may have more fine roots than CB. But the difference in SRL could be attributed to multiple factors such as difference in root thickness, photosynthetic capacity and the pattern of photosynthate allocation (Eissenstat, 1992). Lack of these information, comparing SRL between CB and AB does not provide much insights in their root biomass investment in the production of root length. The comparison of SRL between AB and ZJ may provide more information because they have similar RLD in horizons. AB had more fine roots than ZJ at 30–120-cm horizons. Given that generating fine roots for exploring soil

water (Eissenstat, 1992) is more energy efficient, AB may have the advantage compared with ZJ during dry down (Eissenstat, 1991). But it needs to be acknowledged that thicker roots can take up larger amount of water and are better in withstanding soil drying due to larger capacity of water storage and hydraulic lift for water from deeper soil profile to the surface (Caldwell et al., 1998; Huang 1999).

Zoysia japonica had larger RRDD and total RLD than ZM. Specific RLD differences between these two species are the result of their RLDs at the deepest horizon (90–120 cm). In addition, ZJ has been reported to exhibit faster coverage than ZM (Pompeiano et al., 2012; Steinke et al., 2013). These characteristics may provide ZJ an advantage to survive seasonal drought periods or short-term droughts, especially when the onset of drought occurs soon after planting.

Genotypic comparisons. Genetic variability for potential RRDD, RLD and distribution, RWD and distribution, and SLR were also found within species, and this would contribute to their differences in drought responses. Less genetic variability was found in AB, where UFCT42 AB distributed greater RLD distributed in its deepest horizon (90–120 cm) than UFCT33. But it should be noted that more genotypes were included in CB, ZJ, and ZM than AB. When RLD variation is extensive, the relationship between RLD and turf performance under drought would be more relevant (Qian et al., 1997) than when the variation in RLD is limited. A poor correlation between RLD and turf performance under drought was attributed to a lack of RLD variation (Zhou et al., 2014). In that case, the authors suggested that root diameter, rhizome production, and root viability-related parameters were more relevant in selecting drought-resistant bermudagrass.

One CB genotype, UFCD347, demonstrated greater RLDs in deeper horizons

compared with Celebration (commercial standard), and it ranked low in SRL. The lower rank in SRL does not necessarily translate to low efficiency for root production because of other factors that might be involved such as photosynthetic capacity and the pattern of photosynthate allocation in this genotype. Further research is needed to elucidate the meaning of the SRL with the aforementioned information available. UFCD12 and UFCD295 CB were comparable to UFCD347 in RLD at the midprofile horizons (30–90 cm) and they exhibited rapid RRDD.

For ZJ, UF182 ranked consistently in the top statistical group for RRDD and RLDs in every horizon. PristineFlora (ZM) had higher RRDD and Zeon had higher RLD in the upper horizon (1–30 cm). As discussed above, greater RLD deeper in the soil profile would likely enhance the drought resistance of ZM.

Summary

This study identified variability for RRDD and root profile characteristics between species and genotypes within AB, CB, ZJ, and ZM. These rooting characteristics would likely contribute to drought resistance. Uniform root distribution throughout the soil profile, as observed for CB, would be an advantageous trait to identify in other species and genotypes. Genotypes with desired rooting traits such as high RRDD and uniform rooting distribution, and high RLD at deeper soil depths were compared with the commercial cultivars to be forwarded for further evaluation. The high RLD values, observed for some genotypes in the upper soil profile, could be an inefficient use of photosynthate in terms of effective water uptake after a certain threshold value of RLD is reached (Lopes et al., 2011). But the threshold value can be difficult to determine because it can be affected by a lot of factors such as plant species, soil physical and chemical properties, and the season of the year.

This study did not evaluate rooting characteristics of warm-season turfgrasses under drought stress. However, under soil drying, a rapid RRDD would delay the onset of water stress (Huang, 2000). Root plasticity of turfgrass species during drought needs further exploration and would add value to the existing understanding of these genotypes. For example, SRL was found to increase during drought in Kentucky bluegrass (*Poa pratensis* L.) (Huang and Fry, 1998). This could indicate the production of finer roots as a strategy during drought to enhance water acquisition with minimal energy input.

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