

1 **Analogous response of *Cynodon dactylon* x *C. transvaalensis* and *Zoysia matrella* to soil**
2 **moisture stress using water-table depth gradient tanks in a controlled environment**

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12
13 **Abstract.**

14 Previous research involving turfgrass response to soil moisture utilized methodology that may
15 compromise root morphology or fail to control outside environmental factors. Water-table depth
16 gradient tanks were employed in the greenhouse to identify habitat specialization of hybrid
17 bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy] and manilagrass
18 [*Zoysia matrella* (L.) Merr.] maintained at 2.5 and 5.1 cm. Turfgrass quality (TQ), normalized
19 difference vegetation index (NDVI), canopy temperature (CT), and root biomass (RB) were used
20 as metrics for plants grown in monoculture in sandy clay loam soil. Mowing height did not affect
21 growth of turfgrass species in response to soil moisture. Turfgrass quality, NDVI, and RB were
22 greatest, while CT was lowest at wetter levels [27 to 58-cm depth to the water-table (DWT)] of
23 each tank where plants were growing at or above field capacity. However, bermudagrass RB was
24 greatest at 27-cm DWT, while manilagrass RB at 27-cm DWT was lower than RB at 42.5 to
25 73.5-cm DWT in 2013 and lower than all other levels in 2014. Both species responded similarly
26 to droughty levels (120 to 151-cm DWT) of the tanks. Turfgrass quality, NDVI, and RB were
27 lowest, while CT was highest at higher, droughty levels. Bermudagrass may be more competitive
28 than manilagrass when soil moisture is high, while both species are less competitive when soil
29 moisture is low.

30
31 **Additional keywords:** canopy temperature, drought, NDVI, root biomass, turfgrass.

32

33 Summary Text

34 Turfgrasses function to enhance quality of life and protect our environment in urban areas;
35 however, fluctuations in water availability affect their growth and survival. Our research
36 examined the response of two major turfgrass species to soil moisture using a technique that
37 eliminates rooting constraints and outside environmental factors. Although mowing height did
38 not impact turfgrass performance, hybrid bermudagrass was more competitive than manilagrass
39 under high soil moisture, while both species were less competitive under low soil moisture.

40

41 Introduction

42 The effects of drought and water conservation efforts on turfgrass quality have been well
43 documented for arid and semi-arid regions (Garrot and Mancino, 1994; Kneebone and Pepper,
44 1982; Meyer and Gibeault, 1986). However, anthropogenic climate change from large migratory
45 influxes into urban areas has triggered an increase in severe, acute drought events throughout the
46 southeastern United States (U.S.) (Seager et al., 2009). Several new policies have been ratified in
47 recent years to regulate potable water and restrict water use for supplemental irrigation (Dai,
48 2011; Manuel, 2008; Seager et al., 2009). Unfortunately, legislature concerning water use is
49 often drafted and implemented with little regard for short- or long-term effects on managed
50 turfgrass environments. Reductions in turfgrass quality and plant health in response to water
51 restrictions not only affect turfgrass playability, but may significantly reduce recreational
52 revenue and property values. Investigation into methods for reducing turfgrass water
53 consumption while maintaining quality may provide a partial solution to this specific problem.

54 Hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burt-Davy] and
55 manilagrass [*Zoysia matrella* (L.) Merr.] are two of the primary warm-season turfgrass species
56 utilized for home lawns, athletic fields, and golf courses in the southeastern U.S. (Christians et
57 al., 2016; Turgeon, 2011). Previous research examining the response of turfgrass species to soil
58 moisture has predominantly focused on field and container studies that are limited in their design
59 and implementation (Aronson et al., 1987; Carrow, 1996; Hook and Hanna, 1994; Huang and
60 Gao, 2000; Huang et al., 1997a; Marcum et al., 1995; Qian and Fry, 1997; Qian et al., 1997;
61 Zhou et al., 2012). These studies clearly demonstrated variability in drought response based on
62 turfgrass selection and cultural management practices. However, specific findings are

63 inconsistent and fairly contradictory, further supporting the need for additional research and
64 alternative experimental designs.

65 Water stress symptomology typically manifests as reduced shoot growth, desiccation and
66 wilting of leaf tissue, and an overall loss of turfgrass quality as a result of compromised cellular
67 growth, root stress, and increased root mortality (Fry and Huang, 2004). Turfgrasses often
68 employ drought avoidance mechanisms including investment in below-ground tissue to
69 maximize water uptake and above-ground tissue to maximize transpiration (Carrow, 1996; Hays
70 et al., 1991; Huang et al., 1997b; Qian et al., 1997). Bermudagrass (*Cynodon* spp.) generally
71 tolerates higher temperatures and limited water resources better than other turfgrass species
72 (McCarty et al., 2011; Wherley et al., 2014). This may be attributed to the production of a
73 deeper, more extensive root system and aggressive, hardy rhizomes (Duble, 2001). Although
74 zoysiagrass (*Zoysia* spp.) often produces a shallower root system, intraspecific variability in
75 rooting response has been reported (Zhang et al., 2013). Additionally, Qian and Fry (1997)
76 speculate that leaf rolling in zoysiagrass may act as an additional drought avoidance mechanism
77 to reduce overall transpiration by conserving the integrity of the boundary layer.

78 Mowing is one of the most basic cultural practices performed on turfgrass environments
79 and can have a major impact on water use efficiency (Harivandi and Gibeault, 1990; Shahba et
80 al., 2014; Wherley et al., 2014). The periodic removal of a portion of shoot growth causes a lot
81 of stress on turfgrass plants. This stress significantly affects the ability of turfgrass to withstand
82 abiotic and biotic pressure by inhibiting photosynthetic activity, limiting carbohydrate
83 production and storage, reducing water uptake, and compromising lateral growth (Fry and
84 Huang, 2004). Removal of the cuticle during mowing can also introduce pathogenic stress and
85 lead to increased evaporative losses (Turgeon, 2011). Higher mowing heights typically support
86 deeper, more vigorous roots that have access to larger water reservoirs within the soil profile
87 (Christians et al., 2016). However, increased vegetative material has been found to increase
88 evapotranspiration rates and ultimately increase plant water requirements (Biran et al., 1981;
89 Feldhake et al., 1983; Feldhake et al., 1984). Minimal research has examined the interaction of
90 soil moisture and mowing height on bermudagrass and zoysiagrass growth and turfgrass quality.
91 Wherley et al. (2014) investigated the response of zoysiagrass to mowing height and soil
92 moisture using a linear gradient irrigation system (LGIS), but observed variability among
93 cultivars.

94 A variety of experimental approaches have been employed to evaluate the response of
95 plants to soil moisture. Each of these systems presents unique challenges to providing a
96 comprehensive view of plant-water relations. Container studies that utilized drip irrigation and
97 partial wetting of the upper soil profile to examine cotton (*Gossypium hirsutum* L.) growth
98 revealed significant disruptions in natural root distribution and restrictions in rooting volume
99 within the plastic cylinders (Plaut et al., 1996). Krizek et al. (1985) suggested that root restriction
100 commonly observed in pot studies can mimic the effect of soil moisture stress even when
101 sufficient moisture is present for normal plant growth. Furthermore, Carrow (1996) established
102 intraspecific and interspecific variability in root response to drought at depths between 20 and 60
103 cm, asserting that evaluation of deep rooting is critical in determining total drought response.
104 Containers that significantly limit root depth under water deficit may not provide a complete
105 illustration of plant response to soil moisture, particularly for deep-rooting species such as
106 bermudagrass. In recent years, several studies have used LGIS in the field to evaluate turfgrass
107 response to soil moisture (Qian and Engelke, 1999; Wherley et al., 2014; Zhang et al., 2013;
108 Zhang et al., 2015). While LGIS create a continuous and complete moisture gradient, this
109 approach is often subject to environmental variables including precipitation, wind disruption, and
110 malfunctioning irrigation heads. Mueller-Dombois and Sims (1966) developed an alternative
111 method that avoids several of these shortcomings. This approach utilizes water-table depth
112 gradient tanks that promote natural capillary rise of soil water and offer the opportunity for
113 surface irrigation to simulate rainfall. However, a large amount of greenhouse space, labor, and
114 materials are required to build and house these tanks on site. A standpipe in the front of the tank
115 regulates the water-table depth while capillary rise keeps the low end of the tank at field
116 capacity. Plants are subjected to progressively lower soil moisture levels and greater depth to the
117 water-table when grown at higher elevations of the tank. This methodology allows investigators
118 to measure reduction in turfgrass quality/growth characteristics in response to irrigation
119 restrictions and mowing height on native soil within a controlled environment. Therefore, the
120 objective of our research was to evaluate the response of hybrid bermudagrass and manilagrass
121 to a soil moisture gradient and mowing height.

122

123 **Materials and methods**

124 *Experimental setup and maintenance*

125 Four water-table depth gradient tanks were constructed at the Crop and Soil Sciences greenhouse
126 complex in Athens, GA (33° 55' N, 83° 21' W) during the summer of 2013 (modified from
127 Mueller-Dombois, 1965; Mueller-Dombois and Sims, 1966; Henry et al. 2009). Tanks were
128 steeply sloped and oriented to the south. The tanks measured 2.4 m long, 1.2 m wide, and were
129 0.3 m high at one end and 1.8 m high at the other end with a volume of nearly 4 m³. (Fig. 1A).
130 Each tank was lined with a double layer of 0.076-mm (3-mil) black plastic and had a 10-cm base
131 of pea gravel to provide a uniform substrate for water movement. The pea gravel was covered
132 with 3 cm of course sand to reduce soil movement into the gravel layer. All four tanks were
133 filled with a steamed 2:1 mixture of Cecil sandy clay loam (fine, kaolinitic, thermic Typic
134 Kanhapludults) and Wakulla sand (siliceous, thermic Psammentic Hapludults). A 1.9-cm valve at
135 the high end of the tank regulated water inflow while a standpipe (2.5 cm) at the low end of the
136 tank regulated the water-table height. Tank surfaces were divided into nine levels ranging in
137 depth to the water-table (DWT) of 27 cm (Level 1) to 151 cm (Level 9).

138 Turfgrass species (hybrid bermudagrass or manilagrass) were randomly assigned to tank
139 pairs at the beginning of each experimental run. Hybrid bermudagrass ('Tifway 419') and
140 manilagrass ('Zeon') sod (1-year-old) were transplanted on 5 June 2013 and 13 Jan. 2014. Soil
141 was washed from sod prior to transplant to encourage rooting and discourage layering of
142 contrasting soil textures. A starter fertilizer (18 N-9 P₂O₅-18 K₂O) (The Andersons Lawn
143 Fertilizer Inc., Maumee, OH) was applied at transplant and once more during establishment at a
144 rate of 49 kg N ha⁻¹. Surface irrigation provided through hand-watering was employed every
145 other day (0.4 cm d⁻¹) for approximately 12 wk during sod establishment to give a greater
146 opportunity for uniform recruitment (stopped on 29 Aug. 2013 and 6 Apr. 2014) and
147 occasionally thereafter to alleviate permanent wilting. Tap water was used for both surface and
148 groundwater. Natural light was supplemented with artificial light at 500 μmol m⁻² s⁻¹
149 photosynthetic photon flux in a 12-h day to approximate summer light intensity and photoperiod.
150 Conditions in the greenhouse were maintained at day/night temperatures of 32/24°C. All gradient
151 tanks were mowed once a week using sheep shearers (Oster Professional Products, McMinnville,
152 TN) to a height of 3.8 cm. Tanks were divided in half vertically two weeks prior to trial
153 establishment. Mowing treatments (2.5 or 5.1 cm) were randomly assigned to each tank. Each
154 mowing treatment was gradually reduced or increased over the next two weeks until they
155 reached desired mowing heights. Soil cores (2.5 cm) were removed from several levels of each

156 tank to check rooting uniformity at the initiation of the study (29 Aug. 2013 and 6 Apr. 2014).
157 Each experiment was a split-block design with two replications.

158 Capillary rise was determined at the conclusion of each trial by excavating the soil profile
159 at each level and measuring moisture with a FieldScout TDR 300 Soil Moisture Meter (Spectrum
160 Technologies Inc., Aurora, IL) equipped with two probes (7.6 cm long) spaced 3.3 cm apart. Soil
161 moisture readings for all four tanks were averaged in order to create a profile of the capillary
162 fringe (Fig. 1B). The capillary fringe of hybrid bermudagrass and manilagrass tanks rose
163 approximately 81 cm from the water-table. Percent volumetric water content (VWC) was 21.2,
164 10.6, 3.1, 0, and 0% in the upper 7.6 cm of the soil profile for levels 1, 3, 5, 7, and 9,
165 respectively. Therefore, a gradual change in soil moisture near the surface was recorded from
166 Level 1 to Level 9 in each tank regardless of turfgrass species.

167

168 *Data acquisition*

169 Turfgrass quality (TQ), plant health (NDVI), canopy temperature (CT), and root biomass
170 (RB) were determined at the conclusion of each trial (26 Nov. 2013 and 6 July 2014). Visual
171 ratings of TQ were recorded on a scale of 1 to 9 with a rating of 6 considered acceptable TQ
172 (Morris and Shearman, 2000). Plant health was recorded with a Field Scout CM 1000 NDVI
173 (normalized difference vegetation index) chlorophyll meter (Spectrum Technologies Inc.,
174 Aurora, IL). A vegetative index $[\{NDVI = [(R770 - R 660) / (R770 + R 660)]\}]$ was calculated (0
175 to 1, where 1 is best) from the reflectance readings. An average of three readings were obtained
176 per level per mowing treatment in each tank. Canopy temperature (°C) was recorded using an
177 Oakton TempTester infrared thermometer (OAKTON Instruments, Vernon Hills, IL). An
178 average of three readings were obtained per level per mowing treatment in each tank. A 10.2 cm
179 golf course cup-cutter was used to remove the above-ground biomass and corresponding root
180 system together as a plug (to a depth of 20.3 cm) in three locations per level per mowing
181 treatment in each tank. Roots were washed, separated from above-ground tissue, dried in an oven
182 at 50°C for 7 d, and weighed to determine biomass (g).

183

184 *Statistical analysis*

185 This experiment was replicated over time by performing two runs. Homogeneity of
186 variance of data was confirmed by plotting residuals. Analysis of variance (ANOVA) was

187 performed separately on hybrid bermudagrass and manilagrass data. Analysis of variance was
188 conducted using the Mixed procedure to conduct both split-plot and autoregressive (to control
189 for possible autocorrelation of soil moisture levels, which could not be randomized; Bivand,
190 1980; Cliff and Ord, 1981) analyses (SAS Institute, Cary, NC). In the split-plot analysis,
191 turfgrass species was treated as the whole-plot and mowing height as the subplot factor, while
192 soil moisture level was considered a stripped factor. Similar analytical structure was utilized in
193 the autoregressive model analyses. Study repetition was considered a random factor. Correlation
194 coefficients were calculated using the PROC CORR function in SAS to determine the strength
195 and direction of relationship between all measured plant and soil properties (Clifford et al., 1989;
196 Dutilleul, 1993). Linear regression was performed on the data using SigmaPlot 12.5 (Systat
197 Software, San Jose, CA) in order to evaluate the response of hybrid bermudagrass and
198 manilagrass to soil moisture levels.

199

200 **Results**

201 Correlation coefficients evaluating the relationships between TQ, NDVI, CT, RB, and DWT for
202 hybrid bermudagrass and manilagrass are outlined in Table 1 and Table 2. There were strong,
203 significant relationships between all parameters with the exception of root biomass, which did
204 not consistently correlate to any other variable for either hybrid bermudagrass or manilagrass. No
205 significant effect of mowing height was observed for either species, so data were pooled across
206 mowing heights to evaluate individual species response to soil moisture gradient levels.

207

208 *Hybrid bermudagrass response*

209 Turfgrass quality was negatively correlated to CT (2013, $r = -0.71$; 2014, -0.76) and DWT (2013,
210 -0.56 ; 2014, -0.82), and positively correlated to NDVI (2013, $r = 0.85$; 2014, 0.76). Mean
211 separation for TQ with respect to DWT for hybrid bermudagrass was evaluated separately for
212 2013 and 2014. No significant interaction was observed between mowing height and TQ
213 response to DWT; however, TQ was significantly different across years. Mean TQ never reached
214 acceptable levels for 2013, but still demonstrated a discernible response to soil moisture gradient
215 levels. Highest TQ ratings in 2013 were observed at 42.5 and 89-cm DWT ($\bar{x} = 5.8$ and 5.5 ,
216 respectively) with slightly lower TQ ratings at 27, 58, 73.5, and 104.5-cm DWT. Turf quality
217 progressively declined with increasing DWT. Statistically significant decreases were reported at

218 120-cm DWT and again at 135.5 and 151-cm DWT. Similarly, TQ for 2014 reached acceptable
219 levels at 27 and 42.5-cm DWT ($\bar{x} = 6.0$ and 6.3 , respectively) with the lowest TQ at 135.5 and
220 151-cm DWT ($\bar{x} = 1.8$ and 1.3 , respectively). Simple linear regression models predicting TQ
221 with respect to DWT are shown in Fig. 2A. Goodness of fit was stronger in 2014 ($R^2 = 0.93$)
222 than 2013 ($R^2 = 0.69$).

223 Correlations between NDVI and other parameters can be found in Table 1. Normalized
224 difference vegetation index positively correlated with TQ and negatively correlated with CT
225 (2013, $r = -0.77$; 2014, $r = -0.69$) and DWT (2013, $r = -0.80$; 2014, $r = -0.62$). No significant
226 differences in NDVI were found across years or across mowing heights; therefore, data were
227 pooled for comparison at each soil moisture gradient level. The highest NDVI ratings were
228 observed at 27, 42.5, 58, and 104.5-cm DWT ($\bar{x} = 0.71, 0.67, 0.67, \text{ and } 0.65$, respectively). Data
229 for NDVI at 73.5 and 89-cm DWT were slightly lower ($\bar{x} = 0.62$), indicating that canopy density
230 and color remained relatively uniform for hybrid bermudagrass up to 104.5-cm DWT. A gradual
231 decline in NDVI was observed with increasing DWT ($\bar{x}_{120\text{-cm}} = 0.55$; $\bar{x}_{135.5\text{-cm}} = 0.46$; $\bar{x}_{151\text{-cm}} = 0.39$).
232 The negative relationship between NDVI and DWT was modeled linearly with an R^2
233 value of 0.83 (Fig. 2B).

234 Canopy temperature was negatively correlated to TQ and NDVI, and positively
235 correlated to DWT (2013, $r = 0.66$; 2014, $r = 0.87$). There was no significant effect of mowing
236 height; therefore, data were pooled across mowing heights. Mean separation for CT with respect
237 to DWT was evaluated separately for 2013 and 2014. The lowest CT for 2013 were observed at
238 27 and 73.5-cm DWT (23.2 and 23.7°C , respectively) with only slight increases in temperature
239 at 42.5, 58, and 89-cm DWT. Canopy temperature continued to increase with increasing DWT.
240 The highest temperatures were recorded at 135.5 and 151-cm DWT (27.3 and 27.5°C ,
241 respectively). There was a similar increase in canopy temperature with increasing DWT for
242 2014. Average canopy temperature was lowest at 27-cm DWT (23.8°C) and gradually increased
243 to the highest temperatures between 104.5 and 151-cm DWT, peaking at 32.5°C . Predictive
244 modeling of the relationship between CT and DWT both confirmed positive linear relationships.
245 Canopy temperature had a stronger relationship with DWT in 2014 ($R^2 = 0.94$) than in 2013 (R^2
246 $= 0.88$) (Fig. 2C).

247 Significant relationships between RB and other variables (TQ, NDVI, CT, or DWT) were
248 not consistent. In 2013, a moderately positive correlation was observed with NDVI ($r = 0.42$) and

249 a moderately negative correlation was observed with CT ($r = -0.37$) and DWT ($r = -0.52$), while
250 in 2014, only a moderately positive correlation was observed with TQ ($r = 0.47$). Mean
251 separation for RB with respect to DWT were pooled across experimental runs and mowing
252 heights. Small significant differences between gradient levels did exist, with greatest RB at 27,
253 42.5, and 58-cm DWT ($\bar{x} = 0.83$, $\bar{x} = 1.05$, and $\bar{x} = 0.75$, respectively). Root biomass
254 measurements were slightly lower for 73.5, 89, 104.5, 135.5, and 151-cm DWT, but were
255 statistically similar to 27 and 58-cm DWT. The lowest RB was reported for 120-cm DWT ($\bar{x} =$
256 0.43). Linear regression models predicting RB with respect to DWT are shown in Fig. 2D ($R^2 =$
257 0.60).

258

259 *Manilagrass response*

260 Turfgrass quality showed a strong positive relationship to NDVI (2013, $r = 0.93$; 2014, 0.94) and
261 strong negative relationships to CT (2013, $r = -0.67$; 2014, $r = -0.89$) and DWT (2013, $r = -0.85$;
262 2014, $r = -0.89$). Mean separation for TQ with respect to DWT for manilagrass was pooled
263 across years. The highest TQ ratings were observed between levels 27 to 73.5-cm DWT with
264 acceptable TQ ($\bar{x} \geq 6$) from 27 to 58-cm DWT. Turfgrass quality declined to unacceptable
265 ratings with increasing depth to water-table. The lowest ratings were reported at 135.5 and 151-
266 cm DWT ($\bar{x} = 2.0$ and 1.8, respectively). A linear regression model using DWT to predict TQ
267 confirmed a strong negative relationship ($R^2 = 0.96$) (Fig. 3A).

268 Normalized difference vegetation index showed a strong positive relationship to TQ and
269 strong negative relationships to CT (2013, $r = -0.76$; 2014, $r = -0.82$) and DWT (2013, $r = -0.87$;
270 2014, $r = -0.77$). Mean separation for NDVI with respect to DWT was performed separately for
271 2013 and 2014. There were more significant differences between gradient levels in 2013 than in
272 2014. In 2013, the highest mean NDVI ($\bar{x} = 0.82$) was found at the lowest DWT (27 cm DWT)
273 with a gradual decrease with increasing DWT and the lowest mean NDVI ($\bar{x} = 0.26$) at 151-cm
274 DWT. A similar trend was established in 2014 with higher mean NDVI readings at lower DWT.
275 However, the highest NDVI for this year was observed at 42.5-cm DWT ($\bar{x} = 0.73$) with slightly
276 lower values at 27, 58, and 73.5-cm DWT. As DWT increased, NDVI decreased significantly,
277 first at 89-cm DWT and then reached its lowest levels between 104.5 and 151-cm DWT, never
278 dropping below $\bar{x} = 0.38$. Linear regression models predicting NDVI with respect to DWT are

279 shown in Fig. 3B. For both 2013 and 2014 data, strong negative trends were observed for 2013
280 and 2014 ($R^2 = 0.95$ and $R^2 = 0.90$, respectively).

281 Canopy temperature showed strong negative relationships to TQ and NDVI, and a strong
282 positive relationship to DWT (2013, $r = 0.79$; 2014, $r = 0.91$). Mean separation for CT with
283 respect to DWT was performed separately for 2013 and 2014 data. General trends were
284 consistent for both years, showing clear positive trends with CT increasing with increasing
285 DWT. In 2013 and 2014, lowest CT were both observed at 27-cm DWT ($x = 22.5$ °C and 23 °C,
286 respectively). Similarly, the highest CT were observed at 120 and 135.5-cm DWT for both years,
287 peaking at 29.1 °C in 2013 and 31.3 °C in 2014. Linear regression models (Fig. 3C) confirmed
288 strong, positive correlations between canopy temperature and DWT for both 2013 and 2014 data
289 ($R^2 = 0.82$ and 0.94, respectively).

290 Root biomass showed a moderately positive correlation with TQ and NDVI, $r = 0.57$ and
291 $r = 0.68$, respectively, in 2013, but no correlation to these two variables in 2014. A moderately
292 negative correlation was observed between RB and CT ($r = -0.42$), but this correlation was not
293 evident in 2014. Linear regression models predicting RB with respect to DWT for 2013 and 2014
294 are shown in Fig. 3D ($R^2 = 0.42$ and 0.22, respectively).

295

296 **Discussion**

297 Utilization of water-table depth gradient tanks allowed for trial conductance without rooting
298 constraint concerns typically observed in greenhouse pot studies or environmental impacts
299 associated with LGIS. Potential for root restriction was reduced since turfgrass plants were
300 grown in large volumes of soil (4 m³), therefore allowing three months of trial duration.
301 Excavation of each tank to determine capillary rise confirmed an even distribution of moisture
302 throughout the soil profile. Nevertheless, space limitations, labor, and material needed for tank
303 construction may limit experimental use and adoption of this technique in greenhouses.
304 Typically, plant position within each moisture level row should affect intraspecific plant
305 competition and resource acquisition; however, differences in turfgrass growth along tank edges
306 with fewer neighbors were not apparent.

307 Mowing height did not have an effect on either turfgrass species growth response to soil
308 moisture levels. Although higher mowing heights are often associated with more robust,
309 vigorous root systems (Christians et al., 2016), the accumulation of more canopy tissue can

310 increase evapotranspiration rates and plant water requirements (Biran et al., 1981; Feldhake et
311 al., 1983; Feldhake et al., 1984). Burns (1976) saw no effect of mowing height on the water
312 consumption of tall fescue (*Festuca arundinacea* Schreb.), while Biran et al. (1981) observed a
313 temporary increase (\approx 6 weeks) in turfgrass vigor by increasing the height of common
314 bermudagrass [*Cynodon dactylon* (L.) Pers.] and manilagrass. Wherley et al. (2014) reported that
315 mowing height (1.3, 2.5, and 5.1 cm) did not significantly influence irrigation requirements of
316 any bermudagrass cultivars evaluated in a LGIS study, including Tifway 419. However, Zeon
317 manilagrass maintained at 1.3 cm exhibited greater TQ with less irrigation compared to the same
318 plants maintained at 5.1 cm (Wherley et al., 2014). It was theorized that manilagrass thatch
319 accumulation was greater at higher mowing heights; therefore, reducing rooting depth and water
320 infiltration leading to reduced turfgrass tolerance to deficit irrigation and drought. This trend was
321 not consistent among all manilagrass cultivars examined and did not occur among Japanese
322 lawngrass (*Zoysia japonica* Steud.) cultivars in the same trial.

323 Our findings suggest a correlation between hybrid bermudagrass success and high soil
324 moisture content. Turfgrass quality, NDVI, and RB were greatest and CT was lowest at the
325 lower, wetter levels (27 to 58-cm DWT) of each gradient tank where plants were continuously
326 growing at or above field capacity for the duration of the study. Tan et al. (2010) noted that
327 bermudagrass can endure waterlogged conditions through lower metabolic activity, high
328 carbohydrate reserves, and detoxification of activated oxygen species. Changes in bermudagrass
329 morphology when subjected to high soil moisture may provide insight into its ability to perform
330 well under those conditions. Tan et al. (2013) reported that bermudagrass develops aerenchyma
331 tissue, air channels that allow for gas exchange between roots and shoots, in response to
332 waterlogged conditions. Although TQ and NDVI for manilagrass in our research were greatest at
333 the lower, wetter levels (27 to 58-cm DWT) of each gradient tank, RB at 27-cm DWT was lower
334 than RB at 42.5 to 73.5-cm DWT in 2013 and lower than all other levels in 2014. *Zoysia* spp.
335 prefer well-drained soils (Christians et al., 2016; Emmons, 2000); therefore, high soil moisture
336 content at the lowest level of the tank may be responsible for limitations in RB production.

337 In a similar water-table depth gradient tank experiment, Henry et al. (2009) observed a
338 decrease in Tifway 419 hybrid bermudagrass survival above level 4 (73.5-cm DWT) 3 months
339 after trial initiation when grown in sand and sandy loam soil. Greater survival and TQ in our
340 study may be attributed to the use of a sandy clay loam soil with higher moisture retention and

341 capillary rise. Hybrid bermudagrass TQ was 3.5 to 4.5 in 2013 and 1.3 to 3.0 in 2014 in the
342 droughty levels (0% VWC in the upper 7.6 cm of soil) of the gradient tanks. Steinke et al. (2011)
343 observed similar TQ (3 and 4.5) of Tifway 419 hybrid bermudagrass after 55 and 61 days of
344 drought, respectively. Wherley et al. (2014) observed TQ of 3.5 to 4.0 for Tifway 419 during the
345 spring following summer drought. Although hybrid bermudagrass RB decreased as DWT
346 increased, RB was similar from 73.5 to 151-cm DWT. Manilagrass TQ was 1.8 to 2.7 in the
347 droughty levels (120 to 151-cm DWT) of the gradient tanks. Although Wherley et al. (2014)
348 noted that manilagrass required more supplemental irrigation to maintain acceptable quality (>
349 6.0), TQ of non-irrigated Zeon was 4.1 to 6.0, regardless of mowing height. Wherley et al.
350 (2014) also noted that Zeon manilagrass exhibited shallower roots. This was only evident in our
351 research in 2013. Several other studies have compared hybrid or common bermudagrass with
352 Japanese lawngrass subjected to drought conditions. Qian and Engelke (1999) and Carrow et al.
353 (1996) ranked Tifway 419 hybrid bermudagrass higher than 'Meyer' Japanese lawngrass for
354 drought resistance. Fu et al. (2004) theorized that 'Midlawn' bermudagrass could tolerate a lower
355 relative leaf water content and higher level of electrolyte leakage before TQ declined to an
356 unacceptable level ($TQ < 6$) compared to Meyer Japanese lawngrass. Hybrid bermudagrass and
357 manilagrass responded similarly to drought in our research. Comparably, Sifers et al. (1990)
358 ranked bermudagrass and *Zoysia* spp. equal in a greenhouse drought study based on canopy leaf
359 firing.

360 Results of the present experiment demonstrate that hybrid bermudagrass and manilagrass
361 respond relatively similar to soil moisture stress. However, only one cultivar of each species
362 were examined; therefore, additional research with several cultivars of each species may be
363 necessary to further explain the range of potential response to soil moisture using this
364 methodology. Furthermore, hybrid bermudagrass was relatively insensitive to high soil moisture,
365 while manilagrass growth was suppressed under the same moisture conditions. Therefore,
366 manilagrass may become less competitive when grown in low lying areas, under reduced water
367 infiltration, or in heavy clay soils. Both species exhibited reductions in plant health and growth
368 when subjected to extended drought conditions. Consequently, management of either species
369 should emphasize the increase of root depth and biomass in order to minimize the negative
370 effects of reduced soil moisture. Successful application of these water-table depth gradient tanks

371 leads to the endorsement of their use for the investigation of niche differentiation, invasive
372 species, and interspecific competition in response to soil moisture stress.

373

374 **Conflicts of interest**

375 The authors declare no conflicts of interest.

376

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382

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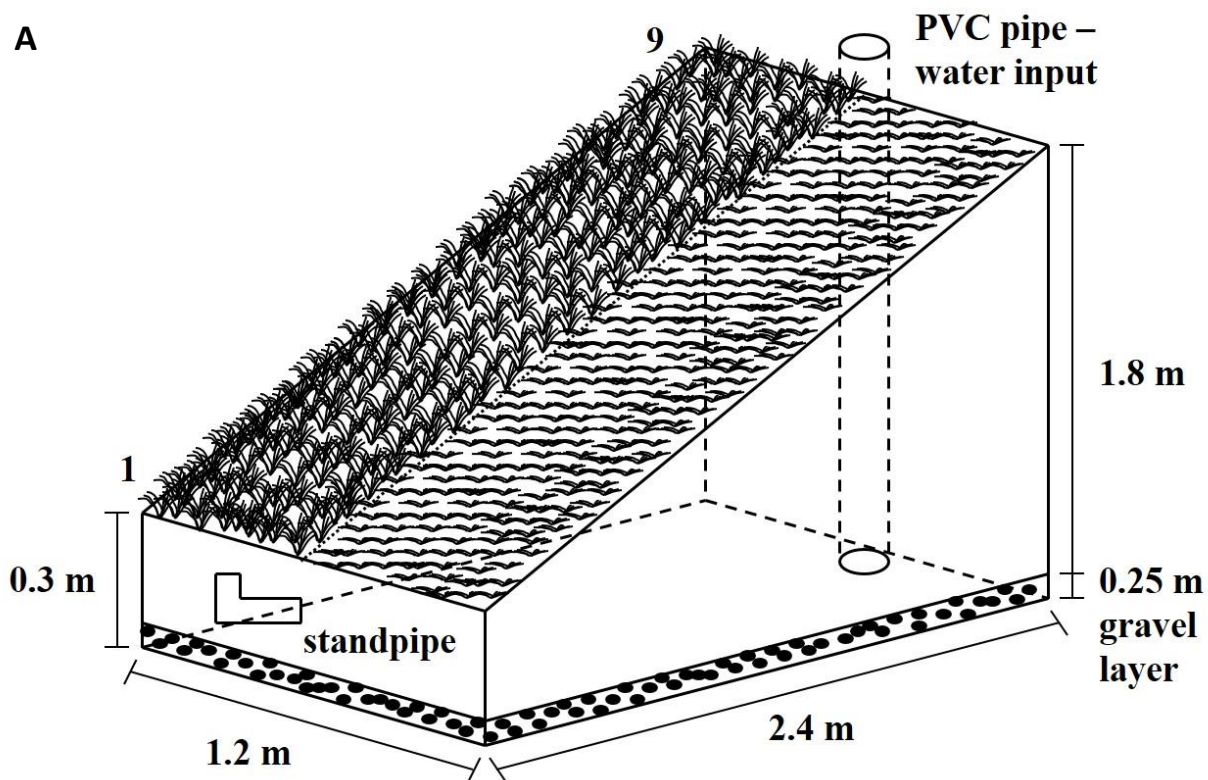
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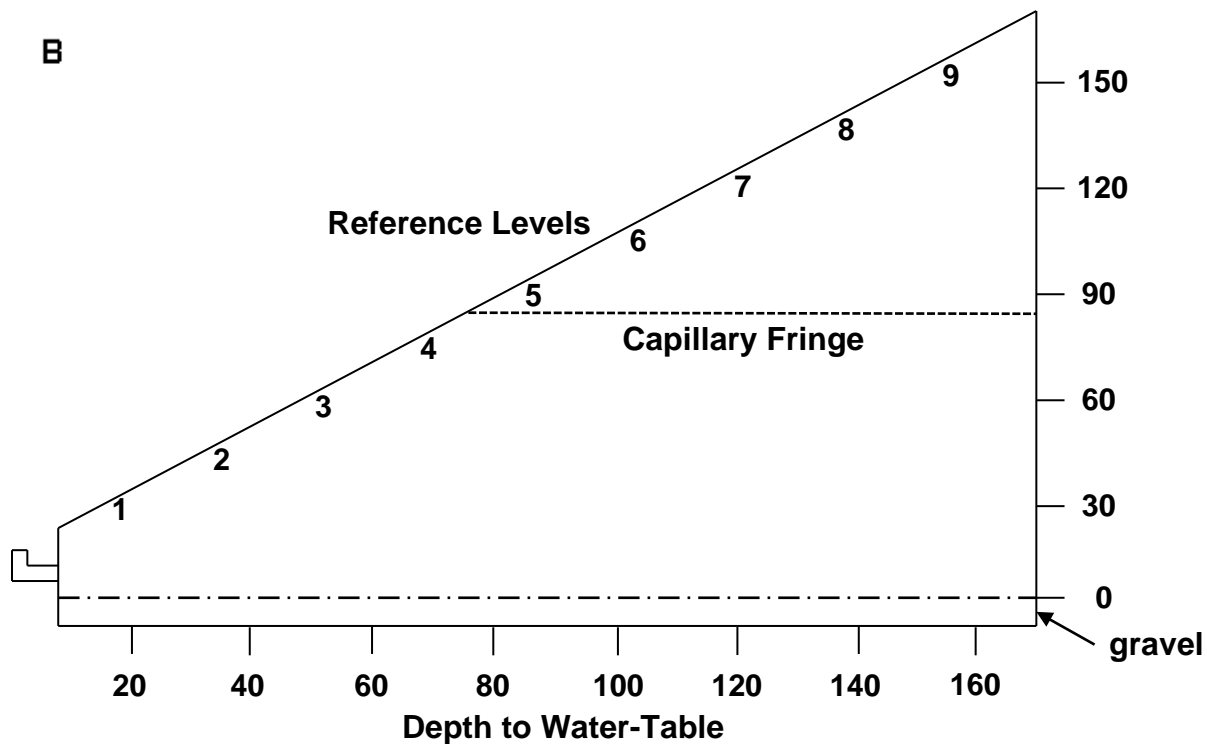
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481



482

483 **Figure 1.** Schematic of water-table depth gradient tank construction (... represents the division
 484 between mowing heights) (A). Cross section through a tank showing the capillary fringe. PVC =
 485 polyvinyl chloride (B).

Table 1. Correlation coefficients between turfgrass quality (TQ), canopy temperature (CT), NDVI, root biomass (RB), and depth to water-table (DWT) for ‘Tifway 419’ hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy] in 2013 and 2014.

2013					
	TQ	NDVI	CT (°C)	RB (g)	DWT (cm)
TQ	1	0.85***	-0.71***	0.26	-0.56***
NDVI		1	-0.77***	0.42***	-0.80***
CT			1	-0.37*	0.66***
Root Biomass				1	-0.52***
DWT					1
2014					
TQ	1	0.76***	-0.76***	0.47**	-0.82***
NDVI		1	-0.69***	0.13	-0.62***
CT			1	-0.14	0.87***
Root Biomass				1	-0.21
DWT					1

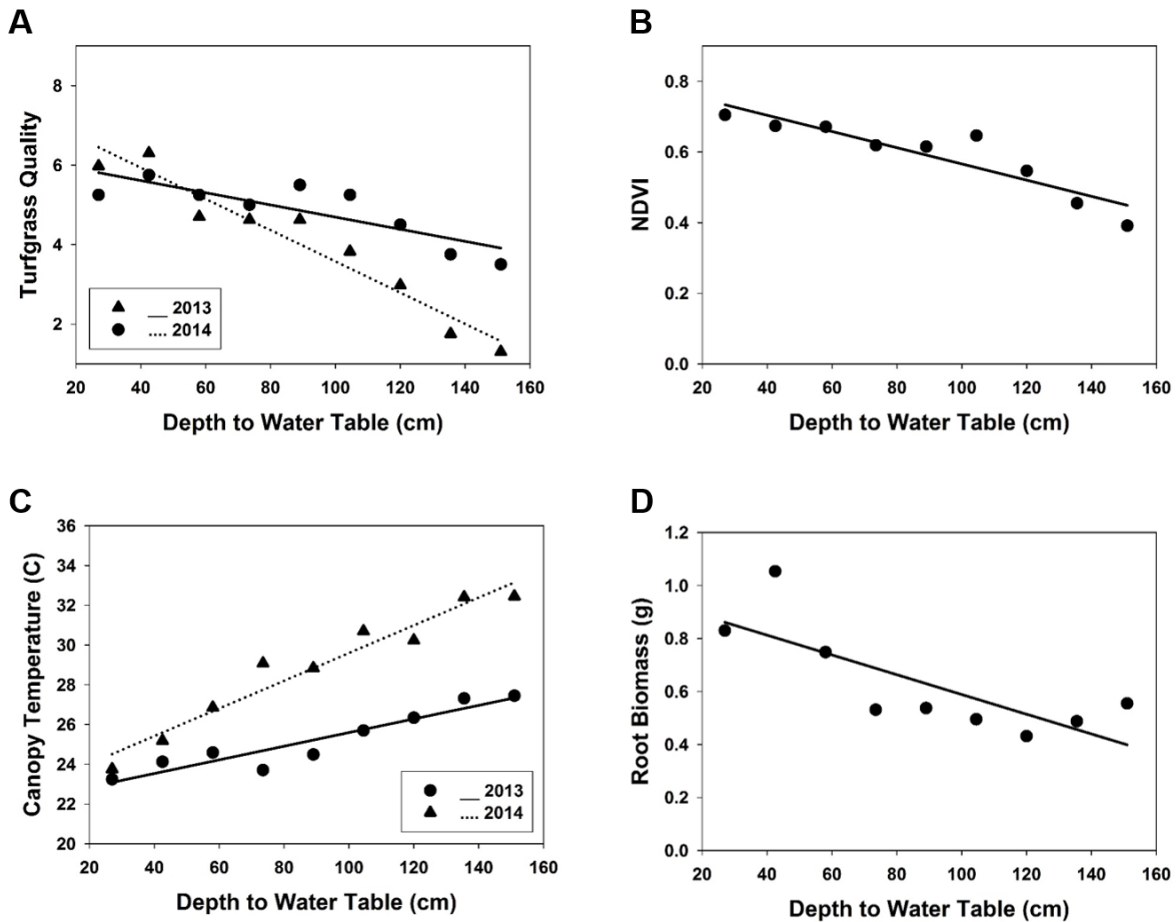
486 Significant correlations (* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$).

Table 2. Correlation coefficients between turfgrass quality (TQ), canopy temperature (CT), NDVI, root biomass (RB), and depth to water-table (DWT) for ‘Zeon’ manilagrass [*Zoysia matrella* (L.) Merr.].

2013					
	TQ	NDVI	CT (°C)	RB (g)	DWT (cm)
TQ	1	0.93***	-0.67***	0.57***	-0.85***
NDVI		1	-0.76***	0.68***	-0.87***
CT			1	-0.42*	0.79***
Root Biomass				1	-0.52***
DWT					1
2014					
TQ	1	0.94***	-0.89***	0.14	-0.89***
NDVI		1	-0.82***	0.14	-0.77***
CT			1	-0.15	0.91***
Root Biomass				1	0.01
DWT					1

487 Significant correlations (* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$).

488

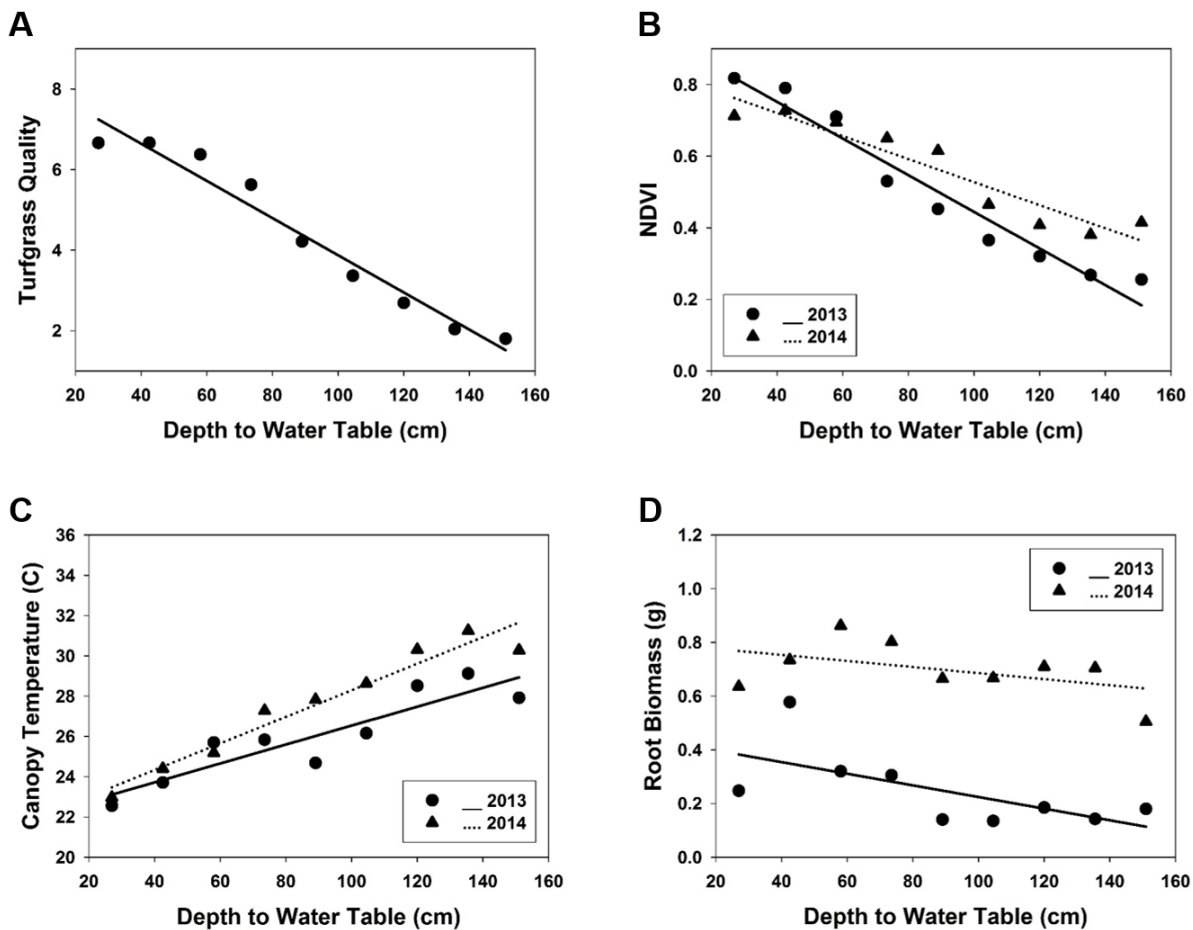


489

490 **Figure 2.** ‘Tifway 419’ hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis*

491 Burt-Davy] response to soil moisture levels: turfgrass quality (TC) (A), NDVI (B), canopy

492 temperature (CT) (C), and root biomass (RB) (D). Linear equations: TQ 2013, $y = 6.225 -$ 493 $0.015x$, $R^2 = 0.69$; TQ 2014, $y = 7.511 - 0.039x$, $R^2 = 0.93$; NDVI, $y = 0.796 - 0.002x$, $R^2 =$ 494 0.83 ; CT 2013, $y = 22.16 + 0.034x$, $R^2 = 0.88$; CT 2014, $y = 22.62 + 0.069x$, $R^2 = 0.94$; RB, $y =$ 495 $0.962 - 0.003x$, $R^2 = 0.60$.



496

497 **Figure 3.** ‘Zeon’ manilgrass [*Zoysia matrella* (L.) Merr.] response to soil moisture levels using
 498 water-table depth gradient tanks: turfgrass quality (TC) (A), NDVI (B), canopy temperature (CT)
 499 (C), and root biomass (RB) (D). Linear equations: TC, $y = 8.492 - 0.046x$, $R^2 = 0.96$; NDVI
 500 2013, $y = 0.956 - 0.005x$, $R^2 = 0.95$; NDVI 2014, $y = 0.849 - 0.003x$, $R^2 = 0.90$; CT 2013, $y =$
 501 $21.84 + 0.047x$, $R^2 = 0.82$; CT 2014, $y = 21.69 + 0.066x$, $R^2 = 0.94$; RB 2013, $y = 0.441 -$
 502 $0.002x$, $R^2 = 0.42$; RB 2014, $y = 0.799 - 0.001x$, $R^2 = 0.22$.