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Performance Assessment of Three Turfgrass Species, in Three Different Soil Types, and their Responses to Water Deficit in Reinforced Cells, Growing in the Urban Environment

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ABSTRACT. Reinforcement cells are used to aid grass growth and taken together, this serves to extend greenery beyond the conventional spaces of lawns, tree pits, gardens, and parks, and is advantageous to urban cities since space for greening is often limited. Drought has variable effects on plant life and the resilience of turf to drought resistance also varies with species. Changes in photosynthetic ability were more pronounced for media rather than grass species. The media of sand without organic matter was found to be least suited for drought resistance. Normalized difference vegetation index (NDVI) and digital image analysis (DIA) data were generally in favour of *Zoysia* species as oppose to *A. compressus*. In *A. compressus,* selective traits such as, a more extensive root system and lower specific leaf area (SLA) were not an underlying factor that assisted this grass with enhanced drought resistance. Generally, WUE was found to be strongly related to plant characterises such as overall biomass, photosynthetic features as well as the lushness indexes, and specific leaf area. This study found a strong relationship between WUE and a suite of plant characteristics. These traits should serve as useful selection criteria for species with the ability to resist water stress.

Key words: Biomass, Digital image analysis, Drought, Normalized difference vegetation index, Turfgrasses

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Introduction

Erratic and insufficient rainfall is a major constraint to turfgrasses. Drought of various intensities and duration severely limits grass growth and increases the likelihood of die back, and subsequent bare patches. Although some agronomic interventions to conserve soil moisture and enhance water use efficiency (WUE), which is an indication of water used in plant metabolism against the amount of water lost, is available (Youngner et al., 1981; Liu and Stutzel, 2004), but the effects may not necessarily work for every grass (Pound and Street, 2001). Developing turf varieties tolerant to drought and efcient in water use is preferable as it is a long term and cost effective solution to the uncertainty of water availability (Mittler, 2006). So far, the approach to breeding varieties with superior performance under limited water conditions has remained in most part, empirical, with few exceptions (Hayatu and Mukhtar, 2010). More rapid progress may be achieved through *a prioir* knowledge of the physiological basis of turfgrass performances. These include the ability of root systems to capture water at greater depths, specic leaf area (SLA; ratio of leaf area to leaf dry weight), grass growth that may be achieved through a chlorophyll reading (e.g. measuring F_v/F_m, photosynthetic efficiency) (Songsri et al., 2009), optical sensors measuring the normalized differences in vegetation index (NDVI), and turf digital colour analysis (Leinauer et al., 2014).

In this study, grasses in turf reinforcement cells were exposed to drought conditions. Reinforcement cells (TurfPave®, Elmich, Pte Ltd) (Fig. 1) are particularly suited for the urban landscapes where grasses can be integrated into spaces used for parking, and on access roads, or even a driveway. Turf reinforcement cells are lightweight, high strength interlocking plastic pavers that provide a scaffold for the even distribution of grass growth and the cells are built to hold vehicular loads. In urban areas approximately 70 to 90% of building sites are paved to accommodate podiums, parking

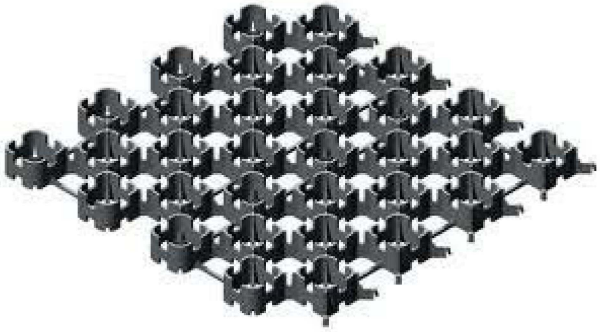

Fig. 1. Reinforced cell with dimension: 500 mm (L) × 500 mm (W) × 40 mm (H) .

lots, driveways or walkways (Gartland, 2012; Li, 2015). Most paved areas are constructed from impermeable materials such as concrete, bitumen, stone, and tiles (Li, 2015). These materials retain a vast amount of heat, increasing the ambient temperature (Gartland, 2012).

To mitigate the negative effects of extensive impermeable materials in an urban environment, turf reinforcement cells may be used as an alternative to asphalt and concrete, and can serve to stabilise turf surfaces against erosion. The application of these cells will allow for grass growth to replace impervious surfaces given the high load strength, and so the ability to extend greenery beyond the conventional spaces of lawns, tree pits, gardens, and parks that will be advantageous to urban cities where spaces for greening is often limited yet highly sort after.

The resilience of turf to drought resistance can vary extensively between species and soil type (Jiang and Huang, 2001). The basis to drought resistant is essentially the enhanced ability to mine water from the soil (Qian and Fry, 1997; Songsri et al., 2009). This might be achieved through the selection for larger, deeper root systems, and smaller leaf area (for better drought adaptation). The ability for the soil to retain moisture is therefore, inextricably linked to drought avoidance in grasses (Songsri et al., 2009).

Accumulated information on WUE and its related traits demonstrated in turfgrasses showed that it is negatively correlated with SLA and this finding generally covered a wide range of species (Liu and Stutzel, 2004). Conversely, a strong and positive relationship was found between F_v/F_m and WUE (Muhammad et al., 2007; Marcelo et al., 2013). Extensive empirical work on grasses have been focused primarily on conventional growing conditions, in the ground (Huang and Gao, 1999; Qian and Engelke, 1999; Jiang and Huang, 2001; Kowalewski et al., 2013) with very limited empirical information available for growth within reinforcement cells, and much lesser involving drought conditions. Therefore, this study was set up to better understand how different species of turf grasses would respond to a 4-month period of drought stress, and to investigate the traits of WUE and changes in physiological parameters with drought stress. These were coupled with the assessment of soil type on the potential of drought avoidance. Three turf grass species and three different soil media were used with the intent to address the following questions: (1) which species was better suited for drought conditions and does these drought resistant species differ in WUE, DIA, NDVI, biomass accumulation, SLA and F_v/F_m (2) Which media was better suited for drought resistance? (3) What are the relationships between WUE, rooting parameters, DIA, NDVI, SLA and $F_v/F_{m,}$ in response to drought stress? (4) Was there a difference in post-drought stress recovery between different turf grasses and was the type of media influential in recovery? Therefore, the objectives of this study were to, (i) evaluate physiological variations in WUE, DIA, NDVI, rooting parameters, SLA and F_v/F_m among turf species growing in different soil types, to assess their responses to drought, and (ii) assess the relevance of the various physiological traits to WUE in turf grasses under receding soil moisture.

Materials & Methods

Plant materials and experimental procedures

A controlled experiment was conducted under glasshouse conditions at the Research Station within the confines of an exhibitory horticulture park located in Singapore (Latitude 1.5° N and Longitude 104° E) for one year (February 2014 to February 2015). Temperatures ranged between 27 –33 and 22- –29°C for day and night time (Table 2), respectively. No artificial lighting was used in this study except for natural light from the sun with a mean daily photosynthetic photon flux density (PPFD) of 2000 μmol m^{-2} s^{-1} (Licor line quantum sensor, LI-191R coupled with the light sensor logger, LI-1500; Lincoln Nebraska, USA). The mean relative humidity was between 73 and 80%.

Fifty four cells (inclusive of controls) and three turfgrasses species (*Zoysia matrella (L.) Merr., Axonopus compressus* (Sw.) P. Beauv. and *Zoysia japonica (Steud.)*) were used in this experiment. The experiment was further divided into 3 soil types. One with equal proportions of loam, clay and organic matter (Type A), and another which had only sand and organic matter (Type B), and the third which was made up of loamy soil and sand without organic matter (Type C). The set up and combinations were planted in a randomized complete block design (RCBD) with three replications. The experiment had two key stages which were, a) the establishment phase, and b) the drought phase. Wherein, the aim was to compare the effect of drought across 90 and 120 days, on the species of grasses across different soil types.

Two soil moisture levels which were, full capacity (FC) and total water deprivation were used to control irrigation. The moisture levels on the experimental site were evaluated using moisture probes placed at a depths of between 10 to 15 cm from the surface (Theta-probe soil moisture sensor, Delta-T Devices Ltd, Cambridge, United Kingdom). The proportion of soil in type A is made up of 60% clay, 25% loam, and 15% organic matter (by volume). Soil type B (by volume) is made up of sand and organic matter in the proportions of 80% and 20%, respectively. Soil type C is made up of 65% sand and 35% loamy soil (by volume). The soils were mixed thoroughly to ensure a well-blended, consistent product using a wheelbarrow.

Reinforced cells were in the dimensions of 500 mm (L) × 500 mm (W) × 40 mm (H), weighing some 1.1 kg (Fig. 1). Cells were made of polypropylene and are resistant against chemical and biological degradation. Each cell also possessed a compressive strength of >2,000 kN m^{-2} when unfilled. Under filled conditions, the strength is estimated to increase by some 20 to 40%. Each cell was set up with 2-10 mm gravel to provide support for weight-bearing loads, following which, the cells were positioned on the compacted gravel and the respective growing media (types A, B and C) were installed (~40 mm). Lastly, the different turfgrasses were planted. An establishment period of 30 days was allocated after sowing (DAS).

Water was applied to all cells to bring them to FC (80-85% soil moisture). The moisture for all plots was maintained at FC until 30 DAS. After 30 DAS, the irrigation treatments were initiated. Soil water levels were maintained uniformly at full capacity from planting until harvest in the control plots, while the moisture levels in the drought-treated plots were allowed to gradually decrease until they reached levels of visible stress which occurred between 90 to 120 days from the onset of treatment. Moisture levels at 90 to 120 days from the onset of treatment were within the ranges of 5 to 12%

Measurement of water use efficiency (WUE)

Water use efficiency (Songsri et al., 2009; Marcelo et al., 2013) is deemed here as the photosynthesis rate, *Pn* at the leaf level divided by evapotranspiration, *ET*.

Water Use Efficiency (WUE) = Pn/ET

Measurement of chlorophyll fluorescence

Chlorophyll fluorescence was measured using a portable fluorescence spectrometer (Hansatech Instruments Ltd, England, United Kingdom). Measurements were recorded as in Percival and Sheriffs (2002). Fluorescence responses were induced by a red light, which peaked at 650 nm at a light intensity of 600 W m^{-2}. The light intensity was provided by six light-emitting diodes. The potential for a species to tolerate water stress can be effectively assessed through a decline in the F_v/F_m ratio representing the maximum quantum yield of PS II which is correlated to the quantum yield of net photosynthesis. This ratio has been widely used as a measure of plant vitality and as a means to diagnose early signs of stress (Resco et al., 2008). Chlorophyll fluorescence was measured once a week on two samples per cell throughout the phases of establishment and drought. Every effort was made to ensure that measurements were conducted on cloudless days and measurements were taken between 1000 h to 1400 h for the purpose of consistency.

Specific leaf area (SLA)

The leaf area was measured with a leaf area meter (LICOR-3100C, Nebraska, USA) and leaves were oven dried at 80°C between 48-72 h for leaf dry weight measurements. Immediately after drying, the leaves were weighed and the SLA was derived as leaf area per unit leaf dry weight ($cm^2\ g^{-1}$).

The SLA was calculated using the following formula:

$SLA = Leaf\ Area\ (cm^2)\ /\ Leaf\ Dry\ Weight\ (g)$

Root dry weight and root length

Grasses were harvested at the end of the experiment (120 days from the onset of treatment). The plant material was clipped at the soil surface and removed before roots were sampled for length measurements. Roots were washed and oven-dried at 80°C for 48-72 h (Pessarakli et al., 2008) and dry weights were recorded.

Digital image analysis for green foliage estimates

Digital images were obtained with a Panasonic LUMIX DMC-FZ 10 (Panasonic Corporation, Osaka, Japan) digital camera mounted on a tripod set at approximately 1 m in height so that the camera was positioned such that an image could be obtained directly above the cell without any obstructions. The collected images were saved in JPEG (Joint photographic experts group) format, with a colour depth of 16.7 million colours, and an image size of 1280 by 960 pixels. Camera settings included a shutter speed of 1/400 sec, an aperture of F4.0, and a focal length of 35 mm. Images were taken on days with full sunlight between 1300 and 1500 h.

Digital images were downloaded to a personal computer and analysed individually by Systat SigmaScan Pro (version 5.0, SPSS, Inc., Chicago, IL). The colour threshold feature in the SigmaScan software allowed the user to search a digital image for a specific colour or a range of colour tones. Previous work with similar images indicated that a hue range between 55 to 110, and a saturation range of 0 to 100 would allow for selective identification of green foliage in the images. After developing a fingerprint of the green areas on the image, the measurement tools in the software were used to count the total number of selected green pixels. The number of green pixels in each image was then divided by the total pixel count of the image so as to determine the percent leaf/green cover in each image.

Normalized Difference Vegetation Index (NDVI)

The TCM500 NDVI meter (Field Scout, Spectrum Technologies, Inc. Plainfield, IL, USA) was used in this study. The equipment can work in three different modes (Bremer et al., 2011). The first is the Normalized Difference Vegetative Index (NDVI) which is defined as:

NDVI = (NIR – Red)/ (NIR + Red)

Where:

NDVI = Normalized Difference Vegetation Index

NIR = Reflectance in the band of 850 ± 5 nm

Red = Reflectance in the band of 660 ± 5 nm

The second is that of the grass index which works on a scale of 1 to 9 and approximates the rating a visual observer would assign to the turf grass. This is generally a very subjective parameter and was omitted from this study. The third mode is that of reflectance where the percent of incident light of each wavelength (band) that is reflected back to the optical sensor in the meter is recorded and these same reflectance values are used to calculate NDVI and the grass index. This parameter was used alongside the first mode as a means of verification.

Statistical Analysis

All data collected were subjected to an analysis of variance (ANOVA) and where appropriate, mean separation was performed using least significant difference tests (SAS Institute, software Version 9.4, Cary, NC, USA). Treatment means were compared by least significant difference to determine whether means of the dependent variable were significantly different at $P = 0.05$, and also to identify significant differences between media and species. Linear regressions were used to determine the relationships of rooting parameters, SLA, DIA, NDVI and F_v/F_m against WUE.

Results

Soil Moisture

The results showed reasonably good management of soil moisture (Figs. 2a and 2b). Water levels were significantly lower in the plants experiencing drought as compared to the controls. Visual observations also showed severe wilting in the

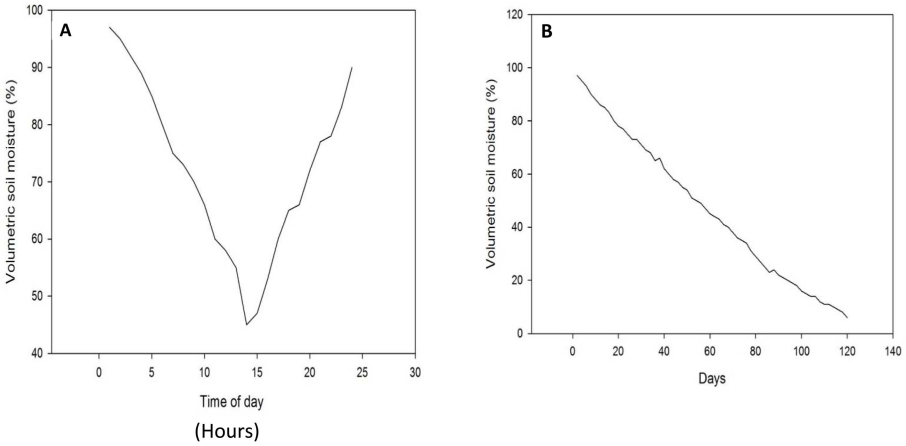

Fig. 2. Typical soil volumetric content (%) for controls over a 24-hour cycle (A), Typical soil volumetric content (%) for turf exposed to water deprivation between 0 to 120 days from the onset of treatment (B).

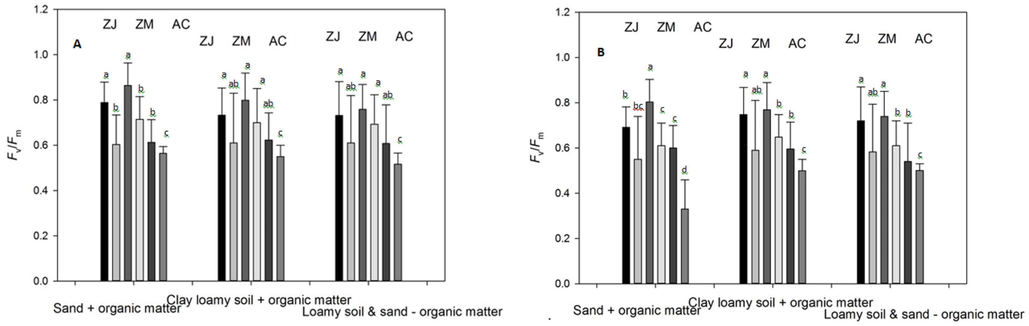

Fig. 3. Mean F_v/F_m indexes for control and water deprived turf, 90 days from the onset of treatment across three different soil types (A). Mean F_v/F_m indexes for control and water deprived turf, 120 days from the onset of treatment across three different soil types (B). Controls are represented by dark bars for each species of grass. ZJ stands for Zoysia japonica; ZM stands for Zoysia matrella; AC stands for Axonopus compressus.

treated cells at 120 days (following the commencement of treatment). (data not shown).

F_v/F_m indexes

Ninety days from the onset of water deprivation, all 3 species of grasses grown on sand with organic matter exhibited a significant decline in the F_v/F_m ratio when compared against the controls (Fig. 3a). However, at 120 days from the onset of treatment the rate of decline was less prevalent in *Z. japonica* (compared against the controls) while the other 2 species continued to exhibit a decline in this ratio (Fig. 3b).

Generally, the effect of drought on the F_v/F_m ratio was less intense for grasses grown on clay loamy soil with organic matter. Zoysia grasses showed no significant decrease in this ratio at 90 days following drought. *A. compressus* was the only species that exhibited a significant decline in this ratio (Fig. 3a). At 120 days from the onset of treatment, it was apparent that water deprivation had taken a toll on most of the grasses except for the *Z. japonica* (Fig. 3b).

The effect on the F_v/F_m ratio for grasses grown in loamy soil and sand without organic matter was similar to what was observed in the grasses grown in clay loamy soil with organic matter at 90 and 120 days from the onset of treatment (Fig. 3a and 3b). The exceptional species tended to be the *Z. japonica* which was least affected by water deprivation.

Digital image analysis (DIA)

The controls across grasses and soil types were not significantly different at 90 and 120 DAS (Table 2). The outlook of the controls was generally lush, with very few brown spots and just a handful of wilted blades. For grasses

Table 1. Effect of drought stress on specific leaf area (SLA) across different grasses growing in different soil types at 120 days from the onset of treatment.

Soil Type	SLA ($cm^2 g^{-1}$)					
	Control			Drought		
	Zoysia japonica	*Zoysia matrella*	*Axonopus compressus*	*Zoysia japonica*	*Zoysia matrella*	*Axonopus compressus*
Clay loamy soil with organic matter	37a(b)	41a(b)	73a(a)	17a(b)	22a(b)	32a(a)
Sand with organic matter	35a(b)	40a(b)	75a(a)	15a(a)	15a(a)	20b(a)
Loamy soil and sand without organic matter	35a(b)	42a(b)	77a(a)	19a(a)	17a(a)	20b(a)

Different alphabets indicate significant differences across media type. Alphabets in parentheses indicate significant differences across species for drought and control grosses.

Table 2. Mean values for Digital Image Analysis (DIA) for control and drought exposed turf across 3 different soil types at 90 and 120 days from the onset of treatment.

Soil Type	Digital Image Analysis (%)											
	90 Days						120 Days					
	Control			Drought			Control			Drought		
	Zoysia japonica	*Zoysia matrella*	*Axonopus compressus*	*Zoysia japonica*	*Zoysia matrella*	*Axonopus compressus*	*Zoysia japonica*	*Zoysia matrella*	*Axonopus compressus*	*Zoysia japonica*	*Zoysia matrella*	*Axonopus compressus*
Clay loamy soil with organic matter	$95^{a(a)}$	$92^{a(a)}$	$97^{a(a)}$	$59^{a(a)}$	$55^{a(a)}$	$38^{a(b)}$	$98^{a(a)}$	$94^{a(a)}$	$95^{a(a)}$	$46^{a(a)}$	$43^{a(a)}$	$25^{a(b)}$
Sand with organic matter	$88^{a(a)}$	$87^{a(a)}$	$91^{a(a)}$	$30^{b(a)}$	$28^{b(a)}$	$21^{b(b)}$	$90^{a(a)}$	$90^{a(a)}$	$92^{a(a)}$	$19^{b(a)}$	$18^{b(a)}$	$10^{b(b)}$
Loamy soil and sand without organic matter	$91^{a(a)}$	$90^{a(a)}$	$94^{a(a)}$	$53^{a(a)}$	$51^{a(a)}$	$42^{a(b)}$	$95^{a(a)}$	$92^{a(a)}$	$95^{a(a)}$	$40^{a(a)}$	$39^{a(a)}$	$21^{a(b)}$

Different alphabets indicate significant differences across media type; Different alphabets in parentheses indicate significant differences across species for drought and control grasses (for 90 & 120 days, respectively).

Table 3. Mean values for NDVI for control and drought exposed turf across 3 different soil types at 90 and 120 days from the onset of treatment.

Soil Type	NDVI											
	90 Days						120 Days					
	Control			Drought			Control			Drought		
	Zoysia japonica	*Zoysia matrella*	*Axonopus compressus*	*Zoysia japonica*	*Zoysia matrella*	*Axonopus compressus*	*Zoysia japonica*	*Zoysia matrella*	*Axonopus compressus*	*Zoysia japonica*	*Zoysia matrella*	*Axonopus compressus*
Clay loamy soil with organic matter	$0.89^{a(a)}$	$0.821^{a(a)}$	$0.726^{a(b)}$	$0.79^{a(a)}$	$0.773^{a(a)}$	$0.653^{a(b)}$	$0.854^{a(a)}$	$0.781^{a(a)}$	$0.702^{a(b)}$	$0.702^{a(a)}$	$0.701^{a(a)}$	$0.56^{a(b)}$
Sand with organic matter	$0.83^{a(a)}$	$0.789^{b(a)}$	$0.663^{b(b)}$	$0.70^{b(a)}$	$0.65^{b(a)}$	$0.441^{b(b)}$	$0.795^{a(a)}$	$0.741^{a(a)}$	$0.631^{a(b)}$	$0.651^{b(a)}$	$0.612^{b(b)}$	$0.4^{b(c)}$
Loamy soil and sand without organic matter	$0.857^{a(a)}$	$0.837^{a(a)}$	$0.687^{b(b)}$	$0.752^{a(a)}$	$0.751^{a(a)}$	$0.63^{a(b)}$	$0.812^{a(a)}$	$0.795^{a(a)}$	$0.65^{a(b)}$	$0.701^{a(a)}$	$0.707^{a(a)}$	$0.52^{a(b)}$

Different alphabets indicate significant differences across media type; Different alphabets in parentheses indicate significant differences across species for drought and control grasses (for 90 & 120 days, respectively).

Table 4. Root biomass and root length data across species and soil types following 120 days from the onset of treatment.

Species	Clay loamy soil with organic matter		Sand with organic matter		Loamy soil and sand without organic matter	
	Biomass (g)	length (cm)	Biomass (g)	length (cm)	Biomass (g)	length (cm)
Zoysia japonica	$130^{a(c)}$	$8^{a(b)}$	$105^{b(b)}$	$9^{a(b)}$	$120^{a(c)}$	$10^{a(b)}$
Zoysia matrella	$190^{a(b)}$	$10^{a(b)}$	$132^{b(b)}$	$10^{a(b)}$	$200^{a(b)}$	$9^{a(b)}$
Axonopus compressus	$300^{a(a)}$	$20^{a(a)}$	$252^{c(a)}$	$15^{a(a)}$	$272^{b(a)}$	$16^{a(a)}$

Different alphabets indicate significant differences across media type; Alphabets in parentheses indicate significant differences across species for drought and control grasses.

exposed to drought, those grown in sand with organic matter tended to fair worse at 90 & 120 DAS (Table 2). All 3 grass species grown in this media was negatively affected by water deprivation. The DIA values for grasses grown in clay loamy soil with organic matter and loamy soil without organic matter were generally not significantly different though marginal superiority was observed in grasses grown in clay loamy soil with organic matter (Table 2).

A. compressus was the least tolerant against water stress. It exhibited significantly lower DIA values and was seen with the greatest degree of wilted blades, brown patches, and die back at 90 and 120 days from the onset of treatment. The mean decline in DIA values from 90 through to 120 days from the onset of treatment was some 50% for *A. compressus* while *Z. japonica* and *Z. matrella* exhibited a mean decline in DIA values of between 20 to 40%.

Table 5. Correlation coefficient between dry matter and WUE, between species and soil types for drought exposed grasses.

Species	Coefficient value	Soil type	Coefficient value
Zoysia japonica	*0.985*	Clay loamy soil with organic matter	*0.896*
Zoysia matrella	0.846	Sand with organic matter	0.409
Axonopus compressus	0.412	Loamy soil and sand without organic matter	0.729

NDVI

The findings from NDVI readings were consistent with the data observed with DIA. Controls across grasses and soil types were not significantly different at 90 and 120 days from the

Table 6. Prediction of WUE of grasses based on physiological components at P≥0.0001 through simple linear regressions for root biomass, DIA, NDVI, SLA and F_v/F_m parameters.

Species	Root biomass (R^2)	DIA (R^2)	NDVI (R^2)	SLA (R^2)	F_v/F_m (R^2)
Zoysia japonica	0.823	0.830	0.783	0.687	0.707
Zoysia matrella	0.787	0.735	0.811	0.712	0.685
Axonopus compressus	0.414	0.31	0.462	0.501	0.312

#Results across soil types have been pooled together.

onset of treatment (Tables 3) and grasses grown in sand with organic matter tended to fair worse at 90 & 120 days from the onset of treatment than the other soil types (Table 3). There was generally no significant difference between grasses grown in clay loamy soil with organic matter and those grown in loamy soil without organic matter.

Similarly, NDVI values also suggested that *A. compressus* was the least tolerant against water stress (Table 3). The decline in NDVI values from 90 through to 120 days from the onset of treatment was between 9 to 17% for *A. compressus* while *Z. japonica* exhibited a 7 to 11% decline. *Z. matrella* exhibited some 6 to 9% decline in NDVI.

Specific leaf area (SLA)

SLA was measured at 120 days from the onset of treatment. It is noteworthy for this parameter to understand that the *A. compressus* possessed a different growth habit (i.e. wide, thick leaf blades with lateral stems that develop aboveground, along the surface of the soil) from *Zoysia* grasses. Despite the differences in growth form and habit, it was evident from the data that water stress had a negative impact on SLA for drought exposed grasses (Table 1). For example, SLA as a function of clipping dry weight (CDW) exhibited a significant reduction and this was consistent across species and media (data not shown). At 120 days from the onset of treatment, SLA values indicated that *A. compressus* was the exception where SLA was significantly lower for those grown in the media of sand with organic matter and loamy soil and sand without organic matter (Table 1). The decline in SLA values was greatest for *A. compressus,* between the ranges of 50 to 75% while the *Zoysia* grasses generally exhibited a smaller decline of between 40 to 60%.

Root biomass and root length

Generally, biomass data for all 3 grasses were significantly lower when grown in sand with organic matter (Table 4). Across species, *Z. japonica* had the lowest biomass values and this finding was significant for the soil types of clay loam with organic matter and loamy soil and sand without organic matter. Soil type had no effect on root length across species (Table 4), but given the growth habit and form of *A. compressus,* it tended to be superior to the *Zoysia* grasses in both aspects of root biomass and root length.

Overall dry matter and Water Use Efficiency (WUE)

A strong linear relationship was observed in species when comparing dry matter and WUE for *Zoysia* grasses. A weaker relationship was found with *A. compressus* (Table 5). With soil type, a strong relationship was found in grasses grown in clay loamy soil with organic matter and loamy soil and sand without organic, but a weak relationship was seen in the media of sand with organic matter (Table 5). Generally, biomass data indicated a negative correlation between drought and overall dry matter. The magnitude was greater for *A. compressus* (data not shown).

Root biomass, DIA, NDVI, and F_v/F_m indicated strong relationships between these parameters and WUE (Table 6). The exception was with *A. compressus* where the relationship was some 50% weaker in most parameters. A negative relationship between SLA and WUE was observed.

Discussion

An understanding of the traits associated with WUE such as the ability of roots to increase water uptake and maintain high photosynthetic capacity is important for turf survival under drought stress (Connellan, 2013). This information should provide a better understanding on how different species adapt to low soil water levels and will have important implications on selection of drought resistant turfgrasses. The effect of drought on photosynthetic ability was more pronounced for media rather than species type. The results were generally in favour of the *Zoysia* grasses as a drought resistant grass as oppose to *A. compressus.*

Drought adaptive traits have been correlated with large root systems (Nageswara et al., 1995; Comas et al., 2013) and greater root length while greater root density was found to be ideal at shallower depths (Songsri et al., 2009). These aspects have been used as selection criteria for drought resistance in turfgrasses. The data here suggest that sandy soils were not beneficial to root biomass but this limitation did not affect root length. It is noteworthy that the superiority of root length and biomass findings for *A. compressus* observed in this study may be attributed to its stoloniferous growth nature which was made up of stout culms, wide leaves, long spikelets and a dense mat formation. This was in stark contrasts to the Zoysia grasses that tended to develop through rhizomes with fine textured leaf blades.

The species with the largest root system did not necessarily translate into stronger resistance against water deprivation (Richardson et al., 2008). In *A. compressus*, the more extensive root system may have contributed to vegetative growth but less to stress resistance. This species exhibited thicker leaves (lower SLA) which are usually indicative of higher chlorophyll per unit leaf area and hence a greater photosynthetic capacity compared with thinner leaves (Choudhary et al., 2015) and may in part explain the significant decline in the F_v/F_m ratio when exposed to drought. The F_v/F_m is an indicator of the photosynthetically active light-transmittance characteristics of the leaf, which is dependent on the unit amount of chlorophyll per unit leaf area (chlorophyll density) (McMillen and McClendon, 1983; Richardson et al., 2002). Signicant and positive correlations between F_v/F_m and chlorophyll content (Akkasaeng et al., 2003; Arunyanark et al., 2008) have been confirmed in other reports which may explain the significant effect drought had on this species of grass.

In this study, the Zoysia grasses were better able to maintain their F_v/F_m ratios under drought stress and were also more tolerant to drought as confirmed through digital image analysis and corresponding NDVI data. The media of sand with organic matter was the least suited for drought resistance for all grasses. This may be attributed to the greater degree of porosity which results in enhanced loss of soil moisture through drainage.

Negative correlations between SLA and WUE were observed across all species and this had been supported by previous reports (Nageswara et al., 2001; Upadhyaya, 2005; Nigam et al., 2003, 2005; Nigam and Aruna, 2008). SLA decreased with drought stress, in all species and across all soil types.

The strong linear relationship between WUE and overall dry matter in the Zoysia grasses may be associated to the variation in photosynthetic capacity per unit leaf area (Wright and Nageswara, 1994; Nageswara et al., 1995; Anwar et al., 1999). Their leaves were thinner than those of the *A. compressus* which in turn, is suggestive of a lower density of chlorophyll per unit leaf area, resulting in reduced photosynthetic capacity. Even so, the Zoysia grasses still fared better under conditions of water deprivation based on observations made with the other parameters. This provides good evidence of resilience and will potentially support the rationale for higher F_v/F_m and lower SLA alongside greater resilience against drought. All this may have been possible thorough enhanced photosynthetic machinery per unit leaf area.

The findings also indicated that WUE was strongly dependent upon various plant characterises (Simioni et al., 2004; Lawson and Blatt, 2014) such as, SLA, overall biomass, photosynthetic features as well as the lushness indexes of DIA and NDVI. It is noteworthy however, that these associations were less pronounced for *A. compressus.*

In summary, the findings here open up research potential for more in depth analysis into the effects of species and soil type on the molecular and biochemical nature of turfgrass responses to drought stress. In addition, aspects of traffic and shade on turfgrasses may be studied alongside the effects of water deprivation so as to have a holistic understanding on how various turfgrasses adapt to stressful growing conditions.

Conclusions

The effect of drought on photosynthetic ability was more pronounced for media rather than species. The media of sand without organic matter was found to be the least suited for drought resistance for all grasses However, the photosynthetic, NDVI and DIA results were generally in favour of the *Zoysia* grasses as a drought resistant species as oppose to *A. compressus*. The data showed that greater root dry weights and a more extensive root system did not necessarily translate into enhanced drought avoidance capabilities. The turfgrass which had the more extensive root system and lower SLA was not superior in its ability to maintain higher WUE under water stress. WUE was strongly related to plant characterises such as overall biomass, photosynthetic features as well as the lushness indexes of DIA, NDVI, and SLA (though the relationship was a negative one). This study found a strong relationship between WUE and a suite of plant characteristics. Therefore, when grasses are exposed to drought, these traits could serve as useful selection criteria for species with the ability to resist water stress.

This study identified *Z. japonica* as the outstanding species for drought resistance. Aspects of photosynthesis was least affected by water stress and this grass generally fared better for all other measured parameters.

With post drought recovery, there were no clear effects brought about by media but the rate of recovery tended to be in favour of Zoysia grasses with *Z. japonica* possessing marginal superiority.

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