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Performance of *Zoysia* spp. and *Axonopus compressus* Turf on Turf-Paver Complex under Simulated Traffic

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ABSTRACT. Vehicular traffic on turf results in loss of green cover due to direct tearing of shoots and indirect long-term soil compaction. Protection of turfgrass crowns from wear could increase the ability of turf to recover from heavy traffic. Plastic turf-pavers have been installed in trafficked areas to reduce soil compaction and to protect turfgrass crowns from wear. The objectives of this study were to evaluate traffic performance of turfgrasses (*Zoysia matrella* and *Axonopus compressus*) and soil mixture (high, medium and low sand mix) combinations on turf-paver complex. The traffic performance of turf and recovery was evaluated based on percent green cover determined by digital image analysis and spectral reflectance responses by NDVI-meter. Bulk density cores indicated significant increase in soil compaction from medium and low sand mixtures compared to high sand mixture. Higher reduction of percent green cover was observed from *A. compressus* (30-40%) than *Z. matrella* (10-20%) across soil mixtures. Both turf species displayed higher wear tolerance when established on higher sand (>50% sand) than low sand mixture. Positive turf recovery was also supported by complementary spectral responses. Establishment of *Zoysia matrella* turf on turf-paver complex using high sand mixture will result in improved wear tolerance.

Key words: Green coverage, NIR reflectance, Normalized difference vegetation index, Soil compaction, Spectral reflectance

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Introduction

Turf exposed to excessive traffic (vehicular or pedestrian) is subjected to mechanical tearing and crushing that can injure turf crown tissues (Shearman et al., 1980). In addition, the traffic load brings about loss in soil permeability to air and water (O'Neil and Carrow, 1983; Guertal and Shaw, 2004; Sawhill, 2005). These combined traffic impacts are the contributing stress factors to loss of turf color, growth and density. Thus, understanding turfgrass tolerance to traffic should examine tolerance to wear injuries and soil compaction. The ability of turf to tolerate wear injury is dependent on several factors: biotic-physiological, anatomical and morphological characteristics of turf e.g. higher percent of lignified cells and sclerenchyma tissues (Shearman and Beard, 1975a, b; Shearman, 1988), and abiotic-cultural turf management practices e.g., higher mowing height (Youngner, 1962). On the other hand, tolerance to soil compaction by turf depends on soil structure of root zone environment as well as adaptations by plant systems to low oxygen and water levels (Guertal and Shaw, 2004; O'Neil and Carrow, 1983).

Evaluation of turf quality (see Beard, 1973; Krans and Morris, 2007 for definition) is conventionally conducted by visual rating methods. However, assessment has been criticized as poorly defined and subjective (Horst et al., 1984; Trenholm et al., 1999a; Krans and Morris, 2007; Leinauer et al., 2014). Quantitative assessment methods to evaluate turf quality such as digital image analysis (Karcher and Richardson, 2003) have been successfully used as alternatives to visual ratings in several turfgrass studies (e.g., traffic: Sorochan et al., 2006; drought: Carrow and Duncan, 2003; Leinauer et al., 2014). In addition, spectral reflectance to determine irradiance from turfgrass canopy covers was also utilized as an objective tool to evaluate turf visual quality (Trenholm et al., 1999a; Jiang et al., 2003, Guertal and Shaw, 2004; Jiang, 2008; Leinauer et al., 2014). For example, Trenholm et al. (1999b) found that spectral reflectance in the visual (VIS), near-infrared (NIR) spectrum and computed NDVI ratio were correlated with visual turf quality, shoot density and wear injury of bermudagrass and seashore paspalum under traffic.

Plastic turf-pavers comprise a grid of interconnected cells with open notches and base areas. Manufacturers of turf-pavers have asserted that turf-pavers are designed to minimize soil compaction by distributing the vertical traffic load to the sub-base below. Furthermore, the open cells have also been suggested to allow the roots to develop with minimal restriction thereby, resulting in a stable grass surface. Turf-pavers have been installed as green permeable pavements in overflow parking areas, emergency vehicular access lanes or for pedestrian footpaths in Singapore. The popularity of such permeable pavements lies in their purported function to reduce urban heat island effect by cooling pavement surfaces via plant evapotranspiration (Asaeda and Ca, 2000). Moreover, the turfed pavement can increase stormwater infiltration and reduce runoff (Sawhill, 2005; Ferguson, 2005). Furthermore, a functional green pavement could serve to optimize green spaces within a building development (Ong, 2003).

A study by Shearman et al. (1980) concluded that turf established on paver-blocks showed improved turfgrass wear tolerance and recuperative potential in several cool-season grasses. However, no parallel studies have been conducted to examine performance of tropical turfgrasses and root zone mixture on turf-pavers to traffic treatments. Hence, this study is conceived to examine if turf established on turf-pavers could better tolerate wear under the influence of several root zone mixtures. The objectives of the study were to: (1) evaluate the performance of *Zoysia matrella* and *Axonopus compressus* turf on turf-paver complex to simulated traffic conditions and (2) examine the relative soil compaction of different sand content soil mixtures within turf-paver complex. Recommendations of suitable turfgrass and root zone mixture will be proposed to ensure the optimal functionality of the permeable pavements.

Materials and Methods

This research consisted of two studies conducted consecutively on *Zoysia matrella* and *Axonopus compressus* turf. The turfgrasses, purchased from local nursery, were supplied as sod pieces (*Z. matrella*) or turf plugs (*A. compressus*). In 2014, Study 1 was conducted from 19 August to 19 September, while Study 2 ran from 9 December to 9 January, 2015. The two trial periods coincided with two unplanned rainfall weather patterns-Study 2 with higher rainfall received than Study 1. Nonetheless, Study 2 was continued to examine how the higher rainfall received impacted the performance of turf under traffic. The environmental conditions for the two studies were summarized in Table 1.

Table 1. Mean temperature, relative humidity and total rainfall obtained for period of trial in Study 1 & Study 2. Weather data provided by National Environment Agency (NEA), Singapore. DAT, days after treatment.

Period of trial	Mean temp. (°C)	Relative humidity (%)	Total rainfall (mm)
	19 August-19 September 2014		
0-7DAT	28.55	60.00	3.00
8-14DAT	27.64	85.06	4.10
15-21DAT	28.17	83.16	1.16
22-28DAT	29.09	79.85	0.33
	9 December 2014-9 January 2015		
0-7DAT	28.08	79.96	11.50
8-14DAT	26.81	89.10	18.67
15-21DAT	26.26	87.80	14.50
22-28DAT	27.20	80.10	8.90

Turf-paver complex installation & turf establishment: Single turf-paver complex (20 m^2) was formed by 40 jointed pieces of polypropylene turf-pavers (TurfPave™, Elmich Pte Ltd, Singapore); each piece measuring 50×50×4 cm with 32 open cells. Each turf-paver complex defines a distinct soil mixture-(1) High sand (coarse-medium particles): clay mixture [80: 20] (80.4% sand, 16.3% clay, 3.3% silt); (2) Medium sand (coarse-medium particles): clay mixture [50: 50] (50.4% sand, 40.3% clay, 9.3% silt); (3) Low sand (coarse-medium particles): clay mixture [40: 60](40.4% sand, 49.3% clay, 10.3% silt). Organic matter (5%) was mixed into all three soil mixtures before they were used for the studies. The three soil mixtures investigated in this study represent the common planting soil mixtures used in the construction of lawn and permeable pavements. The reported soil texture composition and sand sieve analyses were performed by lab services at AVA (Agri-Food & Veterinary Authority of Singapore). Installation of turf-paver complexes largely followed manufacturer's instructions. The turf-paver complex was installed above a layer of compacted crushed gravel (10 cm). A root-barrier sheet was used to separate the turf-paver complex from the gravel layer and also to reduce migration of soil mixtures into the gravels. The turfgrasses were installed directly above each experimental turf-paver unit (50×50 cm) within the paver-complex: *Zoysia* turf was laid down as sod pieces while individual *Axonopus* soil-bearing turf plugs were sodded closely. The turf was established to full coverage (10 weeks) before traffic treatments were administered: fertilizer was applied at 5 g N m^{-2} (24: 3: 10 + Trace elements) monthly with daily irrigation to prevent drought stress. However, irrigation was withdrawn on rainy days and on day of trampling. Mowing was done bi-weekly for *A. compressus* at 4.0 cm while *Z. matrella* was kept at 3.0 cm weekly with rotary mower. The height and mowing frequency of *Zoysia* and *Axonopus* turf followed the maintenance practices adopted for public facilities in Singapore.

Traffic treatment: Traffic treatment was applied via a customized Kesmac (Kesmac Inc., ON, Canada) studded roller device (250 kg) that comprises of a roller drum with a studded jacket to create wear injury as well as soil compaction. The width of the traffic roller drum measures 76 cm with stud spacing of 10 cm apart and height of 20 mm; yielding 25 tines onto each turf-paver surface of 0.25 m^2. Traffic simulation caused by similar studded-roller machines, in other studies, has been shown to result in significant turfgrass injury and soil compaction (Kowalewksi et al., 2013). The traffic simulator device is approximately 6X lighter than an average compact sedan car (~1250 kg). Therefore, traffic was applied as 10 passes weekly bearing in mind that the minimum number of passes administered should not be less than 6.

Digital image analysis: Digital image analysis to determine percent green cover was conducted based on photographs taken with a tripod- mounted camera for an area covering 0.9×0.9 m. Percent green coverage was determined using SigmaScan Pro 5 (Systat Software Inc., San Jose, CA) following the macros and methods described in Karcher and Richardson (2003).

Canopy spectral reflectance: Canopy spectral reflectance and Normalized Difference Vegetation Index (NDVI) measurements were obtained with a hand-held FieldScout® TCM500 NDVI Turf Color Meter (Spectrum Technologies Inc., Aurora, IL) fitted with filter wavelengths to measure reflectance at 660 and 850 nm. The NDVI meter includes an internal light source to negate effects of varying external ambient light conditions and measures reflectance from a 7.6 cm diameter section of turf surface. The measurements were obtained by gently pressing the device downwards against the grasses, especially for the taller *A. compressus* turf, to block out any ambient light from saturating the meter. The NDVI was computed from two reflectance readings (r) taken at 660 nm (red) and 850 nm (near-infrared): NDVI=(ρ_{850}-r_{660})/ (ρ_{850}+ρ_{660}). Digital images and spectral reflectance measurements were taken from 0900-1100 within 2 days of one another.

Soil bulk density: Relative soil compaction of each root zone mixture was determined from 0-4 cm (the volume of each turf-paver cell and as defined by the root-barrier sheet) by measuring soil bulk density cores at 28 DAT in both studies. Each soil core was removed from the cell with a metal pipe measuring 4×4 cm after the turfgrass shoots were stripped from the surface of the turf-paver unit. The average of five bulk density readings, obtained from 5 different cells within each experimental turf-paver unit, was reported as the final bulk density (BD). The BD was calculated as Dry weight (soil core)/Volume (soil core). The dry weight of the soil cores were measured after drying in a convection oven (80°C) for 48 hours.

Experimental design & statistical analyses: The experimental design was a randomized complete block design of 3 (soil)×2 (turf) factorial arrangement with three replications. Statistical analyses were performed using SPSS (version 22.0, Armonk, NY: IBM Corp). The percent green cover and spectral reflectance measurements were obtained weekly until the end of traffic treatment (28 days after treatment, DAT) and after 21 days of rest (recovery) in both studies. All data collected were subjected to analysis of variance, ANOVA at significance $P<0.05$. Means were separated using Tukey-Kramer test at $P<0.05$. The data from both studies were combined for the evaluation of various correlation coefficients (r) between percent green cover and spectral reflectance indices. The corresponding association was also assessed by calculating the coefficient of determinations (r^2). A total of 180 observations (3 replications by 4 dates by 2 studies) were used in the regression analysis. No significant interaction between parameters from study 1 and study 2 was observed therefore, the results from both studies were pooled for discussion. In addition, pooling the data from both studies can also allow us to evaluate the overall performance of the turf × soil combinations through the dry and wet periods of the year.

Results & Discussion

Turf surfaces, soil mixtures & relative soil compaction

The high sand:clay (80:20) mixture, collected from both turfgrass species and studies, has collectively lowest bulk density compared to medium sand:clay (50:50) and low sand:clay (40:60) mixtures (Table 2). No significant increase in bulk density with the control (plot with no traffic treatment) was detected from the soil mixtures in study 1. The medium and low sand mixtures in study 2 showed significant increase in bulk density relative to the control; with the highest measurement observed from the low sand mixture.

The differential degree of soil compaction, as inferred by soil bulk density, in both studies could likely be due to a difference in the amount of rainfall received prior to traffic treatments or natural processes of drying and gravity. More significantly, there was about 10 fold more rainfall days during study 2 compared to study 1 (Table 1). Consequently, the rainfall received during each weekly trampling period in study 2 most likely caused an increase in soil moisture content of the medium and low sand mixtures. Though no soil moisture data was collected to complement the observed rainfall patterns in this study; we can lend evidence from studies that have shown strong positive relationship between soil moisture and clay soils after a downpour (e.g., Nicholson and Farrar, 1994; Yoo et al., 1998). Hence, we infer that the higher degree

Table 2. Soil bulk density data obtained from soil cores (n=5) extracted from cells within each experimental turf-paver unit that was filled with High (80:20), Medium (50:50) and Low (40:60) sand: clay soil mixtures in *Zoysia matrella* (Z) and *Axonopus compressus* (A) turf.

Turf × Soil	Study 1 (Aug-Sep '2014)		Study 2 (Dec' 14-Jan'15)	
	Control	28 DAT	Control	28 DAT
Z-High	0.99 ns[y]	1.01b[z]	1.09 ns[y]	1.19c[z]
Z-Medium	1.29 ns	1.31a	1.33**	1.44b
Z-Low	1.17 ns	1.24a	1.35**	1.53a
A-High	0.98 ns	1.11b	1.19 ns	1.29c
A-Medium	1.18 ns	1.28a	1.31**	1.42b
A-Low	1.13 ns	1.29a	1.34**	1.53a

[y]Independent t-test (P<0.05) between Control and 28DAT (between columns) **P<0.01, ns non-significant.
[z]Means followed by the same letter within column for each turf x soil combination are not significantly different (P<0.05) based on Tukey-Kramer test.

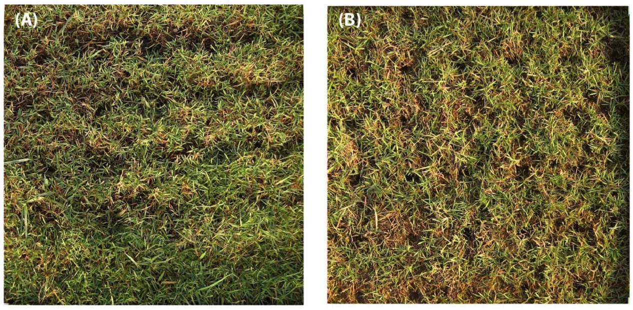

Fig. 1. Turf cover of *Zoysia matrella* on high sand mixture (A) and low sand mixture at end of traffic treatment during Study 2 (B).

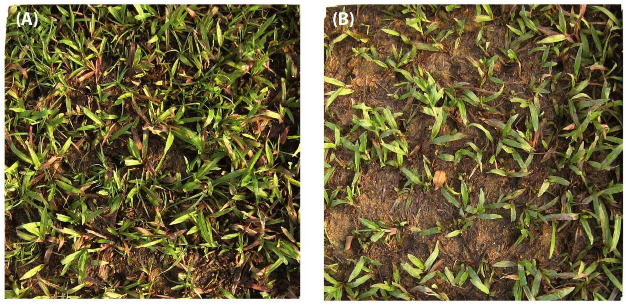

Fig. 2. Turf cover of *Axonopus compressus* on high sand mixture (A) and low sand mixture at end of traffic treatment during Study 2 (B).

of soil compaction observed in the medium and low sand mixtures were due to the higher retained soil moisture. Moreover, the relationship between soil moisture and soil compaction level is well demonstrated (Soane and van Ouwerkerk, 1994). The highest degree of soil compaction observed in the low sand mixture (40% sand) was consistent with Swartz and Kardos (1963) who had demonstrated that soil mixtures with 50% or less sand content will receive higher soil compaction at high soil moisture content relative to mixtures with 70% sand content.

Turf surfaces, soil mixtures & percent green cover

Traffic resulted in significant loss of green cover % in both species (Fig. 1 and 2; Table 3). The reduction of green cover %, relative to 0 DAT (defined as green cover % prior to traffic), was significantly higher in *A. compressus* (30-43%) compared to *Z. matrella* turf (10-20%) at the end of applied traffic (28 DAT) across soil mixtures. There was no significant difference in *Zoysia* turf cover across all soil mixtures (Fig. 1). In contrast, a significantly lower green cover was observed in *Axonopus* that was established on low sand mixture compared to high and medium sand mixtures (Fig. 2). Recovery of green cover was significant in all turf after three weeks of rest ranging from (5-10%) across all soil mixtures (Table 3).

The higher turf cover remaining after traffic treatments in *Zoysia*, across all soil mixtures, compared to *Axonopus* suggests that *Zoysia* is more wear tolerant than *Axonopus* turf. This conclusion is well supported by several traffic studies conducted with *Z. matrella* (e.g., Youngner, 1961; Shearman,

Table 3. Percent green cover, NIR-R850 and canopy NDVI ratio obtained from *Zoysia matrella* (Z) and *Axonopus compressus* (A) turf at end of traffic treatment (28DAT) and after 21 days of recovery (R) across soil mixtures (High, Medium and Low sand: clay mixtures).

Turf x Soil	Green cover	Green cover-R	NIR	NIR-R	NDVI	NDVI-R
Z-High	78.26±1.87a[z]	87.23±0.73a	32.92±1.46a	34.66±1.50 ns	0.54±0.011a	0.63±0.012a
Z-Medium	84.50±4.29a	90.03±1.11a	36.16±1.35a	37.37±1.52 ns	0.59±0.014a	0.65±0.014a
Z-Low	74.30±2.97a	83.76±1.43b	29.37±1.24b	32.59±2.30 ns	0.52±0.022b	0.58±0.029c
A-High	60.65±3.24b	69.59±2.71c	32.10±1.94a	33.80±1.92 ns	0.55±0.020a	0.61±0.011b
A-Medium	53.06 ±2.46b	61.02±1.17c	32.07±2.37a	34.05±0.92 ns	0.55±0.024a	0.61±0.009b
A-Low	50.08±2.84c	59.23±2.12d	26.71±1.33c	29.30±2.68 ns	0.48±0.023c	0.54±0.031d

[z]Means±SE followed by the same letter within each column for each turf × soil combination are not significantly different (P<0.05) based on Tukey-Kramer test.

1988; Harivandi, 2002). Turfgrass wear tolerance is largely correlated with the presence of higher lignin and sclerenchyma content in leaves (Shearman and Beard, 1975a, b). The relatively thinner and less fibrous leaf texture of *A. compressus* might have accounted for its increased wear and thus higher loss of green coverage as observed in this study. Furthermore, presence of thatch in *Zoysia* turf (~3.0 cm above turf-pavers at onset of traffic treatment) could have also contributed extra cushioning effect that protects the crowns of the plants from wear (Shearman, 1988). Interestingly, a significant level of lower turf cover was observed in *Axonopus* that was established on low sand mixtures in comparison to *Zoysia* turf. Ease of turf recovery after traffic that was established on turf-pavers was suggested by Shearman et al. (1980) to be contributed by the protection of crown tissues within the turf-paver cells. Our study also supported their observations as turf recovery was positive from all soil mixtures after three weeks of rest (Table 3). Furthermore, we have also observed extensive living underground *Zoysia* rhizomes growing profusely through the notches within the cells as well as growing basal crown tissues of *Axonopus compressus* buried slightly beneath the surface of the cells. Therefore, the protection of these meristematic tissues by the turf-pavers could have facilitated turf recovery after traffic damage. It will be worthy to examine the contribution of surviving stolons and buried crown tissues below soil surface towards the recovery of *Axonopus* and *Zoysia* turf. Such information could help turf manager to better install turf on the turf pavers to ensure turf resilience after heavy traffic.

Turf surfaces, soil mixtures & spectral reflectance changes

The NIR-R_{850} (R850) reflectance and NDVI were significantly reduced at the end of traffic treatment in all turfgrass species across soil mixtures (Table 3). The highest relative decrease (with respect to 0 DAT) in spectral reflectance (R850, NDVI) for both *Z. matrella* (43.86% and 28.28% respectively) and *Axonopus* (52.23% and 29.85% & respectively) was observed from turf established on low sand mixtures. High association of spectral reflectance indices (r^2 0.70-0.77) with percent green cover was determined. The highest r^2 (0.71) was observed in NDVI for *Zoysia* while highest r^2 (0.77) was observed in R850 for *Axonopus*. Correlation coefficient (r) with green cover was generally high and positive (r> 0.75) in all turf. Turf recovery showed complementary improvement in NDVI with higher recovery values observed from turf established on high & medium sand mixtures (Table 3). In comparison, no significant improvement of R850 reflectance was observed in any of the recovery turf.

Good correlation of spectral reflectance data with turf visual quality was reported for bermudagrass and seashore paspalum under traffic stress (Trenholm et al., 1999b; Jiang et al., 2003; Guertal and Shaw, 2004). This was also determined in this study as displayed by the high correlation and association of NDVI and NIR reflectance with percent green cover. The high correlation of NDVI with percent green cover is predictable as both spectral NDVI and digital image analysis produce similar measurements based on changes in green color (Leinauer et al., 2014). On the contrary, reduction of NIR reflectance was likely due to degeneration of internal leaf structure or reduction in healthy green leaf area (Raikes and Burpee, 1998). As leaf surfaces were damaged by wear and tear caused by traffic there was a resulting decrease in NIR reflectance. Moreover, higher degree of NIR reflectance has been used as an indicator for better wear tolerance in several ecotypes of bermudagrass and seashore paspalum (Trenholm et al., 1999b). In this study we observed a similar relationship of higher wear tolerance, based on the higher NIR reflectance, in turf established on higher sand mixtures (Table 3). Conversely, the poor wear tolerance (low NIR reflectance) in turf established on low sand mixture could plausibly be contributed by the detrimental effects of soil compaction on

Table 4. Percent green cover, NIR-R850 and canopy NDVI ratio obtained from *Zoysia matrella* (Z) and *Axonopus compressus* (A) turf at 7 days after treatment (DAT) across soil mixtures (High, Medium and Low sand: clay mixtures).

Turf x soil	Green cover		NIR		NDVI	
	0DAT	7DAT	0DAT	7DAT	0DAT	7DAT
Z-High	95.06±0.92 ns[y]	93.52±0.95 ns[z]	50.50±1.54*[y]	44.87±2.00 ns[z]	0.72±0.019*[y]	0.65±0.015 ns[z]
Z-Medium	94.12±0.98 ns	92.45±1.08 ns	51.12±1.83*	46.37±1.74 ns	0.73±0.018*	0.68±0.012 ns
Z-Low	93.71± 0.54 ns	91.89±1.65 ns	48.97±1.68*	45.05±1.73 ns	0.71±0.014**	0.64±0.017 ns
A-High	88.95±2.75 ns	91.48±0.75 ns	55.87±0.86**	47.70±2.67 ns	0.70±0.017*	0.66±0.030 ns
A-Medium	88.90 ±3.23 ns	88.62±1.44 ns	53.01±1.29**	45.25±2.62 ns	0.66±0.027*	0.62±0.040 ns
A-Low	87.96±2.09 ns	86.71±1.27 ns	52.21±0.98**	45.86±2.12 ns	0.67±0.019**	0.63±0.027 ns

[y]Independent t-test between 0DAT & 7DAT (between columns) **P<0.01; *P<0.5; ns non-significant.
[z]Means±SE followed by the same letter within column for each turf x soil combination are not significantly different (P<0.05) based on Tukey-Kramer test.

turf quality. Further studies will be needed to evaluate the strict effects of soil compaction on spectral response data to better establish this relationship. Turf recovery was significant in both species after three weeks of rest as observed by the gradual increase in NDVI (Table 3). On the other hand, the high variance in our R850 reflectance data could have resulted in poor statistical power to produce any significant inference on turf recovery. Although percent green cover and NDVI displayed predictable relationships based on their changes in green colors, early detection of traffic stress by R850 reflectance and NDVI at 7 DAT compared to digital percent green cover data was evident (Table 4). Thus, the components of NDVI (Red & NIR) could offer stronger discriminating power than percent green cover data. Reduction in NIR reflectance has been strongly formulated as one of earliest symptoms of plant stress and such reduction was reported to appear before visible symptoms become apparent (Nilsson and Johnsson, 1996; Raikes and Burpee, 1998). Moreover, early degeneration of internal leaf structure might not elicit visible degradation or senescence of leaf tissues that are significantly visible to naked eyes or digital camera. Hence, the sensitivity of NIR reflectance in detecting 'invisible' stress symptoms is promising to monitor plant stress that effect in degradation of cellular structures.

Conclusions

The turf-paver complex is not able to resist soil compaction especially under wet soil conditions. Nonetheless, our results have supported the ability of root zone mixtures with higher sand content (>50%) to reduce impacts of soil compaction. This study has further corroborated that *Zoysia matrella* is wear-tolerant relative to *Axonopus compressus*. There appeared to be significant interactions between higher sand mixtures with turf wear tolerance as both *Zoysia* and *Axonopus* turf performed worst on low sand mixtures. Such differential response in wear tolerance could be attributed by the antagonistic impacts of soil compaction on turf growth. However, the mechanistic effect of soil compaction on turf injury is unknown. Ease of turf recovery from traffic treatments might be contributed via the protection of turf crown tissues within the turf-paver complex.

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