https://doi.org/10.17221/173/2022-HORTSCI

Changes in growth and leaf hyperspectral reflectance of zoysiagrass (*Zoysia japonica* Steud.) under various soil compaction intensities

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Citation: Choi J.E., Song K.E., Hong S.H., Konvalina P., Chung J.I., Kim, M.C., Jung J.S., Shim S.I. (2024): Changes in growth and leaf hyperspectral reflectance of zoysiagrass (*Zoysia japonica* Steud.) under various soil compaction intensities. Hort. Sci. (Prague), 51: 127–140.

Abstract: This study was conducted to determine the effect of traffic stress by soil compaction on zoysiagrass by analyzing the aerial and underground parts and hyperspectral analysis. Zoysiagrass plants were subjected to a compaction strength gradient from 35 to 80 kgf/cm^2 to confirm the compaction resistance and recoverable limit and measure the physiological change during stress. Changes in leaf color, photosynthesis, and hyperspectral reflectance due to continuous weak and strong traffic stress were measured, and vegetation indices were evaluated for the critical traffic stress injury assessment. As a result, the stem of the zoysiagrass was severely damaged up to 70 kgf/cm^2 based on soil hardness. The recoverable limit strength of soil compaction was 55 kgf/cm^2 under weak response pressure conditions. Collectively, our results show that the damage of weak compaction strength on the zoysiagrass was quickly recovered after the stop of traffic stress, especially since the growth of the underground part was increased by weak traffic stress. However, if the compaction strength above 65 kgf/cm^2 lasted for a long time, the growth of the underground part is limited by lowering the energy supply for the recovery occurred, in turn, the recovery occurred slowly after the compaction was stopped. Among the vegetation indices obtained from hyperspectral data, pigment specific simple ratio for chlorophyll *a* (PSSRa), pigment specific simple ratio for chlorophyll *b* (PSSRb), and pigment specific simple ratio for carotenoids (PSSRc) were effective in evaluating the damage of traffic stress.

Keywords: traffic stress; turfgrass; soil hardness; recovery; drought stress

Zoysiagrass (*Zoysia japonica* Steud.) is a warm-season turfgrass and has a characteristic of active growth of runner and rhizome showing active lateral growth and short shoot growth characteristics. It is a species that grows in a wide range of soil pH 4.5 to 7.5 and is widely used as a lawn in Korea and has a high resistance to traffic stress among turfgrass species (Harivandi 2020). As zoysiagrass is often used in golf courses, athletic grounds, and playgrounds where the zoysiagrass is subjected to soil compression and mechanical wound stress caused by traffic (Loch et al. 2017), therefore, growth

Supported by the Korean Ministry of Environment (Grant No. 2021002270004) and the Korea Forest Service.

https://doi.org/10.17221/173/2022-HORTSCI

and proliferation could be inhibited (Wolkowski 1990; Batey 2009).

Soil compaction causes an increase in soil bulk density and lowers the proportion of air phase in soil. In addition, direct mechanical resistance to root penetration negatively affects the absorption of water and nutrients due to the reduced range of rhizospheres (Unger, Kaspar 1994; Lipiec et al. 2012). On the other hand, soil compaction with low bulk density also increases the mobility of unsaturated moisture and increases contact between roots and soil surfaces, thereby promoting crop growth (Unger, Kaspar 1994; Batey 2009; Alameda et al. 2012). The migration of nutrients in the soil is affected by compaction, which promotes under dry conditions and reduces in wet conditions. There are also differences in the effects of compaction among plant species, which are known to cause severe damage in dicots compared to monocots (Batey et al. 2009; Nawaz et al. 2013; Arvidsson, Hånskanson 2014). Roots are not directly affected by wear stress, which often occurs when compaction occurs, but root characteristics are known to change by soil compaction (Kohlmeier, Eggens 1983; Lulli et al. 2012). As soil compaction occurs, the total root length decreases, and the root diameter and thickness of the root epidermis increase. However, in some cases, root function increases even if root growth is limited (Unger, Kaspar 1994; Lipiec et al. 2012). On the other hand, it was reported that it was difficult to distinguish the influences of soil compaction and soil moisture stress on root anatomical characteristics (Iijima, Kato 2007).

Hyperspectral analysis is a technology that simultaneously acquires and utilizes images in many adjacent bands spectrometrically. Hyperspectral image analysis has evolved significantly over the past 30 years and has been used effectively in many fields (ElMasry, Sun 2010; Khan et al. 2018). Hyperspectral technology allows for the prediction and identification of changes in plant conditions based primarily on leaf reflectance (Lowe et al. 2017; Moghimi et al. 2018). The light reflectance by the plant surface depends on the chemical and morphological characteristics of the plant. Plant species, moisture content, and canopy properties influence the hyperspectral reflectance in each spectrum band, with visible light regions consisting of blue (450–495 nm), green (495–570 nm), and red regions (620–750 nm) and near-infrared and mid-infrared regions (850–1700 nm) mainly used (Xue, Su 2017).

This study was conducted to investigate the effect of soil compaction on the shoot and root growth and the threshold of recoverability from compaction damages in zoysiagrass using hyperspectral analysis.

MATERIAL AND METHODS

Plant material. The experiment used Korean native zoysiagrass (*Zoysia japonica* Steud.) grown for 9 years from 2012 at the experimental farm of Gyeongsang National University in Jinju, Korea. The round sods of zoysiagrass were cut on 1 January 2021 using a hole cutter before transplanting. After the round sods were transplanted in a pot (diameter 11.5 cm/height 10 cm), the plants were grown in a greenhouse with 30 ± 5/20 ± 4 (day/night) during the experiment. To facilitate root elongation and shoot growth, pots were subjected to a daily watering scheme to maintain the soil moisture to 65 % of the field capacity. The shoot height was adjusted to 1 cm from the ground before compaction started.

Experimental design and treatments. The experiment was organized as a randomized complete block design with three treatments untreated control, weak compaction, and strong compaction in 2021. Each treatment has four replications. Soil compaction treatments for the compaction gradient experiment started after five days of mowing using a hand compactor with a rubber head the same size as the diameter of a pot, the levels of compaction were adjusted to 35, 40, 45, 50, 55, 55, 60, 65, 70, 75, and 80 kgf/cm^2 based on the soil hardness at the 60th day of compaction initiation. Compaction was continuously carried out two times a day with about 1.0 J until the soil hardness became a targeted value. To maintain proper soil moisture conditions, 40 mL of water was irrigated per pot every day.

Based on the soil compaction gradient experiment results, the conditions of no compaction, weak compaction, and strong compaction were set, and the responses of the zoysiagrass were evaluated. The sods (5 cm × 30 cm) of zoysiagrass grown for nine years at the experimental farm of Gyeongsang National University were transplanted in a plastic box (36 cm × 56 cm × 13 cm) filled with a mixture of loam soil and sand (2 : 1). After one month of transplanting, the shoots were mowed at 1 cm, and then the compaction treatments were performed at hitting energy of 9.2 J using an electric hammer (Hr4030C, Makita, Japan) with a steel plate head

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of 21 × 29 cm. The compaction level of no, weak, and strong compaction was adjusted to around 20, 40, and 55 based on the final soil hardness. Recovery commenced at 16 weeks after initial compactions by stopping the compaction treatments.

Analysis of growth and physiological characteristics and soil hardness measurement. Growth analysis was performed at eight weeks of treatment. The degree of damage caused by mechanical wear during soil compaction treatment was evaluated as a visual injury rate. The visual injury was determined as a good state of 10, a poor state of 5, and a dead state of 0. Chlorophyll content was determined using a SPAD meter (SPAD 502, Minolta Japan)

Root viability was measured based on the reduction of triphenyl tetrazolium chloride (TTC) by dehydrogenase (Knievel 1973). After collecting the roots using a hole cutter (10 cm), wash the roots well, and cut the roots into 1 cm lengths. The root sample (200 mg) was transferred to a test tube containing 0.6% TTC and 0.05% ortho X-77 in 0.05% phosphate buffer. The tubes were placed for 1 hour under reduced pressure using a vacuum pump to allow the solution to penetrate well into the cell and leave it in the dark for 15–20 hours. The stained roots were washed with distilled water. The root cells were then destroyed by adding 5 mL of 80% ethanol and heating at 80 °C for 15 to 30 minutes, centrifuge at 10 000 g for 3 minutes, and absorbance was measured at 520 nm using a spectrophotometer (UV-1700, Shimadzu, Japan).

The soil hardness was measured at 10 cm soil depth using a soil penetrometer (TYD-2, Nanbei Instrument, China). Soil hardness was measured three times for each treatment at six hours after the irrigated surface water disappeared.

The samples of 10 plants were selected randomly from each replication to measure root activity and physiological and growth characteristics. The sample leaves which fully expanded and with no symptoms of diseases were used for physiological analysis.

Analysis of hyperspectral reflectance and calculation of vegetation indices. Hyperspectral images were collected using a portable hyperspectral camera (Specim IQ, Specim Co, Finland) under natural sunlight with a reference plate coated with 99% barium. The reflectance was measured on the adaxial surface of fully-expanded leaves fixed on a hard board plate. Hyperspectral analysis was performed by extracting reflectance values from visible to infrared light using ENVI 5.1 (Exelis Visual Information Solution, Inc. Pearl East Circle Boulder, Co, USA) program after image acquisition using snap-shot hyperspectral cameras (Specim IQ, Specim Ltd, Oulu, Finland). Vegetation indices were calculated using the reflectance at each band from hyperspectral data (Table 1).

Statistical analysis. All data for hyperspectral reflectance, physiological and growth characteristics, and root activity are represented as mean values over four replications. Regression analysis was performed with the soil hardness and visual injury rate as independent and dependent variables, respectively. Analyses of variance and regression analysis were performed using the SAS software (ver. 9.3, SAS Institute, Cary, NC), and then mean values were compared using Duncan's multiple range test ($P < 0.05$).

RESULTS AND DISCUSSION

Responses of zoysiagrass to soil compaction levels. In the soil compaction gradient con-

Table 1. Vegetation indices calculated from hyperspectral reflectance in the experiment.

Index	Formula*
Normalized difference vegetation index (NDVI)	(R800 – R680)/(R800 + R680)
Normalized difference 750/710 red edge NDVI (RE-NDVI)	(R750 – R710)/(R750 + R710)
Modified normalized difference 705 (MRE NDVI)	(R750 – R705)/(R750 + R705 – 2 × R445)
Enhanced vegetation index (EVI)	(R860 – R660)/(R860 + 6 × R660 – 7.5 × 460 + 1)
Vogelmann index (VOG REI 1)	R740/R720
Green chlorophyll index (GCI)	(R780/R550) – 1
Green normalized difference vegetation index (GNDVI)	(R750 – R550)/(R750 + R550)
Pigment specific simple ratio (chlorophyll *a*) (PSSRa)	R800/R680
Pigment specific simple ratio (chlorophyll *b*) (PSSRb)	R800/R635
Pigment specific simple ratio (carotenoids) (PSSRc)	R800/R500

*RXXX – the reflectance value at a specific wavelength (XXX nm)

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ditions, the biomass of the zoysiagrass decreased as the soil compaction increased. At 9 weeks after treatment, the shoot of the zoysiagrass could not grow at a compaction strength of 70 or more. Unlike the aerial part, the growth of the underground part increased at a low compaction strength, but the growth also decreased at 70 or higher. At the soil compaction strength of 40 kgf/cm^2, the growth of the aerial part decreased drastically, but the growth of the underground part increased by 50%. Overall, the response of zoysiagrass by the soil compaction decreased significantly in the aerial part as the intensity of the compaction strength increased, but the underground part showed the highest at the weak response pressure (40 kgf/cm^2) and then continued to decrease. The soil compaction by traffic including walking causes wear damage directly in the aerial part, and in the underground part, a change occurs in the rhizosphere due to an increase in soil bulk density (Lipiec et al. 1991; Lipiec et al. 2003). The damage to the zoysiagrass by soil compaction was greater in the aerial part than the root, and the aerial part was almost eliminated in the soil compaction treatment of 65 or more, but the underground part did not show a significant decrease in dry weight compared to the 80 compaction. This result shows that only the aerial part in which photosynthesis occurs, not the underground part, was affected by wear damage during traffic stress. The limited supply of photosynthates from the top led to a gradual decrease in root growth that depends on the photosynthetic activity of shoots (Figure 1).

The responses of the underground part are the changes in the absorption of nutrients and water according to the change in the bulk density of the rhizosphere along with the mechanically applied wear stress. Therefore, the leaf spectral reflectance also can reflect the response to these changes (Figure 2). Wear to aerial part primarily damages the cuticle layer on the leaf surface, increasing water evaporation and lowering biomass accumulation by reducing photosynthesis due to mechanical damage in tissue. In soil, it has a negative effect on root respiration by reducing the water storage capacity and reducing the air space of soil. On the other hand, appropriate compaction can also increase the contact between the root surface and soil particles, thereby increasing the absorption of mineral nutrients and water to some extent. Nawaz et al. (2013) reported that severe soil compaction causes the deformation of roots and inhibition of growth, and this study also showed that the growth of zoysiagrass was inhibited by traffic stress of 70 or more (Figures 1 and 2).

In zoysiagrass, a perennial plant that prioritizes reproduction by rhizomes rather than reproduction by seeds, compression on the aerial part lowers soil covering and degrades lawn quality (Canaway, Baker 1993; McCurdy et al. 2022). Because soil compaction causes less damage to the underground part than

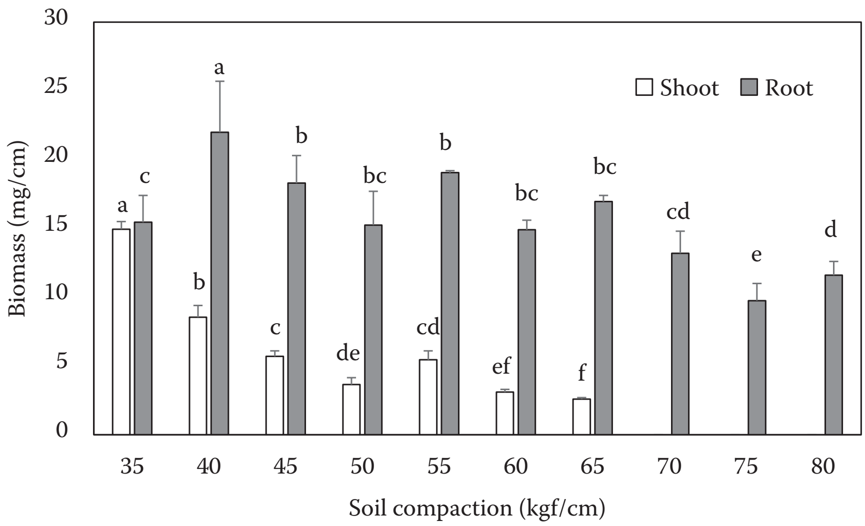

Figure 1. Changes in biomass of aerial and underground parts of zoysiagrass under various soil hardness levels imposed by artificial soil compaction

The soil hardness indicates the hardness values measured 60th days after the beginning of compaction treatment; biomass was measured after drying the plant parts at 80 °C for 48 hours; values are means ± SD, and different letters indicate significant differences between the treatments by Duncan's multiple range test (P < 0.05); n = 3

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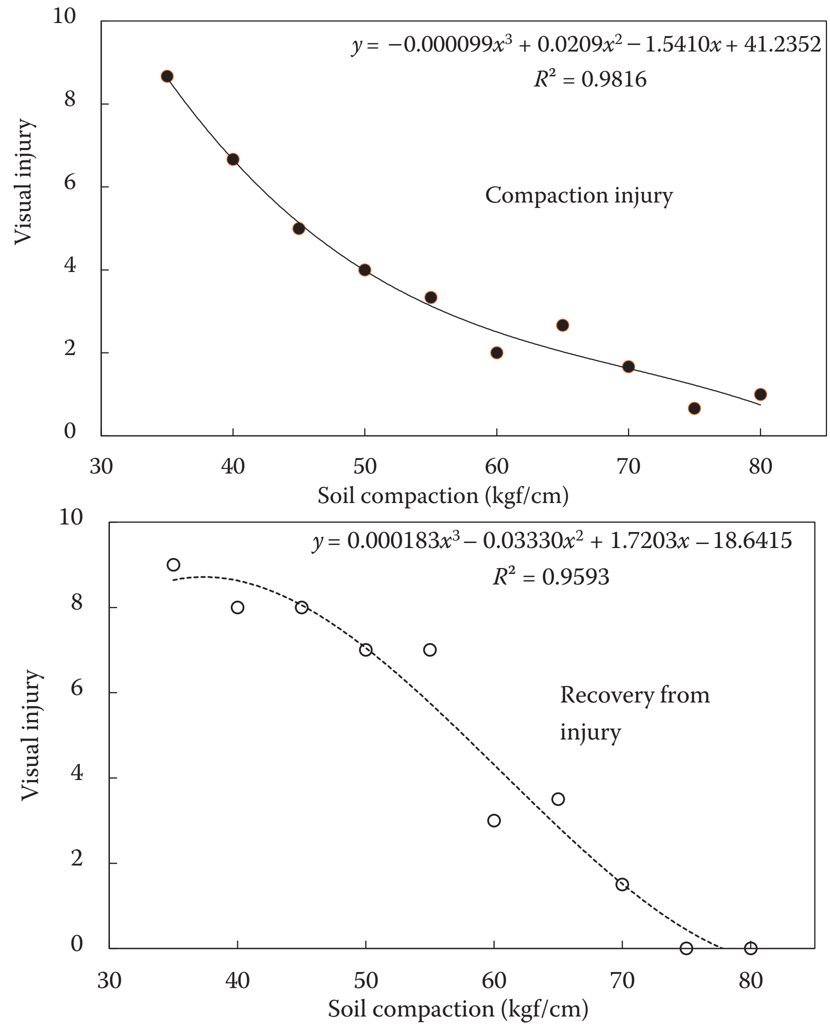

Figure 2. Relationship between soil hardness and visual injury according to soil compaction gradient

Visual injury at 7 weeks after soil compaction treatments, visual injury at 6 weeks after the stop of soil compaction treatments; the visual injury was determined based on the 0–10 scale; 0 – complete dead; 10 – no visual injury

shoots, roots can use the stored nutrients like carbohydrates to recover the damaged shoots if wear damage caused by soil compaction stops. Therefore, the level of underground damage might be a critical factor in the recovery of zoysiagrass under traffic stress.

The visual injury rate of the aerial part, according to the soil compaction, decreased sharply until the soil compaction strength of 55 and then gradually increased. In this study, the visual injury was evaluated only on the aerial part. After the end of traffic stress it recovered to a normal condition up to 55 treatment at 6 weeks after treatment, but the injury recovery was poor in the compaction treatment of 60 or more. It is known that zoysiagrass slowly recovered from the injury of compaction and wear due to the slow growth rate (Youngner 1961; Lulli et al. 2012). Nevertheless, resistance to compaction and wear stress is a reason that this species is preferred in the athletic field and golf course because of its short and tough leaves and slow growth (Patton 2009; Patton et al. 2017). On the other hand, the recovery after stopping the compaction treatment was greater in the relatively weak compaction treatments. Therefore, zoysiagrass recovered up to 55 of compaction strength, indicating that the damage caused by this weak compaction could be recovered (Figure 2).

It is difficult to determine the condition of the underground part from the hyperspectral reflectance of the aerial part. Normalized difference vegetation index (NDVI), which is most frequently used for diagnosing plant conditions, was well reflected in the compaction damage. Vegetation indices are indicators that reflect the nutritional state or water

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status of plants and reflect their response to environmental conditions (Penuelas et al. 1995; Gamon et al. 1997; Sims, Gamon 2002; Suárez et al. 2008; Römer et al. 2012; Mahlein et al. 2013; He et al. 2016; Pandey et al. 2017). Plants exhibit mechanical and physical damage by soil compaction. Hyperspectral reflectance showed differences in response to soil compaction in 600 nm to 700 nm and near-infrared wavelengths of 750 nm or more (Figure 3). Carrow (1980) reported that the ground covering rate and visual quality of zoysiagrass decreased due to wear damage during traffic stress. Our results also showed that the compaction greater than 70 in soil hardness caused damages in the aerial part due to wear. This damage was also confirmed by the lowered reflectance in the range of red light and near-infrared light in the wear-damaged leaves of zoysiagrass leaves. As the soil traffic stress continued, the reflectance around 650 nm increased rapidly, and the difference was evident in the near-infrared band. On the other hand, at a wavelength near 550 nm, the difference by soil compaction was small. The vegetation indices obtained from the hyperspectral reflectance showed differences according to the soil compaction strength. NDVI initially did not differ significantly in the response compaction strength of 45 or higher, but the difference appeared as the compaction continued (Figure 4). However, at 7 weeks after treatment, it was divided into two groups, 35–65 and 70–80 of compaction strength. This index showed little change in the control but decreased over time as the compaction strength increased.

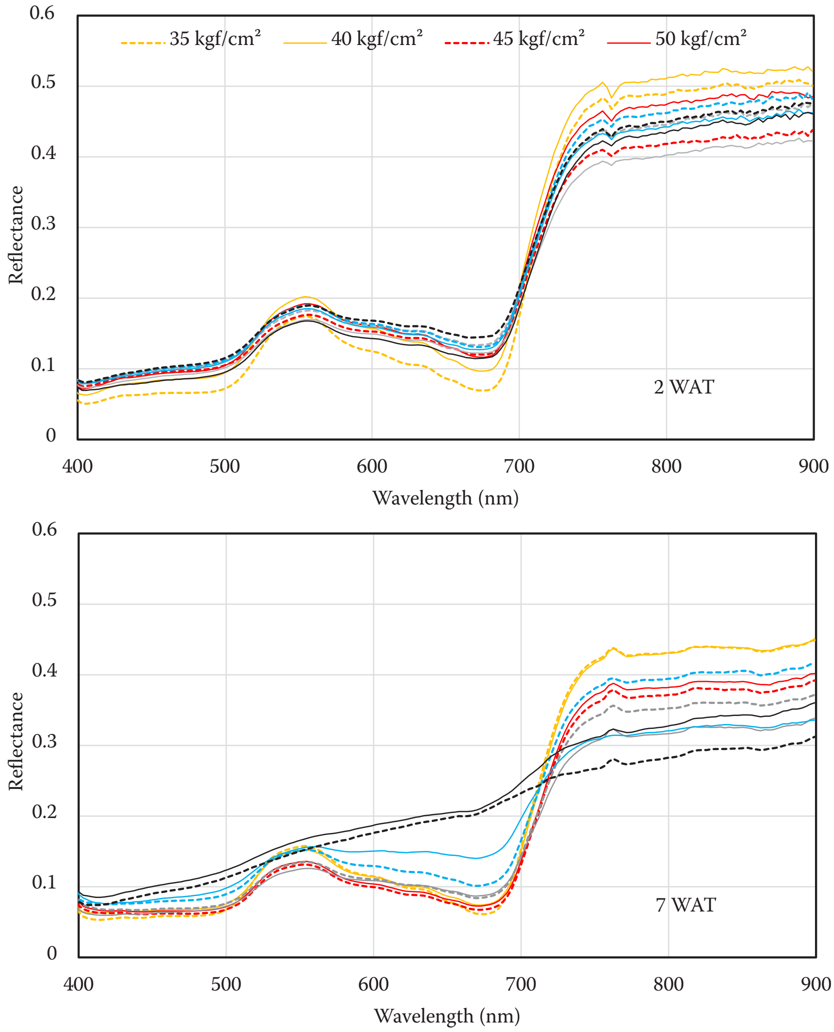

Figure 3. Hyperspectral reflectance of zoysiagrass grown under different soil compaction conditions; hyperspectral reflectance was measured on the central part of the recent fully expanded leaf

Measurements were carried out 2 and 7 weeks after treatment (WAT); hyperspectral graphs were made with the mean value of three replications measured on the adaxial surface of the same leaf

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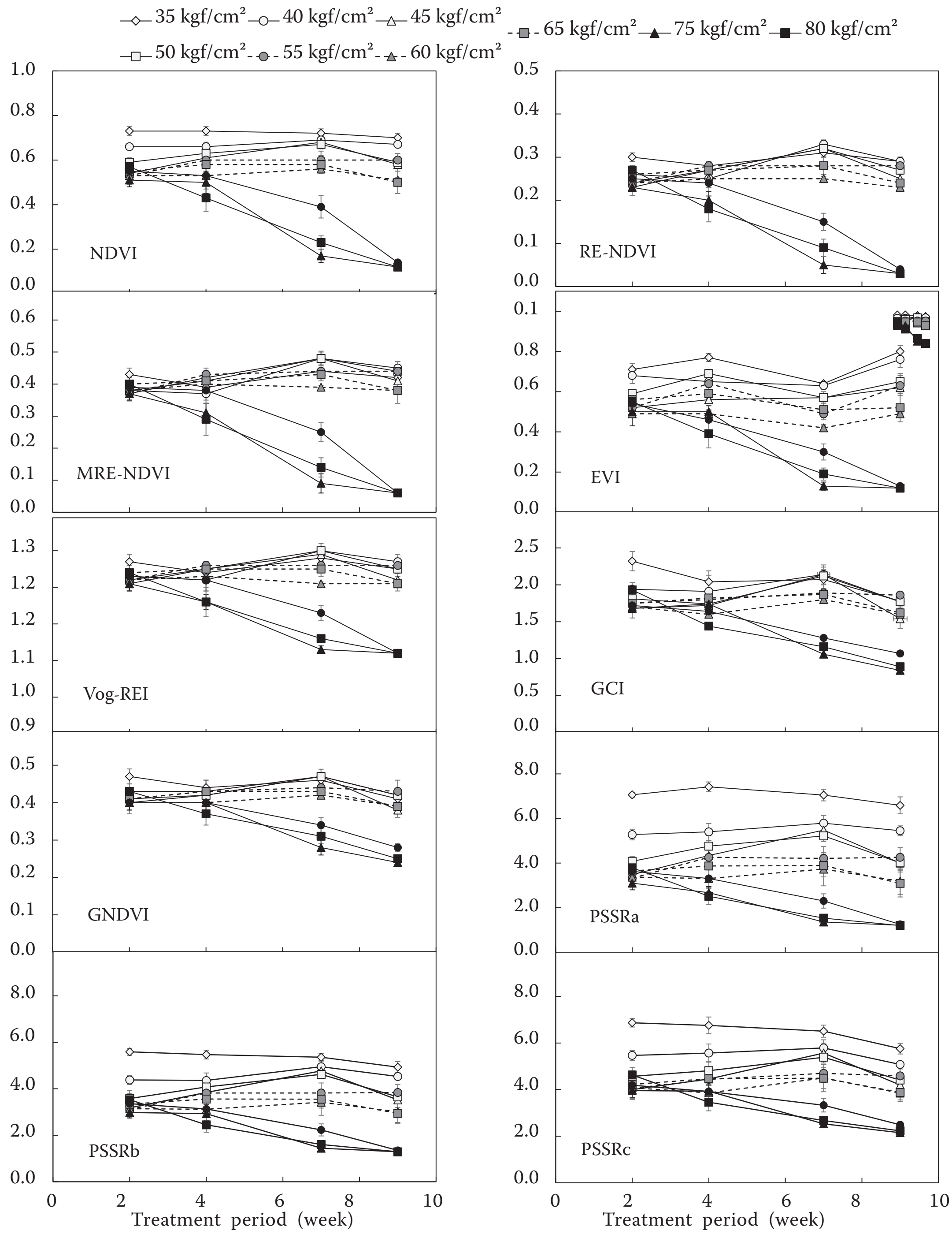

Figure 4. Vegetation indices of zoysiagrass with different soil compactions. The indices were calculated from the spectral reflectance of leaves from 2 to 9 week after treatment (WAT)

Normalized difference vegetation index (NDVI): (R800 – R680)/(R800 + R680), red edge normalized difference vegetation index (RE-NDVI): (R750 – R710)/(R750 + R710), modified red edge normalized difference vegetation index (MRE-NDVI): (R750 – R705)/(R750 + R705 – 2 × R445), enhanced vegetation index (EVI): (R860 – R660)/(R860 + 6 × R660 – 7.5 × 460 + 1), Vohelmann index (Vog REI1): R740/R720; Vog REI2: (R734 – R747)/(R715 + R726); green chlorophyll index (GCI): (R780 – R550)–1; green normalized difference vegetation index (GNDVI): (R750 – R550)/(R750 + R550); specific simple ratio for chlorophyll *a* – (PSSRa): R800/R635, specific simple ratio for chlorophyll *b* (PSSRb): R800/R635, specific simple ratio for chlorophyll c (PSSRc): R800/R500; hyperspectral images were collected in the fully-expanded leaves and calculated with 4 replications; vertical bars indicate standard deviation (n = 4)

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Red edge normalized difference vegetation index (RE-NDVI) and modified red edge normalized difference vegetation index (MRE-NDVI) also showed similar results to normalized difference vegetation index (NDVI), but the difference in response pressure stress was not reflected well when the compaction strength was weak. The indices that efficiently reflect the damage by soil compaction were pigment specific simple ratio for chlorophyll *a* (PSSRa), pigment specific simple ratio for chlorophyll *b* (PSSRb), and pigment specific simple ratio (PSSRc), and from the beginning of compaction, they showed a decrease as the compaction strength increased. After 6 weeks of treatment, these indices were divided into three groups: weak compaction, intermediate compaction, and strong compaction. The PSSR indices were divided into three groups: 35–50, 55–65, and 70–80 kgf/cm^2, based on 6 weeks after the compaction treatment. Overall, the indices that efficiently reflect the influences of the compaction strength were NDVI, enhanced vegetation index (EVI), PSSRa, PSSRb, and PSSRc. RE-NDVI, MRE-NDVI, Vogelmann red edge index (Vog-REI), and green normalized difference vegetation index (GNDVI), on the other hand, did not show much difference between weak and intermediate compaction, but the effect of strong compaction (65 <) was reflected well. The vegetation indices slightly reflect the effect of the compaction at the beginning of treatment but showed the effect of compaction when the compaction continued, and visual injury increased. High NDVI is related to leaf greenness and turf density in lawns, but low NDVI reflects stressed lawns (Richardson et al. 2001; Xiong et al. 2007). Therefore, in this study, the low NDVI in the zoysiagrass with compaction stress at 70 or more shows that the turfgrass is in poor condition.

The hyperspectral reflectance can reflect the influence of the aerial and underground part caused by the soil compaction, and the difference in the soil compaction strength was well reflected at the period as the damage was greater than at the beginning of the compaction treatment. From 7 weeks after the compaction treatment, unusual hyperspectral characteristics in the visible light band were shown in the treatment of more than 75 kgf/cm^2, which means that there was great damage to normal physiological activities such as photosynthesis and transpiration in zoysiagrass leaves.

Changes of growth characteristics of zoysiagrass by the strength of the soil compaction. The soil hardness of the control was 17.8 and 22.6 at 8 and 14 WAT (weeks after treatment). The hardness was changed to 37.9 and 56.4 at 8 WAT and 43.0 and 54.9 at 14 WAT by weak and strong compaction, respectively (Figure 5). The chlorophyll content of the leaves was initially lower than that of treatment in both weak and strong response pressure by soil compaction but increased after 9 weeks. The SPAD value was 26.5 ± 1.4 for control, and 35.6 ± 1.6 and 32.2 ± 1.5 for weak and strong compaction treatment at 9 WAT, respectively, showing increased chlorophyll content according to soil compaction (Figure 6).

In the growth of the aerial part, the plant height initially decreased by strong soil compaction but increased later over time. The leaf length showed the same result as plant height, and the degree of increase in weak compaction treatment was greater

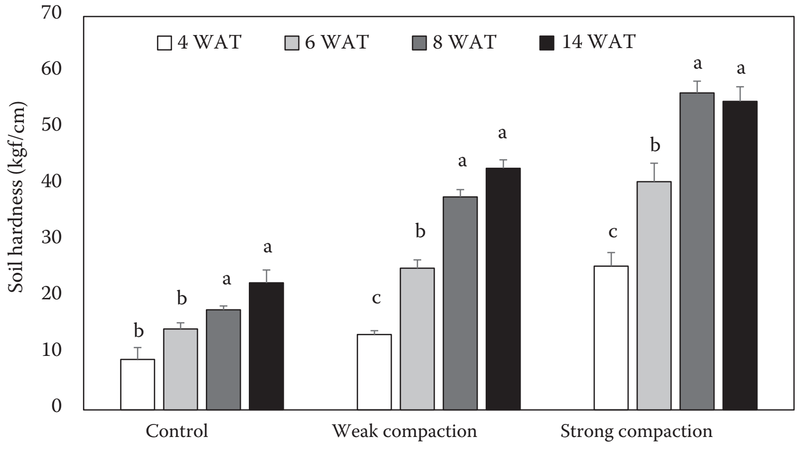

Figure 5. Soil hardness of control, weak compaction, and strong compaction treatment
Values are means ± SD, and different letters above the bars indicate significant differences by Duncan's multiple range test ($P < 0.05$); $n = 4$; WAT – week after treatment

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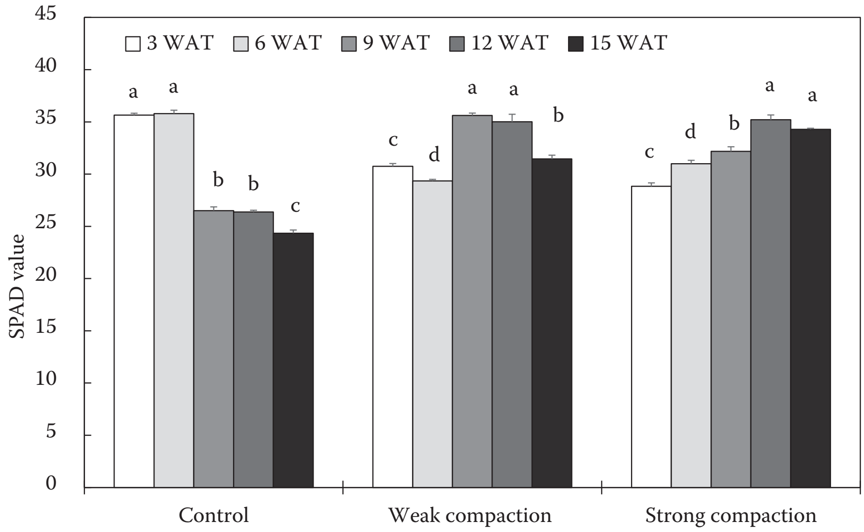

Figure 6. Leaf chlorophyll content (SPAD) of zoysiagrass grown in the soil having different soil hardness. SPAD indicates the mean value of 10 measurements detected in the mid-region of the uppermost leaf

Values are means ± SD, and different letters above the bars indicate significant differences by Duncan's multiple range test (*P* < 0.05); *n* = 40; WAT – weel after treatment

than that of strong compaction over time (Figure 7). Unlike the dry weight of the aerial part, the SPAD value representing leaf chlorophyll content was not significantly affected by soil compaction, and the decrease in leaf chlorophyll over time in the control is believed to be due to a lack of nitrogen in the soil (Mangiafico, Guillard 2005; Xiong et al. 2015). It is thought that the thickening of the leaf color due to the compaction was relatively less deficient in mineral nutrients due to the decrease in the

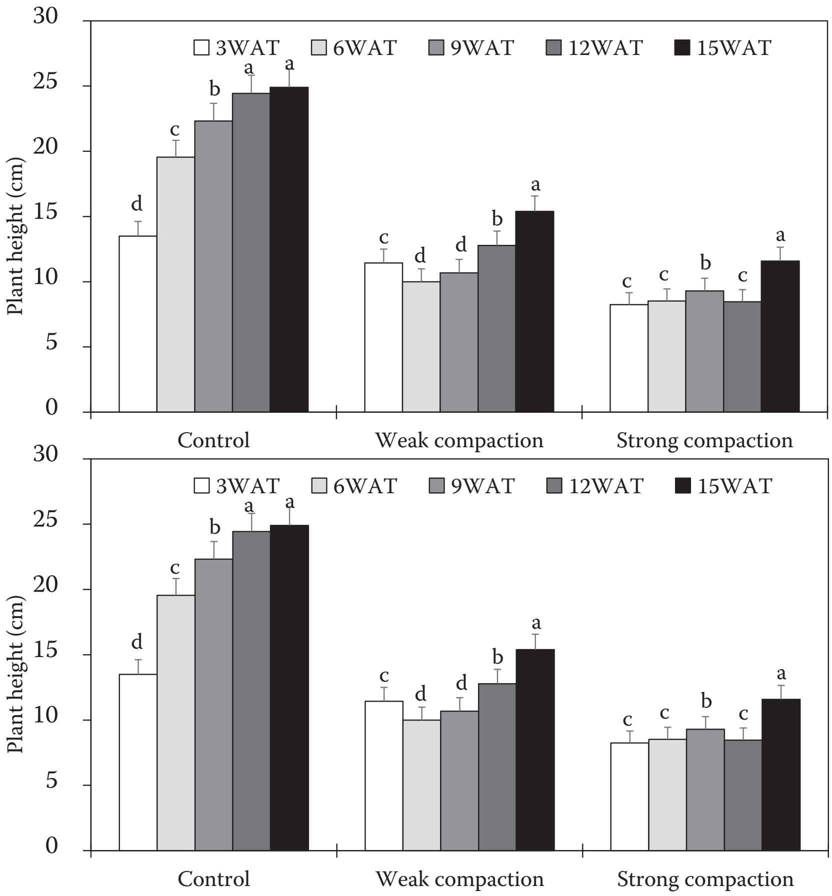

Figure 7. Plant height and leaf length of zoysiagrass grown in the soil having different soil hardness caused by compaction. Leaf length was measured for the 3 largest leaves in a plant

Values are means ± SD, and different letters above the bars indicate significant differences by Duncan's multiple range test (*P* < 0.05); *n* = 20; WAT – week after treatment

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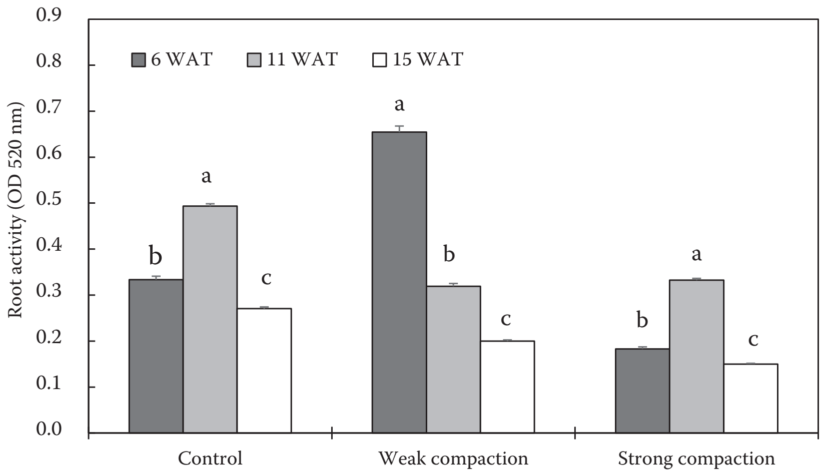

Figure 8. Root activity of zoysiagrass grown in the soil having different soil hardness. Root samples were collected from the middle part of the rhizosphere

Values are means ± SD, and different letters above the bars indicate significant differences by Duncan's multiple range test (P < 0.05); n = 40; WAT – week after treatment

growth of the aerial part, and the decrease in leaf greenness occurred only after 12 weeks. But chlorophyll content was partly decreased due to the wear damage (Mohamadi et al. 2017).

The activity of the underground root increased by compaction rapidly in the case of weak compaction in the early period. However, strong compaction decreased root activity regardless of the treatment period (Figure 8). The root activity increased at 6 WAT and rapidly lowered at 11 WAT and 15 WAT in weak soil compaction. However, strong compaction that showed low root activity increased activity at 11 rather than 6 WAT. This implies that the increase in root activity in weak compaction treatment was initially rapidly increased, but the increase occurred late in the strong compaction treatment.

The growth of the aerial part was strongly suppressed by soil compaction compared to the underground part, and the degree of suppression was greater when the compaction strength was strong. However, the dry weight of the underground part increased due to the strong compaction compared to the weak compaction (Figure 9). Soil compaction restricts root growth and may slow root system development (Cor-

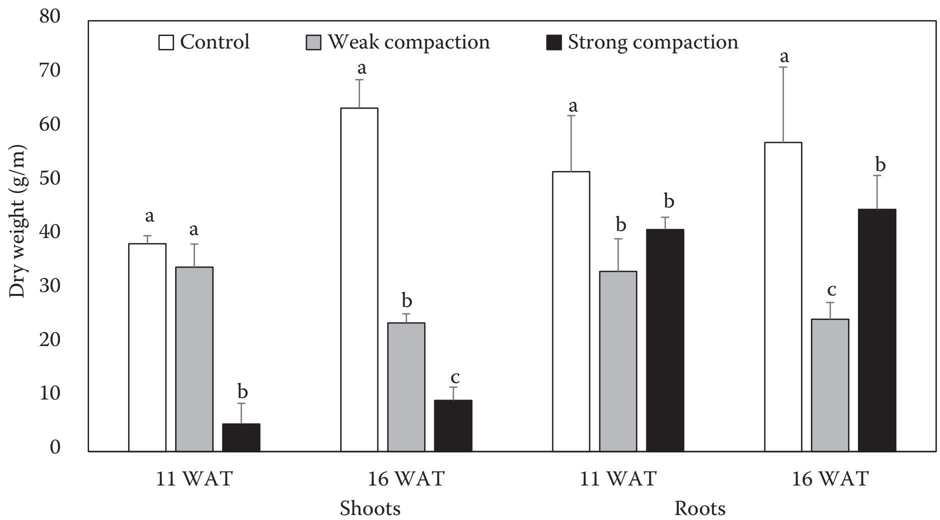

Figure 9. Shoot and root dry weight of zoysiagrass grown in soil with different soil hardness. Shoot includes leaves, stems, rhizomes, and even the part located in the soil

Values are means ± SD, and different letters above the bars indicate significant differences by Duncan's multiple range test (P < 0.05); n = 20; WAT – week after treatment

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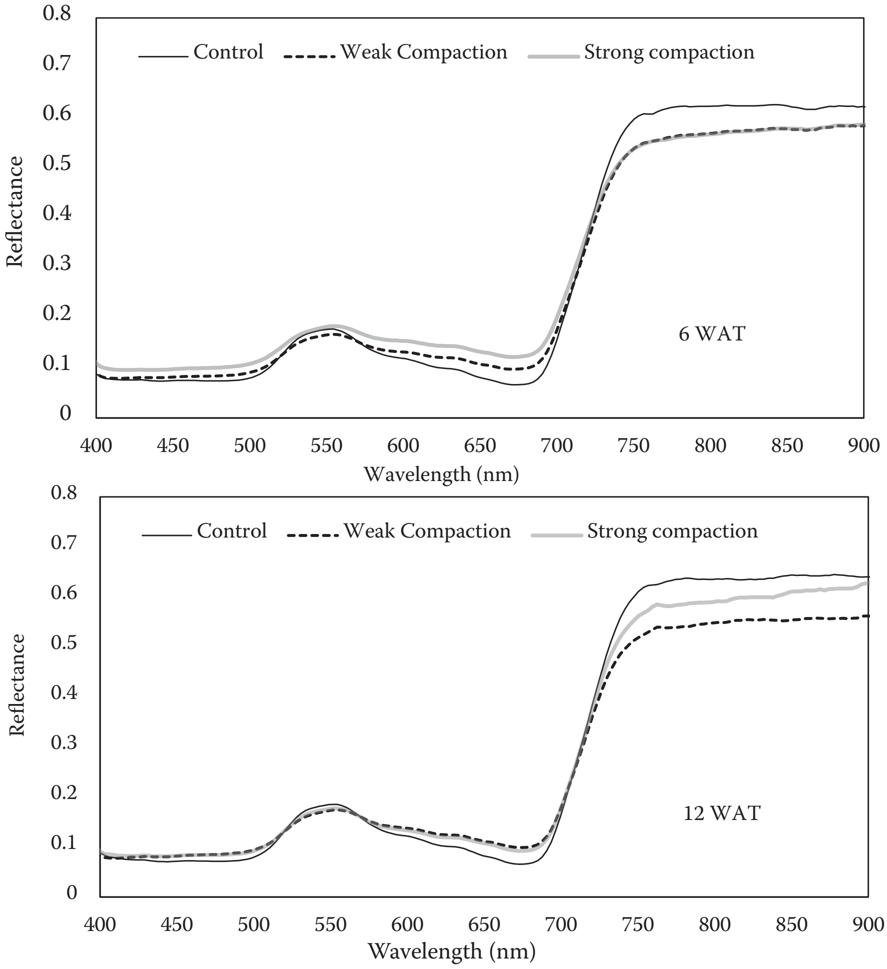

Figure 10. Comparisons of hyperspectral reflectance of zoysiagrass leaves at 6 and 12 weeks after treatment (WAT). Zoysiagrass plants were grown with different soil compaction intensities. Hyperspectral graphs represent the mean value of three repeated measurements conducted on the central region of the canopy under sunlight

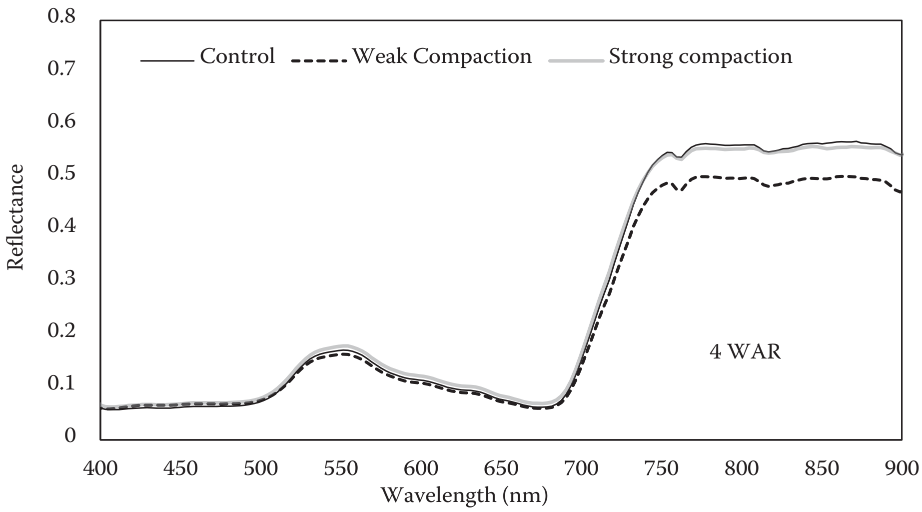

Figure 11. Hyperspectral reflectance of zoysiagrass at 4 weeks after recovery initiation (WAR). Recovery begins by stopping the compaction treatment

Hyperspectral graphs represent the mean value of three repeated measurements conducted on the central region of the canopy under sunlight

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Table 2. Changes in vegetation indices based on the hyperspectral reflectance according to a soil compaction gradient (WAT – week after treatment; WAR – week after recovery initiation)

Indices	6 WAT			12 WAT			4 WAR		
	Control	Weak compaction	Strong compaction	Control	Weak compaction	Strong compaction	Control	Weak compaction	Strong compaction
NDVI	0.79 ± 0.01	0.69 ± 0.01	0.64 ± 0.01	0.79 ± 0.01	0.72 ± 0.02	0.68 ± 0.01	0.78 ± 0.02	0.76 ± 0.01	0.76 ± 0.01
RE-NDVI	0.43 ± 0.01	0.37 ± 0.01	0.33 ± 0.01	0.41 ± 0.02	0.38 ± 0.02	0.35 ± 0.02	0.40 ± 0.02	0.38 ± 0.01	0.40 ± 0.02
MRE-NDVI	0.59 ± 0.01	0.53 ± 0.01	0.50 ± 0.01	0.56 ± 0.02	0.54 ± 0.02	0.50 ± 0.02	0.55 ± 0.02	0.52 ± 0.02	0.56 ± 0.02
EVI	0.92 ± 0.02	0.76 ± 0.02	0.71 ± 0.02	0.93 ± 0.03	0.82 ± 0.03	0.73 ± 0.03	0.82 ± 0.03	0.81 ± 0.01	0.79 ± 0.02
Vog REI 1	1.46 ± 0.01	1.39 ± 0.02	1.33 ± 0.02	1.45 ± 0.03	1.38 ± 0.03	1.34 ± 0.02	1.46 ± 0.03	1.41 ± 0.02	1.45 ± 0.04
GCI	2.95 ± 0.09	2.82 ± 0.18	2.48 ± 0.14	2.80 ± 0.24	2.71 ± 0.23	2.48 ± 0.21	2.67 ± 0.22	2.42 ± 0.15	2.32 ± 0.10
GNDVI	0.54 ± 0.01	0.53 ± 0.01	0.50 ± 0.01	0.54 ± 0.02	0.53 ± 0.02	0.50 ± 0.02	0.52 ± 0.02	0.50 ± 0.01	0.50 ± 0.01
PSSRa	9.41 ± 0.41	5.77 ± 0.19	4.67 ± 0.25	9.67 ± 0.80	6.51 ± 0.49	5.59 ± 0.28	8.95 ± 0.97	7.90 ± 0.33	8.24 ± 0.68
PSSRb	7.71 ± 0.27	5.27 ± 0.13	4.30 ± 0.21	7.67 ± 0.56	5.56 ± 0.39	4.91 ± 0.23	7.24 ± 0.57	6.56 ± 0.21	6.78 ± 0.42
PSSRc	7.89 ± 0.37	6.28 ± 0.27	5.35 ± 0.23	8.13 ± 0.62	6.61 ± 0.48	5.92 ± 0.35	7.97 ± 0.70	7.04 ± 0.48	6.69 ± 0.30

NDVI – normalized difference vegetation index; RE-NDVI – normalized difference 750/710 red edge NDVI; MRE-NDVI – modified normalized difference 705; EVI – enhanced vegetation index; Vog REI – Vogelmann index; GCI – green chlorophyll index; GNDVI – green normalized difference vegetation index; PSSRA – pigment specific simple ratio (chlorophyll *a*); PSSRb – pigment specific simple ratio (chlorophyll *b*); PSSRc – pigment specific simple ratio (carotenoids); WAT – week after treatment; WAR – week after recovery initiation

rea et al. 2019). In this study, however, the increase of root viability in the early of weak traffic stress seems to be an activity for zoysiagrass plants to adapt to traffic stress because roots can increase their activity under slightly adverse environments (Calleja-Carera et al. 2020). The dry weight of the underground part is less affected than that of the aerial part because there is no wear damage in the underground part, but this feature is thought to be the reason that zoysiagrass shows strong resistance to compaction. Therefore, it is plausible that compaction resistance occurs when the damage to the underground part is small during traffic stress. Zoysiagrass is a plant resistant to traffic stress (Patton et al. 2017), and the reason can be inferred in two aspects. First, the photosynthesis of the shoots can be maintained well due to the small wear damage on the relatively tough and robust shoot tissue. Second, the relative proportion of the underground part less affected by compression than the shoots is large, so more nutrients stored in the underground part can supply to the aerial part to recover the damages in the shoots. Mechanical damage to the aerial part caused by continuous traffic stress caused a change in leaf color, and the visual injury rate based on the condition of the leaf was significantly different under weak compaction treatments and less different in strong compaction treatments. The relatively strong wear tolerance is related to the high content of plant fibers of zoysiagrass (Shearman, Beard 1975; Washburn, Seamans 2012). Zhang et al. (2020) reported that 550 nm in the visible light range is a band that shows green color well in turfgrass. However, in this study, the reflectance at 550 nm at 6 WAT under strong traffic stress was high, and the SPAD value was high in the control (Figures 6, 10). Therefore, it is not reasonable to evaluate the green color of zoysiagrass only with the reflectance at 550 nm.

Hyperspectral reflectance changes caused by weak and strong compaction treatment initially differed in the visible light band but decreased as the compaction treatment progressed. The difference occurred in the near-infrared band depending on the intensity of soil compaction (Figure 10). When recovered for 4 weeks after the compaction treatment was stopped, the hyperspectral reflectance difference was insignificant in the visible light band (Figure 11). Nevertheless, the vegetation indices of PSSRa, PSSRb, and PSSRc showed a clear difference between the treatments. After recovery, most vegetation indices were somewhat higher or similar in the strong compaction treatment, except

https://doi.org/10.17221/173/2022-HORTSCI

for PSSRc (Table 2). These indices are thought to be able to be used to evaluate not only the damage caused by compaction but also the degree of recovery in zoysiagrass.

CONCLUSION

The results of this study indicate that the impact of traffic stress on zoysiagrass varies depending on the intensity and that weak traffic stress inhibits the growth of the shoots but promotes the growth of the underground part. Moreover, since weak traffic stress quickly recovers, a weak level of traffic stress can show its beneficial effect on promoting the growth of the underground part. Contrary to the evaluation of the apparent injury, a hyperspectral reflectance is a helpful tool because it can effectively determine the injury caused by traffic stress and calculate the PSSR, PSSRc, and RE-NDVI, which are efficient vegetation indices for injury evaluation.

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Received: December 15, 2022
Accepted: September 19, 2023