ABSTRACT

MATTHIEU III, DONALD EDWIN. Assessment of Turfgrass Root Growth in Compacted Soils. (Under the direction of D. Keith Cassel).

Soil compaction often prevents turfgrass roots from growing to deeper sources of water and nutrients. Root response of ten turfgrass species to a compacted subsurface layer was examined in a greenhouse experiment. Research objectives were to determine if a compacted subsurface soil layer reduces root penetration and shoot growth for each of ten turfgrass species and to determine the bulk density of a subsurface layer at which root growth is impaired for each of ten turfgrass species. Ten turfgrass species were grown for four to eight weeks in 13-cm diameter x 25-cm long columns filled with loamy sand soil material. Each column was divided into three sections. The top and bottom sections were packed to a bulk density of 1.6 Mg cm^{-3}, and the middle (treatment) layer was packed to 1.6, 1.7, 1.8, 1.9, or 2.0 Mg m^{-3}. Soil compaction reduced root growth for each of the ten turfgrass species; the effect of compaction on root and shoot growth varied among species. Root penetrability varied among species and bulk densities as determined by the amount of root dry mass recovered in the bottom of each column. Root biomass in the bottom layer decreased as bulk density of the middle layer increased, with the most significant reduction occurring between 1.7 and 1.8 Mg m^{-3} for Kentucky bluegrass, bentgrass, perennial ryegrass, tall fescue, St. Augustinegrass, and paspalum. A significant growth reduction occurred between 1.8 and 1.9 Mg m^{-3} for zoysiagrass, centipedegrass, bermduagrass, and buffalograss. Better turf growth can be expected if management practices are used which eliminate compacted subsurface layers or reduce soil compaction prior to turf establishment.

ASSESSMENT OF TURFGRASS ROOT GROWTH IN COMPACTED SOILS

By

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PERSONAL BIOGRAPHY

Donald Edwin Matthieu, III was born July 22, 1980 in Decatur, Illinois. He spent most of his formative years in Decatur, and attended high school for one year at Dwight D. Eisenhower High School. At age 15, he moved with his family to Summerfield, North Carolina. He attended the Dalton L. McMichael High School in Mayodan, North Carolina for the remaining three years of high school and graduated in 1998. In the fall of 1998, he enrolled in North Carolina State University. He received his Bachelor of Science Degree in Natural Resources, with a Soil and Water Systems emphasis, from the Department of Soil Science in 2003.

In the fall of 2003, he began graduate studies under the direction of Dr. Keith Cassel, Dr. Dan Bowman, Dr. Bir Thapa, and Dr. Tom Rufty studying the effect of soil compaction on root growth of turfgrass species. He completed the degree in March 2006, and graduated in May 2006 with an M.S. in Soil Science.

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INTRODUCTION

Compacted soils are prevalent on turfgrass areas such as athletic fields, home lawns, and golf courses. Compaction occurs during land clearing and construction activities that use heavy equipment, and as a result of topsoil removal and topsoil redistribution when turf areas are prepared for seeding or sodding. Soil physical properties altered during soil compaction include aeration porosity, bulk density, soil strength, and pore size distribution (O'Neil and Carrow, 1982). In addition to, or perhaps as a result of these changes, a restriction in root growth can occur because of poor aeration and increased mechanical impedance (Materechera et al., 1992). Much information about the effect of compaction on root growth for agronomic crops is available (Bengough and Young, 1993; Schuurman, 1965; Barley et al., 1965; Iijima and Kono, 1991; Hemsath and Mazurak, 1974; Oussible et al., 1992). Some information is available on the effect of whole soil profile compaction on turfgrass root growth (Sills and Carrow, 1982, 1983; Carrow, 1980; O'Neil and Carrow, 1982), but little information on the impact of a compacted soil layer on root growth of various turfgrass species is available.

After land clearing and construction is finished, a layer of compacted soil below the soil surface is often present on many developed sites. Consequently, roots may be restricted to the upper soil layer, reducing the volume of soil available for root growth, as well as reducing water and nutrient availability (Ishaq et al., 2001). As long as water and nutrients are adequate, compaction effects may not be noticeable (Marschner, 1986). However, severe growth reduction can occur if the uncompacted surface soil layer dries out, since shallow roots cannot access water stored deeper in the soil profile (Materechera et al., 1992). For turfgrass growing on compacted soils, reductions in root growth, shoot growth, and carbohydrate reserves occur, and turf quality declines (O'Neil and Carrow, 1982).

Greenhouse studies using uniformly packed soil columns have been used to identify root-inhibiting compaction levels. Such studies for turfgrass are reported by O'Neil and Carrow (1983) and Sills and Carrow (1983) and for agronomic crops or trees by Iijima and Kono (1991), Hemsath and Mazurak (1974), Yapa et al. (1988), Mosena and Dillenburg (2004), Pabin et al. (1998), Misra and Gibbons (1996), and Theodorou et al. (1991). Profiles with a distinct compacted subsurface layer have been used to study agronomic crops (Rosolem et al., 2002; Bengough and Young, 1993; Schuurman, 1965; Barley et al., 1965). Cook et al. (1996) used columns containing compacted soil to evaluate the root growth of three species, including perennial ryegrass (*Lolium perenne L.*). They tested soil compacted to penetration resistance levels of 0.25, 1.40, and 2.30 MPa, rather than soils compacted to a range of bulk densities. Root and shoot dry mass decreased as mechanical impedance increased. Total root length of perennial ryegrass was lowest at the highest mechanical impedance treatment.

Rosolem et al. (2002) evaluated root penetration of broadleaf species and grass species through a sandy loam soil layer compacted to bulk densities ranging from 1.31 to 1.70 Mg m^{-3}. The penetration resistance, rather than the bulk density, at which root growth was reduced to half of the maximum was determined for several species. Grasses were more sensitive to compaction than broad-leaved plants. Similarly, Bengough and Young (1993) measured root elongation rate, rather than the biomass, of pea (*Pisum sativum* [cv. Helka]) seedling roots in the middle and bottom sections of a three-layered soil column. The middle section contained sandy loam material compacted to bulk densities ranging from 0.85 to 1.4 Mg m^{-3}.

Carrow (1980) compacted field plots of several turfgrass species growing in a silt loam, resulting in soil bulk density treatments of 1.27, 1.32, and 1.34 Mg m^{-3}. For Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass, and tall fescue (*Festuca arundinacea* Schreb.), the root-limiting bulk density was 1.34 Mg m^{-3}. A similar study by O'Neil and Carrow (1982) found the root limiting bulk density for Kentucky bluegrass on a silt loam soil to be greater than 1.38 Mg m^{-3}.

The objectives of this study were to 1) determine if a compacted loamy sand compacted subsurface soil layer reduces root penetration and shoot growth for each of ten turfgrass species; and 2) determine the bulk density of the subsurface layer at which root growth is impaired for each of ten turfgrass species.

MATERIALS AND METHODS

A greenhouse study was conducted to assess the effect of bulk density of a subsurface layer on shoot and root growth of ten turfgrass species. Soil columns measuring 25 cm high by 12.7-cm inside diameter were constructed from PVC pipe. Each column consisted of three separate sections measuring 8 (top section), 6 (middle section), and 11 cm (bottom section) high, which were assembled using duct tape. A 16-cm-square, 6-mm-thick plate was affixed to the base of the assembled column. A ceramic extraction cup (2.2 cm diameter, 5.7 cm length) was positioned at the base of the column to provide drainage. The cup was connected with tubing to a 3L collection bottle, which was in turn connected to a vacuum manifold maintaining a suction of 20 kPa.

The columns were designed to provide a highly defined layer of compacted soil in the middle section, sandwiched between the top and bottom layers of uncompacted soil. Topsoil from a Wagram loamy sand (loamy siliceous thermic arenic paleudult; 86% sand, 10% silt, 4% clay; pH 6.2) was chosen for the study. Under natural conditions this soil is easily compacted.

Columns were filled with soil by layer. The bottom layer was packed first, using a pre-weighed amount of oven dried soil and gently tapping the column until the soil settled flush with the top of the section, to a bulk density (Db) of 1.60 Mg m^{-3}. Before packing the middle layer, the 6-cm high section was sealed at the bottom with commercial plastic wrap, and then it was filled incrementally with pre-weighed soil. Each increment of soil was moistened slightly and compacted using a metal plate and drop hammer. The number of hammer drops per soil increment varied between 10 and 25 depending on the target bulk density. After compaction, the plastic was removed and the middle layer was carefully placed on top of, and taped to, the previously filled bottom layer.

The described method could not be used to pack the middle soil layer for the 1.6 and 1.7 Mg m^{-3} treatments because the soil was too loose and fell out of the middle column section during transfer. For these two bulk density treatments, the middle sections were taped to a filled bottom layer and then packed in place. Pre-weighed soil was added to the middle section in increments and compacted with a drop hammer, but water was not added. The soil columns were completed by taping the empty top section to the middle layer and filling it with soil to a Db of 1.55 Mg m^{-3}. Bulk density measurements made at termination of the study revealed that this procedure resulted in a slightly higher Db in the bottom layer and a slightly lower Db in the middle layer. For the 1.7 Mg m^{-3} treatment, the actual Db's for the middle and bottom layers were 1.65 and 1.62 Mg m^{-3}, respectively. For the 1.6 Mg m^{-3} treatment, the actual Db's for the middle and bottom layers were 1.59 and 1.61 Mg m^{-3}, respectively.

The turfgrasses used in this study included six warm season species (St. Augustinegrass, *Stenotaphrum secundatum*; centipedegrass, *Eremochloa ophiuroides*; bermudagrass, *Cynodon dactylon*; buffalograss, *Buchloe dactyloides*; zoysiagrass, *Zoysia japonica*; seashore paspalum, *Paspalum vaginatum*) and four cool season species (tall fescue, *Festuca arundinacea*; Kentucky bluegrass, *Poa pratensis*; perennial ryegrass, *Lolium perenne*; creeping bentgrass, *Agrostis palustris*). Perennial ryegrass was seeded at a rate of 300 kg ha^{-1}, while creeping bentgrass was planted as sod harvested from a sand-based putting green. The remaining eight species were planted as rooted sprigs at a rate of either 7 or 9 sprigs per column. Prior to planting, all sprigs were clipped to a height of approximately 7 cm and this height was kept equal for all sprigs for each species, except creeping bentgrass and perennial ryegrass. The planted columns were transferred to one of two greenhouses at the North Carolina State University Phytotron. The cool season species were grown at 26/22˚C day/night, while the warm season species were grown at 30/26˚C day/night.

Columns were watered daily with an average of 2 cm of water to prevent wilting. A liquid fertilizer solution was applied weekly to supply N, P, and K at rates of 12.3, 5.5, and 10.5 kg ha^{-1}, respectively.

The turfgrasses were grown for four to eight weeks, depending on establishment and growth rate of each species. At the end of this period, shoots were harvested by cutting level with the soil surface. Each column was then cut with a sharp knife into three sections as defined by the three PVC sections. Roots in each section were separated from the soil using a 2 mm sieve, followed by washing on a 1 mm sieve. The roots for all species and the shoots for all species except creeping bentgrass were oven dried 3 days at 65˚C, and weighed. When harvesting the creeping bentgrass, it was impossible to cut the shoots so that all soil material was excluded from the samples. The creeping bentgrass shoot samples were oven dried for 3 days at 65°C, and ground to a powder. A homogeneous 4 g subsample of the ground material was combusted at 525°C. The mass percentage of soil in each subsample was used to calculate the mass of soil in each whole aboveground biomass sample and this soil mass was subtracted from the mass of the shoot biomass sample to find the actual biomass of the creeping bentgrass shoots.

Due to resource and greenhouse space limitations, each species was investigated separately (i.e. at a different time), using a completely randomized design with six replications. Root and shoot mass data for each species were analyzed separately using

ANOVA in the General Linear Model procedure in SAS (SAS Institute, 2002-2003). When significant differences were found, means were separated using Duncan's multiple range test.

RESULTS AND DISCUSSION

This greenhouse study used packed soil columns to examine the ability of turfgrass roots to penetrate compacted subsurface soil layers. The constructed three-section column was designed to provide a well-defined subsurface zone of compacted soil. Successful root penetration of the compacted layer was evidenced as root growth into the compacted layer and into the subtending layer containing non-compacted soil. A broad range of compaction treatments was used to define the rooting response of ten turfgrass species.

Soil compaction can limit root growth directly by physically restricting root penetration, which redistributes root growth and confines roots to the soil above the compacted layer. Soil compaction can also limit turf growth indirectly by causing a stress condition that limits overall growth of roots or shoots. Water and nutrient stresses are those most likely to occur, due to root confinement within a shallow layer of soil, and we attempted to minimize these stresses with frequent irrigation and fertilization. We also estimated indirect turf growth reductions by measuring total shoot and root biomass.

The mechanical impedance of the center soil layer impacts root proliferation into it and into the bottom layer. The soil strength of each center layer, measured when the plants were harvested (Table 1), increased gradually as bulk density in the center layer increased. Unfortunately, water content of the soil was not measured at this time. Irrigation of the columns was stopped three days prior to harvesting the plants. The plants were noticeably wilted and soil in the top layer generally appeared drier than that of the center and bottom layers, and the bottom layer generally appeared to have the highest moisture content of the layers.

Cool Season Species

Shoot and root biomass varied considerably among species, due to differences in growth rates and duration of each experiment. To facilitate comparison, shoot and total root biomass data for each species will be presented as relative values, normalized to the mean total shoot and root biomasses, respectively, for the 1.6 Mg m^{-3} treatment. To normalize the shoot biomass data for a given species, the shoot biomasses for the six replicates of the 1.6 Mg m^{-3} bulk density treatment were first averaged. Then, each shoot biomass datum for the 1.7 Mg m^{-3} treatment replicates was divided by the average of the 1.6 Mg m^{-3} shoot biomasses. This procedure produced six numbers that were averaged to give a normalized value for the shoot biomass of the 1.7 Mg m^{-3} treatments for that species. The same procedure was repeated for the shoot biomasses of the 1.8, 1.9, and 2.0 Mg m^{-3} treatments. Total root biomass for each species was normalized in the same manner. Root distribution data for each soil layer will be presented as a fraction of the total root biomass for the bulk density of that particular center soil layer.

There were small but significant changes in shoot biomass with change in subsurface compaction for perennial ryegrass, tall fescue, and Kentucky bluegrass (Fig. 1). Shoot growth of perennial ryegrass and Kentucky bluegrass followed a noticeable pattern, decreasing significantly between 1.7 and 1.8 Mg m^{-3}, and it is possible that soil compaction caused this decrease in shoot growth. Cook et al. (1996) found that increases in mechanical impedance caused by soil compaction reduced shoot growth of grass species independently of the effect of water and nutrient deficiency for perennial ryegrass. Other greenhouse studies, such as those of O’Neil and Carrow (1983) and Sills and Carrow (1983), also found a reduction in perennial ryegrass shoot growth as bulk density increased. In these studies, however, the whole soil profile was compacted, instead of a distinct layer in the subsurface. A field study by O'Neil and Carrow (1982) conducted on a silt loam soil compacted to bulk densities of 1.28 Mg m^{-3} (control) and 1.38 Mg m^{-3} also showed that Kentucky bluegrass shoot growth generally decreased with increasing compaction. Unfortunately, a direct comparison cannot be made between these studies and the current study, but the results give general support to the idea that soil compaction reduces shoot growth.

The shoot biomasses of tall fescue exhibited high variability but statistically significant differences occurred among the bulk density treatments (Fig. 1). A slight overall decrease in shoot biomass occurred between the 1.6 and 2.0 Mg m^{-3} treatments, and this decrease could have been caused by direct effects of soil compaction. Tall fescue shoot growth seems to be less sensitive to soil compaction than the shoot growth of Kentucky bluegrass and perennial ryegrass. In contrast to the other cool season species, shoot biomass of creeping bentgrass was not affected by bulk density (Fig. 1).

Total root biomass was unaffected by soil compaction for each cool season species (Table 2). The total root biomass varied considerably among the species and ranged from 473.7 g for perennial ryegrass at 1.9 Mg m^{-3} to 10.4 g for Kentucky bluegrass at 1.8 Mg m^{-3}. Rosolem et al. (2002) also found that total root biomass did not change with increase in bulk density for Indian hemp (*Crotalaria juncea*), showy crotalaria (*Crotalaria spectabilis*), sunflower (*Helianthus annuus*), pearl millet (*Pennisetum americanum*), and guinea sorghum (*Sorghum bicolor* ssp. *bicolor* race *guinea*).

Having ascertained that no significant difference in total root biomass as a function of bulk density occurred, we proceeded to determine if differences in rooting distribution throughout the three soil layers occurred. Changes in root biomass in the middle and bottom soil layers can be ascribed to root impedance of the middle soil layer because no significant differences in the total root biomass occurred as a function of bulk density.

Root biomass was distributed among the three soil layers in a fairly consistent pattern for all four cool season species (Fig. 2). The majority of roots (0.51 to 0.96) were found consistently in the top soil layer, the fraction increasing with increase in bulk density of the middle layer. The fraction of roots in the middle soil layer remained fairly constant across compaction treatments at 0.03 to 0.22 of the total. Root biomass in the bottom layer mirrored that in the top layer, but the fraction was lower (0 to 0.31). Soil compaction resulted in a significant reduction in root growth into the bottom layer, with the greatest reduction occurring between 1.7 and 1.8 Mg m^{-3}. In fact, with the exception of perennial ryegrass (Fig. 2C), there was little or no biomass in the bottom layer at bulk density treatments $\geq$ 1.8 Mg m^{-3}. This becomes more apparent when root biomass for the bottom layer for each cool season species is expressed on a relative basis, normalized to the root biomass for the 1.6 Mg m^{-3} (control) treatment (Fig. 3). Note that perennial ryegrass is the only species with a significant fraction of root biomass present in the bottom soil layer at bulk densities > 1.8 Mg m^{-3}, suggesting that roots of perennial ryegrass are more vigorous and better able to penetrate compacted zones, and that 1.8 Mg m^{-3} is a critical bulk density that severely reduces root growth for creeping bentgrass, Kentucky bluegrass, and tall fescue (Fig. 3). The large root biomass of perennial ryegrass (Table 2) certainly suggests vigor, but it is also possible that the longer growing period gave the roots a better chance of penetrating the middle layer. Perennial ryegrass and creeping bentgrass both grew for eight weeks and the other species grew four weeks. No root growth of Kentucky bluegrass into the bottom layer occurred at bulk densities $\geq$ 1.8 Mg m^{-3}, suggesting that Kentucky bluegrass is highly sensitive to compaction. Tall fescue root growth was less sensitive to soil compaction than Kentucky bluegrass, as indicated by the normalized root biomass values at 1.8 Mg m^{-3} (Fig. 2B and 2D).

Both the bottom layer root growth and the shoot growth data support the idea that Kentucky bluegrass is more sensitive to soil compaction than perennial ryegrass. The root biomass in the bottom layer of the Kentucky bluegrass columns decreased at a lower bulk density than the shoot biomass of Kentucky bluegrass (Figs. 1 and 2B), but the root biomass in the bottom layer for perennial ryegrass decreased at the same bulk density as the shoot biomass of perennial ryegrass (Figs. 1 and 2C). Although the bulk density at which the shoot biomasses of perennial ryegrass and Kentucky bluegrass decreased is the same, the biomass of the Kentucky bluegrass shoots decreased more than that of perennial ryegrass. This result supports the idea that shoots of Kentucky bluegrass are more sensitive to compaction than shoots of perennial ryegrass.

Creeping bentgrass root growth is also sensitive to compaction, as indicated by the lack of biomass in the bottom layer for bulk densities $\geq$ 1.8 Mg m^{-3}, as well as the fact that the root masses in the middle layer are consistently low for all bulk densities (Fig. 2A). Although results from a field study by Carrow (1980) support the fact that Kentucky bluegrass is more sensitive to compaction than perennial ryegrass and tall fescue, and that the root growth of Kentucky bluegrass declines with increasing compaction, the results are not directly comparable because Carrow (1980) used a soil with surface compaction, not subsurface compaction. Few studies specifically support the idea that turfgrass root growth decreases below a compacted subsurface layer. Research by Bengough and Young (1993) measured root elongation rate, rather than biomass, of pea seedling roots, rather than turfgrass, in the middle and bottom layers of a three-layered column with bulk densities ranging from 0.85 to 1.4 Mg m^{-3} in the center layer. The elongation rate in the bottom layer decreased as bulk density increased. This reduction in elongation rate is comparable to the reduction in biomass in the bottom layer of the current study. Another column study (Rosolem et al., 2002) found that root length density increased in the upper column layer for some species as bulk density increased, although none of the species studied were turfgrass species. These results lend indirect general support to results of the current study.

Warm Season Species

Small, but significant reductions in shoot biomass occurred with increasing soil compaction for all species except St. Augustinegrass and zoysiagrass (Fig. 4). The bermudagrass shoot biomass decreased significantly between 1.8 and 1.9 Mg cm^{-3}, and the centipedegrass shoot biomass decreased significantly between 1.7 and 1.8 Mg m^{-3}. In contrast, shoot biomass for paspalum decreased only slightly between 1.6 and 2.0 Mg m^{-3}. These decreases likely were caused by soil compaction. We cannot explain the differences in shoot biomass of buffalograss with increasing bulk density.

The total root biomass for the entire column varied considerably among the warm season species (Table 2), with the following ranking: bermudagrass > paspalum > centipedegrass > St. Augustinegrass > zoysiagrass > buffalograss. Of the six species, total root biomass decreased as bulk density increased only for bermudagrass and centipedegrass (Fig. 5), hence, root biomass in any or all layers might have decreased as the bulk density increased. Thus, it is possible that a portion of the root biomass in the bottom layer can be attributed to a decrease in total root biomass. It is possible that the decrease in shoot growth could be due, in part, to the decrease in total root growth. For paspalum, buffalograss, St.

Augustinegrass, and zoysiagrass, no indirect effect of soil compaction on root growth was observed, and changes in root growth into the bottom layer can be attributed entirely to the compacted center layer. Root distribution data by soil layer for each warm season species is presented in Figure 6.

Root distribution among the top, middle, and bottom soil layers was similar for bermudagrass (Fig. 6A), buffalograss (Fig. 6B), paspalum (Fig. 6E), and zoysiagrass (Fig. 6F) in that root biomass in the bottom layer generally mirrored root biomass in the top layer. The largest fraction of roots (0.43 to 0.95) was located in the top layer, 0.05 to 0.40 in the middle layer, and 0 to 0.56 of the roots was found in the bottom layer. The root distribution among the three soil layers followed a different pattern for St. Augustinegrass (Fig. 6D) and centipedegrass (Fig. 6C), with 0.31 to 0.90 of the St. Augustinegrass roots in the top layer and 0.25 to 0.66 of the centipedegrass roots in the top layer.

Root biomass in the bottom layer decreased as bulk density increased, with the greatest reduction occurring between 1.8 and 1.9 Mg m^{-3} for bermudagrass (Fig. 6A), buffalograss (Fig. 6B), centipedegrass (Fig. 6C), and zoysiagrass (Fig. 6F). For paspalum (Fig. 6E), the greatest reduction in the bottom layer occurred between 1.7 and 1.8 Mg m^{-3}, and for St. Augustinegrass (Fig. 6D), a large reduction occurred between 1.6 and 1.8 Mg m^{-3}. For St. Augustinegrass and paspalum, little or no biomass occurred in the bottom layer at Db $\geq$ 1.8 Mg m^{-3}. Buffalograss and centipedegrass had little or no biomass in the bottom layer at bulk densities $\geq$ 1.9 Mg m^{-3}, and at 2.0 Mg m^{-3}, no biomass was present in the bottom layer for bermudagrass and zoysiagrass. This data suggests that St. Augustinegrass and paspalum have the least vigorous roots of the warm season species studied. Additionally, buffalograss and centipedegrass are better able to grow through compacted soils than St. Augustinegrass and paspalum, and can penetrate soil compacted up to 1.9 Mg m^{-3}.

Of the six warm season species studied, bermudagrass and zoysiagrass have highly vigorous root systems. The immediate decrease in the root biomass of St. Augustinegrass shows that its root system is sensitive to compaction. The sensitivity to compaction becomes more apparent when the data are examined on a normalized basis (Fig. 7). A sharp decrease in St. Augustinegrass root growth into the bottom layer occurred as bulk density increased from 1.6 to 1.8 Mg m^{-3}; at 1.8 Mg m^{-3} no roots were in the bottom layer. The lack of biomass in the bottom layer of the paspalum columns at Db 1.9 and 2.0 Mg m^{-3} indicates that this species is also sensitive to compaction. The normalized root biomass of paspalum is much less at 1.8 Mg m^{-3} than for bermudagrass, buffalograss, centipedegrass, and zoysiagrass.

Related studies on agronomic crops yielded critical bulk densities that were lower than those found in the current study. Root growth of oats started to decrease at 1.38 Mg m^{-3}, and failed to penetrate sandy soil at a bulk density of 1.52 Mg m^{-3} (Schuurman, 1965). A field study with wheat on a sandy clay loam by Oussible at al. (1992) found that a subsurface bulk density of 1.52 Mg m^{-3} reduced root length density, root elongation rate, and grain and straw yields compared to a non-compacted control layer of 1.33 Mg m^{-3}.

Although the root biomass found in the bottom layer is important for showing whether a compacted layer reduces root growth in the soil below the compacted layer, the root growth into and through the center layer can be considered to examine the overall effect of a compacted layer on root growth. If the roots can grow into the top of the compacted center layer, it is possible that with more time, the roots will eventually grow through the center layer and into the bottom layer. Consequently, the fraction of root biomass in the middle and bottom layers is important for determining whether root growth is reduced by subsurface soil compaction. Root systems for most of the cool and warm season species encountered some difficulty in growing through the higher bulk density center layers and into the bottom layer, but if the experiment had run longer, a higher biomass of roots might be present in the bottom layer for many of the species. Evidence supporting this idea can be found in Ishaq et al. (2001). A two-year field study found that a bulk density of 1.93 Mg m^{-3} significantly reduced the root length density of wheat within a compacted layer. In the second year of the study, another wheat crop was planted and no reduction in the root length density occurred in the same compacted layer. This can be attributed to the creation of fissures by roots growing in the soil, along with old root channels from the first crop. These fissures could have created spaces for the roots of the second crop to grow in. If the current experiment had been conducted for a longer period of time, some roots would die and create root channels, which would allow more roots to penetrate the bulk density treatment layer. In addition, as roots grow and take up water, small, localized fluctuations in soil water content would cause variations in soil strength. Soil strength would be lower in the wetter regions and would allow easier penetration of roots.

In addition to changes in root distribution within a soil profile, changes in root morphology can occur when roots grow into soil with a higher bulk density. Roots tend to thicken as bulk density of the soil in which they are growing increases. Materechera et al. (1992) found that roots of some plant species thicken in response to soil mechanical impedance. Oussible et al. (1992) found changes in the anatomy and/or morphology of wheat roots growing in a compacted zone. As bulk density increased, the root thickness increased and length:mass ratio of the roots decreased. Root length:mass ratios were also higher in the loose upper horizon in the compacted treatments, meaning that roots were longer and finer in the top section as the bulk density increased.

CONCLUSION

This greenhouse study showed that the effect of a compacted subsurface soil layer on root growth varied among four cool and six warm season species of grasses studied, but that a reduction in root growth below the compacted layer occurred for all species. A reduction in total root growth occurred for two species, and small, but significant reductions in shoot biomass occurred for most of the cool and warm season species.

For the Wagram loamy sand soil studied, it appears that the critical bulk density range that significantly reduces root growth is 1.7 to 1.8 Mg m^{-3} for bentgrass, Kentucky bluegrass, tall fescue, and perennial ryegrass, even though roots of the latter can penetrate soil compacted to 2.0 Mg m^{-3} (Fig. 8). The critical bulk density range for St. Augustinegrass and paspalum is 1.7 to 1.8 Mg m^{-3}, and the critical bulk density for zoysiagrass, buffalograss, bermudagrass, and centipedegrass is 1.8 to 1.9 Mg m^{-3}.

Due to greenhouse space and equipment limitations, the species were grown at separate times, creating difficulty making statistical comparisons among species. However, ranking the species according to their ability to tolerate a compacted loamy sand layer in the soil profile is (see Fig. 8):

perennial ryegrass > bermudagrass > zoysiagrass = buffalograss = centipedegrass > tall fescue = paspalum = bentgrass = Kentucky bluegrass = St. Augustinegrass

The root and shoot data collected in this study provide baseline data for important grass species encountering compacted subsurface soil layers, and that this compacted soil has a negative impact on root growth. Future studies should determine the effect of a compacted soil layer on root growth in other turfgrass species, as well as cover crops, and explore the impact of bulk density on turfgrass root morphological changes when the roots encounter, and grow through, a compacted soil layer. Under field conditions, water and nutrient limitations may occur, and these will generally reduce plant growth. In this study, water and nutrients were applied in high enough quantities so that growth limitations did not exist. Studies should be conducted that examine the effect of reduced water and nutrient availability, in combination with a compacted soil layer, on root growth of turfgrass and cover crop species.

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Table 1. Geometric mean value of mechanical impedance at harvest averaged across all species versus bulk density of middle layers. Soil strength was measured after a three day period with no irrigation.

Bulk Density ($Mg\ m^{-3}$)	Geometric Mean of Mechanical Impedance ($kg\ cm^{-2}$)
1.6	8.38
1.7	9.97
1.8	11.77
1.9	13.64
2.0	15.02

Table 2. Total root biomass by species as affected by bulk density of the middle layer.

	Species									
	Cool Season				Warm Season					
Bulk Density (Mg m^{-3})	Creeping Bent-grass	Kentucky Blue-grass	Perennial Ryegrass	Tall Fescue	Bermuda-grass	Buffalo-grass	Centipede-grass	St. Augustine-grass	Paspalum	Zoysia-grass
1.60	170.2	11.4	311.5	22.8	21.3	11.8	21.8	16.6	18.6	13.5
1.70	194.8	11.8	274.0	17.7	20.1	12.4	19.2	17.1	25.1	12.1
1.80	213.4	10.4	429.2	21.3	19.7	12.6	15.0	14.7	15.1	16.3
1.90	102.8	15.1	473.7	20.7	16.0	9.9	14.4	15.7	13.6	15.4
2.00	142.5	16.6	364.8	16.9	12.6	9.9	12.4	12.1	13.3	11.3

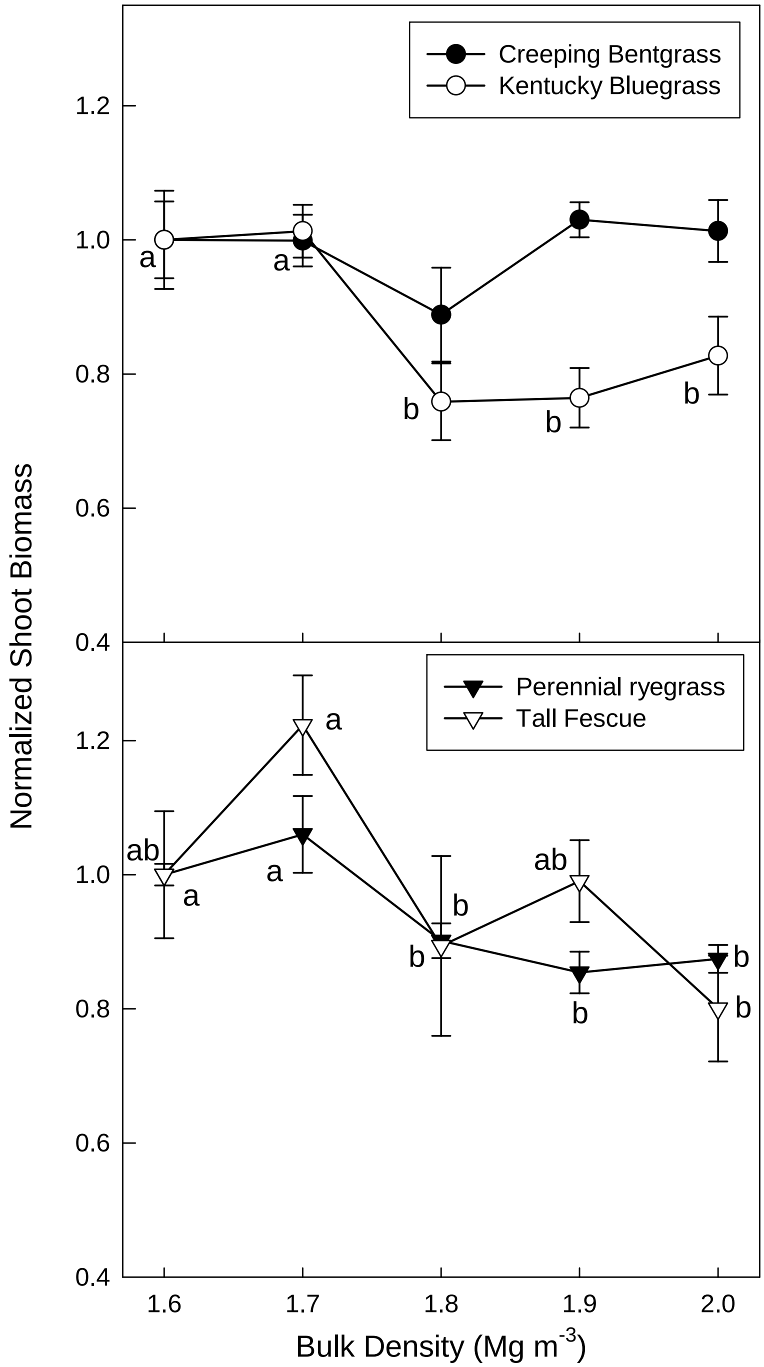

Figure 1. Normalized shoot biomass for cool season turfgrass species. Data for species is normalized to the biomass of shoots produced in the 1.6 Mg m^{-3} treatment. The vertical line through each datum is the standard error of the mean. Means of all species except creeping bentgrass were different at the p = 0.05 level.

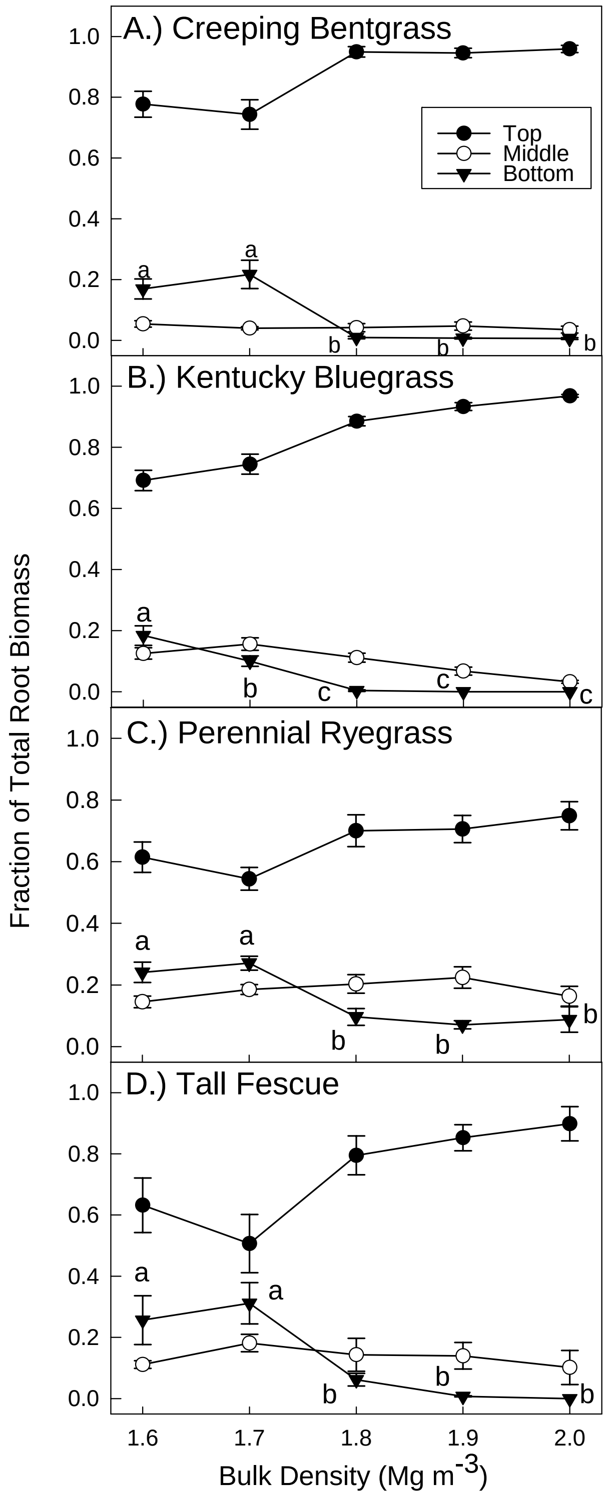

Figure 2. Fraction of total root mass in the top, middle, and bottom layers for four cool season grasses. Means are significantly different at the p = 0.05 level. The vertical line through each datum is the standard error of the mean.

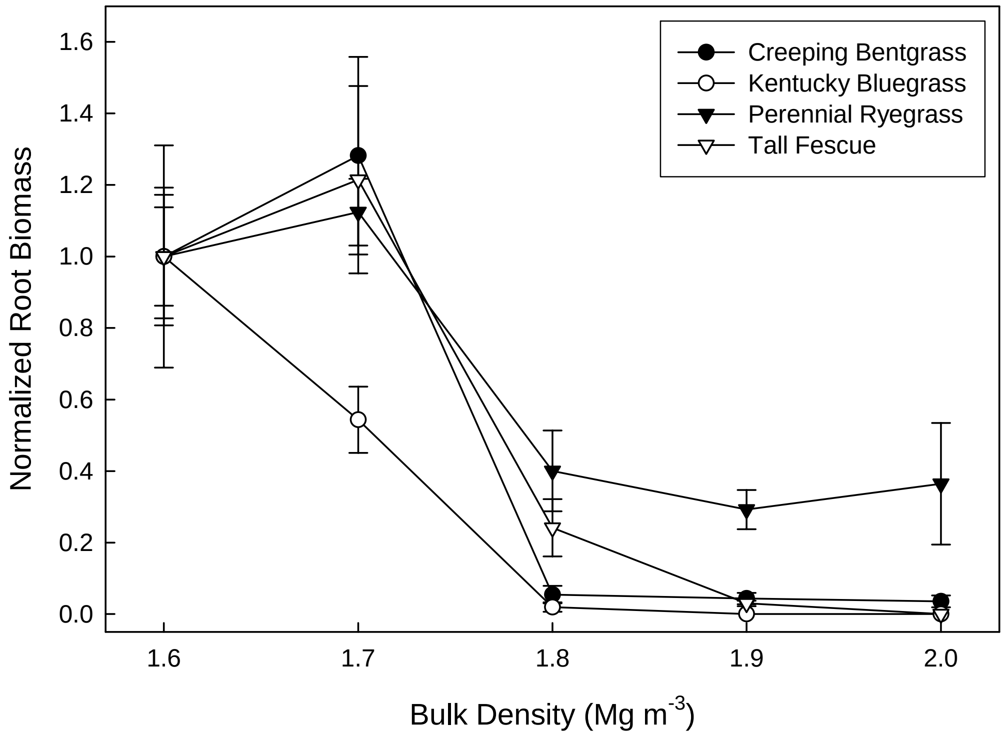

Figure 3. Normalized fraction of root biomass in bottom layer for four cool season species as a function of bulk density of the middle soil layer. Each species was normalized to the bottom section root mass of the 1.60 Mg m^{-3} bulk density treatment for that species. The vertical line through each datum is the standard error of the mean.

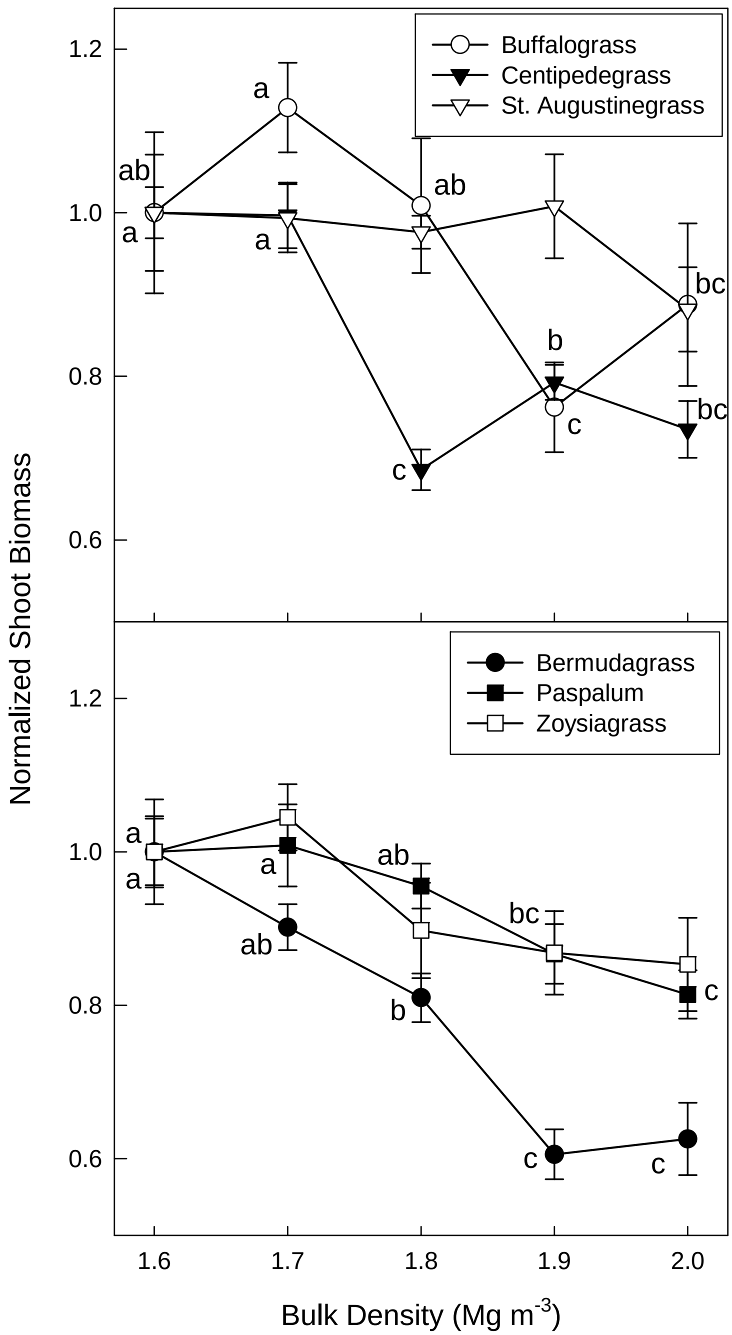

Figure 4. Normalized shoot biomass for six warm season turfgrass species. Data for each species is normalized to the mass of shoots produced in the 1.6 Mg m^{-3} treatment for that species. The vertical line through each datum is the standard error of the mean. Means for St. Augustinegrass and zoysiagrass were not different at the p = 0.05 level.

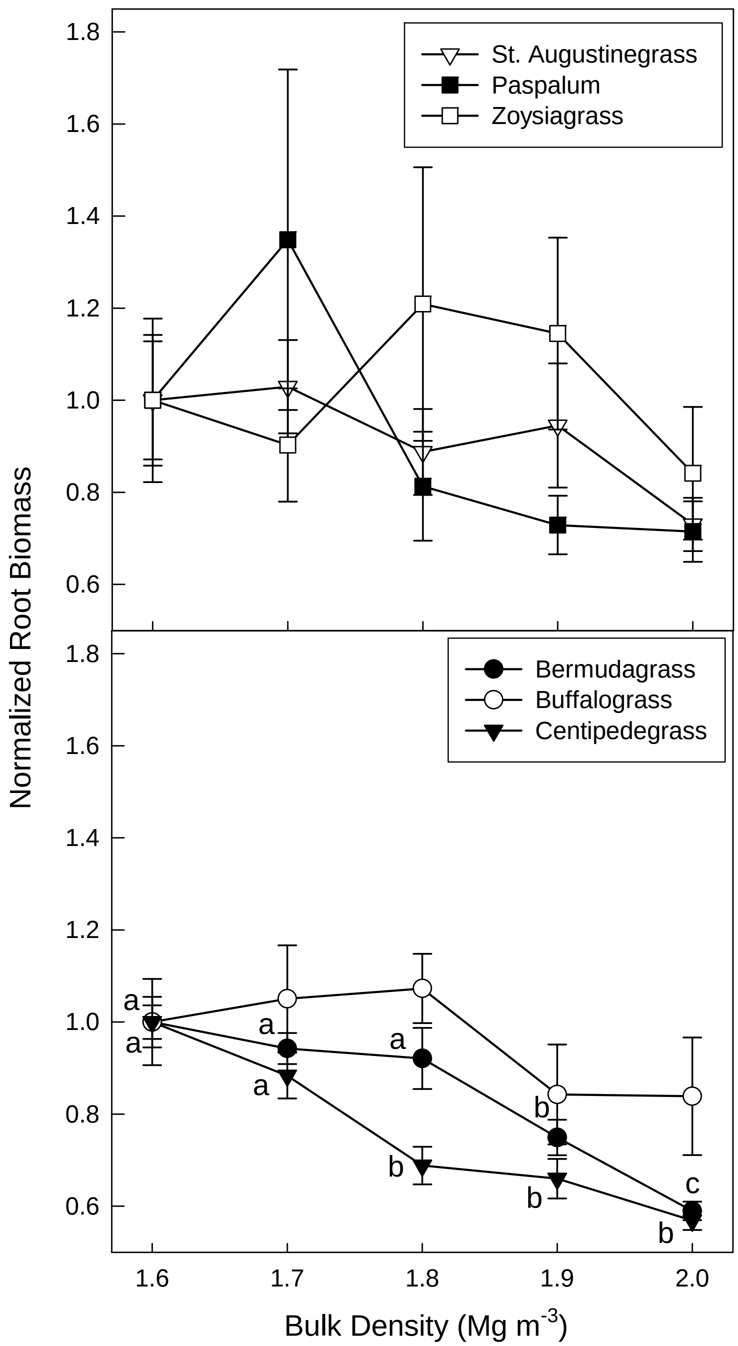

Figure 5. Normalized total root biomass for the warm season species. Each species is normalized to the mass of roots produced in the 1.6 Mg m^{-3} treatment for that species. The vertical line through each datum is the standard error. Means for buffalograss, St. Augustinegrass, paspalum, and zoysiagrass were not different at the $p = 0.05$ level.

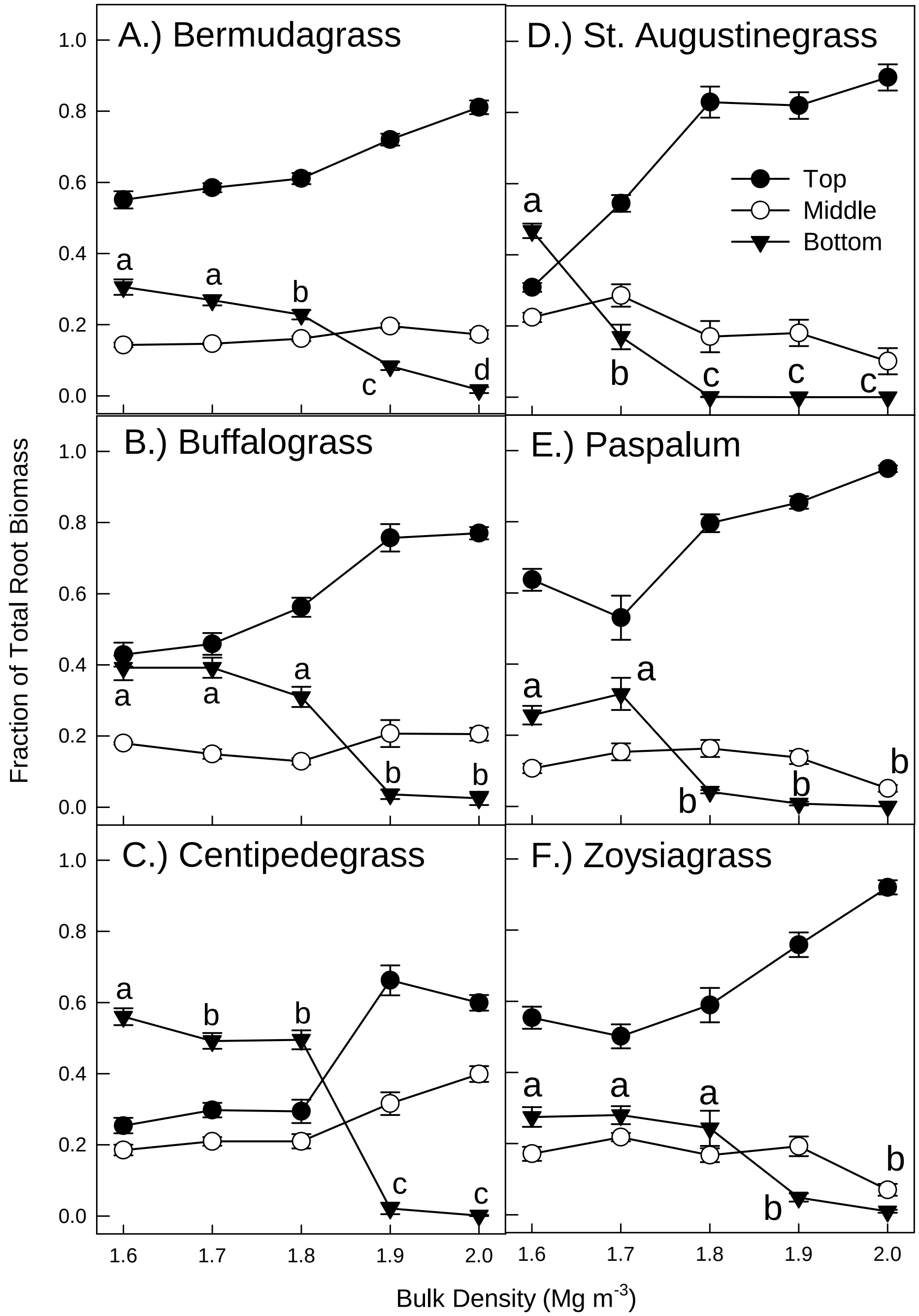

Figure 6. Fraction of total root biomass in top, middle, and bottom layers for six warm season turfgrass species. Means are significantly different at the p = 0.05 level. The vertical line through each datum is the standard error of the mean.

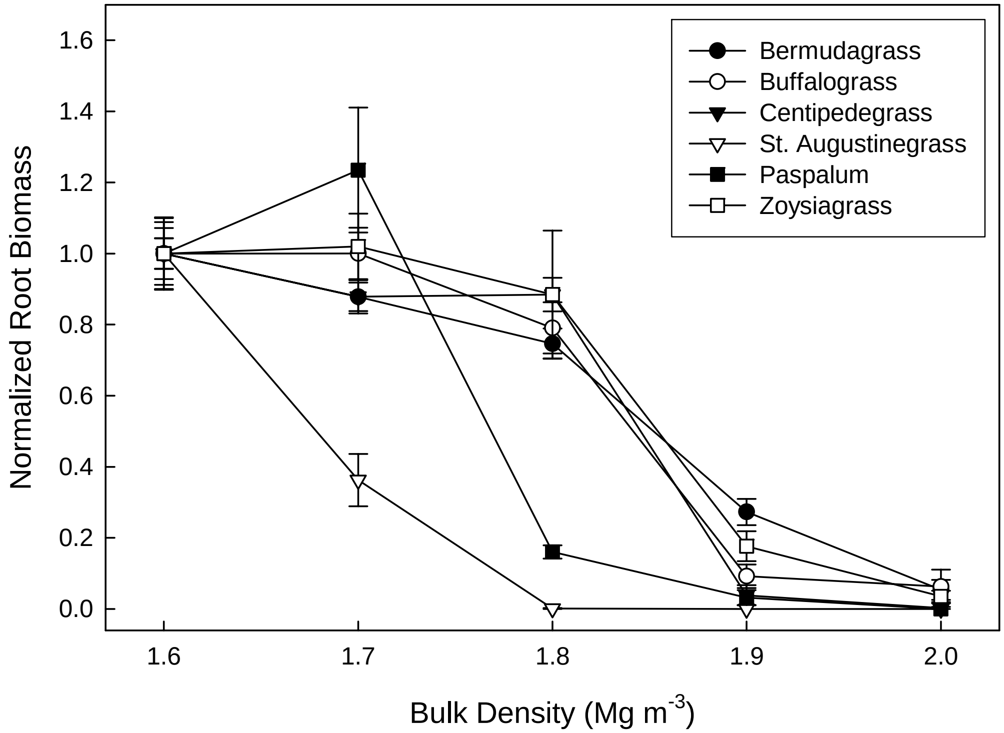

Figure 7. Normalized fraction of root biomass in bottom layer for six warm season species as a function of bulk density of the middle soil layer.

Each species is normalized to the 1.60 Mg m^{-3} bulk density treatment for that species. The vertical line through each datum represents the standard error of the mean.

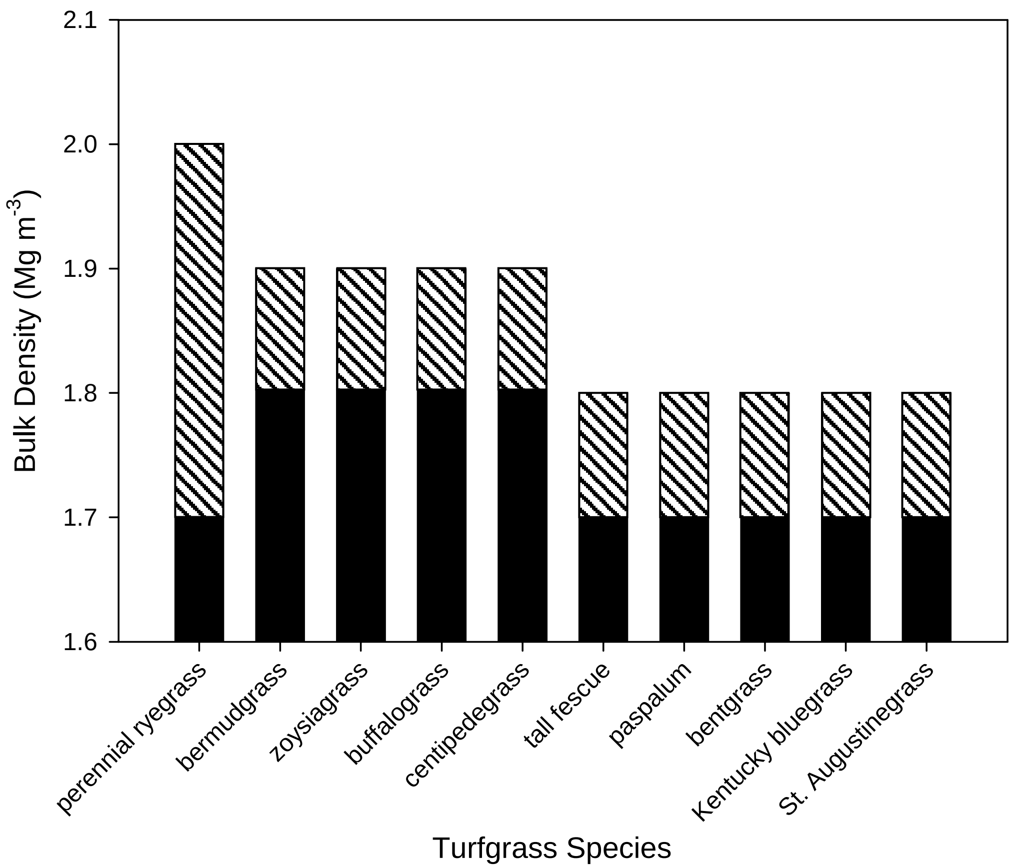

Figure 8. Bulk density that caused a significant biomass reduction in the bottom soil layer. The cross hatched region shows the bulk density range at which a significant reduction in root biomass in the bottom layer occured. At the maximum bulk density for each bar, a significant ($p = 0.05$) decrease in root growth into the bottom layer occurred. Although perennial ryegrass root growth into the bottom soil layer decreased substantially at 1.80 Mg m^{-3}, roots penetrated the 2.0 Mg m^{-3} treatment.

Appendix

Appendix Table 1. Root and shoot biomass data for ten turfgrass species.

Species	Repetition	Bulk Density ($Mg\ m^{-3}$)	Top Layer Biomass (g)	Middle Layer Biomass (g)	Bottom Layer Biomass (g)	Total Root Biomass (g)	Shoot Biomass (g)
Bentgrass	1	1.6	13.755	1.922	6.415	22.092	33.551
Bentgrass	2	1.6	27.206	1.286	2.949	31.441	10.529
Bentgrass	3	1.6	24.758	1.005	5.007	30.77	21.051
Bentgrass	4	1.6	27.682	1.288	4.475	33.445	17.162
Bentgrass	5	1.6	16.927	2.24	6.006	25.173	12.678
Bentgrass	6	1.6	23.744	0.972	2.604	27.32	8.717
Bentgrass	1	1.7	38.69	1.69	7.451	47.831	8.133
Bentgrass	2	1.7	23.777	0.956	7.641	32.374	7.491
Bentgrass	3	1.7	40.68	2.909	7.674	51.263	7.502
Bentgrass	4	1.7	17.932	0.73	6.281	24.943	8.528
Bentgrass	5	1.7	8.672	0.893	6.823	16.388	10.007
Bentgrass	6	1.7	19.246	0.746	2.006	21.998	10.131
Bentgrass	1	1.8	47.43	1.868	0.156	49.454	5.694
Bentgrass	2	1.8	51.11	2.943	0.469	54.522	6.233
Bentgrass	3	1.8	26.79	0.472	0.166	27.428	7.811
Bentgrass	4	1.8	41.02	0.544	0.191	41.755	9.499
Bentgrass	5	1.8	24.593	0.665	0.08	25.338	8.398
Bentgrass	6	1.8	12.967	1.506	0.441	14.914	13.728
Bentgrass	1	1.9	27.539	0.39	0.171	28.1	8.89
Bentgrass	2	1.9	11.711	0.544	0.118	12.373	16.582
Bentgrass	3	1.9	18.235	0.476	0.043	18.754	9.849
Bentgrass	4	1.9	17.68	1.717	0.373	19.77	16.443
Bentgrass	5	1.9	17.111	0.404	0	17.515	9.733
Bentgrass	6	1.9	5.671	0.563	0.045	6.279	26.13
Bentgrass	1	2	19.607	0.301	0.099	20.007	9.59
Bentgrass	2	2	18.27	0.064	0	18.334	15.95
Bentgrass	3	2	35.107	0.875	0.249	36.231	7.592
Bentgrass	4	2	5.251	0.476	0	5.727	31.09
Bentgrass	5	2	50.81	2.235	1.004	54.049	8.618
Bentgrass	6	2	7.713	0.361	0.044	8.118	24.238
Bermudagrass	1	1.6	1.309	0.455	1.209	2.973	10.384
Bermudagrass	2	1.6	2.136	0.461	1.165	3.762	9.348
Bermudagrass	3	1.6	2.081	0.602	1.215	3.898	9.384
Bermudagrass	4	1.6	2.023	0.564	0.949	3.536	9.665
Bermudagrass	5	1.6	2.22	0.455	0.953	3.628	8.257
Bermudagrass	6	1.6	2.051	0.508	0.974	3.533	7.726
Bermudagrass	1	1.7	2.063	0.517	0.931	3.511	7.333
Bermudagrass	2	1.7	1.942	0.463	1.011	3.416	8.569
Bermudagrass	3	1.7	1.898	0.435	0.783	3.116	8.262
Bermudagrass	4	1.7	2.25	0.567	0.913	3.73	8.083
Bermudagrass	5	1.7	1.539	0.427	0.94	2.906	9.298
Bermudagrass	6	1.7	2.098	0.539	0.788	3.425	7.837
Bermudagrass	1	1.8	1.887	0.559	0.901	3.347	8.02
Bermudagrass	2	1.8	1.884	0.506	0.776	3.166	7.051
Bermudagrass	3	1.8	1.63	0.43	0.503	2.563	7.474

Bermudagrass	4	1.8	2.392	0.755	1.022	4.169	8.405
Bermudagrass	5	1.8	2.363	0.576	0.67	3.609	6.667
Bermudagrass	6	1.8	1.795	0.361	0.638	2.794	6.727
Bermudagrass	1	1.9	1.742	0.584	0.347	2.673	6.476
Bermudagrass	2	1.9	1.701	0.459	0.175	2.335	4.708
Bermudagrass	3	1.9	2.279	0.585	0.263	3.127	6.02
Bermudagrass	4	1.9	1.913	0.455	0.11	2.478	4.688
Bermudagrass	5	1.9	2.22	0.523	0.267	3.01	5.87
Bermudagrass	6	1.9	1.66	0.515	0.186	2.361	5.399
Bermudagrass	1	2	1.725	0.369	0	2.094	4.732
Bermudagrass	2	2	1.559	0.457	0.107	2.123	7.661
Bermudagrass	3	2	1.901	0.284	0.035	2.22	6.019
Bermudagrass	4	2	1.534	0.312	0	1.846	5.064
Bermudagrass	5	2	1.813	0.448	0.076	2.337	5.16
Bermudagrass	6	2	1.657	0.303	0	1.96	5.629
Buffalograss	1	1.6	0.875	0.434	0.939	2.248	4.269
Buffalograss	2	1.6	0.769	0.304	0.665	1.738	3.861
Buffalograss	3	1.6	0.799	0.259	0.335	1.393	2.622
Buffalograss	4	1.6	0.944	0.476	1.242	2.662	3.953
Buffalograss	5	1.6	0.61	0.293	0.804	1.707	3.317
Buffalograss	6	1.6	0.916	0.35	0.749	2.015	3.105
Buffalograss	1	1.7	0.8	0.184	0.384	1.368	3.471
Buffalograss	2	1.7	1.198	0.579	1.089	2.866	4.843
Buffalograss	3	1.7	0.766	0.344	0.98	2.09	3.676
Buffalograss	4	1.7	0.729	0.238	0.521	1.488	3.869
Buffalograss	5	1.7	1.051	0.248	0.974	2.273	3.926
Buffalograss	6	1.7	0.981	0.286	1.008	2.275	4.056
Buffalograss	1	1.8	1.213	0.279	0.599	2.091	4.085
Buffalograss	2	1.8	1.106	0.274	1.065	2.445	3.33
Buffalograss	3	1.8	1.353	0.341	0.726	2.42	4.61
Buffalograss	4	1.8	1.095	0.231	0.662	1.988	2.918
Buffalograss	5	1.8	1.45	0.23	0.532	2.212	3.634
Buffalograss	6	1.8	0.84	0.24	0.385	1.465	2.734
Buffalograss	1	1.9	1.43	0.605	0.11	2.145	3.216
Buffalograss	2	1.9	1.712	0.57	0.01	2.292	2.638
Buffalograss	3	1.9	1.168	0.523	0.136	1.827	2.485
Buffalograss	4	1.9	1.112	0.048	0.081	1.241	2.33
Buffalograss	5	1.9	0.786	0.197	0	0.983	2.138
Buffalograss	6	1.9	1.131	0.264	0.03	1.425	3.296
Buffalograss	1	2	1.543	0.467	0	2.01	3.706
Buffalograss	2	2	2.263	0.415	0.021	2.699	4.47
Buffalograss	3	2	0.82	0.302	0	1.122	2.212
Buffalograss	4	2	0.954	0.241	0	1.195	2.646
Buffalograss	5	2	0.908	0.197	0.145	1.25	2.462
Buffalograss	6	2	1.21	0.344	0.039	1.593	3.258
Centipedegrass	1	1.6	0.93	0.71	2.37	4.01	6.14
Centipedegrass	2	1.6	0.84	0.81	2.31	3.96	5.34
Centipedegrass	3	1.6	0.93	0.78	1.58	3.29	6.18
Centipedegrass	4	1.6	0.86	0.56	1.48	2.9	5.08
Centipedegrass	5	1.6	1.32	0.52	2.3	4.14	5.81

Centipedegrass	6	1.6	0.63	0.61	2.22	3.46	5.83
Centipedegrass	1	1.7	1.04	0.84	1.54	3.42	5.96
Centipedegrass	2	1.7	0.85	0.63	1.14	2.62	5.23
Centipedegrass	3	1.7	0.98	0.64	1.56	3.18	5.43
Centipedegrass	4	1.7	0.69	0.61	1.83	3.13	6.73
Centipedegrass	5	1.7	1.08	0.49	1.39	2.96	5.62
Centipedegrass	6	1.7	1.04	0.83	2.05	3.92	5.3
Centipedegrass	1	1.8	0.71	0.61	1.15	2.47	3.53
Centipedegrass	2	1.8	0.53	0.63	1.51	2.67	4.26
Centipedegrass	3	1.8	0.79	0.33	0.71	1.83	3.86
Centipedegrass	4	1.8	0.57	0.64	1.22	2.43	4.35
Centipedegrass	5	1.8	0.88	0.37	1.57	2.82	4.03
Centipedegrass	6	1.8	0.83	0.56	1.37	2.76	3.55
Centipedegrass	1	1.9	1.85	1.06	0.03	2.94	4.58
Centipedegrass	2	1.9	1.78	0.35	0	2.13	4.36
Centipedegrass	3	1.9	1.51	0.79	0	2.3	4.47
Centipedegrass	4	1.9	1.09	0.81	0.21	2.11	4.92
Centipedegrass	5	1.9	1.94	0.86	0	2.8	4.82
Centipedegrass	6	1.9	1.34	0.7	0.04	2.08	4.1
Centipedegrass	1	2	1.34	0.93	0	2.27	4.16
Centipedegrass	2	2	0.9	0.86	0	1.76	3.96
Centipedegrass	3	2	1.37	0.8	0.02	2.19	4.04
Centipedegrass	4	2	1.21	0.84	0	2.05	5.133
Centipedegrass	5	2	1.29	0.85	0	2.14	4.26
Centipedegrass	6	2	1.33	0.64	0	1.97	3.72
St. Augustinegrass	1	1.6	1.17	1	1.9	4.07	11.71
St. Augustinegrass	2	1.6	0.91	0.75	1.35	3.01	11.81
St. Augustinegrass	3	1.6	0.32	0.21	0.65	1.18	6.06
St. Augustinegrass	4	1.6	0.96	0.78	1.29	3.03	10.5
St. Augustinegrass	5	1.6	1.39	0.85	1.6	3.84	10.74
St. Augustinegrass	6	1.6	0.45	0.28	0.72	1.45	7.66
St. Augustinegrass	1	1.7	1.2	0.44	0.49	2.13	9.4
St. Augustinegrass	2	1.7	1.21	0.76	0.33	2.3	10.51
St. Augustinegrass	3	1.7	1.84	1.55	0.46	3.85	10.84
St. Augustinegrass	4	1.7	1.9	0.75	0.8	3.45	8.28
St. Augustinegrass	5	1.7	1.47	0.69	0.74	2.9	8.89
St. Augustinegrass	6	1.7	1.57	0.78	0.09	2.44	10.17
St. Augustinegrass	1	1.8	2.49	0.27	0.01	2.77	10.41
St. Augustinegrass	2	1.8	1.73	0.71	0	2.44	9.19
St. Augustinegrass	3	1.8	1.85	0.28	0	2.13	9.37
St. Augustinegrass	4	1.8	1.68	0.09	0	1.77	9.03
St. Augustinegrass	5	1.8	1.42	0.65	0	2.07	9.57
St. Augustinegrass	6	1.8	3.06	0.48	0	3.54	9.52
St. Augustinegrass	1	1.9	1.86	0.47	0	2.33	9.71
St. Augustinegrass	2	1.9	2.09	0.15	0	2.24	9.75
St. Augustinegrass	3	1.9	3.55	0.27	0	3.82	10.75
St. Augustinegrass	4	1.9	2	0.8	0	2.8	9.6
St. Augustinegrass	5	1.9	0.94	0.26	0	1.2	7.28
St. Augustinegrass	6	1.9	2.49	0.79	0	3.28	11.85
St. Augustinegrass	1	2	1.84	0.39	0	2.23	9.68

St. Augustinegrass	2	2	1.62	0.53	0	2.15	9.42
St. Augustinegrass	3	2	1.76	0.15	0	1.91	9.52
St. Augustinegrass	4	2	2.51	0.1	0	2.61	6.56
St. Augustinegrass	5	2	1.53	0.08	0	1.61	7.75
St. Augustinegrass	6	2	1.57	0.03	0	1.6	8.64
Kentucky Bluegrass	1	1.6	1.226	0.398	0.274	1.898	2.157
Kentucky Bluegrass	2	1.6	1.28	0.212	0.673	2.165	2.328
Kentucky Bluegrass	3	1.6	1.086	0.154	0.174	1.414	1.618
Kentucky Bluegrass	4	1.6	1.132	0.125	0.142	1.399	1.956
Kentucky Bluegrass	5	1.6	1.43	0.319	0.425	2.174	2.446
Kentucky Bluegrass	6	1.6	1.596	0.23	0.538	2.364	2.25
Kentucky Bluegrass	1	1.7	1.507	0.466	0.273	2.246	2.321
Kentucky Bluegrass	2	1.7	2.179	0.3	0.091	2.57	2.13
Kentucky Bluegrass	3	1.7	0.874	0.285	0.133	1.292	2.097
Kentucky Bluegrass	4	1.7	1.498	0.375	0.354	2.227	2.356
Kentucky Bluegrass	5	1.7	1.05	0.147	0.1	1.297	1.791
Kentucky Bluegrass	6	1.7	1.741	0.238	0.228	2.207	2.226
Kentucky Bluegrass	1	1.8	2.454	0.201	0.02	2.675	1.329
Kentucky Bluegrass	2	1.8	1.082	0.186	0.018	1.286	1.57
Kentucky Bluegrass	3	1.8	1.215	0.094	0	1.309	1.752
Kentucky Bluegrass	4	1.8	1.27	0.173	0	1.443	1.398
Kentucky Bluegrass	5	1.8	1.266	0.137	0	1.403	1.487
Kentucky Bluegrass	6	1.8	1.881	0.356	0	2.237	2.142
Kentucky Bluegrass	1	1.9	0.926	0.104	0	1.03	1.542
Kentucky Bluegrass	2	1.9	3.385	0.397	0	3.782	2.031
Kentucky Bluegrass	3	1.9	2.607	0.084	0	2.691	1.588
Kentucky Bluegrass	4	1.9	1.772	0.148	0	1.92	1.656
Kentucky Bluegrass	5	1.9	1.719	0.079	0	1.798	1.319
Kentucky Bluegrass	6	1.9	3.674	0.171	0	3.845	1.615
Kentucky Bluegrass	1	2	2.911	0.057	0	2.968	1.409
Kentucky Bluegrass	2	2	4.453	0.119	0	4.572	2.262
Kentucky Bluegrass	3	2	3.728	0.175	0	3.903	1.916
Kentucky Bluegrass	4	2	1.881	0.089	0	1.97	1.771
Kentucky Bluegrass	5	2	1.729	0.062	0	1.791	1.547
Kentucky Bluegrass	6	2	1.342	0.032	0	1.374	1.647
Paspalum	1	1.6	1.742	0.348	0.778	2.868	3.92
Paspalum	2	1.6	1.336	0.223	0.267	1.826	3.959
Paspalum	3	1.6	1.671	0.3	0.781	2.752	4.643
Paspalum	4	1.6	2.898	0.21	1.158	4.266	5.074
Paspalum	5	1.6	1.597	0.218	0.538	2.353	4.603
Paspalum	6	1.6	2.353	0.665	1.528	4.546	3.896
Paspalum	1	1.7	2.691	1.67	4.262	8.623	5.045
Paspalum	2	1.7	2.607	0.79	1.531	4.928	4.417
Paspalum	3	1.7	2.251	1.376	2.017	5.644	4.827
Paspalum	4	1.7	1.845	0.292	1.083	3.22	4.607
Paspalum	5	1.7	0.939	0.142	0.267	1.348	3.831
Paspalum	6	1.7	0.899	0.169	0.27	1.338	3.589
Paspalum	1	1.8	1.68	0.308	0.109	2.097	4.222
Paspalum	2	1.8	1.585	0.622	0.087	2.294	4.388
Paspalum	3	1.8	3.57	0.419	0.122	4.111	4.33

Paspalum	4	1.8	1.143	0.243	0.087	1.473	3.886
Paspalum	5	1.8	1.816	0.385	0.076	2.277	3.662
Paspalum	6	1.8	2.429	0.356	0.101	2.886	4.444
Paspalum	1	1.9	1.643	0.46	0	2.103	3.67
Paspalum	2	1.9	1.771	0.343	0	2.114	3.843
Paspalum	3	1.9	2.405	0.336	0.055	2.796	4.05
Paspalum	4	1.9	1.356	0.155	0	1.511	3.196
Paspalum	5	1.9	2.361	0.333	0.082	2.776	4.37
Paspalum	6	1.9	2.039	0.23	0	2.269	3.494
Paspalum	1	2	1.954	0.1	0	2.054	3.461
Paspalum	2	2	1.305	0.027	0	1.332	3.047
Paspalum	3	2	2.23	0.086	0	2.316	3.745
Paspalum	4	2	2.628	0.149	0	2.777	3.806
Paspalum	5	2	2.314	0.228	0	2.542	3.9
Paspalum	6	2	2.159	0.124	0	2.283	3.283
Perennial Ryegrass	1	1.6	41.71	11.839	13.366	66.915	9.325
Perennial Ryegrass	2	1.6	31.612	7.028	15.415	54.055	9.461
Perennial Ryegrass	3	1.6	55.17	6.384	10.571	72.125	8.731
Perennial Ryegrass	4	1.6	10.636	5.147	8.834	24.617	9.106
Perennial Ryegrass	5	1.6	27.726	8.238	14.15	50.114	9.181
Perennial Ryegrass	6	1.6	31.722	4.421	7.512	43.655	9.825
Perennial Ryegrass	1	1.7	20	6.843	9.75	36.593	12.402
Perennial Ryegrass	2	1.7	40.66	8.43	14.163	63.253	9.026
Perennial Ryegrass	3	1.7	27.551	10.967	13.364	51.882	9.086
Perennial Ryegrass	4	1.7	19.358	7.803	10.362	37.523	9.897
Perennial Ryegrass	5	1.7	13.381	7.771	12.648	33.8	9.418
Perennial Ryegrass	6	1.7	32.21	7.229	11.512	50.951	9.15
Perennial Ryegrass	1	1.8	12.423	6.952	5.33	24.705	8.932
Perennial Ryegrass	2	1.8	88.97	17.966	4.118	111.054	8.691
Perennial Ryegrass	3	1.8	37.49	17.091	4.21	58.791	7.566
Perennial Ryegrass	4	1.8	110.91	16.475	5.424	132.809	8.286
Perennial Ryegrass	5	1.8	41.97	7.235	4.824	54.029	8.917
Perennial Ryegrass	6	1.8	30.997	10.88	5.905	47.782	7.762
Perennial Ryegrass	1	1.9	80.67	21.185	4.249	106.104	7.767
Perennial Ryegrass	2	1.9	59.32	14.188	8.178	81.686	8.915
Perennial Ryegrass	3	1.9	32.404	7.878	3.027	43.309	7.58
Perennial Ryegrass	4	1.9	34.371	28.004	8.376	70.751	8.41
Perennial Ryegrass	5	1.9	44.88	11.572	2.638	59.09	6.873
Perennial Ryegrass	6	1.9	84.91	22.284	5.526	112.72	7.972
Perennial Ryegrass	1	2	20.96	2.529	9.207	32.696	8.246
Perennial Ryegrass	2	2	29.753	16.061	5.498	51.312	8.751
Perennial Ryegrass	3	2	35.973	7.684	2.396	46.053	8.425
Perennial Ryegrass	4	2	54.03	10.081	3.118	67.229	8.069
Perennial Ryegrass	5	2	71.37	11.185	1.324	83.879	7.493
Perennial Ryegrass	6	2	69.96	11.708	1.944	83.612	7.663
Tall Fescue	1	1.6	2.993	0.857	1.801	5.651	6.174
Tall Fescue	2	1.6	2.117	0.394	0.737	3.248	6.104
Tall Fescue	3	1.6	3.122	0.376	0.443	3.941	6.684
Tall Fescue	4	1.6	1.538	0.216	0.43	2.184	4.169
Tall Fescue	5	1.6	2.451	0.19	0.203	2.844	3.631

Tall Fescue	6	1.6	1.252	0.661	3.031	4.944	6.329
Tall Fescue	1	1.7	2.516	0.921	1.491	4.928	7.713
Tall Fescue	2	1.7	1.548	0.351	0.705	2.604	6.961
Tall Fescue	3	1.7	1.963	0.319	0.405	2.687	6.396
Tall Fescue	4	1.7	1.146	0.19	0.257	1.593	4.979
Tall Fescue	5	1.7	0.236	0.53	1.113	1.879	7.622
Tall Fescue	6	1.7	1.449	1.002	1.582	4.033	6.804
Tall Fescue	1	1.8	1.726	0.169	0.052	1.947	3.95
Tall Fescue	2	1.8	1.921	0.111	0.076	2.108	3.493
Tall Fescue	3	1.8	1.24	0.093	0.076	1.409	2.566
Tall Fescue	4	1.8	4.263	3.263	0.585	8.111	6.207
Tall Fescue	5	1.8	1.868	0.428	0.43	2.726	6.61
Tall Fescue	6	1.8	4.367	0.471	0.123	4.961	6.755
Tall Fescue	1	1.9	2.968	0.165	0.008	3.141	5.477
Tall Fescue	2	1.9	1.844	0.126	0.023	1.993	4.228
Tall Fescue	3	1.9	3.813	2.008	0.009	5.83	5.35
Tall Fescue	4	1.9	2.533	0.467	0.025	3.025	6.825
Tall Fescue	5	1.9	2.283	0.269	0.036	2.588	5.409
Tall Fescue	6	1.9	3.616	0.506	0.033	4.155	5.486
Tall Fescue	1	2	1.969	0.057	0	2.026	4.082
Tall Fescue	2	2	1.679	0.093	0	1.772	2.921
Tall Fescue	3	2	2.783	0.092	0	2.875	4.487
Tall Fescue	4	2	1.674	0.036	0	1.71	3.77
Tall Fescue	5	2	3.272	1.957	0	5.229	5.495
Tall Fescue	6	2	2.951	0.335	0	3.286	5.73
Zoysiagrass	1	1.6	1.5	0.397	0.862	2.759	7.119
Zoysiagrass	2	1.6	0.956	0.296	0.353	1.605	7.113
Zoysiagrass	3	1.6	1.041	0.198	0.279	1.518	5.186
Zoysiagrass	4	1.6	0.836	0.454	0.438	1.728	6.01
Zoysiagrass	5	1.6	1.656	0.497	0.992	3.145	8.118
Zoysiagrass	6	1.6	1.313	0.401	0.978	2.692	5.683
Zoysiagrass	1	1.7	1.001	0.512	0.545	2.058	7.387
Zoysiagrass	2	1.7	1.009	0.657	0.899	2.565	7.513
Zoysiagrass	3	1.7	1.175	0.446	0.587	2.208	6.675
Zoysiagrass	4	1.7	1.284	0.568	0.936	2.788	6.943
Zoysiagrass	5	1.7	0.603	0.171	0.166	0.94	5.577
Zoysiagrass	6	1.7	0.786	0.342	0.456	1.584	6.899
Zoysiagrass	1	1.8	1.859	0.741	1.429	4.029	7.111
Zoysiagrass	2	1.8	1.497	0.561	0.669	2.727	6.394
Zoysiagrass	3	1.8	0.4	0.078	0.146	0.624	4.309
Zoysiagrass	4	1.8	0.562	0.19	0.063	0.815	5.273
Zoysiagrass	5	1.8	1.963	0.618	1.71	4.291	6.44
Zoysiagrass	6	1.8	2.783	0.428	0.56	3.771	5.685
Zoysiagrass	1	1.9	1.918	0.654	0.051	2.623	5.714
Zoysiagrass	2	1.9	1.755	0.156	0.045	1.956	4.852
Zoysiagrass	3	1.9	1.604	0.524	0.133	2.261	5.39
Zoysiagrass	4	1.9	3.398	0.801	0.34	4.539	7.349
Zoysiagrass	5	1.9	1.897	0.746	0.248	2.891	5.56
Zoysiagrass	6	1.9	0.913	0.18	0.033	1.126	5.2
Zoysiagrass	1	2	1.466	0.088	0.01	1.564	5.87

Zoysiagrass	2	2	1.13	0.044	0	1.174	4.249
Zoysiagrass	3	2	1.539	0.077	0.011	1.627	6.454
Zoysiagrass	4	2	1.275	0.063	0	1.338	4.617
Zoysiagrass	5	2	2.747	0.474	0.059	3.28	5.613
Zoysiagrass	6	2	2.063	0.205	0.063	2.331	6.669

Appendix Table 2. Soil strength data of the middle layer for all experimental columns.

Species	Repetition	Bulk Density (Mg m^{-3})	Soil Strength (kg cm^{-2})
Bentgrass	1	1.6	7.5
Bentgrass	2	1.6	5
Bentgrass	3	1.6	6.75
Bentgrass	4	1.6	10
Bentgrass	5	1.6	9.5
Bentgrass	6	1.6	13.75
Bentgrass	1	1.7	10
Bentgrass	2	1.7	5
Bentgrass	3	1.7	6.25
Bentgrass	4	1.7	4.5
Bentgrass	5	1.7	10
Bentgrass	6	1.7	3.75
Bentgrass	1	1.8	5.25
Bentgrass	2	1.8	7.25
Bentgrass	3	1.8	15
Bentgrass	4	1.8	15
Bentgrass	5	1.8	13.75
Bentgrass	6	1.8	10
Bentgrass	1	1.9	15.5
Bentgrass	2	1.9	14.75
Bentgrass	3	1.9	16.25
Bentgrass	4	1.9	13.75
Bentgrass	5	1.9	10.25
Bentgrass	6	1.9	NR*
Bentgrass	1	2	18.5
Bentgrass	2	2	16
Bentgrass	3	2	18.75
Bentgrass	4	2	15.75
Bentgrass	5	2	16.75
Bentgrass	6	2	18.75
Bermudagrass	1	1.6	6.25
Bermudagrass	2	1.6	NR
Bermudagrass	3	1.6	11.25
Bermudagrass	4	1.6	15
Bermudagrass	5	1.6	15.5
Bermudagrass	6	1.6	11.25
Bermudagrass	1	1.7	7.5
Bermudagrass	2	1.7	6.5
Bermudagrass	3	1.7	14.75
Bermudagrass	4	1.7	13.75
Bermudagrass	5	1.7	14.5
Bermudagrass	6	1.7	11.25
Bermudagrass	1	1.8	13
Bermudagrass	2	1.8	15
Bermudagrass	3	1.8	11.25

Bermudagrass	4	1.8	11
Bermudagrass	5	1.8	12.25
Bermudagrass	6	1.8	10.5
Bermudagrass	1	1.9	14.75
Bermudagrass	2	1.9	15
Bermudagrass	3	1.9	11
Bermudagrass	4	1.9	15
Bermudagrass	5	1.9	12.5
Bermudagrass	6	1.9	17.5
Bermudagrass	1	2	8
Bermudagrass	2	2	3.25
Bermudagrass	3	2	10
Bermudagrass	4	2	12.75
Bermudagrass	5	2	12.5
Bermudagrass	6	2	18.75
Buffalograss	1	1.6	3
Buffalograss	2	1.6	5.25
Buffalograss	3	1.6	4.75
Buffalograss	4	1.6	5.75
Buffalograss	5	1.6	10
Buffalograss	6	1.6	7.25
Buffalograss	1	1.7	7.25
Buffalograss	2	1.7	5.25
Buffalograss	3	1.7	7
Buffalograss	4	1.7	6.25
Buffalograss	5	1.7	6.25
Buffalograss	6	1.7	6.75
Buffalograss	1	1.8	8
Buffalograss	2	1.8	6.25
Buffalograss	3	1.8	7.5
Buffalograss	4	1.8	6.25
Buffalograss	5	1.8	5.5
Buffalograss	6	1.8	9
Buffalograss	1	1.9	10
Buffalograss	2	1.9	10
Buffalograss	3	1.9	5.25
Buffalograss	4	1.9	8.5
Buffalograss	5	1.9	10.75
Buffalograss	6	1.9	10
Buffalograss	1	2	9.5
Buffalograss	2	2	12.75
Buffalograss	3	2	11.25
Buffalograss	4	2	8.75
Buffalograss	5	2	12.5
Buffalograss	6	2	13.25
Centipedegrass	1	1.6	9
Centipedegrass	2	1.6	17
Centipedegrass	3	1.6	11.75
Centipedegrass	4	1.6	17
Centipedegrass	5	1.6	17.75

Centipedegrass	6	1.6	11.25
Centipedegrass	1	1.7	10
Centipedegrass	2	1.7	11.25
Centipedegrass	3	1.7	17
Centipedegrass	4	1.7	12.5
Centipedegrass	5	1.7	18.75
Centipedegrass	6	1.7	15
Centipedegrass	1	1.8	14
Centipedegrass	2	1.8	16.75
Centipedegrass	3	1.8	16.25
Centipedegrass	4	1.8	13.5
Centipedegrass	5	1.8	13
Centipedegrass	6	1.8	14.5
Centipedegrass	1	1.9	17
Centipedegrass	2	1.9	17.5
Centipedegrass	3	1.9	15
Centipedegrass	4	1.9	18.75
Centipedegrass	5	1.9	13
Centipedegrass	6	1.9	20
Centipedegrass	1	2	14.25
Centipedegrass	2	2	23
Centipedegrass	3	2	17.75
Centipedegrass	4	2	18.75
Centipedegrass	5	2	18
Centipedegrass	6	2	19.5
St. Augustinegrass	1	1.6	4.25
St. Augustinegrass	2	1.6	7.25
St. Augustinegrass	3	1.6	4
St. Augustinegrass	4	1.6	5.5
St. Augustinegrass	5	1.6	6.75
St. Augustinegrass	6	1.6	NR
St. Augustinegrass	1	1.7	9.375
St. Augustinegrass	2	1.7	6.25
St. Augustinegrass	3	1.7	7.5
St. Augustinegrass	4	1.7	10.5
St. Augustinegrass	5	1.7	10
St. Augustinegrass	6	1.7	16
St. Augustinegrass	1	1.8	12
St. Augustinegrass	2	1.8	12.5
St. Augustinegrass	3	1.8	14
St. Augustinegrass	4	1.8	10.625
St. Augustinegrass	5	1.8	11.25
St. Augustinegrass	6	1.8	12
St. Augustinegrass	1	1.9	12.75
St. Augustinegrass	2	1.9	14
St. Augustinegrass	3	1.9	16.5
St. Augustinegrass	4	1.9	18.75
St. Augustinegrass	5	1.9	24.5
St. Augustinegrass	6	1.9	13.75
St. Augustinegrass	1	2	21.75

St. Augustinegrass	2	2	15.75
St. Augustinegrass	3	2	25
St. Augustinegrass	4	2	NR
St. Augustinegrass	5	2	19.75
St. Augustinegrass	6	2	16.75
Kentucky Bluegrass	1	1.6	11.25
Kentucky Bluegrass	2	1.6	9.5
Kentucky Bluegrass	3	1.6	12.5
Kentucky Bluegrass	4	1.6	13.25
Kentucky Bluegrass	5	1.6	5
Kentucky Bluegrass	6	1.6	9.25
Kentucky Bluegrass	1	1.7	16
Kentucky Bluegrass	2	1.7	10.5
Kentucky Bluegrass	3	1.7	5
Kentucky Bluegrass	4	1.7	13.75
Kentucky Bluegrass	5	1.7	9.5
Kentucky Bluegrass	6	1.7	14
Kentucky Bluegrass	1	1.8	16.25
Kentucky Bluegrass	2	1.8	16.25
Kentucky Bluegrass	3	1.8	17
Kentucky Bluegrass	4	1.8	11.25
Kentucky Bluegrass	5	1.8	15
Kentucky Bluegrass	6	1.8	10.5
Kentucky Bluegrass	1	1.9	11.75
Kentucky Bluegrass	2	1.9	12.5
Kentucky Bluegrass	3	1.9	17
Kentucky Bluegrass	4	1.9	12.75
Kentucky Bluegrass	5	1.9	17.5
Kentucky Bluegrass	6	1.9	15.5
Kentucky Bluegrass	1	2	13.25
Kentucky Bluegrass	2	2	9.5
Kentucky Bluegrass	3	2	14
Kentucky Bluegrass	4	2	20.75
Kentucky Bluegrass	5	2	16.25
Kentucky Bluegrass	6	2	17
Paspalum	1	1.6	10.5
Paspalum	2	1.6	12.75
Paspalum	3	1.6	5.25
Paspalum	4	1.6	6.25
Paspalum	5	1.6	10.25
Paspalum	6	1.6	10
Paspalum	1	1.7	3.25
Paspalum	2	1.7	14.25
Paspalum	3	1.7	10
Paspalum	4	1.7	11
Paspalum	5	1.7	10.5
Paspalum	6	1.7	15
Paspalum	1	1.8	10.75
Paspalum	2	1.8	6.75
Paspalum	3	1.8	8.75

Paspalum	4	1.8	15.25
Paspalum	5	1.8	8.75
Paspalum	6	1.8	11
Paspalum	1	1.9	11.5
Paspalum	2	1.9	15.75
Paspalum	3	1.9	15
Paspalum	4	1.9	15.75
Paspalum	5	1.9	12
Paspalum	6	1.9	15
Paspalum	1	2	11.5
Paspalum	2	2	11.5
Paspalum	3	2	22.5
Paspalum	4	2	14.75
Paspalum	5	2	18.5
Paspalum	6	2	14.25
Perennial Ryegrass	1	1.6	17
Perennial Ryegrass	2	1.6	15
Perennial Ryegrass	3	1.6	15
Perennial Ryegrass	4	1.6	12.5
Perennial Ryegrass	5	1.6	15
Perennial Ryegrass	6	1.6	14.25
Perennial Ryegrass	1	1.7	17.5
Perennial Ryegrass	2	1.7	15.5
Perennial Ryegrass	3	1.7	16
Perennial Ryegrass	4	1.7	15.5
Perennial Ryegrass	5	1.7	10.25
Perennial Ryegrass	6	1.7	16.25
Perennial Ryegrass	1	1.8	16.25
Perennial Ryegrass	2	1.8	15.5
Perennial Ryegrass	3	1.8	14.5
Perennial Ryegrass	4	1.8	16.5
Perennial Ryegrass	5	1.8	17
Perennial Ryegrass	6	1.8	17.5
Perennial Ryegrass	1	1.9	8.75
Perennial Ryegrass	2	1.9	20.25
Perennial Ryegrass	3	1.9	17.5
Perennial Ryegrass	4	1.9	23.75
Perennial Ryegrass	5	1.9	17
Perennial Ryegrass	6	1.9	23.75
Perennial Ryegrass	1	2	14.75
Perennial Ryegrass	2	2	7.75
Perennial Ryegrass	3	2	18.75
Perennial Ryegrass	4	2	22.25
Perennial Ryegrass	5	2	23.75
Perennial Ryegrass	6	2	22.25
Tall Fescue	1	1.6	6.25
Tall Fescue	2	1.6	8.75
Tall Fescue	3	1.6	10.5
Tall Fescue	4	1.6	10.25
Tall Fescue	5	1.6	11.25

Tall Fescue	6	1.6	7.5
Tall Fescue	1	1.7	10.5
Tall Fescue	2	1.7	11.5
Tall Fescue	3	1.7	8.5
Tall Fescue	4	1.7	15
Tall Fescue	5	1.7	15.5
Tall Fescue	6	1.7	15
Tall Fescue	1	1.8	13
Tall Fescue	2	1.8	13.75
Tall Fescue	3	1.8	16.25
Tall Fescue	4	1.8	13.75
Tall Fescue	5	1.8	18.5
Tall Fescue	6	1.8	15
Tall Fescue	1	1.9	18.75
Tall Fescue	2	1.9	18
Tall Fescue	3	1.9	23.75
Tall Fescue	4	1.9	22.25
Tall Fescue	5	1.9	20.5
Tall Fescue	6	1.9	19.5
Tall Fescue	1	2	25
Tall Fescue	2	2	23.75
Tall Fescue	3	2	23.5
Tall Fescue	4	2	25
Tall Fescue	5	2	22.5
Tall Fescue	6	2	22.5
Zoysiagrass	1	1.6	6.25
Zoysiagrass	2	1.6	10
Zoysiagrass	3	1.6	7.75
Zoysiagrass	4	1.6	7.5
Zoysiagrass	5	1.6	8
Zoysiagrass	6	1.6	8.5
Zoysiagrass	1	1.7	10.25
Zoysiagrass	2	1.7	10
Zoysiagrass	3	1.7	8.75
Zoysiagrass	4	1.7	6.5
Zoysiagrass	5	1.7	8.75
Zoysiagrass	6	1.7	11.25
Zoysiagrass	1	1.8	9.5
Zoysiagrass	2	1.8	10.25
Zoysiagrass	3	1.8	10.5
Zoysiagrass	4	1.8	12.5
Zoysiagrass	5	1.8	8.75
Zoysiagrass	6	1.8	8.75
Zoysiagrass	1	1.9	10
Zoysiagrass	2	1.9	10
Zoysiagrass	3	1.9	8
Zoysiagrass	4	1.9	12.5
Zoysiagrass	5	1.9	12.5
Zoysiagrass	6	1.9	8.5
Zoysiagrass	1	2	17.5

Zoysiagrass	2	2	18.5
Zoysiagrass	3	2	18
Zoysiagrass	4	2	14.5
Zoysiagrass	5	2	13
Zoysiagrass	6	2	15

*NR refers to a missing soil strength reading.