Bermudagrass Growth in Soil Supplemented with Inorganic Amendments

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Abstract. Various inorganic soil amendments have been promoted as a means of improving the chemical and physical properties of certain soils. To test this hypothesis, a marginally productive soil was supplemented with 20%, 40%, 60%, and 80% (v/v) of either selected inorganic amendments or sand. Amendments consisted of commercially available diatomaceous earth, calcined clay, zeolite, and crystalline SiO₂. The soil material was extracted from the argillic horizon of a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhap-ludults). Ability of these soil-amendment mixtures to promote 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt D. Davy] growth was evaluated under greenhouse conditions, and contrasted to that obtained in nonamended soil. Selected chemical and physical properties that are pertinent to plant growth were also evaluated. The experiment, which was conducted 3×, began with a ≈60-day period in which both water and nutrients were optimum. This was followed by a 30-day drought. During optimum water and nutrients, no soil-amendment treatment(s) consistently resulted in superior bermudagrass growth compared to soil alone. However, <2% of the bermudagrass tissue that was produced during the drought became green and succulent with the resumption of irrigation in nonamended soil. This percentage was exceeded by all treatments that contained either ≥60% diatomaceous earth (Axis), or ≥40% calcined clay (Profile); and by 100% zeolite (Clinolite) and 100% silica (Green's Choice). Drought-sustaining ability of soil-amendment mixtures was significantly ($P < 0.05$) correlated with water-holding ability, soil strength, bulk density, and oxygen diffusion rate, but not correlated with either pH or cation exchange capacity (CEC). While certain inorganic amendments did improve the drought-sustaining ability of soil, the amount required was generally ≥40%.

The rooting zone of most modern golf course putting greens, including those that meet United States Golf Association (USGA) specifications (USGA Greens Section Staff, 1993), are constructed by replacing the existing soil with sand that has been mixed with a relatively small amount of organic material, typically peat (Kussow, 1987; USGA Greens Section Staff, 1993). However, some greens are formed by simply shaping the existing soil on the site to the desired contours, possibly incorporating organic matter, such as peat moss, and planting the desired turf species. This type of putting green, termed a push-up green, is less expensive to install but is susceptible to soil compaction (Christians, 1998). Soil compaction in a push-up green can be alleviated by incorporating sand into the surface and/or core aerification, in which case the core holes are back-filled with sand. Unfortunately, these practices often only alleviate compaction temporarily (Christians, 1998).

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Use of inorganic amendments in golf course turf management is increasing. These amendments are used as either: 1) an additional component, or partial alternative to sand, in the sand-peat mixture in excavated-type greens; or 2) an alternative to sand in topdressing and core aerification. In the first case, the amendment generally replaces no more than 10% of the total volume of the sand-based mixture. Use of inorganic amendments in urban landscaping is also increasing. The purported benefits of these amendments, according to manufacturers, include plant pathogen sanitation, resistance to decomposition, and a greater porosity relative to that of sand. Depending upon the particular amendment, the CEC can be nearly equivalent to or greater than that of peat (Wehtje et al., 2000).

Comprehensive reviews on inorganic soil amendments have been prepared by several authors (Daniel and Freeborg, 1979; Grunthal, 1996). Most are produced from three basic types of naturally occurring mineral deposits: 1) clays, including montmorillonite and attapulgite; 2) zeolites, which are composed predominately of the mineral clinoptilolite; and 3) diatomaceous earths, which are the siliceous skeletal remains of diatoms (Wehtje et al., 2000). Mined materials are screened to a narrow particle range, i.e., approximately

equivalent to that of coarse sand (0.5–1.0 mm). Generally, the clay and diatomaceous earth-based products are fired (calcined) at 1500 to 1700 °C to render the particles stable. Zeolite-based amendments are generally not fired.

Published studies dealing with these inorganic soil amendments are limited, and most have focused upon using these amendments as supplements to pure sand. Miller (2000), in a greenhouse study, grew bermudagrass in sand-filled cups. After bermudagrass establishment, cores were removed and back-filled with several different inorganic amendments in a manner that simulated core-aerification. Sand amended in this manner contained up to 16% more transpirable water relative to the nontreated control. This, in turn, reduced drought stress symptoms. Nus and Brauen (1991) evaluated creeping bentgrass (*Agrostis palustris* Huds.) establishment on sand-based putting greens that had been amended with either sawdust, sphagnum peat, or gravel-sized clinoptilolite (zeolite). Clinoptilolite and peat were equally effective in improving creeping bentgrass establishment. Ferguson et al. (1986) and Ferguson and Pepper (1987) noted that germination and establishment of creeping bentgrass, as well as clipping yield and N-use efficiency, were increased by supplementing sand with up to 10% clinoptilolite zeolites. It was noted that the clinoptilolite zeolites evaluated had a high degree of internal tunneling and high CEC. This allowed NH₄⁺ ions to be sorbed and held in an environment possibly void of microbial-based denitrification, while allowing release of N into solution for uptake. Joo et al. (1998) evaluated the physical and chemical properties of sand-based mixtures when a series of inorganic amendments were included at 10% by volume. Depending upon amendment choice, CEC, water retention, and bulk density were positively affected. Bigelow et al. (2001) compared creeping bentgrass performance in pure sand vs. sand amended 10% by volume with either three inorganic amendments or sphagnum peat moss. All amendments were associated with more rapid creeping bentgrass establishment and root development, improved turf quality, greater water retention, and increased CEC relative to that of nonamended sand. Depending upon the specific parameter, the inorganic amendments resulted in a response either equivalent to or greater than sphagnum peat. And while these studies were limited to various amendment-sand scenarios, MacKown and Tucker (1985) reported that adding zeolite to a coarse-textured soil did reduce leaching of NH₄⁺ by increasing the overall CEC.

These aforementioned studies establish that inorganic amendments can improve the pertinent physical and chemical properties and/or turfgrass performance compared with the typical sand-based mixtures. However, whether these amendments are beneficial in improving the agronomic properties of some native soils, as with push-up greens and urban landscape applications, has not been established. Thus, if these amendments are beneficial in enhancing soil productivity, they may have potential outside of golf course

endeavors. The objective of this research was to determine if any of the selected inorganic amendments were beneficial if incorporated into a heavily eroded native soil.

Materials and Methods

General information. The subsurface argillic horizon of Piedmont soils is often exposed due to accelerated erosion and/or constructional excavation. The upper portion of the argillic horizon of a Cecil soil (fine, kaolinitic, thermic Typic Kanhapludults) was collected for this study. The soil was air dried, lightly crushed, and passed through a 2-mm screen. The soil was composed of 503 g·kg⁻¹ clay, and 356 g·kg⁻¹ sand. The clay fraction was dominated by kaolinite, hydroxy-interlayered vermiculite, with lesser amounts of gibbsite and Fe oxides. The low activity nature of the clay minerals results in a low CEC (7.7 cmol·kg⁻¹ soil).

Four inorganic amendments were included: Axis (Eagle-Picher Minerals, Reno, Nev.), Clinolite (Scientific Turf Products, Burnet, Texas), Green's Choice (Premier Environmental Products, Houston) and Profile (Applied Industrial Materials Corp., Buffalo Grove, Ill.). Axis is a nonfired diatomaceous earth primarily composed of poorly crystalline SiO₂. Clinolite is a zeolitic material composed of the mineral clinoptilolite. Green's Choice is composed primarily of crystalline SiO₂, while Profile is a fired clay. Amendment properties, including particle size distribution, surface area determinations, CEC, water-holding capacity, particle density, and electron micrographs of particle surface, have been previously reported (Wehtje et al., 2000). A coarse sand that meets all USGA putting green specifications (USGA Greens Section Staff, 1993) was included as a fifth amendment. According to laboratory analysis (Tifton Physical Soil Testing Laboratory, Tifton, Ga.), total "fines," i.e., particles <0.05 mm in diameter, constituted 7.3% by weight; 75.6% were in the 0.5- to 0.75-mm range.

Experimental procedures. Soil-amendment mixtures were prepared such that the amend-

ments represented either 20%, 40%, 60%, 80%, and 100%, respectively, of the total mixture on a v/v basis. Thus, the experiment consisted of a factorial arrangement of five amendments and five ratios, yielding 25 treatments. Soil alone, i.e., nonamended, was the final treatment. About 8 L of each soil-amendment mixture was prepared and mixed in a rotary cement mixer. A fresh supply of the soil-amendment mixtures was prepared for each of the three experimental repetitions as described below.

Two random grab samples were collected from the bulk preparation of soil-amendment mixtures for determination of pH (Table 1); CEC (Table 1); and soil water content at 33 kPa (field capacity), and at 150 kPa tension, i.e., permanent wilting point (Table 2). The pH of the mixtures was measured in a 1:1 w/v slurry (Soil Survey Investigations Staff, 1996). CEC was measured from the bulk preparations of the soil-amendment mixtures using the NH₄OAc (pH 7) method (Soil Survey Investigations Staff, 1996). All soil-water content measurements were determined using pressure plate apparatus (Soil Survey Investigations Staff, 1996). From the soil-water content at 33 and 150 kPa tension, the available water-holding capacity (AWHC) of each soil-amendment mixture was determined by subtraction (Table 2).

Styrofoam cups (1 L), with the bottoms perforated for drainage, were filled with each of the soil-amendment mixture treatments. Filled cups were watered until water drained through cup perforations. This was repeated daily for 3 d. Additional materials were added to compensate for any settling. 'Tifway' bermudagrass (4-cm-diameter plugs) were collected from established turf at the Auburn Univ. Turfgrass Research Unit. Soil and root material was sliced off below the foliage with the intent of leaving only enough roots for reestablishment. A single plug was planted in each cup. Cups were maintained in a ventilated greenhouse that received only ambient light. Cups were irrigated every Monday, Wednesday, and Friday with 50

mL water per cup. A completely randomized experimental design with four replications was used. The entire experiment was repeated 3×, with the first, second, and third experimental repetitions initiated in Aug. 2000, Mar. 2001, and Aug. 2001, respectively.

Each soil-amendment mixture was fertilized at day 7, 16, 27, 45, and 51 with a water-soluble fertilizer that contained 10.7, 4.2 and 3.2 mol·kg⁻¹ of N, P, and K, respectively. Micronutrients were also included. Nutrient application rates were 2.7, 2.3 and 2.2 g·m⁻² for N, P₂O₅, and K₂O, respectively. To ensure adequate fertility levels were maintained, tissue analyses (Mills and Jones, 1996) were performed on composited bermudagrass clippings taken from the 40% and 100% amendment ratios of the first trial. These analyses established that tissue N averaged 3.10 ± 0.25 g·g⁻¹ for 40% amendment, 2.79 ± 0.23 g·g⁻¹ for 100% amendment; tissue P averaged 0.30 ± 0.04 g·g⁻¹ for 40% amendment, 0.39 ± 0.21 g·g⁻¹ for 100% amendment; and tissue K averaged 1.96 ± 0.30 g·g⁻¹ for 40% amendment, 1.92 ± 0.37 g·g⁻¹ for 100% amendment. These values are all within published sufficiency ranges (Mills and Jones, 1996). The samples were not normalized for pH to allow direct comparison of amendment mixtures with regard to inherent properties. Published bermudagrass turf pH tolerance ranges from 5.5 to 7.0 (McCarty, 2001). Although pH values of many of the soil-amendment mixtures were below the acceptable pH range (Table 1), tissue analyses showed Ca tissue levels to be within acceptable ranges. Calcium levels equaled 0.37 ± 0.10 g·g⁻¹ for 40% amendment, and 0.40 ± 0.10 g·g⁻¹ for 100% amendment. Our intent was to provide ample, if not luxurious, amounts of water and nutrients during bermudagrass establishment and early growth periods.

About 21 d after planting, bermudagrass was clipped with hand scissors to ≈1 cm above the soil surface. This procedure was repeated a minimum of at least 4× on a 10-d schedule.

Table 1. pH and cation exchange capacity of the soil-amendment mixtures.^z

Amendment	Ratio of amendment to soil (v/v)				
	20	40	60	80	100
pH					
Axis	5.1	5.2	5.2	5.3	5.6
Clinolite	5.1	5.1	5.2	5.6	7.4
Green's Choice	5.3	5.7	6.3	7.3	8.7
Profile	5.1	5.3	5.3	5.6	5.9
Sand	5.1	5.1	5.2	5.4	5.5
cmol·kg ⁻¹					
Axis	7.01	7.32	10.41	8.22	6.70
Clinolite	16.62	21.74	33.85	42.01	49.49
Green's Choice	5.87	4.69	3.73	2.20	1.20
Profile	8.67	8.93	10.16	10.68	10.47
Sand	5.07	3.62	2.64	0.90	0.09

^zMeasurement taken on two random grab samples collected from the bulk soil-amendment mixtures. pH and cation exchange capacity of the nonamended soil was 5.1 and 6.79 cmol·kg⁻¹, respectively. Cumulative coefficient of variation across all treatments were 3.5% and 3.8% for these variables, respectively.

Table 2. Soil water content at 33 kPa, i.e., field capacity (top); 150 kPa, i.e., permanent wilting (middle); and available water (bottom) of the soil-amendment mixtures.^z

Amendment	Ratio of amendment to soil (v/v)				
	20	40	60	80	100
%					
Axis	28.27	34.35	38.21	45.65	50.47
Clinolite	23.30	22.55	22.18	17.34	14.88
Green's Choice	21.64	21.96	18.96	19.82	17.83
Profile	28.05	31.00	32.82	33.41	35.30
Sand	17.37	12.59	10.40	7.61	3.32
Axis	20.22	24.74	28.66	39.22	45.40
Clinolite	16.08	15.75	15.21	14.57	14.45
Green's Choice	15.11	14.28	12.62	11.25	12.02
Profile	20.08	22.88	26.22	28.60	32.18
Sand	11.98	9.22	6.09	2.66	0.71
Axis	8.05	9.61	9.55	6.44	5.08
Clinolite	7.22	6.80	6.97	2.77	0.43
Green's Choice	6.53	7.68	6.34	8.57	5.80
Profile	7.97	8.11	6.60	4.80	3.12
Sand	5.39	3.38	4.31	4.95	2.61

^zMeasurement taken on two random grab samples collected from the bulk soil-amendment mixtures. Soil water content at 33 kPa, 150 kPa, and available water of the nonamended soil was 20.89%, 15.98%, and 4.91%, respectively. Cumulative coefficient of variation across all treatments for soil water content at 33 and 150 kPa was 2.4% and 1.4%, respectively.

Clippings were retained on an individual cup basis, dried at 50 °C for 24 h, and weighed. At the completion of the final clipping, i.e., ≈30 d after planting, bermudagrass in some treatments had extended over the edge of the cups.

Irrigation was stopped after the final clipping. During the ensuing 30-d drought, growth eventually ceased and, depending upon the treatment, the grass eventually appeared dead. Irrigation as previously described was subsequently resumed, and a final clipping was taken 1 week later. Clipped tissue was visually separated into either green or desiccated and weighed. Percentage of total tissue that had been produced during the drought period that remained green and succulent with resumption of irrigation was then calculated.

Bulk density, soil strength, and oxygen diffusion rate (ODR) were determined on an individual experimental unit basis during the second experimental repetition of the bermudagrass performance experiment (Table 3). Soil strength was determined using a penetrometer (Pocket penetrometer model 29-5729, ELE International, Pelham, Ala.). Soil strength has been demonstrated to be highly dependent on soil water content (Busscher et al., 1997). Consequently, these measurements were taken 48 h after saturation (≈field capacity), and again 23 d later (i.e., soil strength-dry). Meaningful differences between the individual soil-amendment mixtures were only evident after dry down; consequently, only these data are presented. However, both data sets were included in correlation procedures, as described below. Bulk density was determined by the procedures of Blake and Hartge (1986), after the completion of the second experimental repetition. The ODR was measured during the period of regular irrigations of the

second experimental repetition using only an ODR meter (Model 'E', Jensen instruments, Tacoma, Wash.), which utilized the platinum wire cathode method (Ball and Smith, 1991; Blackwell, 1983). Measurements were taken within 48 h of an irrigation. Volumetric soil water content was determined concurrently with ODR using time domain reflectometry (Tektronix, Beaverton, Ore.). This established that volumetric soil water content averaged 24.4% ± 2.9% across all treatments.

Statistical considerations. Data collected from the bulk soil-amendment preparations (i.e., pH, CEC, and soil-water relationships) were subjected to statistical analysis and a coefficient of variation was determined. Bermudagrass performance, bulk density, soil strength, and ODR data, which were collected only from the structured experiment, were subjected to statistical analysis that reflected the factorial treatment arrangement. Bermudagrass performance data were pooled across experimental repetitions only if statistical analysis revealed no treatment × experimental repetition interaction(s). Assuming that treatment differences were detected, the appropriate least significant difference value at the $P = 0.05$ level that allowed the comparison between individual treatment means was calculated. This value was used to compare bermudagrass performance, bulk density, soil strength, and ODR in nonamended soil to that of the individual soil-amendment treatments.

Correlations between bermudagrass performance and pertinent soil physical and chemical parameters were also performed. In this procedure, data were pooled across all experimental repetitions. Furthermore, this analysis focused upon physical and chemical properties of the soil-amendment mixtures as

pooled across all amendments evaluated. Data from the nonamended soil were excluded.

Results and Discussion

Bermudagrass performance. Statistical analysis revealed that bermudagrass performance during the period of ample water and nutrients, as indicated by collected tissue weight from multiple clippings, varied between experimental repetitions. Consequently, these data are presented on an individual experimental repetition basis.

During the first experimental repetition, tissue production during luxurious watering was influenced by the amendment, the soil-amendment ratio, and by their interaction (Table 4). In general, increasing amendment to soil ratio resulted in increased tissue production. Nonamended soil yielded 34 mg·cm⁻² of bermudagrass tissue after four clippings. This amount was significantly exceeded only by 100% Axis, 100% Green's Choice, and 80% and 100% sand. Conversely, all other soil-amendment treatments were equivalent to nonamended soil with respect to promoting bermudagrass growth. Bermudagrass growth was not influenced by any of the experimental variables in the second experimental repetition (data not shown). In this repetition, nonamended soil yielded 73 mg·cm⁻² after four clippings, and all other treatments yielded an equivalent amount. In the third experimental repetition, bermudagrass growth was again influenced by the amendment, the soil-amendment ratio, and by their interaction (Table 4). Nonamended soil yielded 55 mg·cm⁻² across five clippings. This amount was exceeded by 17 of the soil-amendment mixtures. However, no clear pattern can be discerned as to which par-

Table 3. Bulk density, soil strength (dry) and oxygen diffusion rate of the soil-amendment mixtures.^z

Amendment	Ratio of amendment to soil (v/v)				
	20	40	60	80	100
	g·cm ⁻³				
Axis	0.99 ^y	0.83 [*]	0.72 [*]	0.61 [*]	0.41 [*]
Clinolite	1.07 [*]	1.05 [*]	1.01 [*]	0.92 [*]	0.84 [*]
Green's Choice	1.09 [*]	1.01 [*]	0.98 [*]	0.93 [*]	0.89 [*]
Profile	1.04 [*]	0.97 [*]	0.84 [*]	0.76 [*]	0.58 [*]
Sand	1.24	1.39	1.45	1.51	1.58
	mPa				
Axis	2.44 [*]	1.90 [*]	1.75 [*]	1.58 [*]	0.31 [*]
Clinolite	3.15	3.10	2.54	1.89 [*]	0.29 [*]
Green's Choice	2.52	2.50	2.38 [*]	1.33 [*]	0.25 [*]
Profile	2.56	2.19 [*]	1.92 [*]	1.75 [*]	0.25 [*]
Sand	2.58	2.31 [*]	1.79 [*]	1.15 [*]	0.29 [*]
	μg·cm ⁻² ·min ⁻¹				
Axis	292	283	447 ^y	570 [*]	747 [*]
Clinolite	300	326	440 [*]	549 [*]	721 [*]
Green's Choice	315	316	536 [*]	588 [*]	421 [*]
Profile	259	298	423 [*]	508 [*]	602 [*]
Sand	275	316	370	372	448 [*]

^zAll data collected only from second experimental repetition. Response was influenced by the main effects of amendment, soil-amendment ratio, and by the interaction thereof. Bulk density, soil strength, and oxygen diffusion rate of the nonamended soil were 1.18 g·cm⁻³, 2.88 mPa, and 305 μg·cm⁻²·min⁻¹, respectively.

^yLSD_{0.05} between any two means = 0.07 g·cm⁻³, 0.40 mPa, and 92 μg·cm⁻²·min⁻¹, for these three variables respectively.

^{*}Significance between this value and that of nonamended soil at $P \leq 0.05$.

Table 4. Total tissue produced in soil-amendment mixtures under luxurious water and nutrient in the first (top) and third (middle) experimental repetitions; and proportion of bermudagrass tissue produced during drought that became green and succulent with resumption of irrigation (bottom) as pooled over all experimental repetitions.^z

Amendment	Ratio of amendment to soil (v/v)				
	20	40	60	80	100
	mg·cm ⁻²				
Axis	32	29	38	46	54 ^y
Clinolite	29	35	38	42	42
Green's Choice	28	31	32	42	49 [*]
Profile	42	42	46	38	42
Sand	40	42	43	52 ^y	57 [*]
Axis	66	72 ^y	63	71 [*]	82 [*]
Clinolite	65	68	86 [*]	71 [*]	49
Green's Choice	78 [*]	74 [*]	83 [*]	82 [*]	52
Profile	78 [*]	86 [*]	98 [*]	80 [*]	83 [*]
Sand	65	68	75 [*]	69 [*]	74 [*]
	%				
Axis	4	19	34 ^y	46 [*]	53 [*]
Clinolite	5	10	12	18	26 [*]
Green's Choice	2	2	7	12	49 [*]
Profile	4	28 [*]	46 [*]	27 [*]	59 [*]
Sand	0	0	0	10	0

^zAll response variables were influenced by the main effects of amendment, soil-amendment ratio, and by the interaction thereof. Comparable values for nonamended soil were 34 mg·cm⁻² (top), 53 mg·cm⁻² (middle) and 2% (bottom).

^yLSD_{0.05} between any two means = 14 mg·cm⁻² (top), 16 mg·cm⁻² (middle), and 21% (bottom).

^{*}Significance between this value and that of nonamended soil at $P \leq 0.05$.

ticular soil-amendment treatments resulted in superior growth. The average amount of tissue collected from the nonamended soil across the three experimental repetitions during the period of ample water and nutrients were 8.5, 13.3, and 11.0 mg·cm⁻² per clipping, respectively. As previously mentioned, the three repetitions were conducted in Aug. 2000, Mar. 2001, and Aug. 2001, respectively. Night temperatures were never inhibitory to bermudagrass growth, i.e., below 20 °C. However, daily maximums occasionally exceeded 38 °C during the two repetitions conducted in August. We attribute the lower yields in these two repetitions to transitory temperature stress in conjunction with decreasing day length.

Across all three experimental repetitions, no consistent trend was observed. No particular soil-amendment treatment(s) consistently resulted in superior bermudagrass growth compared to soil alone. Consequently, soil-amendment mixtures offered no clear improvement over soil alone when both water and nutrients were luxuriant.

A clear separation between treatments became evident after the drought period. No treatment × experimental repetition interactions were detected. Consequently, these data were pooled across all three experimental repetitions for further analysis and presentation (Table 4). The proportion of drought-produced bermudagrass tissue that became green and succulent with resumption of irrigation was again influenced by the amendment, the soil-amendment ratio, and by their interaction. Only 2% of the bermudagrass tissue returned to succulence in nonamended soil. This percentage was exceeded by all treatments that contained either a minimum of 60% Axis or 40% Profile; and by 100% Clinolite and 100% Green's Choice.

Our results are in partial agreement with those obtained by Ralston and Daniel (1973). These researchers evaluated the performance of creeping bentgrass (*Agrostis palustris* Huds) under putting green condition in plots

that contained either dune sand, mortar sand, calcined clay, diatomaceous earth, or native soil. Combination of these materials and soil were not included. Drought tolerance was frequently greater with the nonsoil materials, and this was attributed to enhanced water retention relative to native soil. While we also observed greater drought tolerance of bermudagrass in several of the amendments and soil-amendment mixtures, a clear relationship to water-holding abilities was not apparent.

Bermudagrass performance and chemical/physical parameters; comparisons among individual treatments. Attempting to relate the drought-sustaining ability of these particular aforementioned treatments to any one physical/chemical property was difficult. The obvious assumption was that these treatments simply retained more available water than soil alone. While examination of individual treatment means reveals no such relationship, significant correlations were detected in data that had been pooled across all soil-amendment treatments.

The field capacity (soil water content at 33 kPa) of nonamended soil was 20.89% (Table 2). Comparable values among the drought-sustaining treatments ranged from 14.88 (100% Clinolite) to 50.47 (100% Axis). Available water of the nonamended soil was 4.91%. Comparable values among the drought-sustaining treatments ranged from 0.43% (100% Clinolite) to 9.55% (60% Axis). Thus, the drought-sustaining treatments did not consistently have a greater soil water content at field capacity nor a greater available water content relative to that of nonamended soil.

All the soil-amendment mixtures that contained at least 20% of any of the amendments except sand had a lower bulk density than nonamended soil alone, i.e., 1.18 g·cm⁻³ (Table 3). All of the drought-sustaining treatments had significantly lower soil strength than nonamended soil, i.e., 2.88 mPa (Table 3). Soil strength-dry of these treatments did not exceed 2.19 mPa, compared to that of nonamended soil

at 2.88 mPa. However, other soil-amendment treatments, with equally reduced soil strength (notably those that contained sand), were not able to sustain bermudagrass growth during the drought.

All the drought-sustaining treatments except 40% Profile had a significant greater ODR than nonamended soil, i.e., 305 μg·cm⁻²·min⁻¹ (Table 3). Other soil-amendment treatments also had significantly increased ODR relative to soil alone, but were not able to sustain bermudagrass growth during drought. Inspection of the data reveal that the most common physical attribute among the drought-sustaining treatments was a reduction in both bulk density and soil strength-dry, combined with an increase in ODR (Tables 3 and 4).

Bermudagrass performance and chemical/physical parameters; correlations across all treatments. During the pre-drought period, when both water and nutrients were ample, total bermudagrass clipping weights were negatively ($P < 0.05$) correlated with both pH ($r = -0.41$) and CEC ($r = -0.42$) (Table 5). It is unclear why amendment mixtures with higher pH and higher CEC were associated with lower clipping weight. We speculate that the pH effect may be due to micronutrient availability and/or bermudagrass tolerance to acidity. Total bermudagrass clipping weights were positively ($P < 0.05$) correlated to soil water content at 33 ($r = 0.46$) and 150 kPa, ($r = 0.42$). This indicates that the water-holding properties were critical to bermudagrass performance in this study.

After drought, bermudagrass clipping weight was again positively ($P < 0.01$) correlated with soil water content at 33 ($r = 0.78$) and 150 kPa ($r = 0.79$) (Table 5). Clipping weight was also negatively ($P < 0.05$) correlated with bulk density, suggesting that higher bulk densities were more inhibitory to growth after the drought period than before. The percentage by weight of the post-drought bermudagrass clipping that remained green was also correlated ($P < 0.05$) with the soil water parameters, soil

Table 5. Linear correlation coefficients (top) and probability (bottom) between chemical and physical properties of the soil-amendment mixtures in toto and bermudagrass performance parameters.²

Response variable ¹	Ratio ³	pH	CEC	Soil water 33 kPa	Soil water 150 kPa	Available soil water	Soil strength-FC	Soil strength-Dry	Bulk density	Oxygen diffusion rate
Pre-drought										
Clipping #1	0.26	0.04	-0.38	-0.06	-0.07	0.05	0.10	-0.35	0.21	-0.03
	0.22	0.83	0.06	0.79	0.74	0.80	0.62	0.09	0.31	0.88
Clipping #2	-0.20	-0.41	-0.74	-0.02	-0.05	0.14	-0.07	-0.04	0.39	-0.37
	0.34	0.04	<0.01	0.92	0.81	0.51	0.72	0.83	0.05	0.07
Clipping #3	-0.04	-0.37	-0.07	0.56	0.54	0.27	0.22	0.10	-0.39	0.16
	0.85	0.07	0.72	<0.01	0.01	0.19	0.28	0.62	0.05	0.45
Sum #1-#3	-0.06	-0.41	-0.42	0.46	0.42	0.32	0.19	0.02	-0.17	-0.02
	0.78	0.04	0.04	0.02	0.03	0.12	0.36	0.91	0.42	0.91
Post-drought										
Clipping #4	0.08	-0.14	0.02	0.78	0.79	0.20	0.44	-0.12	-0.72	0.19
	0.70	0.50	0.91	<0.01	<0.01	0.33	0.03	0.56	<0.01	0.37
% Green-#4	0.61	0.34	0.08	0.67	0.74	-0.08	0.37	-0.59	-0.78	0.59
	<0.01	0.10	0.71	<0.01	<0.01	0.70	0.07	<0.01	<0.01	<0.01

¹Data pooled over all three experimental repetitions.

²Clippings #1-4 = bermudagrass weight (g) collected. % Green = percentage of clipping #4 that had become green and succulent with irrigation resumption.

³Ratio = % v/v of amendment to soil; CEC = cation exchange capacity (cmol·kg⁻¹). Soil water 1/3 bar and 15 bar is gravimetric water content (%) at 33 and 150 kPa, respectively. Soil strength-FC = penetrometer resistance at field capacity (33 kPa). Soil strength-Dry is same measurement after dry down, i.e., gravimetric water content = 0.05% ± 0.03%. Bulk density expressed as g·cm⁻³ and oxygen diffusion rate as μg·cm⁻²·min⁻¹.

strength, bulk density, and ODR. Conversely, no correlation at $P < 0.05$ was detected between green tissue, pH, and CEC.

In summary, data presented indicate that improvement in bermudagrass performance in soil-amendment mixtures relative to soil alone is most likely related to increased water-holding capacity, and the interrelated physical properties of bulk density, soil strength, and ODR. Conversely, alteration of soil chemical properties, such as pH and CEC, were of lesser importance in this study. The merits of incorporating these amendments into soil was increasingly manifested during the drought. Our data suggest the amount required for a significant improvement over that of soil alone was $\geq 40\%$, and that improvement was somewhat amendment dependent.

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