Variation of soil and plant characteristics among old world bluestem species

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ABSTRACT

Old world bluestems (*Bothriochloa* spp.) have been successfully introduced as grasses for livestock forage in the semiarid Texas High Plains. Questions remain, however, on effects of these grasses on soil resources. We tested the hypothesis that differences in grass species produce differences in soil properties important to crop growth and useful in selecting the optimum species for the Southern High Plains of Texas. Three old world bluestem (*Bothriochloa*) species [C.E. Hubbard 'Caucasian', *B. caucasica* (Trin.); 'WW Spar', *B. ischaemum* (L.) Keng. var *ischaemum* (Hack.); and S.T. Blake 'WW-B Dahl', *B. bladhii* (Retz)] were grown in a randomized complete block design, with three replications, for nine years on a clay loam soil near Lubbock, Texas. Soil samples were collected in the ninth year to determine soil texture, wet aggregate stability, bulk density (BD), soil organic carbon (SOC), particulate organic carbon (POC), and soil strength as measured by the cone pentrometer. The grass species differed in their above-ground biomass and below-ground root production. In the ninth year of production, *Bothriochloa caucasica* and *B. bladhii* produced about twice the above-ground biomass with about 25% fewer roots than *B. ischaemum*. Soils where *B. caucasica* was grown had the highest BD (1.36 mg m^{-3}) and *B. ischaemum* had the lowest (1.31 mg m^{-3}). The soil in which *B. ischaemum* was growing had a lower BD, greatest root biomass, organic matter content, and aggregate stability suggesting superior soil quality for agricultural production. The species *B. bladhii*, however, often exhibited soil properties that were similar to both other species tested. Since *Bothriochloa bladhii* had superior or similar soil properties for plant growth among the species tested and has been shown to be higher in forage quality, animal performance, and carrying capacity than the other species, it appears to be the best choice among these three species to optimize both animal performance and desirable soil properties.

Keywords: Old World Bluestem; Soil Quality; Grasses; Soil Organic Carbon

1. INTRODUCTION

Old world bluestems (*Bothriochloa* spp.) have been among the more successful grasses for livestock feed in the semiarid Texas High Plains [1]. Research has suggested that the nutritive value of old world bluestems is influenced by species, environmental conditions, management, and physiographic location [1-3]. The Southern High Plains is a semiarid region, often subject to extended periods with little rainfall, producing drought stress in plants. Studies of *B. caucasica* and *B. ischaemum* comparing growth characteristics during periods of abundant and restricted water availability suggested that *B. caucasica* has a lower drought performance potential relative to *B. ischaemum* [4-6]. *Bothriochloa caucasica* and *B. ischaemum* have had a relatively long history on the Southern High Plains, compared with the relatively recently released *B. bladii* [7]. Recent studies comparing the three species have shown that, in general, *B. bladii* provided greater mineral concentrations to grazing animals than either *B. caucasica* or *B. ischaemum* [8]. In addition, *B. bladii* has been recently used in an integrated crop-livestock system and shown to provide at least or above average levels of animal performance and profitability [9]. Questions, however, remain on the effect of the grasses on the soil resources.

Grasses or other forages have distinct effects on soil

physical and chemical properties. Grasses and forages provide organic matter to the soil as the roots and surface plant matter die and decompose. Organic matter in soil improves soil structure as well as the ability of soil to hold nutrients and water [10]. Soils under continuous plant cover tend to have a greater amount of associated C than tilled or bare soils [11]. Plots with grasses had significantly greater organic matter and favorable physical conditions than weedy plots [12]. Tillage of crops often greatly reduces soil organic carbon (SOC), whereas no-till systems help maintain and even increase SOC [13-15].

The particulate organic matter (POM) fraction of soils is comprised of large particles of organic matter (250 - 2000 μm) that exists as free organic matter or that is encrusted with soil particles, which in turn offers protection from decomposition [16]. The carbon content of POM is often referred to as particulate organic carbon (POC). Particulate organic carbon seems to be more sensitive to changes in management practices than total SOC [17,18] and has been found to be higher in native sods than cropped soils [17,19]. Increasing POC has been associated with improved soil quality for plant growth [20] and related to other soil and plant properties such as nutrient mineralization, vegetation type, and tillage practices [18].

Grass sods and forage crops have been shown to be effective in improving soil structural stability [21]. Grasses have fibrous root systems provide both chemical and physical benefits to aggregate stability through production of chemical binding agents such as carbonates as well as physically binding roots to the soil particles [16, 22,23]. Grass root growth increases aggregation through the mesh-like network of root hairs and fungal hyphae [24]. These root systems are beneficial even after the plant dies, providing organic matter to the soil, and leaving spaces for water infiltration. In addition, organic matter on the surface of a soil may prevent crusting, increasing water infiltration rates. Water infiltration was found to be higher on a grass-covered soil than on a tilled soil [25]. However, the effect of root biomass on aggregate stability is not always clear. Soils with grass swards have been shown to provide greater aggregate stability than when in crops such as corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] [26]. Nevertheless, root biomass has also been shown to have little or no effect on aggregate stability [27].

Root proliferation affects bulk density (BD) and soil strength, as well. In densely compacted soils, roots grow into cracks in the hard layers [28], and BD is decreased over time by the expansion of roots. For example, the BD of soils with perennial grass cover for 15 years decreased more than soils in annual cropping over the same time period [29]. Bulk density also differs with depth [30]. The bulk density in the top 5 cm of a perennial grass-covered soil was significantly less than at depths below 5 cm [31]. The resistance of soil to penetration by a cone-tipped rod, known as the penetration resistance, is a measure of soil strength and is often related to bulk density. The penetration resistance was greater for grass-covered soil than cultivated [32] or bare, uncultivated soil [33].

Recent studies on the relative benefits of three old world bluestem species have explored several qualities of these grasses, including influence of irrigation on production, water use efficiency, forage nutritive value, and morphology [1,8,34]. We investigated the effects of these different grass species on selected soil properties in the Southern High Plains of Texas. Characteristics explored were aboveground plant biomass, root biomass, soil surface texture and moisture content, total SOC and POC content, soil strength, bulk density, water infiltration rate, and large (<8 mm diameter) and small (1 to 2 mm diameter) wet aggregate stability. We tested the hypothesis that differences in old world bluestem grass species produce differences in these surface soil properties important to crop growth.

2. MATERIALS AND METHODS

2.1. Study Site

This work was part of a larger irrigation study testing the effects of four water irrigation treatments (dryland, low, medium, and high) on three old world bluestem (*Bothriochloa*) species (C.E. Hubbard 'Caucasian', *B. caucasica* [Trin.]; 'WW Spar', *B. ischaemum* [L.] Keng. var *ishaemum* [Hack.]; and S.T. Blake 'WW-B Dahl', *B. bladhii* [Retz]) (Philipp *et al*., 2005). The site was located in northeast Lubbock County, Texas (101˚47′ W; 33˚45′ N; 993 m elevation). The area has a semiarid climate with a mean annual precipitation of 470 mm and an average air temperature of 15.5˚C.

Each species was replicated three times in a randomized complete block design. The grasses were established in 1996 and were used in a lamb (*Ovis aris*) grazing experiment from 1998 to 2000 [35] prior to the irrigation study. Prior to 1996 the site was disked and planted to various forage species. Grazing ended in September 2000. The irrigation study was conducted for three years, 2001 through 2003 [7]. After termination of the irrigation study in 2003, no further irrigation or fertilizer was applied. Plots were mowed once in midsummer each year and above-ground biomass removed as hay in 2004. All plots were mowed in late winter to remove residual herbage before spring growth. Samples used in the current study were collected in the summer

of 2005, two years after the end of the irrigation study. Due to experimental limitations, only the medium water treatment plots were used in our study. The amount of water applied in the medium water treatment during the irrigation study was 66% replacement of potential evapotranspiration (PET) [36] minus precipitation. Irrigation was applied through a surface drip irrigation system.

Each plot was 10 m by 15 m. The soil series was Pullman sandy clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) on a nearly level (0% - 1% slope) land surface. This soil is a very deep, well drained, slowly permeable soil formed in loamy sediments and occupies approximately 1.3 million ha (3.3 million ac) in the Southern High Plains of Texas and Oklahoma [37]. During the irrigation study (2001 to 2003), plots were fertilized equally to meet all soil test recommendations such that N and other nutrients were not limited. Details of precipitation, irrigation and fertilizer applied and application methods are described in Philipp *et al.* [1]. No water or nutrients were applied in 2004 and 2005. Precipitation during these two years was 807 mm for 2004 and 277 mm through mid-August 2005.

2.2. Soil and Plant Sampling and Analyses

Soil samples were collected from depths of 0 - 5 cm and 5 - 15 cm to determine soil texture, wet aggregate stability, BD, SOC, POC in June 2005. Soil samples were screened first through a 2-mm sieve and larger pieces of plant material were removed.

2.2.1. Soil Physical Properties

Soil texture was determined on sieved samples using a Beckman-Coulter LS230 [38] after dispersing the soil in 5 g·L^{-1} sodium hexametaphosphate by shaking overnight in a reciprocating shaker. Bulk density was determined using the soil core method [39]. Samples for BD (two samples from each replication) were collected using a 2-cm diameter push probe with care taken to ensure no compaction occurred during sampling. Soil BD was used to calculate SOC mass on an area basis. *In-situ* soil strength was measured to a depth of 0.3 m with an automated Bush penetrometer [40] (Soil Penetrometer SP1000, Findlay Irvine Ltd.) and observed at 1-cm intervals. The cone-shaped penetrometer tip used for these penetration resistance (PR) measurements had a 30° angle and 12.6 mm diameter base. Fifteen PR measurements were randomly inserted in each plot. Statistical analyses of the soil strength tests were performed on the sum of the PR observations to a depth of 15 cm. In addition, the PR was averaged for the 0 - 5 cm and 5 - 15 cm depths in order to compare with other properties also observed at these depths. Gravimetric soil water content

was measured at the time of PR readings for the depths 0 - 5, 5 - 10, 10 - 15, and 15 - 30 cm to determine interactions of water content and PR readings. Water infiltration was determined using a double-ring infiltrometer at two locations in each replication [41]. Wet aggregate stability was measured on duplicate subsamples of aggregates smaller than 8.0 mm in diameter to determine water-stable aggregate size distribution by wet sieving according the procedure of Kemper and Rosenau [42] and expressed as the mean weight diameter (MWD). Duplicate subsamples of aggregates 1.0 to 2.0 mm in diameter were sieved from a portion of the bulk soil. Wet aggregate stability was also measured on this 1.0 to 2.0 mm in diameter aggregates according to Kemper [43] and expressed as the percentage of aggregates (WAS2).

2.2.2. Soil Chemical Properties

The chemical properties observed in this study consisted of SOC and POC as measured as a concentration (mass per unit mass) by soil depth and mass per unit area. The measurements made on a mass per unit area basis were determined by summing the total amount of each constituent to a depth of 15 cm. Sieved soil samples were used to determine POC according to the method of Gregorich and Ellert [44]. Twenty-five-gram subsamples of sieved samples were first dispersed in 100 mL of 5 g·L^{-1} sodium hexametaphosphate by shaking overnight in a reciprocating shaker. The dispersed soil that was retained on a 53 μm sieve was dried overnight at 60°C before analysis for organic C. These samples, along with twenty-five-gram subsamples of sieved samples used to determine SOC, were ground overnight in a roller-mill (consisting of round bottles with three metal rods inside to pulverize the samples) to a size passing a 150 μm screen and analyzed for C content with an Elementar Vario Macro C-N analyzer (Elementar Americas, Inc., Mt. Laurel, NJ).

2.2.3. Plant Biomass and Roots

Plant biomass was determined by clipping a 1-m^2 plot in each replication of each species in August 2005. Plant biomass samples were dried at 60°C to a constant weight. Root mass was determined from six core samples collected in each grass species and replication with a 5-cm diameter soil probe to a depth of 15 cm.

2.2.4. Statistical Analyses

Statistical analyses were performed using procedures of SAS version 9.1 [45]. Analyses of variance (ANOVA) were performed with Proc Mixed using a randomized complete block with three replications as the model. Grass species was considered the main effect and the blocks were considered as a random effect. When depth

was evaluated, the statistical design was a split-plot with depth as a subplot. Statistical differences were evaluated at the $P \leq 0.05$ level, with the exception of SOC concentration which was evaluated at the $P \leq 0.10$ level, as discussed later.

3. RESULTS

3.1. Soil Physical Properties

Sand and clay content of the surface revealed no significant differences among grass species; however, there were differences among depths (**Table 1**), but no interactions among grass species and depths. The surface 0 - 5 cm contained more sand and less clay than the 5 - 15 cm layer. Among all grass species, the surface had 21.6% clay and 54.4% sand and the second layer had 26.5% clay and 48.3% sand. Despite significant differences in the amount of clay and sand particles between depths, the texture for both depths was a sandy clay loam.

Although the surface 0 to 30 cm total soil water content, taken immediately prior to PR measurements, was not significantly different among grass species (**Table 1**), there was a slight difference in water content with depth. There were no interactions among grass species and depths. The surface 0 - 5 cm had significantly higher water content of about 30.5% while the other depthswere not significantly different and averaged about 23.0% soil water (**Figure 1**).

Soil strength measurements, as determined by PR, identify zones of resistance to an applied force. **Figure 1** shows how PR differed among grass species and among depths within grass species, but the effect of species did not depend on depth (**Table 1**). The lowest strength was
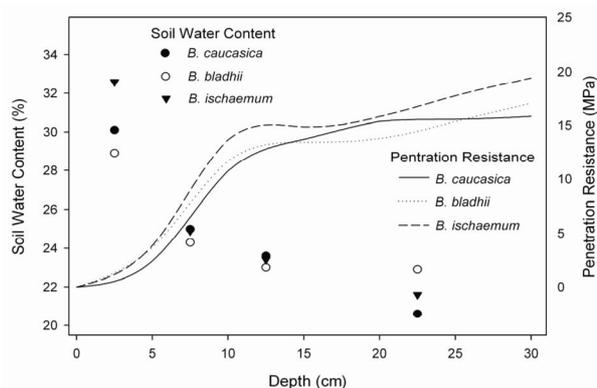

Figure 1. Soil water content and penetration resistance by grass species and depth.

Table 1. Differences among old world bluestem grass species for selected soil and plant properties.

Property	Depth (D)	Treatment (T)	DxT	*B. caucasica* Mean	Standard Error	*B. bladhii* Mean	Standard Error	*B. ischaemum* Mean	Standard Error
		Source of Variation							
Clay Content (%)	<0.0001	0.3	0.6	24	0.7	24.9	0.7	23.3	0.7
Sand Content (%)	0.0004	0.3	0.6	51.3	1.1	50.2	1.1	52.6	1.1
Above Ground Biomass (kg)	N/A	0.0007	N/A	4402.0a	211.6	4148.8a	211.6	2265.3b	211.6
Root Biomass (kf·m⁻³)	N/A	0.003	N/A	10.2b	1.06	11.6b	1.06	15.5a	1.06
Soil Water Content (%)	<0.0001	0.72	0.8	24.8	0.84	24.8	0.84	25.6	0.84
Penetration Resistance (Mpa)	N/A	0.04	N/A	10.6b	0.5	11.3ab	0.5	12.7a	0.5
Bulk Density (mg·m⁻³)	<0.0001	0.03	0.8	1.36a	0.01	1.33ab	0.01	1.31b	0.01
MWD (mm)	<0.0001	<0.0001	0.04	5.16	0.11	5.04	0.1	5.67	0.11
WAS2 (%)	0.02	0.02	0.1	49.5b	2.88	51.4ab	2.9	55.8a	2.87
SOC Concentration (g·kg⁻¹)	<0.0001	0.03	0.05	14.3	0.6	15.7	0.6	16.5	0.6
SOC Mass (MG·ha⁻¹)	N/A	0.09	N/A	26.7b	0.55	27.8ab	0.55	28.8a	0.55
POC Concentration (g·kg⁻¹)	<0.0001	0.005	0.02	5.89	0.37	8.06	0.37	7.95	0.37
POC Mass (MG·ha⁻¹)	N/A	0.04	N/A	9.85b	0.63	12.54a	0.63	12.5a	0.63

Notes: MWD-mean weight diameter; WAS2-wet aggregate stability for aggregates 1.0 - 2.0 mm diameter; SOC-soil organic carbon; POC-particulate organic matter carbon; C and POC mass (MG/ha) represent the total for the 0 - 15 cm depth; Mean clay and sand content, SOC concentration, MWD, WAS2, bulk density, and root mass were measured through a depth of 0 - 15 cm (0 - 5 and 5 - 15 cm depth increments). Soil water content was measured through a depth of 0 - 30 cm (0 - 5, 5 - 10, and 15 - 30 cm depth increments) and penetration resistance was totaled throughout the 0 - 15 cm depth. Significance levels for testing differences among grass species (Treatment) and soil depth (Depth) are indicated by lower case letters. Means within the row with the same letter for SOC mass (MG/ha) are not different among grass species ($P \leq 0.10$). Means within the rows with the same letter for other comparisons among grass species are not different ($P \leq 0.05$). Properties with no letter are not significantly different among grass species ($P > 0.10$) or have interactions of depth and grass species (DxT).

in the surface 0 - 5 cm and increased with soil depth as soil water content decreased (**Figure 1**). We observed significant differences soil strength among species when PR was summed over the 30 cm depth for each species and replication (**Table 1**). *Bothriochloa ischaemum* produced the greatest total resistance to the cone penetrometer and *B. caucasica* had the smallest total resistance. The PR observed in *B. bladhii* was not significantly different from either of the other grass species (**Table 1**). The mean PR was also determined for the 0 - 5 cm and 5 - 15 cm depths and PR by species. The surface 0-5 cm soil strength in the grasses was, on average, about one-fourth the strength found in the 5 - 15 cm layer. Averaged over all species, PR was 6.6 Mpa·cm^{-1} (SE = 0.55) in the surface 0 - 5 and 26.0 Mpa·cm^{-1} (SE = 0.55) in the 5 - 15 cm depth.

Another measure of soil compaction, BD, differed among grass species and among depths within grass species, but the effect of species did not depend on depth (**Table 1**). Averaged over all species, BD was 1.25 Mg·m^{-3} (SE = 0.005) in the surface 0 - 5 cm and 1.41 Mg·m^{-3} (SE = 0.005) in the 5 – 15 cm depth. *Bothriochloa caucasica* had the highest BD (1.36 Mg·m^{-3}) and *B. ischaemum* had the lowest (1.31 Mg·m^{-3}). The bulk density observed in *B. bladhii* was not significantly different from either of the other grass species (**Table 1**).

The mean infiltration rate was 0.97 cm·hr^{-1} (SE = 0.08). Water infiltration readings are very time consuming and variable. Although we made two water infiltration readings on each replication, the double ring infiltration method used in this study still produced significant variation. Given the variability of this method, statistical tests lacked power to be able to detect biologically significant differences.

Wet aggregate stability is a measure of the strength of bonding of individual soil particles into larger aggregates to withstand the force of disruption caused by agitation in water. Two measures of wet aggregate stability were tested; a measure of the stability of large aggregates less than 8 mm diameter, MWD, and a measure of the stability of smaller 1 to 2 mm diameter aggregates, WAS2. These tests produced the same general result, although WAS2 had no interaction between grass species and depth (**Table 1**). In general, the plots with *B. caucasica* had the lowest wet aggregate stability and plots with *B. ischaemum* had the greatest wet aggregate stability (**Tables 1** and **2**). Plots with *B. bladhii* were not significantly different from plots with either of the other grass species. Often, within grass species, the surface 0 - 5 cm had a greater wet stability than the 5 - 15 cm depth. Wet aggregate stability measured by WAS8 had the same MWD with depth in plots with *B. caucasica* and the same percent stability with depth in plots with *B. is-*

Table 2. Differences by depth among old world bluestem grass species for selected soil properties.

Grass Species	Depth (cm)	SOC (g/kg)	POC (g/kg)	POC/SOC Ratio	MWD (mm)
B. caucasica	0 - 5	18.0b	9.1b	0.50b	5.43bc
B. baldhii	0 - 5	21.1ab	13.2a	0.63a	5.65ab
B. ischaemum	0 - 5	22.0a	12.7a	0.57ab	6.07a
B. caucasica	5 - 15	10.6c	2.7c	0.25c	4.89cd
B. baldhii	5 - 15	10.4c	2.9c	0.28c	4.44d
B. ischaemum	5 - 15	10.9c	3.2c	0.29c	5.26bc

Notes: SOC-soil organic carbon, POC-particulate organic matter carbon, MWD-mean weight diameter of wet sieved aggregates. Values with the same letter within columns are not significantly different at the *P* = 0.05 level.

chaemum. Wet aggregate stability measured as MWD or percent stability was significantly different by depth (*P* < 0.05) in plots with *B. bladhii* (**Table 2**).

3.2. Soil Chemical Properties

Soil organic carbon and POC concentration (g·kg^{-1}) were each different between depths (**Table 1**). The greatest concentrations of SOC and POC were found in the surface 5 cm, with about twice the amount of SOC in the surface as in the next 10 cm (**Table 2**). The mean SOC concentration for the surface 5 cm was 20.3 g·kg^{-1} (SE = 0.46) and the 5 - 15 cm layer had 10.6 g kg^{-1}·C (SE = 0.46). The mean POC concentration for the surface 5 cm was 11.7 g·kg^{-1} (SE = 0.20) and the 5 - 15 cm layer had 2.9 g·kg^{-1} C (SE = 0.20). Soil with *B. ischaemum* had greater quantities of SOC and POC in the surface 0 - 5 cm than soils with *B. caucasica,* with no differences among species in the 5 - 15 cm depth (**Table 2**). Soils with *B. bladhii* had the same SOC and POC content as both other species (**Tables 1** and **2**).

When SOC and POC contents were computed on a mass per unit surface area basis, SOC content was different among grass species at the *P* = 0.1 level while POC content was different among grass species at the *P* = 0.05 level (**Table 1**). *Bothriochloa ischaemum* had the greatest SOC and POC mass (MG·ha^{-1}) and *B. caucasica* had the least SOC mass. The SOC mass observed in soil with *B. bladhii* was not different from either of the other grass species. The POC mass observed in soil with *B. bladhii* was not different from only *B. ischaemum*.

3.3. Plant Biomass and Roots

The above-ground plant biomass (herbage) of the grasses differed among species (**Table 1**). The least amount of herbage was produced by *B. ischaemum*, which had about one half the amount of above-ground biomass produced by *B. caucasica* and *B. bladhii*. Interestingly, this is the inverse of the amount of root biomass observed for each grass species. *B. ischaemum* had the

greatest total root biomass in the 0 to 15 cm depth, whereas *B. caucasica* and *B. bladhii* had the least but similar amounts of root biomass (**Table 1**)

4. DISCUSSION

Soil texture can have a significant impact on soil properties that are important for crop growth. For example, a sandy clay loam soil will hold more plant available soil water than a sandy soil. In this study, although there were no differences in the surface sandy clay loam soil texture among grass species plots, we did observe statistical differences in the amount of primary soil particles such as clay content by soil depth (**Table 1**). However, the differences in clay and sand content among grass species were not practically different, with an absolute mean difference of only 1.2% and 2.4% for clay and sand, respectively. The similarity in texture of all plots suggests soil texture was not a factor in differences found in the other variables observed in this study.

Although there were no differences in surface soil texture among grass species, we did observe differences in plant growth. *Bothriochloa caucasica* and *B. bladhii* produced about twice the above-ground biomass with about 25% fewer roots than *B. ischaemum*. These results are consistent with previous research conducted within these plots showing lower aboveground biomass production of *B. ischaemum* than either *B. bladhii* or *B. caucasica* [1,34]. Although these grasses had been grazed or cut in the past, management was similar among these grasses and did not explain differences in productivity. The differences in plant properties seem to have contributed to the differences observed in soil properties.

The differences in root biomass among grass species may have produced differences in soil BD. The grass species plots with the higher soil bulk density (*B. caucasica*) also had the lowest root biomass. The BD values of plots with *B. bladhii* were not different from BD of the plots of the other grasses (**Table 1**). Lower BD in plots with more roots was expected because the mass per unit volume of roots is much lower than the mass per unit volume of the mineral soil material. In addition, when roots decompose they often leave pores that further contribute to a reduction in BD.

Plant roots also add carbon to the soil matrix as demonstrated in this study. The differences among plots in root mass paralleled the differences found in SOC. *Bothriochloa ischaemum* had the greatest root mass and SOC and POC and *B. caucasica* had the least. This trend is the inverse of the trend found in BD, with *B. ischaemum* having the lowest BD and *B. caucasica* the greatest. This is consistent with many past studies where BD and SOC were inversely related [30,46-48]. This apparently anomalous result is explained by considering that roots

contribute organic material to the soil matrix, causing SOC to increase, and also function to decrease the density as described above.

Soil resistance is strongly influenced by both soil water and bulk density [49,50]. **Figure 1** shows the penetration resistance and soil water content measurements by grass species for the 0 to 30 cm depth. The ANOVA of penetration resistance in **Table 1** was performed for only the 0 to 15 cm depth to correspond to the depths observed for bulk density. There were no differences in mean soil water content among grass species, although there were differences in soil water content by depth (**Table 1**). In addition, since there were no interactions of grass species with depth of soil water content, it was not considered a factor in affecting the BD and soil strength results.

The surface 0 - 5 cm had the greatest water content and lowest BD and soil strength. Soil BD and PR are quite variable but are often positively correlated [51]; however, *B. ischaemum* produced a higher PR than *B. caucasica*, which was the inverse of the mean soil BD observations. Rachman *et al*. [52] found a negative correlation of soil strength with BD. Although they did not use an *in situ* cone penetrometer test to measure soil strength as in our study, their soil strength test used a falling cone on intact soil cores and the results can be considered analogous. They interpreted their results to indicate that differences in soil strengths were related to differences in aggregate stability. They and others have concluded that soil management and cropping systems that accumulate organic matter which, in turn, reduce the soil's vulnerability to slaking and dispersion on wetting, increase the soil's resistance to penetration by a dropped cone [52,53].

This relation of soil strength and aggregate stability is supported by our results of the wet aggregate stability tests described in **Tables 1** and **2**. The tests showed that, similar to the trends shown for PR, the aggregate stability of *B. ischaemum* (WAS2) was significantly greater than the stability of *B. caucasica*. The wet aggregate stability (WAS2) in *B. bladhii* was not different from the other grasses (**Table 1**). Additionally, the tests showed that *B. ischaemum* broke down into larger aggregates upon wetting (MWD in **Table 2**), suggesting greater stability. Differences in wet aggregate stability with depth shown in **Table 2** are complicated but, in general they show greater stability for the less dense and resistant surface layer.

Many studies have shown a positive correlation of SOC and aggregate stability [22,52,54,55]. In this study, the trends in SOC and POC mass followed those found for wet aggregate stability; *B. ischaemum* had a greater SOC and POC mass than *B. caucasica*, and the SOC

mass for *B. bladhii* was not different from either of the other grasses (**Table 1**). As mentioned earlier, the greater values for SOC and POC mass are attributed to the greater root biomass found in the soil of the *B. ischaemum* treatment (**Table 1**). The greater root biomass produced more carbon and root structures and chemical binding agents to improve the wet aggregate stability found in the soil of the *B. ischaemum* treatment. **Figure 2** illustrates the similar trends of wet aggregate stability, SOC content, and root biomass.

Studies suggest that POC is more sensitive to changes in management than changes in total SOC [17,18,56]. This is attributed to the faster turnover rate of POC compared with SOC [17,30]. An Australian Vertisol lost organic carbon upon conversion from pasture to cropland with 70% of the loss in SOC coming from POC [57]. The POC/SOC ratio has been used to indicate differences among locations of grass communities in the Argentinean Pampa [30]. Noellemeyer *et al.* [30] found a ratio of 0.54 for communities in the shade and 0.39 for communities in the sun. All of our plots were in full sun. We found differences in the POC/SOC ratio in the surface 0 - 5 cm among bluestem species that paralleled the findings of the individual SOC and POC results (**Table 2**). *Bothriochloa caucasic* had a POC/SOC ratio of 0.50 while *B. bladhii* had a significantly greater ratio of 0.63. The POC/SOC ratio of plots with *B. ischaemum* was not different from the ratios of the plots of the other grasses (**Table 2**). The SOC and POC values were much lower for the 5 - 15 cm layer causing the POC/SOC ratios to be about on half that of the surface 5 cm. The SOC in the second layer was about on half that of the
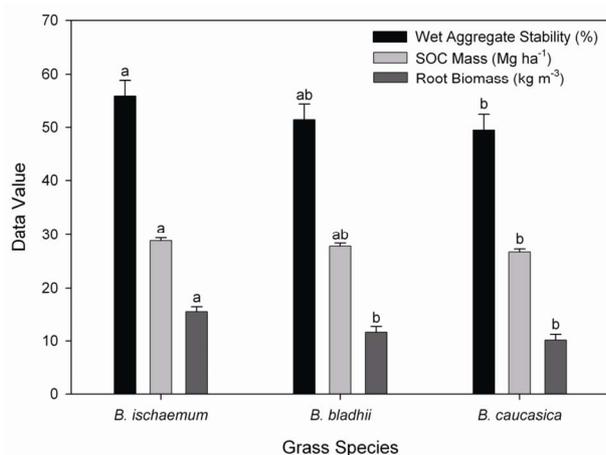
surface while the POC of the second layer was from about one quarter to one third that of the surface layer, supporting a faster turnover rate for the POC in this study.

Since SOC is a key attribute of soils that impacts erosion control, soil structure, water infiltration, conservation of nutrients and other soil properties, the stratification of SOC has been proposed as a simple diagnostic tool to identify land management strategies that improve soil properties [58,59]. In a study comparing plots under long-term conventional and no-tillage, Franzluebbers [59] found the stratification of SOC at shallow depths (the ratio of the SOC at 0 - 3 cm depth divided by that of 6 - 12 cm depth) increased as water infiltration rate and wet stability (as measured by the MWD) increased and was inversely related to BD and PR. Thus, the SOC stratification ratio (SOCSR) tended to increase with soil properties indicating increasing soil quality for plant growth. In our study, the SOCSR was determined as the ratio of the SOC at 0 - 5 cm depth divided by that of 5 - 15 cm depth. *Bothriochloa caucasic* had a mean SOCSR of 1.70 (using data provided in **Table 2**) while *B. bladhii* and *B. ischaemum* were the same, with SOCSRs of 2.03 and 2.02, respectively. These ratios are similar to SOCSRs observed in a study of a silty clay loam soil under no tillage management in south central Texas [58]. Although we did not discern differences in water infiltration among grass species in this study, the trends of SOCSR with the MWD of the 0 - 5 cm depth, bulk density, and penetration resistance were similar to those reported by Franzluebbers [59]. *Bothriochloa caucasic* had the lowest SOCSR, suggesting a lower soil quality than *B. bladhii* and *B. ischaemum*, which were the same.

5. SUMMARY AND CONCLUSIONS

Several Old World Bluestem grass species are commonly used in the Southern High Plains in forage management systems and as conservation reserve grasslands species. Although studies have identified differences in growth and production among these species, little is known about how they affect soil properties. The results of this study support the hypothesis that differences in grass species produce differences in soil properties. The grass species differed in their above-ground biomass and below-ground root production. *Bothriochloa caucasica* and *B. bladhii* produced about twice the above-ground biomass with about 25% less root mass than *B. ischaemum*. This may help to explain observed differences in plant persistence under dryland conditions. The greater root biomass of the *B. ischaemum* also produced a lower soil bulk density than the other species. Although we expected that the density would affect soil strength, this was not the case. Although the soil in which *B. ischae-*

Figure 2. Wet aggregate stability (1 - 2 mm diameter, %), soil organic carbon (SOC) mass (MG·ha^{-1}) and root biomass (kg·m^{-3}) by grass species. Means with the same letter, by data type, are not significantly different at the $P = 0.05$ lever for wet aggregate stability and root biomass and at the $P = 0.10$ level for SOC mass.

mum was growing had a lower bulk density, it had the greatest soil strength. The soil strength was greatest in *B. ischaemum*, which also had the greatest root biomass, organic matter content, and aggregate stability. These three characteristics are related. The root biomass increases the organic matter of the soil. The organic matter provides energy for microbial populations and other soil fauna which produce materials that bind soil particles into aggregates. In addition, roots may provide additional particle aggregation through effects of root exudates and very small root structures.

The species *B. bladhii* usually exhibited desirable soil properties that were similar to both other species tested. Since *Bothriochloa bladhii* also has been shown to be higher in forage quality, animal performance, and carrying capacity than *B. ischaemum,* it appears to be the best choice among these three species to optimize both animal performance and desirable soil properties.

6. ACKNOWLEDGMENTS

7. NOTES

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