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Short-Term Impacts of Pecan Waste By-Products on Soil Quality in Texturally Different Arid Soils

Omololu John Idowu[a], Soumaila Sanogo[b], and Catherine Elizabeth Brewer[c]

[a]Department of Extension Plant Sciences/Department of Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM, USA; [b]Department of Entomology, Plant Pathology and Weed Sciences, New Mexico State University, Las Cruces, NM, USA; [c]Department of Chemical and Materials Engineering, New Mexico State University, Las Cruces, NM, USA

ABSTRACT
Three arid soils (clay loam (CL), sandy clay (SC), and sandy loam (SL)) were amended with pecan waste products (ground pecan shells (PSHs), ground pecan husks (PHUs), and ground pecan shell biochar (PSB)), at a rate of 45 Mg/ha, packed inside cylindrical rings and kept in a humid chamber for 4 weeks. Measurements taken included volumetric moisture content as the soil dried out for 7 days, wet aggregate stability (WAS), permanganate oxidizable carbon (POXC), nitrate-nitrogen, extractable phosphorus (Olsen-P), and water-extractable potassium (K). Significant effects of soil texture, soil amendment, and their interaction were observed for all measurements. Generally, the amendments led to significant improvement in Olsen-P, K, POXC, and WAS, while amendments' impacts on soils of different textures varied. Short-term moisture retention was dependent on soil texture, with PHU and PSB treatments having higher soil moisture retention in SL and CL soils but not in SC soil.

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Introduction

Soil quality, which relates to the capacity of the soil to function and support important ecosystem services (Doran and Parkin 1994), has continued to receive attention among scientists, farmers, and soil managers, especially with the current challenges of climate change and agricultural sustainability. The main objective of soil quality management is to use the soil in a sustainable manner without degradation to the environment. Central to the functioning of the soil is the quality and quantity of the soil organic matter (SOM) (Haynes 2005). Therefore, in assessing and managing soil quality, great importance is placed on the quantity and the quality of the SOM, since organic matter influences several other soil quality indicators such as aggregation, microbial activity, water retention, and nutrient status (Cater 2002).

Arid soils are often characterized by very low levels of SOM. With low organic matter, the soil is subject to rapid degradation through wind and water erosion, poor moisture-holding capacity, and poor structure; therefore, the capacity to support crop production in arid soils is affected. Apart from low organic matter contents, other challenges affecting soil quality improvement in arid regions include low amounts of rainfall, high temperatures, and sparse vegetation cover (Idowu and Flynn 2013; Unger 1991).

Organic matter improvement of arid soils is particularly difficult to achieve, mainly due to lack of easily available organic materials that can be added to the soil. With the recent recurrent droughts in the arid southwestern USA, farmers and other land users have found it very difficult to engage in

CONTACT Omololu John Idowu jidowu@nmsu.edu; johnidowu@yahoo.com Department of Extension Plant Sciences, New Mexico State University, MSC 3AE, PO Box 30003, Las Cruces, NM 88003-8003.

classic cultural methods that could build up SOM. For example, successfully raising cover crops for building SOM puts demand on already limited irrigation water resources (Idowu and Grover 2014). In situations where farmers do not have enough water to grow a targeted acreage of cultural crops, it becomes difficult to engage in cover cropping due to lack of water. Other land managers have suggested using manures to build SOM; however, transportation costs and salinity concerns have limited the use of manure as an amendment for building SOM (Eghball and Power 1994; Hao and Chang 2003; Li-Xian et al. 2007).

To address the organic matter deficits in arid soils and to improve soil quality, it is imperative to look beyond conventional sources of soil organic materials and explore alternative biological wastes as potential sources of organic materials that can be added to the soil.

An attractive option to improve SOM and soil quality is to amend soil with locally available biomass streams often regarded as waste. Pecan tree [*Carya illinoinensis* (Wangenh.) K. Kock] residue is an example of locally generated biomass that is abundant in Doña Ana County, located in southwestern New Mexico. Considerable amounts of pecan wood trimmings, pecan shells (PSHs), and pecan husks (PHUs) are generated annually as biomass wastes. New Mexico ranks third in highest pecan nut production in the USA, with >17,000 pecan orchards over >15,800 ha across the state; Doña Ana County has the highest production at approximately 19,500 Mg annually (Lillywhite et al. 2010). The estimated amount of PSHs produced annually from processing in pecan-producing areas of New Mexico and west Texas ranges from 14,000 to 26,000 Mg.

PSH is a waste by-product that results from cracking and shelling of pecan nuts. PSHs are often sold by commercial pecan-processing plants as mulching material. PHU, or shuck, is the exocarp tissue of the pecan flowers, while the nut forms from the endocarp which encloses the seed. When pecan fruits reach their full size in summer, the husks crack open, dry, and fall off, leaving the pecan nuts. The husk usually represents 25–30% of the total mass of the pecan, thereby providing considerable amount of biomass from the pecan tree.

An increasingly attractive method to improve the efficiency of biomass as soil amendment is to first convert the biomass to biochar before soil application (Sohi et al. 2010). Using biochar instead of raw biomass as soil amendment may provide significant benefit for soil quality improvement and crop yields (Jeffery et al. 2011). Biochar may also help sequester higher levels of carbon in the soil since the process of pyrolysis concentrates higher amounts of stable carbon into biochar, compared to the microbially mediated oxidative decomposition of organic materials (Lehmann 2007).

Relatively few studies have examined the impact of pecan-based waste products on soil quality. Tahboub, Lindemann, and Murray (2008) applied pecan wood chips as a soil amendment in an arid soil in the southwestern USA, and found significant improvement in soil tilth and aggregation. They also found that repeated application of pecan wood chips at high application (18 Mg/ha) rates led to increased SOM content. Soil salinity was unaffected by the incorporation of the pecan wood chips and pH did not change significantly, except in treatments where ammonium sulfate was applied along with the wood chips (Tahboub, Lindemann, and Murray 2008).

Studies with pecan-based waste products, especially in the southeastern USA, have focused on the use of pecan shell biochar (PSB) as a soil amendment. Novak et al. (2009) studied the impacts of PSB on soil fertility of Coastal Plain soils in the United States. Coastal Plain soils are generally sandy and acidic, with low organic matter contents. They found that the addition of PSB to the soil led to increased soil pH, soil organic carbon, calcium (Ca), potassium (K), manganese (Mn), and phosphorus (P). Busscher et al. (2010) found that PSB decreased soil strength and increased soil water-holding capacity in Coastal Plain soils.

From these previous studies, pecan-based waste products appear to be promising for soil quality improvement. Farmers in the study region, especially organic producers, have expressed interest in applying these products as soil amendments. To decrease the likelihood of misuse and potential negative consequences, more information is needed about the effects of the pecan-based waste products on soil properties and nutrient availability in the first few weeks after application. Such information is useful in developing recommendations for application rate limits and possible waiting periods after application. This short-term incubation study attempts to answer how pecan waste materials affect selected soil quality indicators for soils common in arid regions. The objectives of this study were:

(i) to assess the short-term effects of three pecan waste products (PHUs, PSHs, and PSB) on selected soil quality indicators of three texturally different arid surface soils, as compared to soils without amendment, and

(ii) to assess the impact of the amendments on short-term soil moisture retention during water evaporation from the soil.

Materials and methods

The three different soils used in this study were sandy clay (SC) soil collected from Deming, NM, sandy loam (SL) soil, and clay loam (CL) soil collected from Las Cruces, NM (Table 1). These soils were collected from the field, air-dried, and passed through a 2-mm sieve before treatment application.

PSH, PSB, and PHU were ground to pass through a 1-mm sieve before use. Nutrient characteristics of the raw pecan by-products used for amendment are presented in Table 2. Soil treatments with amendments were compared to the non-amended control (CON) soils. The amendment application rate was about 45 Mg/ha, to represent the approximate upper limit of the rate at which growers in the study area apply organic amendments. PSB used for this study was obtained from a commercial vendor, while raw pecan shells and husks were sourced from local orchards in the study area. Amendment materials were carefully weighed out and thoroughly mixed with each of the three soils. After treatment application, the soils were slightly moistened and packed into cylindrical stainless steel rings (8 cm in diameter and 5 cm high) at a bulk density of 1.2 Mg m^{-3}. The soils were saturated and allowed to freely drain (to approximate field capacity), then incubated in a growth chamber for 4 weeks under a day temperature of 28°C and a night temperature of 20°C. Volumetric moisture content at field capacity was 15% for SL soil, 25% for SC soil, and 27.5% for the CL soil. Soil moisture was maintained at 85% of the initial field capacity while in the growth

Table 1. Characteristics of the soil collection sites.

	Site/soil characteristics		
Soil collection sites	Las Cruces, NM	Deming, NM	Las Cruces, NM
Coordinates	N 32.204223, W 106.749355	N 32.243684, W 107.858119	N 32.279397, W 106.774731
Soil Series	Glendale clay loam	Mohave sandy clay loam	Brazito
Elevation (m)	1,205	1,192	1,128
Mean annual rainfall (mm)	200 – 250	200 – 250	200 – 250
Soil texture (0–0.15 m)	Clay loam	Sandy clay	Sandy loam
Sand (%)	44.8	49.6	72.9
Silt (%)	22	10.6	11.9
Clay (%)	33.2	39.8	15.2

Table 2. Chemical properties of pecan by-product materials used as soil amendments.

Amendment	Organic carbon (%)	Phosphorus (mg/kg)	Nitrate-nitrogen (mg/kg)	Potassium (mg/kg)
Pecan husk	51.80	542.00	3.03	34750
Pecan shell	43.49	52.16	1.44	1510
Pecan shell biochar	71.5	168.71	0.66	1076
Soil name				
Glendale (Clay loam)	1.33	9.47	49.97	59.15
Mohave (Sandy clay)	0.90	11.02	9.61	50.15
Brazito (Sandy loam)	0.38	6.12	22.96	35.23

chamber. A period of four weeks was chosen to assess the impacts of the treatments under conditions similar to those in which the treatments were applied to the soil to support the early season crop growth.

After incubation, the soils in the rings were saturated, and dielectric VH400 moisture sensors (Vegetronix™ Inc., Riverton, Utah, USA) were installed inside the soils within the rings. Volumetric moisture content of a soil length of 5 cm was captured by the sensors. The soils were allowed to dry for 7 days under laboratory conditions (room temperature of 26.4°C) and the volumetric soil moisture (VMC) was recorded five times daily. After drying, the moisture sensors were removed and the data downloaded for further analysis. The soils in the rings were broken up, air-dried, and analyzed for multiple soil measurements.

Wet aggregate stability (WAS) was measured using the Cornell portable sprinkle infiltrometer (Ogden, Van Es, and Schindelbeck 1997), designed to measure soil infiltration capacity in the field and aggregate stability in the laboratory. Aggregates between 2 and 4 mm were collected from the broken-up soil samples, placed on a 2-mm sieve, and a simulated rainfall of 2.5 J of energy was applied for 300 s on the aggregates. WAS was calculated by expressing the amount of soil left on the 2-mm sieve after simulated rainfall as a percentage of the total soil initially placed on the sieve. Permanganate oxidizable carbon (POXC) was measured by the technique developed by Weil et al. (2003), while nitrate-nitrogen (N) concentration was measured in a water extract using a cadmium reduction column (Keeney and Nelson 1982). Sodium bicarbonate-extractable phosphorus (Olsen-P) was measured according to Olsen et al. (1954), and the K content was measured in water extract using inductively coupled plasma (ICP) spectroscopy (Cihacek 1983).

The study was conducted as a 4 × 3 factorial experiment with two factors, soil amendment (with four levels) and soil texture (with three levels), in a randomized complete block design with treatment combinations replicated four times. Analysis of variance was used to assess the statistical significance of the effects of soil amendment, soil texture, and their interaction on soil indicator measurements. Additionally, mean separation was performed using the Student–Newman–Keuls test after a significant *F*-ratio ($P \leq 0.05$) was detected. Daily volumetric moisture contents measured by moisture sensors were computed by averaging the five measurements captured by the sensors within a given day. Moisture contents measured on the first day after soil saturation were treated as baseline values for each treatment and were subsequently treated as covariate in the covariance analysis used to assess statistically significant differences in the daily volumetric moisture contents between different treatments. All statistical analyses were performed using SPSS statistical software (IBM, 2013).

Results and discussion

Analysis of variance showed significant effects of amendment treatments and soil texture for all measured soil indicator variables (Table 3). The mean separation of measurements under different amended treatments and soil textures is presented in Table 4. There was a significant effect of the

Table 3. Analysis of variance results of the treatment effects and interaction for measured soil indicators.

Indicators	Soil amendment (SA)	Soil texture (ST)	SA × ST
Extractable phosphorus	**	**	**
Nitrate-nitrogen	**	**	**
Extractable potassium	**	**	**
Permanganate oxidizable carbon	**	**	*
Wet aggregate stability	**	**	**

**: Statistical significance at the 1% level.
*: Statistical significance at the 5% level.

Table 4. Mean separation of amendment treatments and soil texture for measured soil quality indicators.

	Soil amendment				Soil texture		
Indicators	CON	PSH	PHU	PSB	SC	CL	SL
Extractable phosphorus (mg/kg)	8.87C	7.92D	12.02B	12.71A	13.46a	10.70b	6.99c
Nitrate nitrogen (mg/kg)	27.51A	3.50B	0.20B	20.79A	3.48b	18.30a	17.22a
Extractable potassium (mg/kg)	48.18B	53.71B	220.48A	64.64B	76.41c	96.60b	117.25a
Permanganate oxidizable carbon (mg/kg)	480.30B	482.44B	511.24A	475.58B	487.36b	471.51c	502.20a
Wet aggregate stability (%)	13.69D	23.63B	39.02A	17.93C	24.24b	30.51a	18.06c

CON: Control; PSH: Pecan shell; PHU: Pecan husk; and PSB: Pecan shell biochar
CL: Clay loam; SC: Sandy clay; and SL: Sandy loam
A, B, C, D: mean values followed the by same letter within a row are not significantly different at 5% level
a, b, c: mean values followed the by same letter within a row are not significantly different at 5% level

interaction of soil amendment and soil texture on soil indicator measurements, indicating that the impacts of soil amendments were varied across soil texture (Table 3).

Effect of soil amendment treatments

Olsen-P was significantly different between the treatments, with the PSB treatment having the highest Olsen-P level, closely followed by the PHU treatment (Table 4). Though the Olsen-P of the PSH treatment was significantly less than the CON, the difference between their values was just 0.95 mg/kg. Despite the very high levels of P in the raw PHU (542 mg/kg) and PSH (169 mg/kg), these high P levels did not translate into available P in the soil after 4 weeks of incubation (Table 2). This is likely due to P immobilization in the soil as the organic matter was broken down by microbes (Kruse et al. 2015). Based on soil test interpretation for soils of the studied area, Olsen-P value of <10 mg/kg is regarded as low, 10–20 mg/kg is regarded as moderate, while >20 mg/kg is regarded as sufficient (Flynn 2015). The P level was in the low range for PSH treatment and in the medium range for PHU treatment, indicating insufficient P availability for crop growth after 4 weeks of soil incubation despite a very high level of P in the raw materials. This suggests that supplemental P would be needed if PHU or PSH are used as soil amendments, especially in the short term. Though PSB treatment had the highest level of Olsen-P, the amount was still in the medium range (Flynn 2015) and may be insufficient for crop growth (Table 4). This means that a supplementary P fertilization may still be necessary if PSB is used as soil amendment, just less than the amount needed for the non-amended soil (CON), which was in the low Olsen-P range (Table 4).

N content was significantly higher under the CON and PSB treatments compared to the PSH and PHU treatments, which had very low nitrate (NO_3-N) contents (Table 4). Based on soil test interpretation for soils of the studied area, soil NO_3-N value of <10 mg/kg is regarded as deficient, 10–20 mg/kg is regarded as low, 20–30 mg/kg is regarded as moderate, while >30 mg/kg is regarded as sufficient (Flynn 2015). The low NO_3-N levels in the PSH and PHU treatments are probably due to immobilization of nitrogen by soil microbes decomposing these amendments (Schulten and Schnitzer 1997). With less microbial decomposition taking place in the CON and PSB treatments, significant NO_3-N remained in the soil. To avoid short-term nitrogen deficiency, nitrogen application may be necessary in soils receiving PSH and PHU amendments. The level of NO_3-N in the soil after applying PSH and PHU indicates severe nitrogen deficiency for most agricultural crops in the desert Southwest (Flynn 2015). On the other hand, soil NO_3-N levels in CON and PSB treatments were in the moderate range, indicating that little additional nitrogen would be needed to meet crop nitrogen requirements.

The K contents in the soil were not significantly different between the CON, PSH, and PSB treatments (Table 4), and the K levels in these treatments were in the sufficient range for crop growth and development (Flynn 2015). Based on soil test interpretation for soils of the studied area, water-extractable K value of <10 mg/kg is regarded as low, 11–30 mg/kg is regarded as moderate, 30–80 mg/kg is regarded as sufficient, while >80 mg/kg is regarded as excessive (Flynn 2015). For the PHU treatment, the K level was significantly higher than the rest of the treatments and was also in the excessive range (Table 4). The excessive K in the soil amended with PHU could present a crop management challenge in forage production systems since elevated soil K can lead to high K in pasture grasses, which can have harmful effects on animal health when consumed (Kayser and Isselstein 2005). When using PHU as soil amendment, application rates may need to be adjusted, depending on the crop, to avoid excessive K being released into the soil.

POXC is a measure of the labile carbon and is well related to many biological soil indicators such as substrate-induced respiration, basal respiration, microbial biomass carbon, soluble carbohydrate carbon, and total organic carbon (Weil et al. 2003). Only the PHU treatment had significantly higher POXC (Table 4). The higher POXC in the PHU treatment may be an indicator of higher microbial activity; such biological activity is supported by the very low NO_3-N in this treatment, indicating a high level of immobilization by microbes (Table 4). Therefore, adding PHU to the soil may enhance soil biological activity in the short term.

WAS was significantly affected by the amendment treatments, with all amended treatments having significantly higher WAS than the CON (Table 4). Aggregate stability under the PHU treatment was significantly higher than all the other treatments and 2.9 times the WAS of the CON. The WAS of the PSH treatment was 1.7 times the CON treatment, while the WAS of PSB treatment was just 1.3 times that of the CON. The higher level of stability achieved, especially under the PHU and PSH treatments, could have been due to the increase in microbial activity resulting from addition of organic materials. Microbial action on organic materials added to the soil has been shown to lead to improvement in soil aggregation, especially due to microbial products released into the soil during the process of decomposition (Six et al. 2004). Improvement in soil aggregation is very significant for arid and semi-arid soils, since these soils are easily subject to erosion by both wind and water due to their very low SOM. With improvements in aggregation, the soil will allow more water infiltration, more storage of soil moisture, and offer increased resistance to soil erosion.

Effect of soil texture

Though the textural effect was significant, the trend of significance varied with different measurements (Table 4). While Olsen-P was significantly higher in the SC and CL soils compared to SL soil, presumably due to the higher organic matter contents in the heavy-textured soils, the extractable K was significantly lower in the heavy-textured soils compared to the coarse-textured soil (Table 4). Application of the amendment materials led to significant higher retention of K in the sandy soil, which was already in the excessive range (Flynn 2015), indicating caution regarding application of soil amendment materials if animal forage crops are to be grown in the amended soil.

Although the N contents varied significantly among textural treatments (Table 4), the range among treatments was low to very low (Flynn 2015), indicating the need for supplementary N application when amending soils with tested materials.

Significant differences in POXC as a function of soil texture followed the order: SL > SC > CL (Table 4). Since POXC is an indicator of labile carbon, it is possible that the coarse-textured soil experienced higher levels of mineralization compared to the heavy-textured soils. Previous studies have shown higher amounts of mineralizable carbon (C) and N and basal respiration in coarse-textured soils compared to fine-textured soils (Franzluebbers et al. 1996; Hassink 1994).

Results of the stability of soil aggregates showed that the CL soil had the most stable aggregates followed by the SC soil, while the SL soil had the lowest WAS (Table 4). The higher aggregate stability in fine-textured soils may be the result of higher clay contents combined with labile SOM from the decomposing amendments. Clay-SOM complexes have been shown to be significant for soil aggregate stabilization (Six et al. 2004).

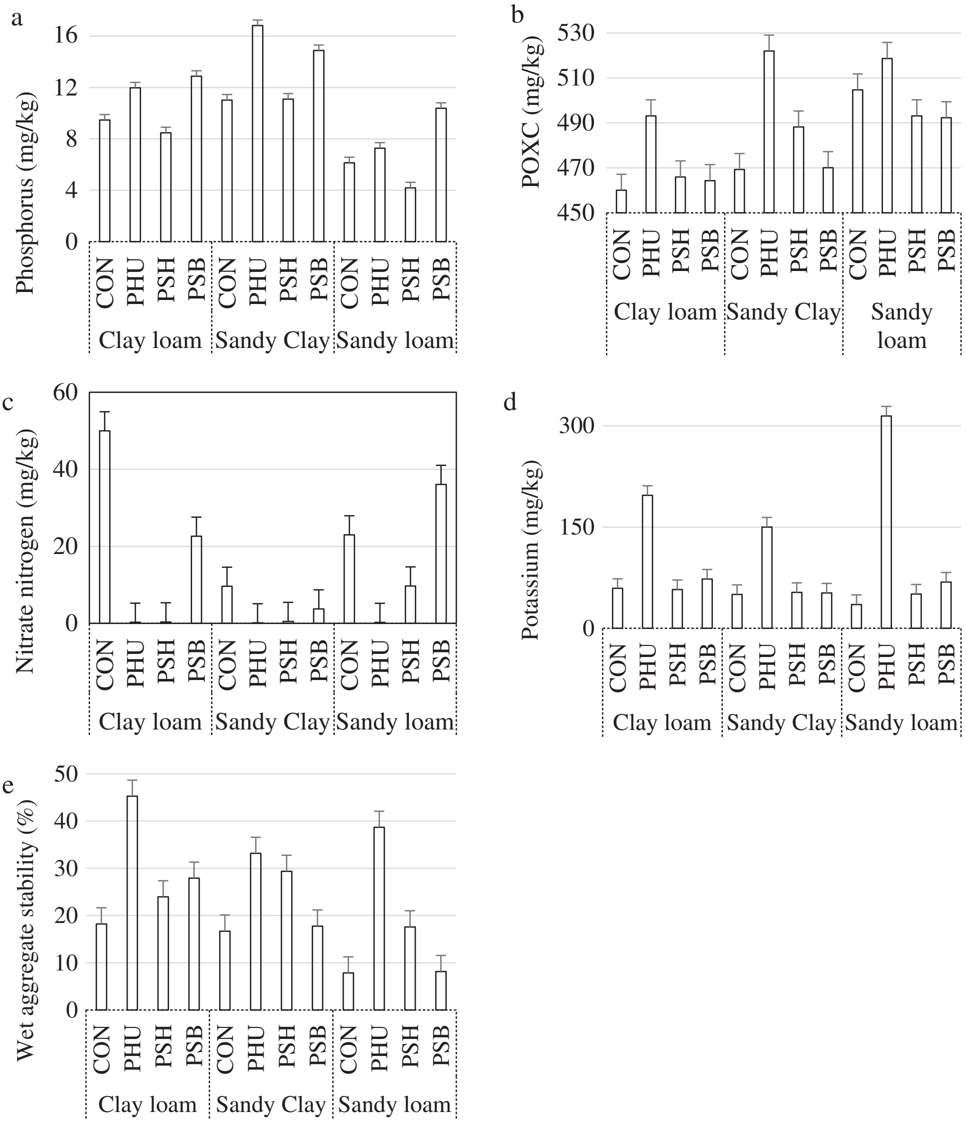

Figure 1. a–f. Mean values of soil measurements as a function of amendment treatments and soil texture.
CON: control; PHU: pecan husk; PSH: pecan shell; PSB: pecan shell biochar; and POXC: permanganate oxidizable carbon.

Interaction effects

All the measurements in this study show significant interaction effects at the 1% or 5% level (Table 3). The results of Figure 1(a–e) clearly show that the amendments exhibited varied responses in texturally different soils. While PSB had significantly higher Olsen-P than the PHU treatment in the CL and SL, the PHU treatment had higher Olsen-P in the SC (Figure 1(a)). POXC for PHU was significantly higher than the CON treatment in CL and SL, but both treatments were not significantly different in SL soil (Figure 1(b)). Similar variations in the response of the amendments to soil texture were also observed for the other indicators (NO_3-N, K, and WAS) that were measured (Figure 1(c-e)). Therefore, a generalization of the effects of these amendments cannot be assumed for all the soil types in the study area. Apart from soil texture, other factors, such as initial state of SOM and the diversity of soil microbes, could also be critical in soils' response to these amendments. More studies are needed that will focus on the mechanics governing the performance of these amendments in different soil types.

Effects of amendments on soil moisture

The effects of the amendment on soil moisture are presented in Figure 2–4. As expected, the VMC in all the soil types decreased through evaporation over a period of 7 days after the soil was saturated (Figure 2–4). In the CL soil, only the PSB treatment had significantly higher VMC compared to the CON on Day 2 and Day 3 (Figure 2). This changed on Days 4–6, with both PSB and PHU treatments having consistently higher VMC than the CON treatment (Figure 2). By Day 7, only the PSH retained significantly higher moisture than the CON, but at this point the VMC was already very low (<10%) (Figure 1).

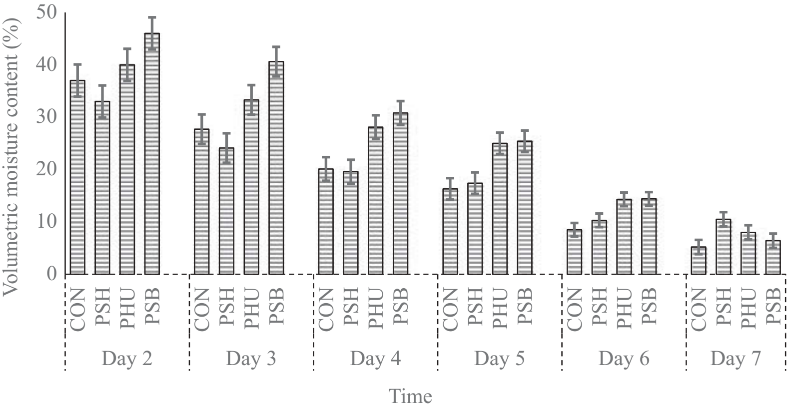

Figure 2. Volumetric moisture content of clay loam soil on different days after saturated soils were allowed to dry under laboratory conditions (standard error bars compare the treatment means within a given day only and not across the days). CON: control; PSH: pecan shell; PHU: pecan husk; and PSB: pecan shell biochar.

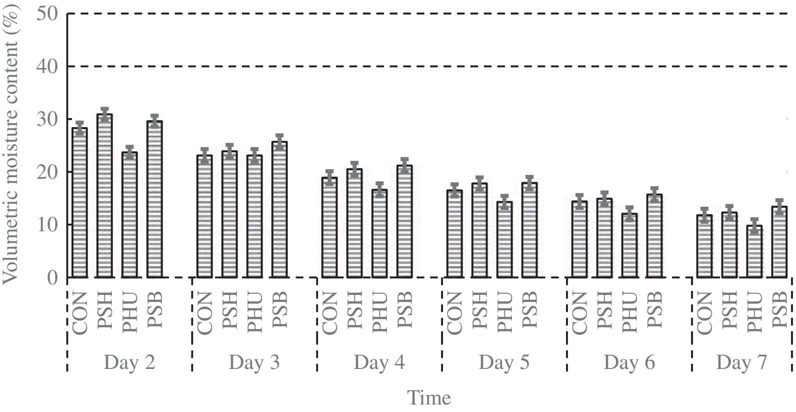

Figure 3. Volumetric moisture content of sandy clay soil on different days after saturated soils were allowed to dry under laboratory conditions (standard error bars compare the treatment means within a given day only and not across the days). CON: control; PSH: pecan shell; PHU: pecan husk; and PSB: pecan shell biochar.

In the SC soil, there were generally no significant differences between the CON treatment and the amended soils until Day 7 (Figure 3). PHU treatment had slightly lower VMC than the rest of the treatments. The specific reason why only PHU treatment depressed VMC was not clear, however, Rawls et al. (2003) reported a decrease in soil water retention in fine-textured soils as the organic matter content was increased. This may indicate that not only the quantity but also the quality of the added organic matter is important when analyzing how it affects moisture retention in texturally different soils.

In the SL soil, PHU and PSB treatments consistently showed higher VMC than the CON treatment from Days 2–5; by Day 7, there were no significant difference among the treatments (Figure 4). The performance of PSB in being able to hold more moisture in the soil compared to the CON treatment confirms earlier finding of Busscher et al. (2010). The soil moisture results clearly show that the effect of these amendments on soil moisture retention capacity was dependent on both the type of amendment and soil texture.

Variations in soil water retention behavior with changes in SOM content in soils of different textures were reported by Rawls et al. (2003). Generally, the sensitivity of water retention to changes is SOM was found to be higher in sandy and silty soils, especially when the soil had initially low SOM (Rawls et al. 2003). The finding of Rawls et al. (2003) was supported by this study, considering the fact that only SL and CL soils, which had high sand and silt contents, respectively (Table 1), gave positive soil moisture response to additions of organic amendments. The moisture content of SC soil, on the other hand, did not respond positively to the amendments added.

PHU and PSB appear to be promising for short-term soil moisture retention in CL and SL soils, while there appears to be no significant impact of amendments on soil moisture retention in SC soil. However, long-term impacts of these amendments need to be studied in different soils and under real field conditions to be able to better evaluate their soil moisture retention benefits for agricultural soils.

Conclusions

Significant improvements in selected soil quality indicators were observed with application of pecan biomass by-products as soil amendments. The observed improvements in soil aggregation and nutrient availability will prove beneficial in the short term for the poor-quality soils in the desert Southwest. The response of soil quality indicators to pecan by-product amendments was influenced

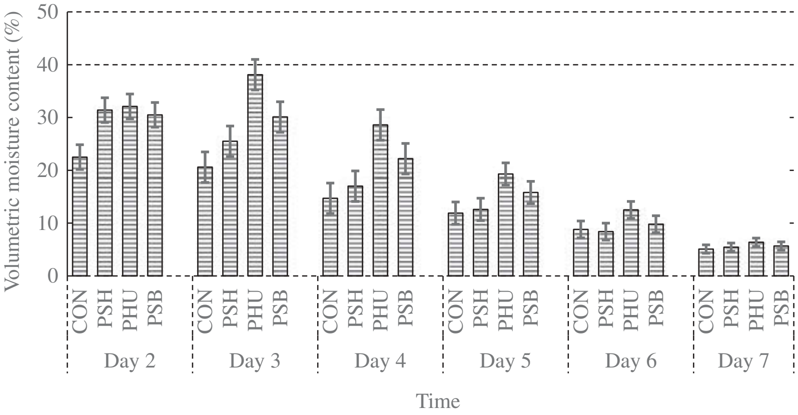

Figure 4. Volumetric moisture content of sandy loam soil on different days after saturated soils were allowed to dry under laboratory conditions (standard error bars compare the treatment means within a given day only and not across the days). CON: control treatment; PSH: pecan shell; PHU: pecan husk; and PSB: pecan shell biochar.

by soil texture and the responses to soil texture varied with different measurements. This indicates that soil type is an important factor for evaluating the benefits of these amendments.

The impact of the amendments on soil moisture retention during evaporation was also dependent on soil texture. Short-term soil moisture retention increases were observed in the SL and CL soils for pecan hulls and PSB treatments. Such an increase was not observed in the SC soil. This further reinforces the critical role of soil type in determining the performance of these amendments.

Field evaluations of pecan biomass by-products are needed in different soil types to document specific short- and long-term benefits of these amendments for soil quality of desert soils.

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