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AMENDMENTS TO INCREASE AGGREGATION IN UNITED STATES SOUTHEASTERN COASTAL PLAIN SOILS

Warren J. Busscher, Jeff M. Novak, TheCan Caesar-TonThat, and Robert E. Sojka

Many U.S. southeastern Coastal Plain soils have a cemented subsurface hard layer that restricts root growth and decreases productivity. Soil properties are improved by tillage but might also be improved by amending the soil. Wheat (*Triticum aestivum* L.) residue and polyacrylamide (PAM) were used to amend a Norfolk soil mix of 90% E horizon (the hard layer) and 10% Ap horizon (to assure microbial presence). Our hypothesis was that incorporation of wheat residue and/or PAM would improve physical properties, making the soil more amenable to root growth. Treatments contained 450 g of soil mix, 6.44 g kg^{-1} ground wheat stubble, and 0, 30, or 120 mg kg^{-1} of PAM (an anionic, linear formulation of size 12 MDa and 35% charge density). Duplicate sets of replicated treatments were incubated at 10% gravimetric water content for 30 and 60 days. Treatments were leached with 1.3 pore volumes of water. After leaching and equilibration to stable water contents, soil strengths were measured with a 3-mm-diameter flat-tipped bench-top penetrometer. At 30 days, the treatments were not significantly different; but at 60 days, treatments differed. Polyacrylamide decreased bulk density when added at the higher rate of 120 mg kg^{-1} to the soil. The higher PAM rate also decreased the amount of water that was added to maintain treatments at 10% water content. Wheat residue amendments decreased penetration resistances and increased aggregation. Wheat residue and PAM amendments improved soil physical properties, especially when treatments were allowed to incubate for 60 days. (Soil Science 2007;172:651–658)

Key words: Aggregation, polyacrylamide, penetration resistance, organic matter, wheat residue.

IN many southeastern U.S. coastal soils, high strengths (penetration resistances) develop especially in subsurface E horizons; strengths are high enough to retard root growth (Blanchar et al., 1978; Busscher et al., 2002). Strengths are typically managed by fracturing the E horizon with noninversion deep tillage that increases root growth and yield (Raper et al., 2000; Reeves and Mullins, 1995). In time, strengths rebuild and yields decrease (Arvidsson et al., 2001; Radford et al., 2001) in a process that takes anywhere from a few years (Busscher et al., 2002; Munkholm et al., 2001) to a growing season (Frederick et al., 1998). As a result, producers deep till annually at a cost of \$30–\$50 ha^{-1} (Khalilian et al., 2002) or more as a result of recent increased cost of fuels.

Coastal Plains Soil, Water, and Plant Research Center, USDA-ARS, Florence, SC. Dr. Busscher is corresponding author. E-mail: warren.busscher@ars.usda.gov

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Tillage can be reduced and costs lowered by adding soil amendments such as organic residue and PAM. It has been known for a long time that organic residue additions improve soil tilth (Waksman, 1937) and reduce strength (Free et al., 1947), even for soils such as those found in the Coastal Plain (Ekwue and Stone, 1995). The problem is that organic residues oxidize rapidly in warm climates because of high summer temperatures (Wang et al., 2000), and they do not increase over time, or they increase only near the surface (Novak et al., 1996). Longer lasting amendments are needed.

Another amendment that can reduce the need for deep tillage is polyacrylamide (PAM).

It can potentially reduce tillage by increasing soil aggregation which would disrupt the massive structure constituting the hard layer that is targeted by deep tillage. Polyacrylamide amendments also have the potential benefit of helping retain organic matter (OM) in the soil by incorporating it into aggregates where it can be protected from decomposition (Goebel et al., 2005; John et al., 2005), increasing the time that OM would be effective in the soil. In the early 1950s, older PAM formulations were used as soil conditioners (Weeks and Colter, 1952). Polyacrylamide and other conditioners were found to improve plant growth by reducing soil physical problems, stabilizing aggregates in the surface 30- to 40-cm depths. Unfortunately, the older formulations required hundreds of kilograms of PAM per hectare with multiple spraying and tillage operations. Newer longer-chain-polymer formulations and better purity have improved PAMs, making them more effective at lower concentrations. Water soluble PAM was identified as a highly effective erosion-preventing and infiltration-enhancing polymer, when applied at rates of 1–10 mg L^{-1} (10 g m^{-3}) in furrow irrigation water (Sojka et al., 1998b). Polyacrylamide achieved this result by stabilizing soil surface structure and pore continuity. Because the effect was limited to the surface few millimeters of soil, efficacy was achieved at application rates of 1–2 kg ha^{-1} per irrigation.

Additionally, PAM does not deteriorate as quickly as OM. When incorporated into soil, PAM degraded at rates of 10% per year as a result of physical, chemical, biological, and photochemical processes and reactions (Azzam et al., 1983; Tolstikh et al., 1992). Because PAM is highly susceptible to UV degradation, its breakdown rate when applied at the soil surface may be approximately 10% per year; but mixing it into the soil slows breakdown. Polyacrylamide is also slow to break down because microbial and chemical attacks are only on the ends of the polymers (Kay-Shoemake et al., 1998).

If mixing PAM into this coastal soil can develop aggregates, it would disrupt the massive structure of the soil and provide paths for root growth between aggregates, reducing the need for deep tillage. We hypothesized that adding low concentrations of a newer formulation of PAM to sandy coastal soils could increase aggregation thereby decreasing bulk density and soil strength.

Our objectives were as follows: (a) to improve the aggregation of sandy coastal soils by understanding how soil amendments affect the soil and (b) to improve soil physical characteristics that will increase the ability of soil to support plant root growth.

MATERIALS AND METHODS

Soil Type

Soil used in the experiment was Norfolk loamy sand (fine-loamy, siliceous, thermic *Typic Kandiudult* in the USDA classification or an Acrisol in the FAO classification). It was collected from a the edge of a 2-ha soybean research plot 2 km northwest of Florence, SC, while the soil was still at field moisture. It was removed from the field and pushed through a 10-mm sieve to remove debris. It was then air dried and pressed through a 2-mm sieve. The soil was massive in structure, abraded easily, and was difficult to penetrate when dry (Busscher et al., 2002).

Norfolk soil formed in Coastal Plain marine sediments; it was well drained with 1.2- to 1.8-m-deep seasonally high water tables. Over the years, the Ap horizon had been tilled to a depth of about 0.20 m. Below the plow layer, the soil had an eluviated E horizon that restricted root growth. The E horizon typically extended to depths of 0.30–0.45 m; it overlaid a sandy clay loam Bt horizon that extended beyond 0.6-m depth. General characteristics for Ap and E horizons were similar with differences based mainly on surface organic matter that was mixed into the Ap through such mechanisms as tillage and tree throws. The Ap and E horizons had 1–3 cmol kg^{-1} cation exchange capacity, 20–80 g kg^{-1} clay, and 2–20 g kg^{-1} of organic matter (Soil Survey Staff, 2006). In this experiment, the soil mix consisted of 90% E and 10% Ap horizon material on a dry weight basis; soil horizons were mixed together in a twin shell dry blender (Patterson-Kelley Co., Inc., East Stroudsburg, PA[1]) for 15 min and used as the treatment medium. The E horizon, the hardest horizon, was the intended medium of study; the 10% Ap horizon was added to assure that the soil would have a microbial presence that could decompose OM. The original texture of the soil was 71.2% sand, 26.5% silt, 2.4% clay for the Ap and 66.4% sand, 29.8% silt, 3.8% clay for

[1] Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

the E; the final soil mix had 66% sand, 30% silt, and 3.8% clay measured using the method of Miller and Miller (1987). The original OM content was 0.66% for the Ap horizon and 0.156% for the E; it was 0.19% for the mixture as measured on a LECO LN2000 (LECO Corp., St. Joseph, MI).

Treatments

Six treatments included all combinations of 450 g of soil mixed with 0 and 6.44 g kg^{-1} wheat stubble that had been ground to a fine powder in a Wiley Mill (6-mm mesh opening, Arthur Thomas, Co., Philadelphia, PA) and 0, 30, and 120 mg kg^{-1} PAM that was linear, anionic of size 12 MDa and 35% charge density (SNF Inc., Riceboro, GA). Organic matter and soil C/N ratios were brought to 20:1 by adding nitrogen in the form of NH_4NO_3 in amounts of 0.157 and 0.456 g kg^{-1} for the treatments with no wheat and wheat stubble, respectively. Treatments were replicated 3 times. Duplicate sets of treatments were prepared and incubated for periods of either 30 or 60 days.

Because a small amount of PAM was added to the soil, it did not mix well as a dry powder; as a result, PAM treatment amounts were dissolved into 45 mL of deionized water and sprayed onto the soil or soil and ground wheat straw while mixing it on waxed paper. Treatments were packed into 10-cm-diameter pots with a 20-mesh nylon screen on the bottom to prevent soil loss from drain holes. Treatments were packed to a bulk density of 1.2 g cm^{-3} by pouring amended soil into the pots and tapping them on the laboratory bench until the treatment mixture settled to a preset line.

Treatments were incubated in a laboratory that was maintained at an ambient temperature of 20–22°C and a mean humidity of 47% that ranged from 33% to 75%. Treatments were maintained at 10% soil-water content on a dry weight basis by weighing and adding water to the pots 2 to 3 times a week.

Measurements

At 28 and 56 days after the beginning of the experiment (about half way through the experiment and at the end of the experiment), pots were leached with 1.3 pore volumes (266 mL, based on the initial bulk density) of water. After pots were leached, they were drained, covered, and allowed to come to equilibrium; this took about 2 weeks. Then, penetration resistance (PR) measurements were taken to determine soil strength. Penetration resistance was measured at 42 and 73 days after the beginning of the experiment on the soil surface with a 3-mm-diameter, stainless-steel flat-tipped probe. The probe was attached to a strain gauge, and a motor geared to penetrate the soil at a rate of 0.28 mm s^{-1} to a depth of 5 mm. Strain gauge output was expressed in millivolts and read at a rate of 100 Hz on a CT-23X Micrologger (Campbell Scientific, Inc., Logan, UT) and subsequently uploaded to a desktop computer for analysis. After probing to 3- to 5-mm depth, PR output either reached a plateau or peaked. In either case, the mean of the top 10 values was used as the reading for each probing. Three probings were taken on the soil surface half way from the center to the edge of the pot at equally spaced positions around the circumference; data for these three probings were averaged and treated as a single data point. Data were converted from millivoltage to penetration resistance using previously developed instrument calibration PR = 0. 512V − 0.021 (r^2 = 0.99) where PR is probe resistance and V is voltage (Busscher et al., 2000).

During the incubation, it was noted that soil settled when water was added for leaching or to bring treatments back to 10%, especially in the early part of the experiment. To document this, soil bulk densities were measured at 14, 24, and 53 days from the beginning of the experiment. In the measurement of bulk density, the weight of the soil was known from the amount added at the beginning of the experiment; the volume was calculated from averages of the distance from the top of the pot to the soil surface at three points along the side of the pot and at the center of the pot. Earlier distances along the side of the pot had been calibrated against volume by sealing the drain holes at the bottom and filling the pot with water to several depths, giving a linear relationship $Vo = 28.0\ d^{1.3322}$ (r^2 = 0.99) where Vo is volume of the pot filled with water and d is depth of water in the pot. Volumes were combined with dry weights of each treatment to calculate bulk densities.

At the end of each treatment's incubation period, 30 or 60 days, soils were removed from pots, and a representative 100-g subsample was taken for aggregate analysis. Aggregate sizes were measured by sieving the subsample through a 4-mm screen and placing it into a nest of sieves with openings 2, 1, 0.5, and 0.25 mm and shaking the nest with an Octagon Digital Sieve Shaker (Endecotts, Inc., London, UK) that was run at a rate of 60 Hz with amplitude of approximately 3 mm for 1 min using the procedure of Sainju et al. (2003).

Data Analysis

Data were analyzed using analysis of variance and least significant difference mean separation procedure (SAS Institute Inc., 2000). When readings for the 30- and 60-day sets of treatments were considered together, the sets were considered main plots with treatments within sets as splits. After 30 days, only one set was available for analysis. Data were tested for significant differences at the 0.05 level unless stated otherwise.

RESULTS AND DISCUSSION

Aggregation

Although aggregates were measured on a nest of sieves (2, 1, 0.5, 0.25 mm), the fractions that remained on the 2 mm and the fraction that fell through the 0.25 mm were not analyzed as aggregates; the fraction more than 2 mm was considered to be a mix of loose organic residue with aggregates, and the fraction less than 0.25 mm was considered to be small aggregates mixed with individual primary soil particles. Not surprisingly, treatments with wheat residue amendments had higher weights on the >2-mm sieve (0.12% versus 0.02%) and less in the <0.25-mm range at 85.6% versus 88.5% when compared with nonamended treatments, indicating that the residue was improving aggregation. The 0, 30, and 120 mg kg^{-1} PAM-amended treatments had negligible differences on the >2-mm sieve with values of 0.06%, 0.07%, and 0.08% respectively. They also had less soil in the <0.25-mm range with values of 89.1%, 84.5%, and 87.6% for the 0, 30, and 120 mg kg^{-1} treatments, showing that the amendment was improving aggregation.

Aggregates analyzed fell in the range 2–1, 1–0.5, and 0.5–0.25 mm. At 30 days, percent aggregation (based on the ratio of aggregate to sample weight) did not differ among the three sizes.

The main effects of PAM and wheat residue amendments were significant, and their interaction was marginally significant (7%). Polyacrylamide and wheat residue were analyzed as main effects, and the interaction was taken into consideration briefly after that.

If aggregation was improving, its percentage was expected to increase with time as seen by others (Pranagal et al., 2005; Watts et al., 2001), and it did. When aggregation was averaged over all treatments, it was 7.3% at 30 days and 8.9% at 60 days (least significant difference [LSD] at 5% = 0.9). At 60 days, the smallest size had the most aggregates and amounts decreased with increasing size; the smallest size had 4.6%, next largest 2.1%, and largest 1.4% (LSD at 5% significance = 0.2). Increasing aggregation with time and more aggregates at smaller sizes are also indicative of improving aggregation as seen by Edwarda and Bremner (1967). They presented a conceptual model where the accumulation of OM was favored by the binding of organic carbon compounds to mineral surface through cation bridging and formation of microaggregates that would then bind together with additional persistent OM compounds to form larger aggregates. Finally, the treatment with no PAM and no wheat residue amendments in this experiment did not have a significant increase in aggregation with 4.9% at 30 days and 5.1% at 60 days.

In this experiment, the amount of aggregation generally increased with increasing amounts of PAM (Table 1 and Fig. 1) as seen by others (Sojka et al., 1998a), although the increase in this experiment was only significant for the 120 mg kg^{-1} treatment at 60 days. Aggregation increased with wheat treatments at both 30 and 60 days, as expected for a treatment with increased amounts of organic amendment (Krull et al., 2005); it implied that in our experiment, the main cause of aggregation was the wheat residue.

The interaction of PAM and wheat residue was only significant at the 7% level. Although the effect of PAM was considered secondary, it was more consistently significant when used with wheat residue amendment (Fig. 1) in

TABLE 1

Percent (%) aggregation developed during the experiment presented as averages for the main treatments of the amendments that ended on 30 and 60 days

Date	PAM (mg kg^{-1})†			Residue	
	0†	30	120	None	Wheat
30					
60					

†Treatments with 0, 30, or 120 mg kg^{-1} PAM and wheat or none added to amend the soil.

‡Means with the same letter are not significantly different based on the LSD mean separation procedure at the 5% level of significance for PAM or residue treatments across rows.

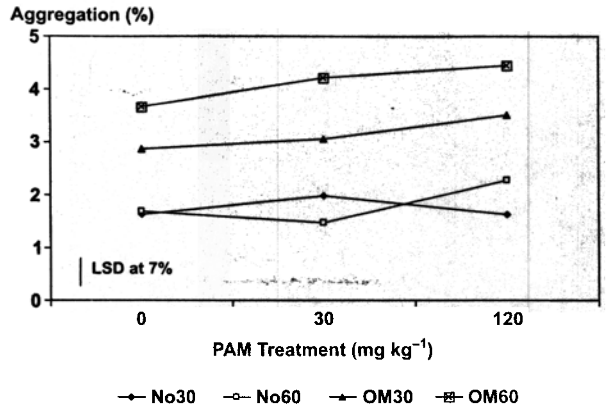

Fig. 1. Aggregation of treatments with no organic matter at 30 (No30) and 60 (No60) days and treatments amended with wheat at 30 (OM30) and 60 (OM60) days. The values shown in this figure are basically the interaction terms for the wheat and PAM treatment values shown in Table 1.

contrast to the results of Lu et al. (2002) where OM interfered with PAM effectiveness, although their results with loamy sand were not as pronounced as with their other soils.

Penetration Resistance

Penetration resistances were measured about 2 weeks after leaching because treatments needed to drain; after leaching, treatments were too wet to give significant readings. Drainage took place while treatments were covered with plastic wrap to prevent their surfaces from drying out. Drainage allowed treatments to come to equilibrium and to come to somewhat similar water content which was beneficial because penetration resistances could be affected by differing water contents with wetter soils having lower readings.

Water contents after drainage are shown in Table 2. Water content listed in the table were obtained from the weight of the treatment and as such were taken over the whole pot, whereas penetration resistances were taken in only the surface 5 mm of soil. There may have been differences in water content in the upper 5 mm that are not reflected in the readings and that may explain some differences in penetration resistance readings, although the pots were covered to maintain as uniform a soil treatment as possible.

For penetration resistance readings taken 42 days after initiation of the experiment, water contents differed for both the wheat and PAM treatments with values of 10.8% for the wheat treated soil and 10.0% for the treatment with no wheat. Water contents increased with PAM amendment for treatments with 0, 30, and 120 mg kg^{-1} PAM, respectively (Table 2). For penetration resistance readings taken 73 days after initiation of the experiment, water contents were not significantly different among treatments with values only ranging from 8.8 to 8.9 g g^{-1}. Water contents would have to be taken into consideration for the first date of penetration resistance measurement.

For either date of measurement, penetration resistance results were the same whether water content was added as a covariant in its statistical analysis, suggesting that the water content differences of 1.4% or less may not be enough to significantly alter results. Furthermore, regressions of penetration resistance with water

TABLE 2

Water contents and penetration resistances for treatments after they were covered and allowed to come to equilibrium for about 2 weeks

Date†	PAM (mg kg^{-1})‡			Residue	
	0	30	120	None	Wheat
Water content (g g^{-1})					
42	9.7c§	10.5b	11.1a	10.1b	10.8a
73	8.8a	8.9a	8.8a	8.8a	8.8a
Penetration resistance (MPa)					
42	0.677ab	0.583b	0.763a	0.681a	0.666a
73	1.284a	0.773c	0.901b	1.162a	0.809b

†Date was defined as days after initiation of the experiment.
‡Treatments with 0, 30, or 120 mg kg^{-1} PAM and wheat or none added to amend the soil. Data are averages over main treatment effects.
§Means with the same letter within rows are not significantly different using the LSD mean separation procedure at P = 5% for either PAM or residue amendments.

TABLE 3

Bulk densities (g cm^{-1}) for wheat residue and PAM amended treatments on 14, 24, and 53 days after beginning of the experiment

Day	PAM (mg kg^{-1})†			Residue		Mean‡
	0	30	120	None	Wheat	
14	1.37§	1.37	1.34	1.37	1.36	
24	1.37	1.38	1.35	1.36	1.37	
53	1.39	1.41	1.36	1.39	1.38	
Mean	1.37a	1.38a	1.35b	1.37a	1.37a	

†Treatments with 0, 30, or 120 mg kg^{-1} PAM and wheat or none added to amend the soil. Data are averages over main treatment effects.

‡Means with the same letter are not significantly different at the 5% level using the LSD test for the PAM treatment means, residue means, and the means by day.

§Mean separation (LSD) for the day by amendment interaction at 5% was 0.01 for both PAM and residue.

contents for the readings taken at 42 days did not reveal any significant relationship, yielding, for example, an r^2 of only 0.01 for a linear regression of the two.

For the measurements taken at 42 days, penetration resistances were marginally higher for the treatment without wheat than for the treatment with wheat (Table 2). And although they differed for the PAM treatments, there was no trend with amount of PAM used; some effects may have been masked by water content differences or effects in the upper 5 mm not seen by measurements for the whole treatment. Although PR was not significantly different at this time, treatments with wheat had higher water contents and lower resistances (consistent with later readings).

For the measurements taken at 73 days, penetration resistances differed among both PAM and wheat treatments; both amendments had lower readings than their nonamended counterparts. Although penetration resistance did not show a trend with increasing amounts of PAM, it was lower for both amended treatments than the nonamended treatment. Decreased penetration resistances have been related to increased aggregation and PAM amendment by Sojka et al. (1998b). Also, lower penetration resistances for treatments with organic matter added and the associated increase in aggregation have been observed by other researchers (Sanchez et al., 2003; Hamza and Anderson, 2005).

Bulk Density

Bulk densities (Table 3) did not vary between wheat and nonwheat treatments, but they did vary among PAM treatments and with time of measurement. Near the end of the incubation, bulk densities were significantly lower for the 120-mg kg^{-1} PAM treatments at 1.35 g cm^{-3} compared with bulk densities of 1.38 and 1.37 g cm^{-3} (LSD at 5% = 0.01) for the 30-mg kg^{-1} and no-PAM treatments, respectively. The decreased bulk density would be caused by the aggregating action of the PAM as seen by Levy and Miller (1999). Bulk densities increased with time, starting at a packed value of 1.2 g cm^{-3} and increasing to 1.39 g cm^{-3} by the end of the experiment which would be associated with an increase in soil strength (Chan and Sivapragasam, 1996) and consistent with increased settling with time as water was added to and leached through the soil (Busscher et al., 2002).

Cumulative Water Added

The amount of water added to each treatment to bring them up to 10% (Table 4) was averaged over the number of days when it was added. Water added was analyzed separately for the treatments that ended at 30 days and those that ended at 60 days, although the same results were attained if data for both sets of treatments were analyzed at 30 days. At 30 days, the amount of water added was not significantly different for the wheat treatments and less for the 30 mg kg^{-1} PAM treatment than for the others. At 60 days, less water was added for the treatments with wheat than for the treatments without wheat, and less water was added to the treatments with PAM than to those without it. In both cases, wheat and PAM amendments, less water added implied that PAM and wheat held water against evaporation and/or drainage. This

TABLE 4

Amount of water added (in grams averaged over the number of days that water was added) throughout the course of the experiment for the treatments that ended with 30 and 60 days of incubation

Date	PAM (mg kg^{-1})†			Residue	
	0	30	120	None	Wheat
30	21.2a‡	20.3b	21.3a	20.9a	21.1a
60	20.0a	19.8ab	19.4b	20.8a	18.9b

†Treatments with 0, 30, or 120 mg kg^{-1} PAM and wheat or none added to amend the soil. Data are averages over main treatment effects.

‡Means with the same letter are not significantly different based on the LSD mean separation procedure at 5% for PAM or residue across rows.

would be consistent with the fact that soils with better aggregation hold more water; it suggests that amendments were altering the soil by increasing aggregation, similar to the study of Chan and Sivapragasam (1996) where PAM stabilized aggregation in hard-setting soils.

CONCLUSIONS

Soils amendments with ground wheat residue or with 120 mg kg^{-1} PAM (an anionic formulation of molecular size 12 MDa and 35% charge density) significantly increased aggregation. The increased aggregation was more significant for the wheat residue additions and when PAM was allowed to incubate for 60 days.

Amended soils needed less water added to replenish them to a preset water content (10%) indicating that more water was being held in the soil against leaching or evaporation. This supported the hypothesis that wheat and PAM increased aggregation.

When ground wheat residue and PAM were added to the soil, penetration resistances did not differ for the first dates of measurement; but it was significantly different for the amended treatments by the end of the experiment. Assuming that increased aggregation decreased penetration resistance, this was consistent with the fact that aggregation was increasing with time.

Bulk densities increased with time as a result of settling; the only treatment that did not settle as much as the its nonamended control was the higher level of PAM addition.

Over the course of the experiment, the amount of water added to maintain 10% was less for the treatments with wheat and the higher PAM addition, indicating that they held more water against drainage, suggesting better aggregation.

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