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Field application of PAM as an amendment in deep-tilled US southeastern coastal plain soils

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ABSTRACT

In sandy soils of the southeastern USA coastal plains, crop production is limited by low water holding capacity and compacted soil layers that reduce root growth and productivity. Polyacrylamide (PAM) was added to sandy coastal plain soils to improve physical properties and yield. Soils were amended with linear and cross-linked PAMs. Treatments and controls included the following: (1) spraying a 600 mg kg^{-1} solution of linear PAM behind a subsoil shank at a rate of 3.93 kg ha^{-1}, (2) spraying a 100 mg kg^{-1} solution at 0.66 kg ha^{-1}, (3) spraying only water at 13.1 m^3 ha^{-1}, (4) dropping a dry PAM powder formulation (3005 KB) behind a subsoil shank at 300 kg ha^{-1}, (5) dropping another dry PAM powder formulation (3005 K2) at 230 kg ha^{-1}, (6) dropping a dry PAM powder formulation 3005 K2 at a lower rate of 55 kg ha^{-1}, (7) applying nothing behind a subsoil shank, and (8) not subsoiling. In each of the 3 years of the experiment, new sets of treatments were set up while the old ones were maintained to look at longevity of the PAM effect. Though treatment effects were dominated by the tillage, the cross-linked PAMs were the only treatments more effective than tillage alone. The cross-linked PAMs may have been more effective because we could add more in dry form than in the spray form. The effect diminished with time similar to or faster than the results seen in tillage only. Though some PAM applications may have reduced cone indices, yields were not affected.

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1. Introduction

In most soils, organic matter can be added to improve tilth, reduce penetration resistance, and increase water holding capacities, even for soils such as those found in coastal plains (Ekwue and Stone, 1995). However, in the southeastern coastal plains of the US, organic matter oxidizes rapidly because of high summer temperatures (Wang et al., 2000); it does not increase over time or it increases only near the surface (Novak et al., 1996).

Other amendments need to be found that can reduce southeastern USA coastal soil's high penetration resistances (Blanchar et al., 1978; Busscher et al., 2002) and increase its low water holding capacities because these factors can retard root growth and stress plants. The whole coastal soil profile can develop high penetration resistances though it is especially troublesome in the 20–40-cm deep E horizons; these horizons have no structure and particles cement. The soil is typically managed by fracturing the E horizon with non-inversion deep tillage that increases root growth and yield (Raper et al., 2000; Reeves and Mullins, 1995). However, the effect is temporary. Within a few years (Busscher et al., 2002; Munkholm et al., 2001) or even over a growing season (Frederick et al., 1998), soils reconsolidate, penetration resistances rebuild, and yields decrease (Arvidsson et al., 2001; Radford et al., 2001).

Root growth restriction by high soil penetration resistance is further aggravated by low soil water contents. Except for years of drought which can be devastating (USGS, 2008a,b), rainfall is abundant, averaging more than 1100 mm y^{-1} (Boyles, 2008; SC DNR, 2008). Yet water limits growth during most years because sandy soils hold little water (0.08 g g^{-1}); this causes yield-reducing stress (Sadler and Camp, 1986) when crops experience 2 or more weeks of no rain (Sheridan et al., 1979; Jalota et al., 2006).

Soil penetration resistance can be reduced and/or water holding capacities increased by polyacrylamide (PAM), depending on its formulation. PAM can reduce penetration resistance by increasing soil aggregation which disrupts the massive structure that constitutes the hard layer. PAM 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). In the early 1950's, older PAM formulations were used as soil conditioners (Weeks and Colter, 1952). These formulations required hundreds of kilograms of PAM per hectare with multiple spraying and tillage operations. Newer longer chain-polymer formulations and increased purity have improved PAMs, making them more

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effective at lower concentrations. For example, water soluble PAM prevented erosion and improved infiltration at rates of 1–10 mg L^{-1} (10 g m^{-3}) in furrow irrigation water (Sojka et al., 1998). When added to the soil, some PAM formulations have the ability to hold water against gravity, providing a potential source of crop uptake (Johnson and Piper, 1997), though some water may be held too tightly for plant growth (Sivapalan, 2006).

PAM also 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, and biological processes (Tolstikh et al., 1992; Entry et al., 2008). Because PAM is susceptible to UV degradation, its breakdown rate when applied at the soil surface may be >10% per year; but, mixing it into the soil slows breakdown. Its slow degradation within soils is attributed to microbial and chemical attacks that only take place at the ends of the polymers (Kay-Shoemake et al., 1998).

The objective of the study was to determine whether or not PAM could decrease soil penetration resistance and increase yield. An additional objective was to determine if the effect would last for at least the 3-year period of the experiment.

2. Materials and methods

2.1. Soils

This study was conducted at the Clemson Pee Dee Research Center located about 10 km northeast of Florence, SC, USA (N34°18′52″, W79°45′6″) with replicates laid out on Norfolk loamy sand (fine-loamy, siliceous, thermic *Typic Kandiudult*) and Bonneau (loamy, siliceous, subactive, thermic *Arenic Paleudult*) soils. These soils were formed in coastal plain marine sediments, had loamy sand surface textures (Table 1), and were categorized as Acrisols in the FAO classification. Both soils had Ap horizons that had been tilled over the years to a depth of about 0.20 m and eluviated E horizons to depths of 0.25–1.0 m that can restrict root growth (http://soils.usda.gov/technical/). The E horizons overlaid Bt horizons.

2.2. Treatments

In spring of 2003, 8 treatments replicated four times were established in 32 plots that were 4.6-m wide by 15-m long. The 8 treatments were organized in a randomized complete block design. They included the following: (1) spraying a 600 mg kg^{-1} solution of PAM (formulation 923 SH, an anionic, linear formulation of size 12 MDa and 35% charge density, SNF Holding Company, Riceboro, GA, USA) under the row behind a subsoil shank; given the speed of the tractor, the nozzle pressure, and the solution concentrations, the amount of PAM sprayed into the soil was 3.93 kg ha^{-1}; (2) spraying a 100 mg kg^{-1} solution of PAM (formulation 923 SH) under the row behind a subsoil shank, leading to a PAM addition to the soil of 0.66 kg ha^{-1}; (3) spraying water only under the row behind a subsoil shank at a rate of 13.1 m^3 ha^{-1}; (4) dropping a dry PAM powder (formulation 3005 KB, a 1-mm diameter, cross-linked version of the PAM) under the row behind a subsoil shank from a Gandy Cam Gauge Row Applicator (Gandy Company, Owatonna, MN, USA) with the settings fully open (setting = 80); based on calibration of the Gandy, the amount of PAM dropped into the soil was ~300 kg ha^{-1}; (5) dropping a dry PAM powder (formulation 3005 K2, a 2-mm diameter, cross-linked version of the PAM) under the row behind a subsoil shank from a Gandy Cam Gauge Row Applicator with the settings fully open (setting = 80) at a rate of ~230 kg ha^{-1}; (6) dropping a dry PAM powder (formulation 3005 K2) under the row behind a subsoil shank from a Gandy Cam Gauge Row Applicator with the settings half open (setting = 40) at a rate of ~55 kg ha^{-1}; (7) applying nothing behind a subsoil shank; (8) not subsoiling.

In 2004 and 2005, duplicate and triplicate sets of 32 plots were established; new plots were adjacent to and the same as the original plots except that treatments were re-randomized. By the end of the experiment, there were 96 plots. In the year of establishment, all plots were disked for seedbed preparation. In years following establishment, plots were planted without any additional treatment or tillage. Plots were planted to maize (*Zea mays* L.) every year after they were established. Before 2003, plots had been planted to soybeans (*Glycine max* L. Merr.) that were drilled in 0.19-m-row widths. After 2003, if plots had not yet been established to maize, they were planted to soybean.

The shank used for deep tillage and PAM injection into the soil was a modified 50-mm wide 45° forward-angled in-row subsoiling implement with a 125-mm long, 64-mm wide shoe. Shanks were spaced 76 cm apart to match the row widths of the planters. Each shank had 50-cm long, 16-cm wide, 6-mm thick plates welded to its sides that flared out at angles of about 20° (Fig. 1). The plates temporarily deflected soil away from the shank more than the shank alone and allowed the liquid or solid PAM to disperse through the soil under the row. For liquid application, a line of six nozzles separated by about 7.5 cm was attached to the back of the shank between the deflector plates to spray the solution into the soil. For solid application, drop tubes from the Gandy were attached between the first and second and between the fourth and fifth nozzles to allow granular PAM to disperse throughout the soil. Treatment application and planting were accomplished in separate applications and matched as closely as possible using experienced drivers and range poles.

Table 1
General soil characteristics based on mapping soils and collecting information from http://soils.usda.gov/technical/classification/scfile/; differences between the Ap and E horizons are based on previous tillage that mixes surface organic matter into the Ap.

Characteristics	Soil type			
	Bonneau		Norfolk	
	Ap/E	Bt	Ap/E	Bt
Texture	Loamy sand	Sandy clay loam	Loamy sand	Sandy clay loam
Water table[a] (m)	1.1–1.5	1.1–1.5	1.2–1.8	1.2–1.8
CEC (cmol kg^{-1})	1–4	2–6	1–3	2–4
OM (g kg^{-1})	5–20	0–5	5–20	0–5
Clay (g kg^{-1})	50–150	130–350	20–80	180–350
Depth (m)	0.50–1.00	0.56–1.25	0.23–0.48	0.36–1.0

[a] Seasonally high depth to the water table.

2.3. Crop management

In March of each year of the experiment, the new set of plots was disked and weeds were controlled by applying cyanazine {2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropanenitrile} and metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide]. In the established plots, weeds were controlled with an initial burndown of glyphosate [N–(phosphonomethyl)glycine], cyanazine, and metolachlor in March and with glufosinate [2-amino-4-(hydroxymethylphosphinyl) butanoic acid] in May. Maize (cv. Pioneer 32K64 in 2003 and Pioneer 32K61 in 2004 and 2005) was planted in late March or early April at a rate of 59,300 seed ha^{-1} on 0.76-m-row spacing. In May of each year, liquid N (urea ammonium nitrate) was surface applied at the rate of 135 kg N ha^{-1}. Maize was harvested in August or September with a Case IH Model 2366 combine.

2.4. Penetration resistance measurements

Penetration resistance was measured as cone index of a 12.5 mm diameter, 30° solid angle cone-tipped recording penetrometer in the

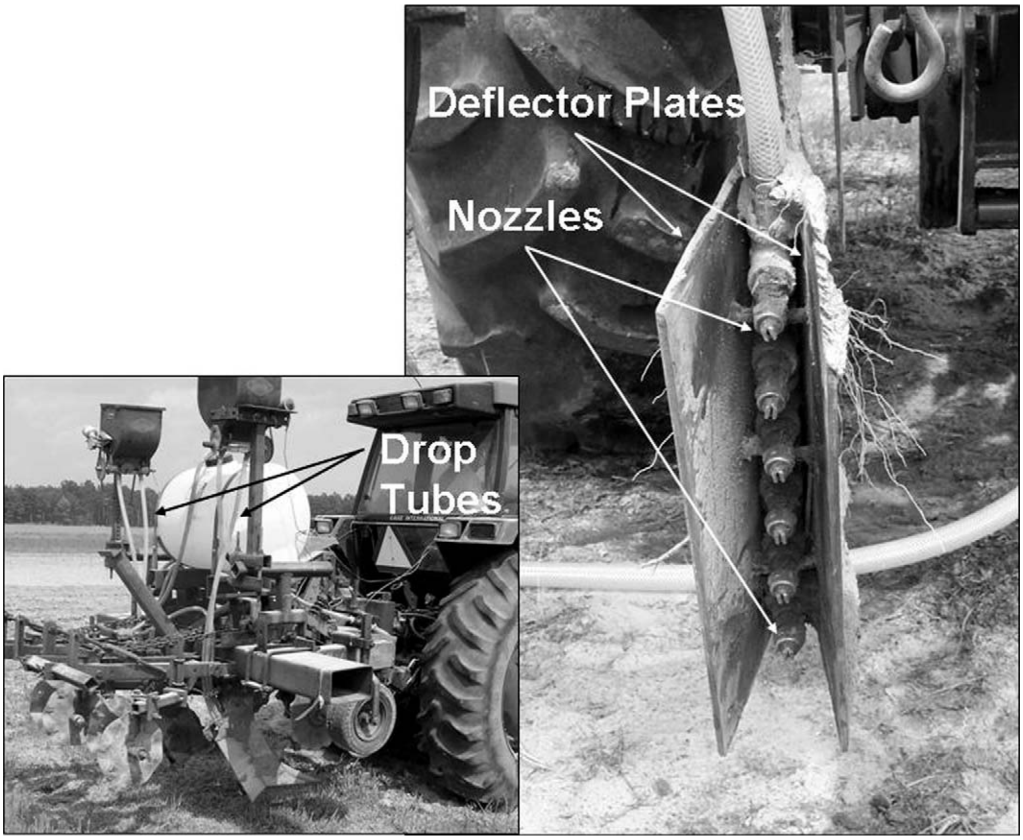

Fig. 1. The subsoil shank modified for PAM solution injection into the profile.

first set of plots on 10 and 11 July 2003 and in all plots after the end of the experiment on 25–27 January 2006. In 2003, penetration resistance data were taken with a hand-held recording penetrometer (Carter, 1967) that measured up to 9 MPa (Busscher et al., 1986). In 2006, penetration resistance data were taken with a custom-built tractor mounted recording penetrometer that measured up to 17.6 MPa. The custom-built penetrometer depended on tractor hydraulics to push three cone-tipped probes that were attached to a small (8 cm × 15 cm × 1.5 m) tool bar into the soil simultaneously. The probes were at the end of 1.5-cm diameter 60-cm long rods that were attached to 900 kg HSW-2k S-type load cells (Transducer Techniques, Temecula, CA). Load cells transmitted signals to a TMO-1 (Transducer Techniques) signal conditioner/amplifier that set the gain. Probe depths were measured with a wire-actuated SGP-2000-P-02-10-X potentiometer (Siko GmbH, Buchenbach, DE); the wire extended as the penetrometer probed deeper into the soil. Transducer and potentiometer signals were converted A/D and input into a laptop computer through a 12-bit, 16-channel PCM-DAS16D/12 PCMCIA card (Measurement Computing, Norton, MA). Data in the laptop were manipulated with a custom Visual Basic program that read the data, saved it, and graphically displayed real-time penetration resistance vs. depth.

Probes measured penetration resistance (three at a time) at nine equally spaced positions along a 0.76 m-transect perpendicular to the rows (95 mm spacings) to a depth of 0.55 m. Measurement positions spanned from a non-wheel-track mid row across a row into a wheel-track mid row. At each probing position, measurements were means of three readings spaced 10 or more apart parallel to the row.

Data taken in 2003 with the hand-held penetrometer were recorded on cards and digitized into a computer at 50-mm depth intervals. Automated data collection in 2006 produced more data with depth than the 2003 data. Because the 2006 data were taken at 20 kHz, they were not necessarily taken at the same depths as the earlier data's digitized depth. To standardize the readings, the 2006 automated data for all depths and all positions were calculated for 50-mm depth intervals and 95-mm width positions using bivariate interpolation in the G3GRID procedure of SAS (2000), resulting in less than the original amount of data for the automated sampling but uniform data for all dates of measurement.

Soil samples were taken along with cone indices to measure gravimetric water contents. Soil samples were taken at 0.1-m intervals to 0.6-m depths at two positions (in the non-wheel-track mid row and in the row) and considered representative of the plot's water content.

2.5. Statistical analyses

Data were analyzed by the general linear models procedure, a least square mean separation procedure, and contrasts between groups of treatments (SAS, 2000). Cone index data were analyzed using the log transformation as recommended by Cassel and Nelson (1979). Because cone index data were collected 2 years apart and because conditions differed from year to year, data were analyzed separately by year. Cone index and water content data were analyzed using a split-plot split-block design. Data were tested for significance at the 5% level unless otherwise stated.

3. Results and discussion

3.1. Gravimetric water contents

In 2003, soil water contents were taken simultaneously with cone indices; they differed significantly only with depth (Table 2) and only for the 0.55-m depth. Water contents with depth ranged

Table 2
Water contents with depth for gravimetric samples taken along with the cone indices.

Depth (m)	Water contents (%)			
	2003[a]	2006[a]		
	2003[b]	2003[b]	2004[b]	2005[b]
0.05	7.6b[c]	9.7bc	9.5ab	10.7a
0.15	6.6b	8.9d	8.9bc	9.9b
0.25	6.6b	9.0d	8.6bc	9.2c
0.35	7.3b	9.0cd	8.4c	9.0c
0.45	8.1b	9.9b	9.0bc	9.9b
0.55	10.1a	11.4a	10.4a	11.1a
Means[d]	7.7	9.7a	9.1a	10.0a

[a] Data taken.
[b] Plots established.
[c] Means with the same letter in the columns are not significantly different using the LSD separation procedure at 5%.
[d] Means with the same letter in the row are not significantly different using the LSD separation procedure at 5%.

Table 4
Cone indices by position across the row where 0 m is in the non-wheel-track mid row, 0.38 m is in the row, and 0.76 m is in the wheel-track mid row.

Position (m)	Cone indices (MPa)			
	2003[a]	2006[a]		
	2003[b]	2003[b]	2004[b]	2005[b]
0.0	1.01c[c]	1.48a	1.32ab	1.34ab
0.10	1.12c	1.41ab	1.26ab	1.21bc
0.19	1.05c	1.30bc	1.04c	0.90d
0.29	0.83d	1.08de	0.90d	0.65f
0.38	0.70e	0.99e	0.77e	0.54g
0.48	1.08c	1.18cd	1.04c	0.79e
0.57	1.47b	1.44ab	1.19b	1.10c
0.67	1.75a	1.50a	1.26ab	1.29ab
0.76	1.80a	1.52a	1.42a	1.37a
Means[d]	1.15	1.31a	1.12b	0.98b

[a] Data taken.
[b] Plots established.
[c] Means with the same letter in the columns are not significantly different using the LSD separation procedure at 5%.
[d] Means with the same letter in the row are not significantly different using the LSD separation procedure at 5%.

from 6.6% to 10.1%. Their differences were considered when analyzing cone index with depth.

In 2006, because of interactions, water content and cone index data were analyzed by year of tillage. Soil water contents generally increased with depth, but did not differ for anything else except for one of the contrasts. The water contents for the contrast were higher for the higher cone indices. In this case, differences in water content would not affect the interpretation of the data because reducing the higher water contents to an equal value would actually increase their values even more, making the differences greater. Water content differences with depth were considered along with the cone index data interpretation below (Table 2).

3.2. *Cone indices*

In 2003, cone indices differed with treatment, soil depth, and position across the row. When cone indices were analyzed with contrast statements by grouping treatments, they were higher for non-subsoiled than subsoiled treatments (Table 3), a result of the loosening effect of the tillage. Cone indices were higher for treatments with liquid PAM sprayed into the soil than for those with granular solids dropped into the soil (1.30 MPa vs. 1.12 MPa; $P < 0.01$) probably a result of being able to add higher amounts of PAM per ha in dry granular form. Though these cone index values were not high enough (<2 MPa) to prevent root growth (Blanchar et al., 1978), they fell in the range of penetration resistances that begin to limit root growth, the range of values where higher cone indices would deter root development.

Table 3
Cone indices for contrasts of grouped treatments comparing 3005 KB high rate, 3005 K2 high rate, 3005 K2 low rate with unamended deep-tilled treatments (water subsoiling only); comparing 923 SH 600 ppm, 923 SH 100 ppm with unamended treatments; and comparing all treatments that were subsoiled (amended or not) with the non-subsoiled treatment.

Grouped treatments	Cone indices (MPa)			
	2003[a]	2006[a]		
	2003[b]	2003[b]	2004[b]	2005[b]
3005 KB high rate, 3005 K2 high rate	0.99b[*]	1.31a	1.15a	0.88b[^]
Water and subsoiling only	1.18a	1.30a	1.09a	0.99a
923 SH 600 ppm and 923 SH 100 ppm	1.21a	1.32a	1.07a	0.91a
Water and subsoiling only	1.18a	1.30a	1.09a	0.99a
Subsoiled	1.12b[*]	1.29a	1.10b[^]	1.44b[*]
Non-subsoiled	1.37a	1.43a	1.23a	0.93a

[a] Data taken.
[b] Plots established.
[*] Contrasted means with the same letter are not significantly different at $P < 5\%$.
[^] Contrasted means with the same letter are not significantly different at $P < 8\%$.

As expected, cone index differences with position exhibited the highest penetration resistance under the wheel-track mid row, next highest in the non-wheel-track mid row, and the lowest penetration under the row (Table 4) where most treatments had been subsoiled. Cone index increased with depth; and this was accentuated by the water content because it also increased with depth in a somewhat dry soil (mean water content 7.7%). Though these soils usually have a hardpan, these plots had been managed with deep tillage in previous years to disrupt them. This management also accounted for the relatively low (>2 MPa) cone indices.

In early 2006, cone indices were measured on all 96 plots, 32 from each of the 3 years of establishment. Cone indices increased with time since establishment; mean values were 1.31 MPa for treatments established in 2003 which was greater than 1.12 MPa for treatments established in 2004 and 0.98 MPa for treatments established in 2005 (Table 4). Water contents taken with the cone indices for these three sets of plots varied; but they were not a significant factor because their differences were small (<1%) with values at 9.7%, 9.1%, and 10% for the plots established in 2003, 2004, and 2005 respectively (Table 2). Although the cone indices increased with time, mean values were still below the accepted root restricting value of 2 MPa after 3 years. And although this indicates that annual tillage may not be needed, especially in a time of high and increasing fuel costs, yields listed below were significantly reduced with time at least partly as a result of higher penetration resistance. Because interactions of treatment cone index data with dates of original tillage were significant, the remaining analyses of 2006 cone index data were performed by year of plot establishment.

For all 3 years of treatment establishment, cone indices differed by position and depth. Cone indices differed across the row position with values beneath the wheel-track mid rows > values under the non-wheel-track mid rows > values where tillage had taken place under the rows (Table 4). Cone index differences and the softer zone below the row are related to the management technique of getting the roots into and through the hard soil into the structured Bt horizon below. Differences by position, especially for the tillage under the rows (greater ranges of values in Table 4),

Table 5
Cone indices by depth within the soil profile.

Depth (m)	Cone indices (MPa)			
	2003[a]	2006[a]		
	2003[b]	2003[b]	2004[b]	2005[b]
0.05	0.24g[c]	0.55d	0.47f	0.47d
0.10	0.40f	0.94c	.067e	0.68c
0.15	0.72e	1.28b	0.90d	0.87bc
0.20	1.02d	1.48ab	1.13c	1.02ab
0.25	1.18cd	1.53a	1.24bc	1.12ab
0.30	1.34cd	1.50a	1.25bc	1.18a
0.35	1.51bc	1.46ab	1.23bc	1.22a
0.40	1.84ab	1.48ab	1.29bc	1.21a
0.45	2.32a	1.54a	1.44ab	1.16a
0.50	2.33a	1.60a	1.59a	1.11ab
0.55	2.17a	1.60a	1.70a	1.06ab

[a] Data taken.
[b] Plots established.
[c] Means with the same letter in the columns are not significantly different using the LSD separation procedure at 5%.

were more pronounced for the years that had been tilled more recently.

Though we expected to see higher cone indices at 0.25–0.40-m depths consistent with a genetic eluviated hard layer, cone indices generally increased in value with depth (Table 5). Differences could be seen where higher cone indices could be found at the depths of the layer; but they were small and not statistically significant. Also, because soil at these depths tended to be drier, their increased hardness could also have been a result of change of water content. Nevertheless, increased cone indices with depth caused by higher penetration resistance, drier soil, or both would limit plant roots. Limited root proliferation, limits crop access to water and nutrients, and limits yield potential.

For data taken in 2006, cone indices exhibited a position by treatment interaction for plots that had been established in 2004 and 2005. The interaction was caused by the low cone indices under the row for in-row tillage treatments 1 through 7 vs. high cone indices in treatment 8 that was not deep tilled (Tables 3 and 6). This could be verified by analyzing the cone index data without the positions in the row middles; in this case, the interactions disappeared. For the data taken in 2003 (plots established in 2003), the same in-row tillage trend could be seen though the interaction was not significant. Conversely, for the data taken in 2006 in the plots established in 2003, the interaction was not seen and was not significant because of settling throughout the years which reduced the tillage effect, similar to results in other studies on these soils (Busscher et al., 2002).

Table 6
Cone indices for the 8 treatments averaged over the soil profile.

Treatment	Cone indices (MPa)			
	2003[a]	2006[a]		
	2003[b]	2003[b]	2004[b]	2005[b]
923 SH 600 ppm	1.17abc[c]	1.45a	1.04b	0.90b
923 SH 100 ppm	1.25abc	1.20a	1.11ab	0.91b
water	1.26ab	1.34a	1.08ab	1.03b
3005 KB high rate	1.02cd	1.39a	1.13ab	0.87b
3005 K2 high rate	0.95d	1.24a	1.17ab	0.88b
3005 K2 low rate	1.13abcd	1.19a	1.08ab	0.93b
Subsoil only	1.10bcd	1.26a	1.10ab	0.95b
Nothing	1.37a	1.43a	1.23a	1.44a

[a] Data taken.
[b] Plots established.
[c] Means with the same letter in the columns are not significantly different using the LSD separation procedure at 5%.

Although treatment effects on cone indices were dominated by deep tillage, other differences could be seen in GLM contrasts where treatments were analyzed in groups (Table 3). That is, when treatments amended with dry PAM (treatments 4 and 5) were grouped, they had lower cone indices than the treatments that had no added PAM (treatments 3 and 7); both sets of treatments were subsoiled. This was true for the most recently treated plots—that is for data taken in 2003 when plots had been plots established in 2003 and for data taken in 2006 when plots had been established in 2005. This difference among PAM amended and non-amended treatments was not significant for data taken in 2006 when plots had been established in 2003 and 2004 suggesting that the effect diminished with time. Treatments where PAM was added in solution (treatments 1 and 2) were also grouped and compared to those with no added PAM (both sets of treatments were subsoiled); but cone index reductions were not significant suggesting that the effect was not lasting and not effective in reducing soil penetration resistance. This was consistent with the fact that the dry PAM had more of an effect on the soil than PAM in solution. Water contents were not significantly different for any of these sets of treatments.

3.3. *Yields*

Yields differed by year of harvest and by year of tillage (Table 7). Yield differences by year of harvest can be at least partially explained by the annual seasonal variations such as rainfall. Yield differences can also be at least partially attributed to year of tillage, as a result of not deep tilling every year, as also seen by others (Raper et al., 2000; Reeves and Mullins, 1995); this can be a result of reconsolidation or traffic or both. In 2004, maize yield averaged 7.55 Mg ha^{-1} for plots that had been subsoiled that year and 4.37 Mg ha^{-1} for plots that had been tilled the year before. Similarly, in 2005, maize yield averaged 7.41 Mg ha^{-1} for plots that had been subsoiled that year, 2.76 Mg ha^{-1} for plots that had been tilled the year before, and 1.94 Mg ha^{-1} for plots that were tilled 2 years earlier. Though not expected, the reduction by year after tillage was also seen in the treatments that were not deep tilled because they had been tilled for soybean production the years before plot establishment.

Aside from not subsoiling or time since subsoiling, ANOVA treatment analyses and contrasts among grouped treatments did not show any significant or consistent differences for maize yield for this soil. Contrasts were made between PAM vs. nothing added, dry vs. wet applications, and dry/wet applications vs. nothing added. None of these supported our hypothesis that PAM would improve yield when applied in this manner.

Table 7
Maize yield for the 3 years of tillage.

Treatment	Yield (Mg ha^{-1})					
	2003[a]	2004[a]		2005[a]		
	2003[b]	2003[b]	2004[b]	2003[b]	2004[b]	2005[b]
923 SH 600 ppm	3.51	4.30	7.96	2.36	2.72	7.70
923 SH 100 ppm	3.12	3.48	6.85	1.27	3.40	7.80
Water	2.27	4.76	7.93	2.24	2.46	7.18
3005 KB high rate	3.10	3.67	7.90	0.78	3.32	7.57
3005 K2 high rate	3.44	4.64	7.55	2.39	3.08	7.95
3005 K2 low rate	3.15	5.18	7.76	1.85	1.88	7.47
Subsoil only	3.34	4.47	7.57	2.78	2.72	7.16
Nothing	2.78	4.21	6.87	1.86	2.45	6.47
LSD 5%	0.62	1.15		1.24		

[a] Data taken.
[b] Plots established.

4. Conclusions

As expected, all tilled treatments had lower cone indices than untilled treatments and more recently tilled treatments had lower cone indices than those that had been tilled a year or two previously. Treatments had higher cone indices below the wheel-track mid rows than below the non-wheel-track mid rows and even lower cone indices below the rows. Treatments with the granular PAM had lower penetration resistances than the treatments with the liquid PAM; this was quite likely because more granular material could be dropped into the soil than dissolved liquid PAM could be sprayed into the soil.

Treatment differences diminished with time which was expected with the subsoiling because of reconsolidation; but it was disappointing that the PAM did not last longer than the tillage in this sandy coastal soil. From the results of this study, it does not appear to be cost effective to add PAM, especially at an estimated cost of \$80–200 ha^{-1}.

Yield responded to subsoiling in the year of planting but not to any of the PAM treatments. Cone index reductions by both subsoiling and PAM diminished over the 3-year course of the experiment.

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