Int. Agrophysics, 2007, 21, 225-231

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Comparison of soil amendments to decrease high strength in SE USA Coastal Plain soils using fuzzy decision-making analyses

W. Busscher[1]*, *E. Krueger*[2], *J. Novak*[1], *and D. Kurtener*[3]

[1]USDA-ARS, Coastal Plain Research Center, 2611 W Lucas St., Florence, SC, 29501, USA
[2]Independent Researcher, 11706 Perry St., Westminster, CO, 80031, USA
[3]Agrophysical Research Institute, Grazhdansky pr. 14, 195220 St. Petersburg, Russia

Received April 23, 2007; accepted May 16, 2007

A b s t r a c t. Cemented subsurface layers restrict root growth in many southeastern USA Coastal Plain soils. Though cementation is usually reduced by tillage, soil amendments can offer a more permanent solution if they develop aggregation. To increase aggregation, we amended 450 g of a Norfolk soil blend of 90% E horizon (the hard layer) and 10% Ap horizon with 0 or 6.44 g kg^{-1} ground wheat (*Triticum aestivum* L.) residue and 0, 30, or 120 mg kg^{-1} polyacrylamide (PAM, 12 x 10^6 Da anionic, linear, and 35% charge density). During a 60-d incubation, parameters measured included water added to maintain 10% soil moisture, soil strength, bulk density, and aggregation. Data were analyzed using a cost-benefit approach with normalized fuzzy logic indicators. Analyses included building normalized decision matrices, calculating weighting vectors, ranking alternatives, and defining the best alternatives. When only physical parameters were analyzed using fuzzy logic indicators, addition of wheat residue with 30 mg kg^{-1} PAM proved to be the best alternative whereas wheat residue with 120 mg kg^{-1} PAM had been selected as the best alternative with analysis of variance because it did not simultaneously analyze all variables. When both physical and economic parameters were included, the best alternative was the treatment with wheat residue and 120 mg kg^{-1} PAM. When using fuzzy logic, judgment of the user was needed to determine which parameters to include and how to weight them.

K e y w o r d s: soil amendment, hardpan, PAM, organic matter

INTRODUCTION

Many USA southeastern Coastal Plain soils have strengths great enough to obstruct root growth, especially in the subsurface E horizons (Blanchar *et al*., 1978). Strengths are typically managed by fracturing the E horizon with non-inversion deep tillage to improve yield (Raper *et al*., 2000). Deep tillage is expensive, costing 30 to 50 USD per ha (Khalilian *et al*., 2002), and becoming more expensive as fuel prices increase. Deep tillage effects are not permanent. Depending on management system and crop, it might have to be repeated in as little as a growing season (Frederick *et al*., 1998) or as much as three years (Munkholm *et al*., 2001).

Soil amendments can reduce strength, decreasing tillage frequency and cost. Amendments of organic matter improve tilth (Waksman, 1937) and reduce strength (Free *et al*., 1947), even for sandy soils (Ekwue and Stone, 1995), such as those in the coastal plain. However, since summer temperatures are high, organic matter oxidizes rapidly (Wang *et al*., 2000). Organic matter does not increase over time or it increases only near the surface (Novak *et al*., 1996).

Polyacrylamide (PAM) amendments may also reduce strength by increasing aggregation and interrupting the continuous bonding in the cemented E horizon that constitutes much of the high strength in these soils. PAM amendments can cause abrupt aggregation which has the potential to trap OM by incorporating it into aggregates where it can be sheltered from rapid decomposition (John *et al*., 2005). In the 1950's, PAM formulations began to be used as soil conditioners (Weeks and Colter, 1952). PAM and other conditioners improved plant growth and soil characteristics by stabilizing aggregates in the surface 30 to 40 cm depths. Older PAM formulations required hundreds of kilograms per hectare, multiple sprayings, and multiple tillage operations. Since then, PAM has improved with newer longer-chain-polymer formulations and better purity, making it 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 to

*Corresponding author's e-mail: Warren.Busscher@ars.usda.gov

© 2007 Institute of Agrophysics, Polish Academy of Sciences

10 mg l^{-1} in furrow irrigation water (Sojka *et al*., 1998b). PAM achieved this result by stabilizing soil surface structure and pore continuity.

PAM does not deteriorate as quickly as organic matter (OM). In soil, it is degraded at rates of 10% per year as a result of physical, chemical, biological and photochemical processes and reactions (Tolstikh, *et al*., 1992). Mixing PAM into the soil slows breakdown by protecting it from ultraviolet-light degradation. Another reason that PAM is slow to break down is because it does not act as a traditional C substrate; microbes and chemicals attack only the ends of polymer chains (Kay-Shoemake *et al*., 1998).

Mixing PAM into this coastal soil may develop aggregation that 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 wheat residue and 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 a) to study the effect of wheat residue and PAM on soil aggregation and b) use fuzzy logic to analyze the data and determine the best possible treatment.

Fuzzy logic was chosen to analyze the data because it could scale parameters from 0 to 1, determine the optimal treatment or treatment combination (Edam *et al*., 2004), and rank treatment combinations in order of priority using information from several scaled parameters at a time. Fuzzy logic has proven to be a practical, useful tool for other soil analyses, such as assessing water pollution and erosion (Muhammetoglu and Yardimci, 2006; Mitra *et al*., 1998) and determining water content in sandy soil (Mohamed and Hawas, 2004). In areas more related to aggregation, fuzzy modeling has been used to predict compaction (de Araújo and Saraiva, 2003) and infiltration (Bárdossy, 1996).

MATERIAL AND METHODS

Experimental setup

Soil used in the experiment was collected from the edge of a research field 2 km northwest of Florence, SC, USA. It was Norfolk loamy sand (fine-loamy, siliceous, thermic *Typic Kandiudult* in the USDA classification or an Acrisol in the FAO classification) that formed in well-drained Coastal Plain marine sediments. Over the years, the Ap horizon was formed by tilling to a depth of about 0.20 m. Below this, an eluviated E horizon had the highest strength within the profile and most potential to restrict root growth; it typically extended to depths of 0.30 to 0.45 m. Below the E horizon was a sandy clay loam Bt horizon that extended beyond 0.6 m depth. The Ap and E horizons were similar with differences based mainly on organic matter that was mixed into the Ap through tillage, tree throws, and animal burrows. The Ap and E horizons had 1-3 cmol kg^{-1} cation exchange capacity, 20 to 80 g kg^{-1} clay, and 2 to 20 g kg^{-1} of organic matter (Soil Survey Staff, 2006). The Ap and E horizons were collected in the field, pushed through a 10 mm sieve to remove debris, air dried, and sieved at 2 mm. The E horizon was the primary medium of study because it was the hardest; 10% Ap horizon was added to the E to assure that the soil would have a microbial population to decompose OM. Horizons were mixed together in a twin-shell dry blender (Patterson-Kelley Co., Inc., East Stroudsburg, PA, USA) for 15 min and used as the final soil. The final soil mix had 66% sand, 30% silt, 3.8% clay (Miller and Miller, 1987), and 0.032 g kg^{-1} organic matter as measured on a LECO LN2000 (LECO Corp., St. Joseph, MI).

Six treatments included 450 g of soil and either 0 or 6.44 g kg^{-1} ground wheat stubble mixed with 0, 30, or 120 mg kg^{-1} PAM. Organic matter and soil C:N ratios were brought to 20:1 by adding NH_4NO_3 in amounts of 0.157 and 0.456 g kg^{-1} for the treatments with no wheat and wheat residue, respectively. The wheat residue had been ground in a Wiley Mill (6 mm mesh opening, Arthur Thomas, Co., Philadelphia, PA, USA*). The PAM formulation was 12 x 10^6 anionic, linear, and 35% charge density (SNF Inc., Riceboro, GA, USA). Treatments were replicated three times.

Because small amounts of PAM were added, it did not mix into the soil well as a dry powder; as a result, treatment amounts were dissolved in 45 ml of deionized water and sprayed on the treatment while mixing it on waxed paper. Treated soils 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 pots and tapping them on the lab bench until the treatment mixture settled to a preset depth. Treatments were incubated for 60 days in a lab that was maintained at 20 to 22°C and mean humidity of 47%. Treatments were rewet to 10% soil water content on a dry weight basis 2 to 3 times a week by adding deionized water to bring the treatments back to a preset weight.

Measurements

After 28 and 56 days from initiation of the experiment, pots were leached with 1.3 pore volumes (266 ml) of water. When pots were leached at the end of the experiment, they were allowed to dry, rewet to 10%, covered, and allowed to come to equilibrium for 3 to 5 days. At 73 days, probe resistance (PR) was measured on the soil surface with a 3 mm diameter, stainless-steel flat-tipped penetrometer probe, that was pushed into the soil at a rate of 0.28 mm s^{-1} using the method of Busscher *et al*. (2006).

*Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Dept. of Agriculture or the Agrophysical Research Institute and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

At 14, 24, and 53 days, soil bulk densities were 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. To determine the volume of soil in a pot, distances along the side of the pot had been calibrated against volume of the pot by sealing drain holes at the bottom and filling the pot with water to several depths. Volumes were combined with known dry weights of each treatment to calculate bulk densities.

At the end of the incubation, soils were removed from pots for analyses. Samples of 100 g were used to measure aggregate sizes by sieving it 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) that was run at a rate of 60 Hz with amplitude of 3 mm for 1 min using the procedure of Sainju *et al*. (2003).

Economic considerations

We assumed that PAM cost 6 USD kg^{-1} while the organic matter (wheat residue) cost 40 USD Mg^{-1}. We also assumed that the amendments were added to 1 Mg of soil in 1 ha. Therefore, wheat residue added would be 6.44 Mg ha^{-1} x 40 USD Mg^{-1} = 258 USD ha^{-1}. PAM added at the low rate would be 30 kg ha^{-1} x 6 USD kg^{-1} = 180 USD ha^{-1} and at the high rate 120 kg ha^{-1} x 6 USD kg^{-1} = 720 USD ha^{-1}. If a spreading fee of 80 USD ha is included, costs would be 338 USD ha^{-1} for wheat residue, 260 USD ha^{-1} for 30 mg kg^{-1} PAM, and 800 USD ha^{-1} for 120 mg kg^{-1} PAM. For the case where both PAM and wheat residue were applied at the same time, the spreading cost was split between the two.

Data analysis

Traditional analyses: Data for traditional analyses were analyzed using General Linear Models and least significant difference mean separation procedure (SAS Institute Inc., 2000). The six treatments were considered main plots. Groups of treatments were analyzed using the contrast statement or by regrouping data. Data were tested for significant differences at the 0.05 level unless stated otherwise.

Kriging: Surfer®, version 8 (http://www.goldensoftware.com), contouring and mapping software, was used to examine the treatment data. Because treatments were irregular, Surfer was used to krig them before analysis. Kriged data (Fig. 1) were used to build contour maps (Fig. 2) and to establish links between rates of PAM application, the time since the start of experiment (day), and soil bulk densities (bden).

Fuzzy multi-attributive decision-making analysis: Data were analyzed to achieve the optimal treatments using various measured parameters. Optimal treatments were selected by simultaneously analyzing multiple attributes. Selection was accomplished using an algorithm and program for

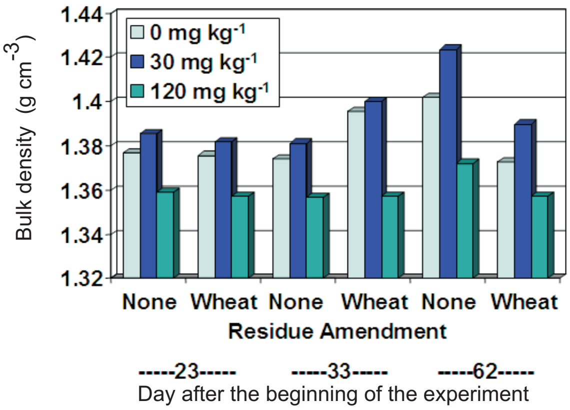

Fig. 1. Bulk density data for the three days of measurement of the experiment.

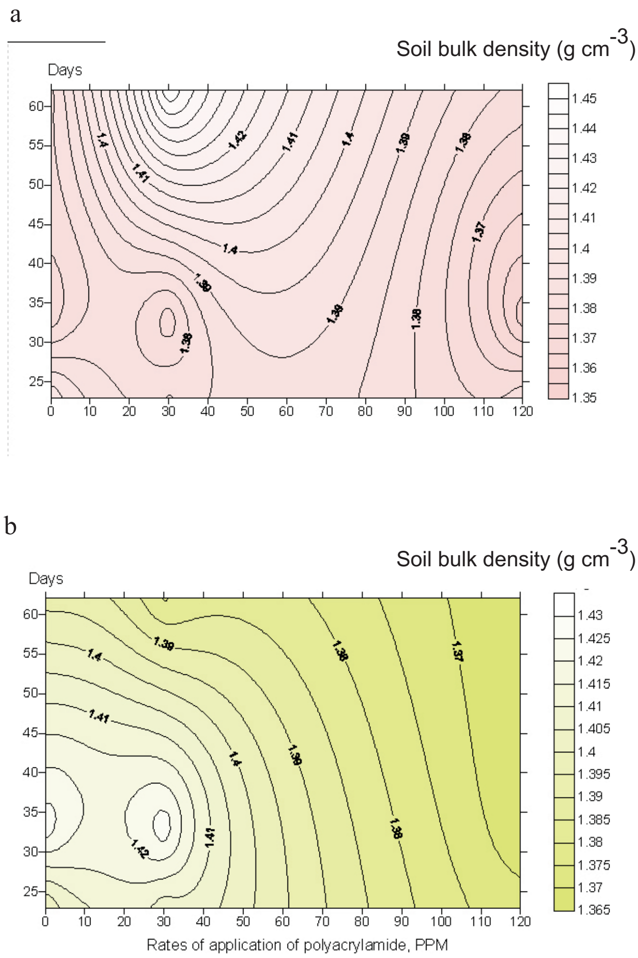

Fig. 2. Relationships between rates of application of polyacrylamide (PPM), the time since the start of experiment (days), and soil bulk densities for special case when wheat residue is: a – not incorporated in soil (none), b – incorporated in soil (wheat residue added).

multi-attributive comparison of agricultural management systems written using the principles of fuzzy logic (Kurtener and Badenko, 2002; Krueger and Kurtener, 2003; Kurtener *et al*., 2006). The algorithm was based on the use of fuzzy indicators and the minimum average weighted deviation method (Li, 1999).

Fuzzy logic indicators were developed from each measured parameter. Two types of fuzzy indicators were developed: benefits and costs. Indicators were selected as benefits or costs based on the judgment of the authors. Then they were modeled by appropriate membership functions that were normalized to values ranging from 0 to 1. Benefit fuzzy indicators were normalized for maximization; while cost fuzzy indicators were normalized for minimization. Benefit fuzzy indicators (Z_b) were defined as follows:

$$Z_b = G_b \, / \, G_{b\max} ,$$

where: G_b is current value of the benefit attribute, $G_{b\,\max}$ is the maximum benefit value. Cost fuzzy indicators (Z_c)were defined as follows:

$$Z_c = G_{c\min} \, / \, G_c ,$$

where: G_c is current value of the cost attribute, $G_{c\,\min}$ is the minimum cost value.

Fuzzy indicators were combined using the minimum average weighted deviation method of Li (1999); the method was based on the assumption that there was an ideal alternative upper bound where all fuzzy indicators equal 1. Actual values were characterized by different values of fuzzy indicators (ranging from 0 to1). The closer values are to 1; the closer they are to the ideal alternative. The absolute value of the deviation or distance of each alternative from the ideal was used as a criterion of choosing them as optimal.

The algorithm for comparison of agricultural management systems (Krueger and Kurtener, 2003) includes several procedures such as problem definition, building a decision matrix, normalizing decision attributes, building a normalized decision matrix, calculation of the weight vectors of the attributes, calculation of the objective functions, ranking alternative, and definition of the best alternative. The best treatment was selected from the six combinations of PAM and OM additions (Table 1) using three parameters or soil attributes which included:

1. the cumulative amount of water added to the pot over the whole experiment (cumadd),

2. the pressure of the penetrometer probing in megapascals (pres), and

3. the weight of aggregates collected on the sieves divided by the total weight (times 100 to give %) and averaged over the data from the three sieves (fract).

After analysis of the physical variables, two economic parameters or attributes were added to the analyses; these were costs of wheat residue and PAM and their application costs. The attributes pres, cumadd, cost of wheat residue added, and cost of PAM were selected as costs and the attribute fract was selected as a benefit.

RESULTS AND DISCUSSION

Bulk density

Figure 2 use kriged data to show contour maps of bulk density as a function of incubation time and PAM without (Fig. 2a) and with (Fig. 2b) wheat residue incorporated into the soil. Contour plots in the two figures were similar indicating that bulk densities did not vary with addition of wheat residue. Bulk densities varied with time and application of PAM reaching maximums at about 35 days of incubation and 30 PPM of PAM. These results agreed with the more traditional General linear models analysis of the data by Busscher *et al*. (2007).

Adding organic matter will usually reduce bulk density; and, in this study, the treatments with wheat residues generally had non-significantly lower bulk densities than those without wheat residue. Organic matter's effect on bulk density in this soil was confounded by leaching of the treatments at 28 and 56 days that caused high variability in soil settling and thus in bulk densities (Fig. 1). The variability was too large to show a clear difference. As a result, bulk density was not used as a variable in the multi-attributive analyses.

Aggregation

As shown with traditional analysis (Busscher *et al*., 2007), treatments with wheat residue amendments (Table 2) had developed more aggregation at 12.3% of the soil by dry weight (averaged over the three sieve sizes measured) verses 5.4% for the soil with no wheat residue added (LSD at 5% = 1.2%). Treatments with PAM also had higher amounts of aggregation than those without it as seen by others (Sojka *et al*., 1998a). Only the higher amount of PAM had significantly more aggregation with 10.1% for the 120 mg kg^{-1} PAM treatment, 8.5% for the 30 mg kg^{-1} PAM treatment, and 8% for the treatment with no PAM (LSD at 5% = 1.6%). PAM treated soils had greater aggregation when used with wheat residue amendment in contrast to the results of Lu *et al*. (2002) where OM interfered with PAM effectiveness, though their results with loamy sand were not as pronounced as with their other soils.

Table 1. Treatments definitions for combinations of soil amendments based on PAM and wheat residue additions

Treatment	Amendment	
	PAM (mg kg^{-1})	Wheat residue
1	0	None
2	30	None
3	120	None
4	0	Added
5	30	Added
6	120	Added

T a b l e 2. Decision matrix for measured parameters before normalization

Treatment	Parameters measured			Cost of amendment (USD)	
	Cone index (MPa)	Water added (g)	Aggregation (%)	Residue	PAM
1	1.579	345.2	5.091	0	0
2	0.864	353.7	4.410	0	260
3	1.045	350.6	6.834	0	800
4	0.989	312.3	11.02	338	0
5	0.681	319.5	12.66	298	220
6	0.757	310.6	13.34	298	760
LSD at 5%	0.155	7.56	3.93	–	–

Penetration resistance

Penetration resistances were measured about two weeks after the final leaching because treatments needed to drain; immediately after leaching, treatments were too wet to have 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 similar water contents; this prevented penetration resistances from differing because of water content variations. After drainage, water contents varied by less than 0.5% (from 8.6 to 9%); they were not significantly different and would not affect penetrometer results.

Penetration resistances differed among PAM and wheat residue treatments (Table 2), both amendments had lower readings than their non-amended counterparts. Penetration resistances were 1.16 MPa for treatments without wheat residue and 0.81 MPa for those with wheat residue amendment (LSD at 5% = 0.09 MPa). Although penetration resistances did not show a trend with increasing amounts of PAM, they were lower for both amended treatments than the non-amended treatment with means of 0.9 MPa for the 120 mg kg^{-1} PAM treatment, 0.77 for the 30 mg kg^{-1} PAM treatment, and 1.28 MPa for the treatment with no PAM (LSD at 5% = 0.11). 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).

Cumulative water added

The amount of water added to each treatment to bring them up to 10% was also listed in Table 2. Less water was added for the treatments with wheat residue than for the treatments without wheat residue. PAM treatments had mixed results with little significance among them. Less water added implied that wheat residue held water against evaporation and/or drainage. This would be consistent with the fact that soils with better aggregation hold more available water.

Fuzzy multi-attributive analysis

The costs and benefits were used to make decision matrix tables for physical parameters and for physical and economic parameters (Table 2). Parameters were normalized to develop fuzzy indicators where the maximum benefits or the minimum costs were equal to 1. The normalized decision matrix (Table 3) shows that treatment combination 1 had the best economic indicators because no PAM or wheat residue had to be added. Treatment combinations 2 and 3 also had one maximum because no wheat residue had to be added and treatment combination 4 had a maximum because no PAM had to be added. Treatment combination 5 had the best (lowest) penetration resistance. Treatment combination 6 had the best (least) amount of water added and the greatest amount of aggregation.

Treatment deviations from the ideal (where all indicators would be 1) were calculated using the methods of Krueger and Kurtener, (2003) and Li (1999). These methods used multi-attribute analyses of indicators and calculated values for the physical indicators only as listed in the first column of Table 4. If only the fraction of soil in aggregates (fract) were used to develop results, treatment combination 6 (wheat residue with 120 mg kg^{-1} PAM) would be the best

T a b l e 3. Normalized decision matrix where the values are normalized to have the lowest cost or highest benefit equal to one

Treatment	Parameters measured			Cost of amendment (USD)	
	Cone index (MPa)	Water added (g)	Aggregation (%)	Residue	PAM
1	0.43129	0.89977	0.38152	1	1
2	0.78819	0.87815	0.33049	1	0.0038462
3	0.65167	0.88591	0.51214	1	0.00125
4	0.68857	0.99456	0.82576	0.0029586	1
5	1	0.97214	0.94852	0.0033557	0.0045455
6	0.8996	1	1	0.0033557	0.0013158

treatment because it had the minimum deviation from the idea. This was the result of more traditional ANOVA analyses as stated in Busscher *et al*. (2007). However, when other physical parameters were included in the analyses as shown here with improvement of soil water holding properties and reduction of penetration resistance, the best treatment combination was 5 (wheat residue with 30 mg kg^{-1} PAM) with combination 6 as the second alternative and the other treatment combinations ranked by increasing deviation from the ideal as shown in Table 4.

T a b l e 4. The absolute value of the deviation of each alternative treatment from the ideal

Treatment	Comparison of alternatives	
	physical parameters	physical and economic
1	0.3906	0.3527
2	0.26613	0.4041
3	0.28192	0.3189
4	0.16157	0.0999
5	0.021348	0.0713
6	0.040291	0.0369

Treatment deviations from the ideal were also calculated using multi-attribute analyses of indicators for both physical and economic indicators as listed in the second column of Table 4. In this case, treatment combination 6 had the minimum deviation from the ideal with combination 5 as a second alternative. The other treatment combinations ranked by increasing deviation from the ideal are shown in the second row of Table 4. In this case, all indicators were weighted the same; however, weighting one factor more than another could change the results.

CONCLUSIONS

1. Using kriged data, bulk densities for the loamy sand did not vary with the addition of wheat residue nor when it was analyzed by amount of PAM added. This agreed with the more conventional ANOVA analysis performed earlier and bulk density was not used in the fuzzy analyses.

2. Data analysis for buildup of aggregation using fuzzy logic indicators included building decision matrices, normalizing decision attributes, building normalized decision matrices, calculating weighting vectors of the attributes, calculating objective functions, ranking alternatives, and defining the best alternative/ ranking alternatives.

3. Using a cost benefit type of analysis with normalized fuzzy indicators of physical parameters, addition of wheat residue with 30 mg kg^{-1} PAM proved to be the best alternative. When both physical and economic parameters were included in the analyses, the treatment option with wheat residue and 120 mg kg^{-1} PAM was best with wheat residue and 30 mg kg^{-1} PAM as second best.

4. Parameters were all weighted equally in this analysis. Analyses that weight one parameter over another may produce different results. For example, the addition of wheat residue with 120 mg kg^{-1} PAM had been selected as the best alternative with previous ANOVA analysis because it did not take other soil attributes into account when selecting the best treatment option. If the percent of aggregation were weighted heavily over the other parameters, all treatments with organic matter added would be preferred over those without it. Similarly, if cost were heavily weighted, the preferred results would be no residue, only PAM at the lower rate or only organic matter. A likely weighting scheme would be to increase the weight of the penetration resistance because that has been related to yield in these soils. In this case, the preferred treatments would be the same as those that were chosen with equal weighting (additions of organic matter and either 30 or 120 mg kg^{-1} PAM) because they had the highest ranking.

5. Care should be taken when weighting variables and interpreting results because parameters such as organic matter and water holding capacities may not be independent.

REFERENCES

Bárdossy A., 1996. The use of fuzzy rules for the description of elements of the hydrological cycle. Ecol. Mod., 85, 59-65

Blanchar R.W., Edmonds C.R., and Bradford J.M., 1978. Root growth in cores formed from fragipan and B2 horizons of Hobson soil. Soil Sci. Soc. Am. J., 42, 437-440.

Busscher W.J., Novak J.M., Caesar-Tonthat T.C., and Sojka R.E., 2006. Soil amendments to decrease high strength in SE Coastal Plain hardpans. Southern Conservation Systems Proc. Conf., June 26-28, Amarillo, Texas.

Busscher W.J., Novak J.M., Caesar-TonThan T.C. and Sojka R.E., 2007. Organic matter and polyacrylamide amendment of Norfolk loamy sand. Soil Sci. (in press).

de Araújo A.G. and Saraiva A.M., 2003. Fuzzy modeling of soil compaction due to agricultural machine traffic. Proc. Conf. EFITA 2003, June 5-9. Debrecen, Hungary.

Edam Y., Berman S., Boteach E., and Mendelson E., 2004. Distributed multi-robot assembly/packaging algorithms. Int. Aut. Soft Comp., 10, 349-358.

Ekwue E.I. and Stone R.J., 1995. Organic matter effects on the strength properties of compacted agricultural soils. Transactions of the ASAE, 38, 357-365.

Frederick J.R., Bauer P.J., Busscher W.J., and McCutcheon G.S., 1998. Tillage management for double cropped soybean grown using narrow and wide row-width culture. Crop Sci., 38, 755-762.

Free E.I., Lamb Jr. J., and Carlton E.A., 1947. Compatibility of certain soils as related to organic matter and erosion. J. Am. Soc. Agron., 39, 1068-1076.

Hamza M.A. and Anderson W.K., 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Till. Res., 82, 121-145.

John B., Yamashita T., Ludwig B., and Flessa H., 2005. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma, 128, 63-79.

Kay-Shoemake J.L., Watwood M.E., Lentz R.D., and Sojka R.E., 1998. Polyacrylamide as an organic nitrogen source for soil microorganisms with potential impact on inorganic soil nitrogen in agricultural soil. Soil Biol. Biochem., 30, 1045-1052.

Khalilian A., Han Y.J., Dodd R.B., Sullivan M.J., and Gorucu S., 2002. Technology for variable depth tillage in Coastal Plain soils. Proc. 7th Conf. Beltwide Cotton, National Cotton Council, Memphis, TN.

Krueger E. and Kurtener D., 2003. Evaluation of cultivation practices using fuzzy multi-attributive decision-making approach. In: Agrophysical and Ecological Problems of Agriculture in the 21st Century. SPBISTRO, St. Petersburg, Russia.

Kurtener D. and Badenko V., 2002. Fuzzy algorithms to support spatial planning. In: Planning Support Systems in Practice (Eds S. Geertman, J. Stillwell), Springer Press, Berlin.

Kurtener D., Krueger E., Krankina O., and Duane M., 2006. Cross-sectoral approach to support spatial planning. Proc. UDMS'2006. May 15-17, Aalborg, Denmark.

Li D.F., 1999. Fuzzy multi attribute decision-making models and methods with incomplete preference information. Fuzzy Sets and Systems, 106, 113-119.

Lu J.H., Wu L., and Letey J., 2002. Effects of soil and water properties on anionic polyacrylamide sorption. Soil Sci. Soc. Am. J., 66, 578-584.

Miller W.P. and Miller D.M., 1987. A micro-pipette method for soil mechanical analysis. Commun. Soil Sci. Plant Anal., 18, 1-15.

Mitra B., Scott H.D., Dixon J.C., and McKimmey J.M., 1998. Applications of fuzzy logic to the prediction of soil erosion in a large watershed. Geoderma, 86, 183-209.

Mohamed A.M.O. and Hawas Y., 2004. Neuro-fuzzy logic model for evaluating water content of sandy soils. Computer-Aided Civil and Infrastructure Eng., 19, 274-287.

Muhammetoglu A. and Yardimci A., 2006. A fuzzy logic approach to assess groundwater pollution levels below agricultural fields. Environ. Mon. Assess., 118, 337-354.

Munkholm L.J., Schjonning P., and Rasmussen K.J., 2001. Non-inversion tillage effects on mechanical properties of a humid sandy loam. Soil Till. Res., 62, 1-14.

Novak J.M., Watts D.W., and Hunt P.G., 1996. Long-term tillage effects on atrazine and fluometuron sorption in Coastal Plain soils. Agric. Ecosys. Environ. J., 60, 165-173.

Raper R.L., Reeves D.W., Burmester C.H., and Schwab E.B., 2000. Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements. Appl. Eng. Agric., 16, 379-385.

Sainju U.M., Terrill T.H., Gelaye S., and Singh B.P., 2003. Soil aggregation and carbon and nitrogen pools under rhizoma peanut and perennial weeds. Soil Sci. Soc. Am. J., 67, 146-155.

Sanchez F.G., Carter E.A., and Klepac J.F., 2003. Adding OM to reduce soil strength: Enhancing the soil organic matter pool through biomass incorporation. Biomass and Bioenergy, 24, 337-349.

SAS Institute Inc., **2000.** SAS/STAT User's Guide, Version 8. SAS Inst. Inc., Cary, NC.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, **2006.** Official Soil Series Descriptions http://soils.usda.gov/technical/classification/osd/index.html. [Accessed 30 June 2006].

Sojka R.E., Lentz R.D., Trout T.J., Ross C.W., Bjorneberg D.L., and Aase J.K., 1998a. Polyacrylamide effects on infiltration in irrigated agriculture. J. Soil Water Conserv., 53, 325-331.

Sojka R.E., Lentz R.D., and Westermann D.T., 1998b. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. Soil Sci. Soc. Am. J., 62, 1672-1680.

Tolstikh L.I., Akimov N.I., Golubeva I.A., and Shvetsov I.A., 1992. Degradation and stabilization of polyacrylamide in polymer flooding conditions. Int. J. Polymeric Mat., 17, 177-193.

Waksman S.A., 1937. Soil deterioration and soil conservation from the viewpoint of soil microbiology. J. Am. Soc. Agron., 29, 113-122.

Wang, Y., Admunson R., and Niu X.F., 2000. Seasonal and altitudinal variation in decomposition of soil organic matter inferred from radiocarbon measurements of CO_2 flux. Global Biogeochem., Cycles, 14, 199-211.

Weeks L.E. and Colter W.G., 1952. Effect of synthetic soil conditioners on erosion control. Soil Sci., 73, 473-484.