ABSTRACT

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The application of mulch products to disturbed soil is frequently used to decrease soil erosion. The addition of polyacrylamide (PAM) has been demonstrated to reduce erosion even further. We conducted rainfall-simulator and field tests on several types of mulch, hydromulch, and erosion control blankets with varying rates of PAM to determine the relative improvements in erosion control and vegetative establishment achieved by different groundcovers and PAM. We also compared applications of granular (37 and 74 kg ha^{-1}) and aqueous (37 kg ha^{-1}) PAM with straw. The tests were done on 2- x 1-m soil boxes tilted to 32% slope and three field locations with similar slopes. Under simulated rainfall, the addition of 37 kg ha^{-1} aqueous PAM to any mulch type tended to reduce runoff turbidity, TSS, and sediment loss, with reductions of 50% or more in some cases. In the absence of PAM, increasing hydromulch rate from 1971 kg ha^{-1} to 2957 kg ha^{-1} significantly reduced turbidity for an experimental cotton product but not for wood fiber. Granular PAM, when applied at a rate equal to that of aqueous PAM, had a significantly higher mean turbidity and TSS; total sediment loss was reduced by dry-PAM only at the higher rate. The lower rate of granular PAM apparently did not reduce erosion but did flocculate the sediment captured in the runoff collection bucket, reducing turbidity. In field experiments, bonded fiber matrix had significantly lower biomass and vegetative cover than all other treatments at one site but differences were not significant at other sites. In one instance where a cotton fiber matrix test product washed off the slope face, runoff turbidity and TSS was significantly higher than other treatments. There were no instances of straw with PAM significantly improving biomass or vegetative cover compared to straw alone.

Performance of Mulches and Polyacrylamide for Erosion Control and Vegetative Establishment

by
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BIOGRAPHY

Deanna Babcock was born in West Branch, Michigan, July 9, 1984 and raised in Tawas City, a small town in Northeastern Michigan. After graduating from Tawas Area High School in 2002, Deanna attended Albion College, where she participated in cross country and track and field at the Division III level. Deanna graduated from Albion in May of 2006 with a B.A. in biology and began graduate school in Soil Science at North Carolina State University.

ACKNOWLEGEMENTS

My two years at NCSU have been life-changing. When I arrived in Raleigh, I took everything in my life for granted. I had loving friends and family, great health, and mental acuity, but I did not often pause to reflect on how blessed every aspect of my life was.

On July 20, 2007, my life changed forever. While I was swimming, my heart stopped and I died. At WakeMed, doctors were able to restart my heart after seven minutes of lifelessness. For the first several days, it appeared extremely unlikely that I would live. My condition improved, and while my parents no longer feared for my death, doctors said it was likely that I would have considerable brain damage. In addition to the high likelihood of brain damage, my parents experienced another painful blow when doctors informed them that, in order to live, my left leg would have to be amputated above the knee.

I was comatose for four weeks. During this time, my parents, who would have been alone in Raleigh, were comforted by the friends I previously took for granted. Apparently there were some pretty fun times when I was down for the count, and I can't thank my friends enough for this.

When I awoke, my friends and family were there because they had been there all along. Chris was there to test my cognitive abilities by asking about manganese concretions, to trash talk about disc golf, and to bring me banana cream pie. Carlin was there to bring me books and cookies. Sara, Wes, and Daniela were there to bring me Krispy Kreme doughnuts, even though doughnuts nauseate me. Rich was there to tell me my plots had fizzled because of the drought. Daren and the triathlon club were there to talk about racing and ask when I was getting back on my bike. My Albion friends were there to talk about running. Thanks.

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CHAPTER 1: LITERATURE REVIEW

Sediment resulting from agricultural and urban erosion is one of the most common water pollutants nationwide. In the 2000 US EPA National Water Quality Inventory, 12% of assessed river and stream miles and 9% of lakes and reservoirs were affected by sedimentation from agriculture, urban runoff, construction, and forestry (USEPA, 2000). Sedimentation is one of the leading causes of stream impairment, second only to pathogenic pollutants (bacteria) (USEPA, 2000).

While agriculture is the source of most eroded soil in the US, construction sites can contribute large amounts of sediment to small areas in short periods of time, and the relative contribution of erosion from active construction sites has been increasing in the past few decades (Kauffman, 2000). In urban areas under development, runoff from construction sites is a major source of sediment (Broz et al., 2003). Although agricultural erosion accounts for the majority (about 1.75 billion tons in 2003, or 10.5 t ha^{-1} yr^{-1} (NRCS, 2003)) of eroded soil in the US, the rates of erosion on construction sites are much higher than most agricultural systems, ranging from 20 t ha^{-1} yr^{-1} to over 600 t ha^{-1} yr^{-1} (Pimentel and Kounang, 1998; Clark and Pitt, 2004). In 1975, urban construction sites released 15 million tons of sediment and road construction released 22 million tons (Lemly, 1982).

To counter high rates of erosion on construction sites and meet erosion and sediment control guidelines, contractors frequently use temporary ground covers with or without soil conditioners, such as linear, anionic polyacrylamide (PAM). Temporary groundcovers, such as mulch or hydromulch, erosion control blankets (ECB's), and geotextiles, have been successfully used to reduce erosion on construction sites for some time. The use of PAM on construction sites is a newer technology, but shows great promise based on current research. The use of temporary ground covers and PAM will be discussed further, with a focus on preventing erosion on active construction sites.

Polyacrylamide is a polymer that is manufactured in cationic, anionic, and neutral forms. The cationic and neutral forms of PAM are not currently used for onsite erosion control because they may be more toxic than the anionic form (Figure 1) and have not been approved by the appropriate regulatory agencies (Sojka et al., 2007). Due to its propensity to adsorb to suspended solids, anionic PAM is rapidly removed from water, and the concentration of anionic PAM in water downstream from an application site should be negligible if PAM is applied at prescribed rates (Sojka et al., 2007).

In addition to differences in net charge, PAM formulations vary primarily by chain length and charge density. As chain length increases, both molecular weight and solution viscosity also increase. Charge density, the substitution of OH^- groups for acrylamide groups along the polymer chain, is related to chain coil size and affects charge interactions between the polymer and clay particles (Green et al., 2000). Chain length and charge density dictate the effect a specific PAM formulation has on a given soil. For example, PAM formulations with long chain lengths have been found to be more effective at binding coarse-textured soil because the longer polymer chains can effectively bridge the large gaps between adjacent soil particles (Green et al., 2000).

Polyacrylamide can be applied to bare soil or in conjunction with a temporary erosion control measure. When using PAM for surface irrigation in areas with low slopes, recommended application rates are approximately 1-2 kg ha^{-1} (Sojka et al., 2007). However, because construction sites often have slopes of 50% or greater, prescribed PAM rates on construction sites are far greater than PAM rates used for low slope furrow irrigation. Rates of PAM on construction sites can range from 10 kg ha^{-1} to over 60 kg ha^{-1}, depending on state regulations and slope steepness. Polyacrylamide has been found to preserve surface aggregate structure, prevent surface crusting, increase infiltration, decrease runoff volume, reduce soil loss, and encourage vegetative growth on steep slopes.

Zhang et al. (1998) found that 20 kg ha^{-1} of PAM applied in solution with gypsum on very low slope prevented surface sealing by "preventing clay dispersion and stabilizing soil aggregates," reducing runoff by 44% compared to a control. Polyacrylamide continued to reduce runoff relative to the control up to 160 days after application, with a 35% reduction in runoff volume relative to the control for a period 126-163 days after application. Additionally, PAM significantly reduced soil loss by 94% and 90% in the first and second storms, respectively, and resulted in a 17% reduction in soil loss compared to the control for the four month duration of the experiment.

Sometimes PAM is applied with gypsum because gypsum provides divalent calcium ions that aid in cation bridging between the PAM molecule and clay colloids. Rapp et al. (2000) found that 5 ton ha^{-1} of phosphogypsum applied with 20 kg ha^{-1} of PAM under simulated rainfall stabilized soil surface structure, prevented dispersion and soil seal formation in a soil with low sodicity, and doubled the rate of emergence of cotton compared to the control. Cook and Nelson (1986) found that PAM applied in a dry, granular form also stabilized soil structure. Granular PAM applied in the field at 22-90 kg ha^{-1} did not adequately disperse and remained as globules, while aqueous PAM more evenly coated soil aggregates. Neither aqueous PAM nor granular PAM improved soil structure, but both stabilized the soil in its original condition.

Flanagan et al. (2002a, 2002b) found that applying 80 kg ha^{-1} of aqueous PAM to a 18° slope resulted in up to a 99% reduction in soil loss compared to bare soil alone. Polyacrylamide also improved aggregate stability on slopes ranging from 35-45%, reduced clay dispersion, made soil less susceptible to surface sealing, and decreased the incidence of rilling. The rougher surface of PAM-treated plots prevented grass seed from running off and resulted in improved establishment of vegetation compared to similar plots without PAM. Rubio (1989) and Cook and Nelson (1986) also found that PAM increased aggregate stability and reduced surface crusting, a major contributor to seed failure, and improved infiltration under conditions of frequent watering. Polyacrylamide improved the rate of grass emergence under frequent watering, and improved the total emergence of grass under less-frequent watering due to decreased surface crusting (Rubio, 1989). Wallace (1987) also found a significant improvement in germination when PAM was applied. Aqueous PAM applied at 2.2 kg ha^{-1} to potted tomato or lettuce seeds in two different soils improved emergence time by several days and increased seedling dry weights by two to eight times compared to treatments without PAM.

Yu et al. (2003) observed that the application of aqueous PAM is time-consuming due to the difficulty of dissolving PAM at high concentrations. Water in which PAM is dissolved becomes slippery and viscous, and the viscosity of the solution can overwhelm pumps that are used to apply PAM on slopes. Due to the difficulty of dissolving and applying PAM in aqueous form, granular PAM application could be easier and more economical, especially in dry regions.

Under simulated rainfall on a silty clay soil at 9.6° slope with 60 kg ha^{-1} of either aqueous or granular PAM, Peterson et al. (2002) found that solution PAM treatments extended time to runoff by about 40 minutes, or about 175%, compared to either the control or granular PAM. Granular PAM had significantly shorter time to runoff compared to the control. The longer time to runoff indicated that the wet PAM reduced surface sealing and promoted increased infiltration. Granular PAM reduced infiltration rate compared to the control, perhaps because the granules "migrated into pore spaces and became enlarged during wetting" (Peterson et al., 2002). Polyacrylamide granules were observed in runoff water from the granular PAM treatment, indicating that PAM granules were adsorbed to soil particles and transported in runoff because they did not have sufficient time to dissolve. Aqueous PAM reduced sediment yield by over 90% compared to the control, while granular PAM reduced sediment by 31% compared to the control. Because PAM reduced sediment yield more than runoff volume, Peterson et al. (2002) concluded that PAM reduced overall soil erodibility. Both aqueous and granular PAM reduced soil erodibility compared to a control, but aqueous PAM was more effective at reducing soil erosion than granular PAM.

Yu et al. (2003) applied 10 kg ha^{-1} and 20 kg ha^{-1} of granular PAM with or without 2 or 4 Mg ha^{-1} of gypsum to a silt loam and sandy clay at 8.5° slope using deionized (DI) simulated rainfall at an intensity of 36 mm hr^{-1} and total rainfall of 72 mm. Granular PAM alone, mixed in the top 5 mm of the soil surface, resulted in infiltration rates (IR) similar to the control (no PAM or gypsum), while PAM with gypsum increased IR by at least 50% relative to the control, which also decreased runoff volume significantly. It was thought that the low electrolyte concentration of rainwater in the absence of gypsum resulted in PAM chains being more straightened out than in the gypsum treatments, while the PAM in the gypsum treatments had coiled tails. The straight tails may have clogged soil conducting pores, while coiled tails did not. Polyacrylamide alone did not prevent surface sealing; granular PAM with gypsum was found to be as effective as aqueous PAM sprayed onto a soil surface treated with gypsum. Conversely, the straight tails of PAM without gypsum may have been more effective at binding soil particles, as the PAM alone treatment had the least soil loss. Soil losses with PAM alone were 15% to 30% of the control for two different soil types and were also significantly less than with PAM with gypsum treatment. Polyacrylamide with gypsum also reduced soil loss relative to the control, but was not as effective as PAM alone. Soil loss with PAM alone was about half that of either PAM with gypsum treatment. Mixing granular PAM with soil alone was not effective in preventing surface sealing or decreasing runoff volume, but was effective in preventing soil loss.

Placing mulch, hydromulch, or erosion control blankets on slopes has long been recognized as an important step in reducing erosion. Erosion control with temporary measures in the short-term is crucial for the long-term stabilization of a slope. The long-term goal for slope stabilization is the establishment of a natural vegetative cover, which was found to reduce soil loss by over 200 times compared to a bare control (Marques et al., 2007).

Temporary erosion control is essential because soil erosion decreases soil productivity and vegetative establishment. Sediment transported in runoff water makes up the fine fraction of the soil, which is rich in organic matter and nutrients (Marques et al., 2007). Aside from depleting organic matter, soil erosion reduces infiltration (Bruce et al., 1995). The loss of soil organic matter and reduced infiltration of water negatively affect soil productivity and the potential for establishment of long-term vegetation (Bruce et al., 1995), resulting in higher erosion rates over time.

Lemly (1982) found that a variety of treatments (asphalt-tacked straw, jute netting, mulch blanket, wood chips, and excelsior blanket) seeded with 2 kg ha^{-1} of tall fescue significantly reduced erosion by as much as 75% compared to the bare soil control. All treatments also significantly increased grass coverage compared to bare soil. Three months after seeding, all treatments had grass coverage in excess of 75%, while the bare soil control only had 40% grass coverage.

Bautista et al. (1996) compared 2000 kg ha^{-1} of straw to a bare soil control in a semiarid post-fire area on slopes ranging from 14-20°. Mulched plots produced less runoff and sediment than the control for all rain events. Total runoff on bare soil was 3.2-15 times greater, and soil loss was 2-16 times greater. Plant cover in mulched plots was only slightly higher than control plots after both one and two years, but ground cover on the mulched plots remained at 80% due to the straw. One of the major causes of crust formation is physical dispersion of surface aggregates caused by the impact energy of raindrops (Agassi et al., 1981). Mulched plots had a lower penetration resistance on the soil surface due to reduced sealing and surface crusting caused by rainfall impact.

Vacher et al. (2003) evaluated the effect of barley mulch alone (2.75 t ha^{-1}) and barley mulch (2.75 t ha^{-1}) with PAM (5-40 kg ha^{-1}) of varying molecular weights on infiltration, surface hardness, and erosion under simulated rainfall and simulated overland flow on a 5.7° slope. They found PAM significantly increased infiltration, reduced surface hardness, and reduced sediment in runoff by 22-54% compared to bare soil control. Infiltration, compared to bare soil control, increased about 33% for low PAM rates (5-10 kg ha^{-1}) and about 133% at higher rates of PAM (40 kg ha^{-1}). Adding straw mulch alone increased infiltration by about five times compared to the control, and about three times compared to PAM treatments. Adding PAM to straw mulch resulted in a small increase in infiltration over straw alone, but this effect was not significant. Similarly, Green and Scott (2000) found that final infiltration rate (FIR) in a sandy loam treated with 20 kg ha^{-1} of PAM was 141-335% of control, and the FIR in a silt loam was 304-488 % of control.

McLaughlin and Brown (2006) found that straw, straw blanket, and bonded fiber matrix hydromulch (BFM) all reduced runoff volume, turbidity, and sediment loss compared to bare soil under natural rainfall at a 2.3° slope. Adding 19 kg ha^{-1} of PAM to mulch reduced average runoff, turbidity, and sediment loss compared to mulch without PAM, but the differences were generally not significant. Under simulated rainfall at 5.7-11.3° slope, all ground covers resulted in reduced runoff turbidity compared to bare soil control but were not significantly different from each other. Polyacrylamide resulted in a significant reduction in turbidity compared to no PAM and also significantly improved ground cover. Straw, with or without PAM, resulted in more complete grass coverage than BFM or bare soil.

Hayes et al. (2005) found that adding low rates of PAM (0.75 kg ha^{-1}-10.5 kg ha^{-1}) to 4.5 t ha^{-1} of straw mulch on slopes of 11.3° or 26.6° rarely resulted in statistically significant improvements in runoff volume, turbidity, or sediment loss compared to mulch alone in natural rainfall events. Seeding and mulching, however, reduced both turbidity and sediment loss in about 60% of all rain events.

Benik et al. (2003) evaluated straw, BFM, straw/coconut blanket, and wood-fiber blanket on a 19.8° slope and found that runoff volume did not differ between treatments in the springtime when there was little to no vegetative cover, though straw mulch tended to have the highest runoff volume. In the fall, runoff volume from bare soil plots was greater than runoff volume from BFM, straw/coconut blanket, and wood-fiber blanket plots. Sediment loss on bare soil in the spring was significantly greater than covered treatments; sediment yield on bare soil was more than five times greater than sediment loss with straw mulch. The bare soil treatment continued to perform poorly in the fall, with sediment loss 3.75 times greater than bare soil, likely due to reduced vegetative establishment. Bare soil averaged about 5% less grass coverage than both straw mulch and BFM, though the differences between bare soil and covered soil were not significant.

CHAPTER 2: RAINFALL SIMULATOR EXPERIMENTS

Introduction

Bare soil, commonly found on construction sites, is far more susceptible to wind and water erosion than covered soil. The effects of soil erosion include loss or redistribution of soil, breakdown of soil structure, decline in organic matter and nutrient content, decline in soil moisture, and reduction in soil productivity (Morgan, 2005; Mostaghimi et al., 1994). Because rain and wind energy are the primary causes of erosion from bare land, soil erosion can be decreased by using mulches for short term soil protection (Pimentel and Kounang, 1998).

Straw alone is frequently used for erosion control on slopes because it is inexpensive yet effective. For example, Barton et al. (2004) found that placing 4 t ha^{-1} rice straw on conventionally tilled corn fields with 27° slope reduced mean annual soil loss by 82% relative to bare soil. Bautista et al. (1996) compared 2000 kg ha^{-1} straw to a bare soil control in a semiarid post-fire area with slopes ranging from 14° to 20° and found that bare soil plots had 3.2 to 15 times greater runoff volume and 2 to 16 times greater soil loss than plots receiving straw mulch.

Common alternatives to straw mulch may include hydromulches and bonded fiber matrices. Such alternatives, though more costly than straw, have been found to significantly reduce erosion relative to straw under some conditions. Benik et al. (2003), on a 20° construction site fill slope, found that straw mulch (4500 kg ha^{-1}) lost roughly 1/10 the sediment lost by a bare control, and that bonded fiber matrix (7850 kg ha^{-1}) lost roughly 1/10 the sediment lost by straw. All three treatments were significantly different from each other.

McLaughlin and Brown (2006), however, did not observe a significant difference in sediment loss between 2200 kg ha^{-1} straw and 3360 kg ha^{-1} BFM under natural rainfall at 2.3°slope. Straw plots lost an average of 0.8 t ha^{-1} of sediment, and BFM plots lost an average of 0.6 kg ha^{-1} sediment over five runoff-generating rainfall events. Using simulated rainfall on 5.7° slopes, the mean runoff turbidity from the same rates of straw, BFM, and wood fiber hydromulch (1680 kg ha^{-1}) were not significantly different.

In addition to the type of mulch used, increasing the rate of mulch applied to a slope tends to reduce soil erosion. Mannering and Meyer (1963) found that as the rate of straw was increased from 0 kg ha^{-1} to almost 9000 kg ha^{-1} on a 2.9° slope, soil loss stopped decreasing at mulch rates above 4500 kg ha^{-1}. Applying straw at rates in excess of 4500 kg ha^{-1} did not further reduce soil loss. Lal (1998) evaluated five rates of straw mulch (0, 1000, 2000, 3000, and 4000 kg ha^{-1}) on a clayey, Kaolinitic Oxic Paleustalf with 4.6° slopes. Only the rate of 4000 kg ha^{-1} of straw significantly reduced soil loss compared to the bare soil control. There was not a significant difference in soil loss among any treatments receiving straw mulch.

Chemical soil stabilizers used in conjunction with mulch may decrease soil erosion relative to mulch alone. A soil conditioner frequently used on construction sites is linear, anionic polyacrylamide (PAM). The results of studies involving the use of PAM for erosion control have been somewhat mixed, but the application of PAM to a slope has generally been found to reduce soil erosion. For example, PAM at rates of 20 kg ha^{-1} to 80 kg ha^{-1} has been reported to reduce rilling and to reduce soil loss by half or even ten-fold compared to a bare control (Agassi and Ben-Hur, 1992; Flanagan et al., 2002a; Flanagan et al., 2002b).

Polyacrylamide has been shown to be effective at moderately low rates. Yu et al. (2003) applied 10 kg ha^{-1} and 20 kg ha^{-1} of granular PAM, and soil loss on PAM-treated slopes was 15-30% of the control for two different soil types. Lower rates of PAM do not appear to be as effective as moderate PAM rates. For example, Hayes et al. (2005) found that low PAM rates (0.75 kg ha^{-1} to 10.5 kg ha^{-1}) did not significantly reduce either turbidity or sediment loss, and Soupir et al. (2004) found that PAM in aqueous form at low rates (1.7 kg ha^{-1} to 6.7 kg ha^{-1}) tended to reduce TSS compared to a bare soil control, though the reductions were not statistically significant.

The purpose of this study was to determine how mulch type, mulch rate, PAM rate, and PAM application method affect soil loss and runoff water quality. It was hypothesized that a high rate of mulch with PAM would be more effective than a low rate of mulch without PAM, and that the same rates of PAM applied either in solution or in granular form would be similarly effective for erosion control. Additionally, it was expected that, at the same rates of mulch and PAM, a manufactured erosion control product would have less soil erosion than natural straw mulch.

Methods and Materials

<u>Treatments</u>

Three mulch types were used: commercial wood fiber hydromulch, an experimental cotton-based hydromulch (cotton fiber matrix test product), and straw. For the cotton and wood fiber hydromulches, mulch rates of 2240 kg ha^{-1} and 3360 kg ha^{-1} were evaluated, and straw was evaluated at 2240 kg ha^{-1}. After performing all experiments, it was noted that no correction factor was used when applying the hydromulches by volume. A laboratory test was conducted in which the recommended amount of hydromulch was added to 1 L of water to determine the displacement that occurred from the hydromulch. This was determined to be 12%, so to account for the volume of "water" occupied by hydromulch during calibration, a 12% correction factor was used. Thus, the nominal 2240 kg ha^{-1} of mulch applied based on volume was actually 1971 kg ha^{-1}, and 3360 kg ha^{-1} of mulch was actually 2957 kg ha^{-1} of mulch. This change did not apply to straw. For the sake of simplicity, the rate of 1971 kg ha^{-1} will be referred to as the "low" rate, and 2957 kg ha^{-1} will be referred to as the "high" rate.

Each mulch type was evaluated both with and without PAM (APS 705, Applied Polymer Systems, Woodstock, GA), dissolved in the hydroseeder with the mulch for the wood fiber and cotton treatments, at a rate of 37 kg ha^{-1}. For the straw treatment, the PAM was dissolved at a concentration of 0.58 g PAM per liter of water, and 13.25 L of water was applied to each plot using watering cans. Two additional PAM treatments were included for the straw treatment, involving the application in the dry, granular form at rates of 37 kg ha^{-1} and 74 kg ha^{-1}. The PAM used was a proprietary blend of linear anionic PAMs of unknown charge density and molecular weight. There were a total of 12 treatments, and each treatment was replicated four times. Outliers occurring due to rainfall simulator malfunction were discarded before analysis, and the trials were repeated when appropriate.

<u>Rainfall Simulator</u>

A total of 163 kg of air-dry soil was placed in wooden boxes with dimensions of 2 m x 1 m. The soil was gently packed and leveled by hand and shovel, and the final depth of soil was approximately 6 cm throughout the box. The estimated soil bulk density, determined by cores taken randomly in prepared boxes, was 1.44 g cm^{-3}. Four soil boxes with randomly assigned treatments were placed on wooden saw horses under two identical rainfall simulator nozzles such that the slope of each box was 18°. Rainfall simulator specifications can be found in McLaughlin and Brown (2006). Surface runoff exited a series of holes at the soil surface at the bottom of the soil boxes and was collected in a tub. The collection tubs were covered with plastic so that rainfall did not contribute to the total runoff volume.

Each four-box run of the rainfall simulator consisted of two sub-tests. The first test was 40 minutes in length, alternating rain 5 s on and 5 s off, resulting in a rainfall intensity of 37 mm h^{-1}. The second test, performed 24 hours after the first run, was 8 minutes long, also alternating 5 s on and 5 s off. The total rainfall was 29.6 mm over both runs.

During the first run, time to initiate runoff and total runoff volume were not recorded because some treatments, such as high rates of cotton or wood fiber, received considerable volumes of water with the hydromulch application, while others, such as straw alone and straw with dry PAM, received no water during experimental setup. As a result, for the first simulation, there was a close relationship between time of runoff initiation, runoff volume, and volume of water used to apply the treatments. For this reason, we did not make any comparisons of runoff volume or time till initiation of runoff for the first event.
After each simulation, samples of the bulk runoff were collected to determine turbidity and total suspended sediment (TSS).

In order to further examine potential differences in water quality related to PAM application method, a second, independent set of experiments was performed. Two treatments, 2240 kg ha^{-1} straw with 37 kg ha^{-1} aqueous PAM and 2240 kg ha^{-1} straw with 37 kg ha^{-1} granular PAM, were set up as previously described. Each simulation consisted of a single rainfall event: 40 minutes of rainfall, with the rainfall simulator alternating on and off every 60 s, for a rainfall rate of 37 mm hr^{-1}. The total rainfall applied was 24.7 mm. Once runoff was initiated, runoff samples were taken every other minute from each soil box. Each sample volume was 30-50 mL, and a minimum of 9 runoff samples were taken from each soil box for each trial. Turbidity and TSS were measured for each sample.

Water Quality

Turbidity was measured using a TC-3000e portable turbidity meter (version 1.5, LaMotte, Chestertown, MD). Measured turbidities were corrected with a standard curve based on formazine standards. Following the Standard Methods for the Examination of Water and Wastewater (Clesceri et al., 1998), TSS samples were filtered with 47 mm glass fiber ProWeigh filters from Environmental Express (Mt. Pleasant, SC) and dried overnight at 103-105° C. Runoff volume and TSS were used to determine total sediment loss in the first experiment, using the following equation:

$$\text{runoff volume (mL)} * \text{TSS (mg L}^{-1}) * 200{,}000 = \text{total sediment loss (kg ha}^{-1})$$

Data Analysis

Statistical software was used to perform all data analyses (SAS version 9.1, SAS Institute, Cary, NC). Assumptions of normality and homoscedasity were evaluated using normal probability plots and Levene's Test for homogeneity of variance, and data was log transformed so that parametric procedures could be used. Multifactor analysis of variance (ANOVA) was used to analyze main effects and interactions. Treatment means were separated using Fisher's least significant differences, and, unless otherwise noted, error rates were controlled at $\alpha = 0.05$ using the Tukey-Kramer adjustment for multiple comparisons. Example SAS code may be found in Appendix 1.

Results

<u>Runoff Initiation</u>

A discussion of water balance may be helpful in understanding runoff initiation and runoff volume. Simulated rainfall that enters the soil box system may either be stored in the system or leave the system through holes at the soil surface as overland runoff. Water may be stored in the soil itself or in the mulch on top of the soil surface. Water that leaves the system may only do so for two reasons: the water storing capacities of the soil and mulch have been exceeded or the rate of simulated precipitation has exceeded the infiltration rate of the soil. As shown in Appendix 2, the total rainfall applied to the soil boxes in two simulations is not enough to fill the estimated pore space within the boxes. Thus, any differences in time of runoff initiation or runoff volume can only stem from differences in storage capacity of the mulch and differences in infiltration rate, both of which may vary based on treatment.

Treatment

There were significant treatment differences during the second rainfall simulation in time to initiate runoff ($p=0.029$, Table 1). The high rate of wood fiber with aqueous PAM delayed runoff significantly compared to straw with 37 kg ha^{-1} granular PAM and the low rate of cotton without PAM. There were no other significant differences.

It is possible that the PAM granules applied to the straw treatment were hydrated slightly by rainfall and then remained at or just below the soil surface, decreasing infiltration.

Lentz (2003) found that as PAM concentration increased from 0 to 500 ppm, the infiltration rates for four soils (silt loam, loamy fine sand, and clay loam) in stirred columns decreased. Lentz stated that in soils with poor to no structure, such as the soils used for the rainfall simulator experiments, PAM may clog soil pores and decrease infiltration. Polyacrylamide is likely to enhance infiltration in well structured soils and soils with dispersible fines (Lentz, 2003).

PAM Treatment

When all treatments were lumped together regardless of mulch type or rate, the presence or absence of PAM did not significantly affect time of runoff initiation (p=0.13, Table 2). Polyacrylamide rate was also not significantly related to time of runoff initiation when treatments were lumped (p=0.27, Table 2). Although not evident in this experiment, PAM has been found to lessen the severity of surface sealing and increase the infiltration capacity of a soil (Flanagan et al., 2002b; Peterson et al., 2002; Zhang et al., 1998), which should delay the onset of runoff.

In order to further determine differences in PAM rate, all treatments that received water during experimental setup were removed from the dataset before analysis. The remaining treatments, all straw, differed only in the amount of granular PAM applied: 0, 37, or 74 kg ha^{-1}. When these treatments were analyzed independently, PAM rate significantly affected time of runoff initiation for the first run (p=0.063, Figure 2). Time of runoff initiation was not different for the two treatments with PAM, but the low rate of PAM initiated runoff sooner than the non-PAM treatment.

There were also significant treatment differences in runoff initiation for the second run (Figure 3, p=0.087), with 37 kg ha^{-1} dry PAM initiating runoff sooner than 74 kg ha^{-1}. Straw without PAM was not significantly different from either PAM treatment. It is likely that, at the high rate, enough PAM remained on the soil surface after the first run to improve infiltration during the second run. At the low rate, most of the PAM washed from the soil surface during the first run, and infiltration was not improved for the second run.

Polyacrylamide has been shown to increase water infiltration (Green et al., 2000), so PAM treatments might be expected to have delayed runoff times compared to non-PAM treatments. Our finding that PAM-treated soil would initiate runoff sooner than untreated soil might have several explanations. A possible explanation for the more rapid initiation of runoff in the 37 kg ha^{-1} PAM treatment is that PAM molecules clogged soil pores, decreasing infiltration. Polyacrylamide in solid, granular form may become hydrated in soil pores, increasing pressure on soil particles. The soil particles are pushed together, causing a reduction in the size and continuity of pores (Lentz, 2007). Lentz (2003) found that PAM can decrease infiltration in soils with poor or no structure, or coarse-textured sands lacking dispersible fines. The soils used did not have natural soil structure, as the soils were sieved, raked, and packed into soil boxes. This would have destroyed natural soil structure, as is common on construction sites, making it possible that PAM actually decreased infiltration rate.

Mulch Rate

When all straw treatments were removed, treatments with a high mulch rate initiated runoff later than treatments with a low rate of mulch (p=0.087, Table 3). When the mean runoff times of treatments without PAM were averaged based on mulch rate, the high mulch rate delayed runoff by 36% compared to treatments with the low mulch rate. This conflicts with Holt et al. (2005), who found that a 50% increase in the rate of a cotton hydromulch did not have a significant effect on time of runoff initiation.

A possible explanation for difference in runoff initiation time between the high rate of wood fiber with PAM and straw with 37 kg ha^{-1} granular PAM is that the granular PAM may have reduced infiltration rate by clogging soil pores, as discussed previously. The difference in time of runoff initiation between the high rate of wood fiber with PAM and the low rate of cotton without PAM may be related to water storage capacity within the mulch layer. More water could have been stored in the high rate of wood fiber than the low rate of cotton, delaying runoff for the wood fiber treatments. The wood fiber mulch appears to have greater loft than the cotton fiber product, which could trap more water.

Mulch Type

The different types of mulch did not have significantly different times of runoff initiation (p=0.29, Table 2). Not having differences in time of runoff initiation implies either that no soil surface crusting occurred or that no single mulch type was either more or less effective at protecting the soil from surface crusting, which would tend to reduce infiltration rate.

<u>Runoff Volume</u>

Treatment

There were no significant treatment differences in runoff volume for the second simulation (p=0.14, Table 2). Runoff volume had a moderate, significant negative correlation with time of runoff initiation ($p=0.0004$, Table 4). As time of runoff initiation increased, or as runoff initiation was delayed, there was less runoff volume ultimately collected for the duration of the test.

PAM Treatment, Mulch Rate, and Mulch Type

The presence or absence of PAM, PAM rate, mulch rate, and mulch type did not have significant effects on runoff volume (Table 2).

<u>Turbidity</u>

Treatment

There were significant treatment differences in turbidity in both the first ($p<0.0005$, Table 2) and second runs ($p<0.0005$, Table 2). There was, however, little separation of treatment means (Tables 5 and 6) due to the high variability within the replications of each treatment. The coefficient of variation of turbidity ranged from 16% to 144% in the first and second runs. In the first simulation, runoff from the low rate of cotton fiber matrix test product had a mean turbidity 10 times that of the high rate of wood fiber with aqueous PAM and runoff from straw alone had a mean turbidity 24 times that of the high rate of wood fiber with aqueous PAM. In the second rainfall simulation, both the low rate of wood fiber without PAM and straw alone had mean runoff turbidities about 10 times that of the high rate of wood fiber with PAM and the low rate of cotton fiber matrix test product with PAM. Among PAM treatments, there were no significant differences in turbidity, regardless of mulch type or mulch rate, in either the first or second run. Similarly, there were no significant differences among non-PAM treatments in the first or second run.

PAM Treatment

Among cotton and wood fiber treatments, the mean turbidity of PAM treatments was significantly lower than the mean turbidity of non-PAM treatments for the first simulation ($p<0.0001$, Table 2). The presence of PAM was a very strong factor controlling turbidity, as treatments with 37 kg ha^{-1} of PAM had mean turbidities within 100 NTU of each other for both the first and second runs regardless of mulch type. In both the first and second runs, the addition of PAM to a low mulch rate reduced turbidity 4.5-7.5 times regardless of mulch type. Adding PAM to the high rate of cotton cut turbidity in half, while adding PAM to the high rate of wood fiber reduced turbidity by 7-11 times for both runs. The mean turbidity of PAM treatments was lower than the mean turbidity of analogous non-PAM treatments in the second run, showing that PAM was still effective after one rainfall event of moderate intensity.

The cotton product used for these tests contained PAM, resulting in approximately 5.5 kg ha^{-1} PAM at the low mulch rate and 8.3 kg ha^{-1} PAM at the high mulch rate. Even though the amount of PAM in the cotton mulch was much less than the amount recommended for erosion control (McLaughlin, 2006), runoff from cotton treatments tended to have lower turbidity than analogous wood fiber treatments.

PAM Application Method

Polyacrylamide application method will only be discussed for the two straw treatments (2240 kg ha^{-1} straw with 37 kg ha^{-1} aqueous PAM and 2240 kg ha^{-1} straw with 37 kg ha^{-1} granular PAM) that were repeated under an independent rainfall simulation with time-series runoff samples.

The mean runoff turbidity of all individual samples was significantly less in the aqueous PAM application compared to the granular application ($p<0.0001$, Table 2). Runoff turbidity from the dry treatment was found to decrease with time, while runoff turbidity for the aqueous PAM treatment was relatively stable with time (Figure 4). The turbidity of runoff from soil treated with dry PAM started about 800 NTU higher than runoff from soil treated with aqueous PAM but leveled off seven minutes after runoff initiation. Even after stabilizing, the mean turbidity of dry PAM samples remained about 130 NTU higher than that of aqueous PAM samples. The differences between aqueous and dry treatments remained significant throughout the test (Table 7). Turbidity appeared to be correlated with the time that the sample was collected, with turbidity decreasing throughout the experiment, but the correlation was not significant ($p = 0.14$, Table 8).

Tang et al. (2006) found that granular PAM applied at a rate of 20 kg ha^{-1} with 2 or 4 Mg ha^{-1} gypsum was effective at increasing the final infiltration rate compared to soil treated with gypsum alone. Additionally, PAM with gypsum reduced seal formation and decreased soil loss relative to a bare soil control. Although dry PAM has been shown to reduce erosion relative to a bare control, Peterson et al. (2002) noted that dry PAM must be wetted to become activated; before activation, dry PAM performs similarly to a control without PAM. Wet PAM reduced sediment yield by over 90% compared to the control, while dry PAM reduced sediment by 31% compared to control (Peterson et al.; 2002). Experimenters also noted PAM granules in runoff water from dry PAM treatment, indicating that PAM granules were transported in runoff because they did not have sufficient time to dissolve.

The fact that aqueous PAM does not need to be activated in order to be effective at reducing turbidity and TSS at the onset of rainfall, unlike granular PAM, must be considered when using PAM to reduce soil loss on slopes. If granular PAM received a gentle rainfall before a more intense period of rain, the polymer chains would have time to hydrate and expand before dramatic soil loss occurred. An intense rainfall immediately after the application of dry PAM may wash PAM off the slope completely, resulting in increased soil loss in the future.

Mulch Rate

In order to analyze the effects of mulch rate on turbidity, all straw treatments were removed from the analysis to balance the experiment. When straw treatments were removed, mulch rate did not significantly affect turbidity in either the first (p=0.26, Table 2) or second (p=0.63, Table 2) runs. Mulch rate was probably not significant because the presence or absence of PAM in combination with a mulch rate was more important than mulch rate alone. When non-PAM cotton and wood fiber treatments were analyzed independently, a 50% increase in the cotton rate resulted in a 63% reduction in turbidity for the first rainfall simulation (p=0.0066, Table 2). There was not a significant reduction in turbidity for the second rainfall simulation (p=0.79, Table 2). Increasing the rate of wood fiber did not result in a significant turbidity reduction for the first (p=0.62) or second (p=0.45) runs (Table 2).

There was a highly significant interaction between mulch rate and PAM rate for both the first and second runs (p<0.0001, Table 2). When turbidity for the first simulation was averaged by mulch rate across cotton and wood fiber mulches together, the turbidity reduction associated with low rates of cotton and fiber was much greater than the turbidity reduction at high rates of cotton and wood fiber (Figure 5). With the addition of PAM, the mean turbidity at both the high and low mulch rates is very similar; however, the mean turbidity of the low mulch rate without PAM is much greater than the mean turbidity with PAM.

Mulch Type

Straw treatments receiving dry PAM were removed from the data set to balance the experiment before analysis; the remaining treatments included straw, cotton and wood fiber at varying rates, all with and without aqueous PAM. Mulch type significantly affected turbidity the first run (p=0.05) but not the second run (p=0.14) runs (Table 2). For the first run, there were no significant differences between mulch types when the error rate was controlled at $\alpha = 0.05$. When the error rate was controlled at $\alpha = 0.10$, both cotton fiber matrix test product and wood fiber were significantly different from straw, but not different from each other (Table 9). The mean turbidity of straw was 2.5 times greater than that of wood fiber and 3.6 times greater than the cotton test product.

<u>Total Suspended Sediment</u>

Treatment

There were significant treatment differences in total suspended sediment (TSS) for the first run and second run (p=0.0006 and p=0.0037, Tables 10 and 11). For both runs, the treatment with the highest TSS was straw with 37 kg ha^{-1} of granular PAM. Cotton and wood fiber with PAM were among the treatments with the lowest TSS for both the first and second runs. In the first run, both the high and low rates of cotton and wood fiber with aqueous PAM had significantly lower TSS than both straw alone and straw with granular PAM. The TSS of straw alone was 9 to 15 times greater than the TSS of any hydromulch with PAM. In the second run, only the high rate of wood fiber with PAM had significantly lower TSS than straw alone. The mean TSS of straw was 7.7 times greater than that of wood fiber with PAM.

PAM Treatment

The presence or absence of PAM across all treatments was significantly related to TSS for both the first (p=0.083) and second (p=0.055) runs (Table 2). Adding 37 kg ha^{-1} of aqueous PAM to the low rate of any mulch type reduced TSS between 63% and 82% in the first run and between 54% and 78% in the second run. Adding the same amount of PAM to high mulch rates reduced TSS by 28% for cotton and 67% for wood fiber in the first run, and by 22% for cotton and 80% for wood fiber in the second run. In nearly all cases, the reduction of TSS caused by the addition of PAM was smaller in the second run than it was in the first run.

It is possible that PAM washes off of the slope little by little with each rainfall event; the decreasing effects of PAM in the second run are evidence for this. It would be possible to add PAM after each rainfall event to ensure maximum erosion control, but this may not be practical for large areas of bare soil. A better approach would be to add a moderate amount of PAM to slopes when mulch is applied. The PAM and mulches, in combination, should control erosion until vegetation can be established.

PAM Application Method

Polyacrylamide application method will only be discussed for the two straw treatments (2240 kg ha^{-1} straw with 37 kg ha^{-1} aqueous PAM and 2240 kg ha^{-1} straw with 37 kg ha^{-1} granular PAM) that were repeated under an independent rainfall simulation. Small samples of runoff were collected every other minute once runoff was initiated.

Mean TSS followed a pattern similar to turbidity (Figure 6). The mean TSS of aqueous PAM treatments was significantly lower than the mean TSS of granular PAM treatments for all sampling times (Table 12). Total suspended sediment started high in the dry PAM treatments but decreased rapidly until stabilizing after seven minutes. Total suspended sediment for the aqueous PAM treatment started much lower and remained relatively stable throughout the 17 minute period during which samples were collected. The significance of these patterns was discussed previously under the turbidity results.

Mulch Rate

Straw treatments were removed from the dataset in order to analyze mulch rate effects on TSS with the experimental data balanced, since only one straw rate was used. When straw treatments were removed, mulch rate was not significant for either the first ($p=0.44$) or second ($p=0.14$) runs (Table 2). As discussed previously, it is likely that the presence or absence of PAM overrode any differences in mulch rate, so the cotton fiber matrix test product and wood fiber treatments without PAM were analyzed independently. For the first run, a 50% increase in the rate of cotton mulch reduced TSS by 35% ($p=0.078$, Table 2). Cotton rate was not significant for the second rainfall simulation ($p=0.42$, Table 2). Increasing the rate of wood fiber did not result in a significant change in TSS for either the first ($p=0.56$) or second ($p=0.28$) runs (Table 2).

When all straw treatments were removed to balance the experiment, there was a significant interaction in TSS between PAM treatment and mulch rate for both the first and second runs ($p=0.0047$ and $p=0.0006$) (Table 2). Adding 37 kg ha^{-1} of PAM to the low rate of cotton reduced TSS by 63%, while adding the same amount of PAM to the higher cotton rate reduced TSS by only 28%. However, adding 37 kg ha^{-1} PAM to the low rate of wood fiber reduced TSS by 70%, while adding PAM to the higher rate reduced TSS by 67%. For both mulch types, the addition of PAM caused a reduction in TSS compared to the non-PAM treatment. Adding PAM to the high rate of cotton did not result in a dramatic reduction of TSS because the cotton product already contained PAM.

Mulch Type

The dry PAM with straw treatments were removed in order to have a balanced data set for the analysis of the effect of mulch type on TSS. For both runs, mulch type alone was significant (p=0.0049 and p=0.02) (Table 2). In the first run, both cotton and wood fiber had significantly lower mean TSS than straw; cotton and wood fiber were not significantly different from each other. The low mulch rates of straw, with or without PAM, had a mean TSS 4.7 times greater than that of cotton treatments at the low mulch rate with or without PAM. The mean TSS of straw was 3.7 times greater than the mean TSS of wood fiber. In the second run, only straw and cotton were significantly different, with straw having a mean TSS 2.4 times greater than that of cotton. Cotton and wood fiber probably had lower mean TSS than straw because both cotton and wood fiber had higher soil coverage than straw, which would protect the soil surface from the impact energy of rainfall, reducing soil detachment. Additionally, the cotton product tested contained PAM. As discussed previously, PAM aids in stabilizing soil aggregate structure, decreasing detachment and soil erosion.

The interaction between mulch type and mulch rate was not significant for the first (p=0.78) or second (p=0.29) runs (Table 2) when all straw treatments were removed from the analysis. In non-PAM treatments, increasing the mulch rate by 50% resulted in a 35% reduction in TSS for cotton in the first run and a 27% increase in TSS for wood fiber. In the second run, increasing the cotton rate by 50% reduced TSS by 54%, and increasing the rate of wood fiber by 50% decreased TSS by 30%. In both the first and second runs, increasing the cotton rate decreased TSS more than increasing the wood fiber rate. As discussed previously, mulch rate alone is not clearly related to TSS. Because of this, it is likely that the positive cotton response is due to the presence of PAM in the cotton mulch, not the amount of mulch itself. Increasing the mulch rate by 50% would concurrently increase the PAM rate from 5.5 to 8.3 kg ha^{-1}, which may have helped reduce TSS.

Total Sediment Loss

Treatment

When all treatments, including straw treatments, were analyzed together, there were significant treatment differences in total sediment loss for both the first and second runs (p=0.0041 and p=0.0005, Table 2). The mean soil loss for each treatment along with treatment differences are shown in Tables 13 and 14. Sediment loss for the first run ranged from 2 kg ha^{-1} for the low rate of cotton with PAM to more than 191 kg ha^{-1} for straw with 37 kg ha^{-1} of dry PAM. For the second run, sediment loss ranged between 0.18 kg ha^{-1} for the high rate of wood fiber with PAM to 19 kg ha^{-1} for straw with 37 kg ha^{-1} of dry PAM.

Although treatment means spanned two orders of magnitude, statistically significant differences were difficult to establish due to wide variation within the treatments. In the first run, only the low rate of cotton with aqueous PAM had significantly less sediment loss than straw with 37 kg ha^{-1} granular PAM. The low rate of cotton with aqueous PAM also lost significantly less sediment than straw with 37 kg ha^{-1} granular PAM for the second rainfall simulation. Additionally, during the second run, the high rate of wood fiber with aqueous PAM lost significantly less sediment than straw with 37 kg ha^{-1} granular PAM. The high rate of wood fiber with aqueous PAM also lost significantly less sediment than straw with aqueous PAM during the second run.

PAM Treatment

Straw treatments were removed from the dataset in order to analyze PAM effects with the experimental data balanced, since only one straw rate was used. When straw treatments were removed, PAM treatments lost significantly less sediment than non-PAM treatments for the first run ($p=0.0011$) and the second run ($p=0.0007$) (Table 2). Compared to non-PAM treatments, the addition of 37 kg ha^{-1} of aqueous PAM reduced total sediment loss in low mulch rates by 9 times in the first run and 5.6 times in the second run. For the high rates of cotton and wood fiber, adding PAM reduced sediment loss by 4.7 times in the first run and 3 times in the second run compared to non-PAM treatments. Adding PAM consistently reduced mean sediment loss regardless of mulch type, and the effects of PAM additions continued to be evident for the second run.

Mulch Rate

Without the straw treatments, mulch rate was not significant for the first run ($p=0.80$) or the second run ($p=0.26$) (Table 2). It is possible that the presence or absence of PAM overrode potential differences in mulch rate, so mulch rate was also analyzed with PAM and non-PAM treatments separated. After independent analysis, mulch rate was still not significant for either PAM or non-PAM treatments in either the first or second rainfall simulations (data not shown). The effect of increasing mulch rate for cotton and wood fiber was mixed. For non-PAM treatments in the first run, increasing the mulch rate by 50% resulted in a 53% decrease in sediment loss for cotton and a 22% increase in sediment loss for wood fiber. Among PAM treatments in the first run, high mulch rates increased sediment loss by 250% for cotton and 25% for wood fiber.

A 50% increase in mulch rate did not significantly reduce sediment loss, probably because the low mulch rate had sufficient groundcover. Mannering and Meyer (1963) found that as straw rates were increased from 560 kg ha^{-1} to 8967 kg ha^{-1}, surface cover correlated with rate of straw application and that soil loss decreased with increasing straw rates. For the cotton and wood fiber products tested, soil surface coverage was nearly 100% even at low mulch rates. Increasing the mulch rate probably did not increase groundcover, so there was no further reduction in soil loss. If the low mulch rate did not cover most of the soil surface, increasing the mulch rate would almost certainly reduce erosion.

When straw treatments were removed, the interaction between PAM treatment and mulch rate was highly significant for the first run ($p=0.0054$) and the second run ($p=0.0042$) (Table 2). The nature of the interaction between PAM treatment and mulch rate is unclear. As discussed previously, the cotton fiber matrix test product used for these experiments contained PAM, likely confounding any clear relationships between mulch rate and PAM treatment.

Mulch Type

After the straw with dry PAM treatments were removed to balance the dataset, mulch type was significantly related to total sediment loss for the first run (p=0.0055) and the second run (p=0.023) (Table 2). In the first run, straw and cotton were significantly different from each other, but neither was different from wood fiber (Table 15); in the second run, wood fiber and cotton were both different from straw, but not different from each other (Table 16).

Cotton averaged the lowest total sediment loss for both runs, while straw averaged the highest sediment loss; recall again, however, that the cotton product contained PAM at a rate of about 5.6 kg ha^{-1}, which aided in reducing sediment loss. Straw plots lost an average of 3 to 5 times more sediment than cotton plots in both the first and second runs.

The interaction between mulch type and PAM treatment was highly significant for both runs (p=0.0003 and p=0.0003) (Table 2). Regardless of mulch type, the addition of PAM to a low mulch rate reduced total sediment loss for the first run. As shown in Figure 7, wood fiber was the most responsive to the addition of PAM, while straw was the least. Straw had the most sediment loss without PAM, and while adding PAM reduced sediment loss, the reduction was not as dramatic as adding PAM to wood fiber. Adding PAM to straw treatments may not have reduced sediment loss dramatically because the straw treatments lost too much soil. Polyacrylamide helps prevent soil detachment, but if the soil surface is not well protected by mulch, PAM alone may not be enough to reduce erosion.

Conclusions

- The addition of PAM to all mulch types tested resulted in reduced runoff turbidity, TSS, and sediment loss.

- The use of cotton and wood fiber mulches resulted in similar reductions in TSS and sediment loss, and both generally had reduced TSS and sediment loss compared to straw.
- Increasing the rate of cotton mulch from 1971 kg ha^{-1} to 2957 kg ha^{-1} significantly reduced turbidity and TSS for the first rainfall simulation. Increasing the rate of wood fiber mulch from 1971 kg ha^{-1} to 2957 kg ha^{-1} did not significantly improve turbidity or TSS for either the first or second rainfall simulation.
- No mulch type either with or without PAM had runoff turbidity lower than 50 NTU. Runoff would require further treatment, such as time in a sediment basin, before being released offsite.
- Polyacrylamide applied in a granular form may be washed off the soil surface and transported with soil particles in periods of intense rainfall, compromising its ability to prevent further soil loss.
- Aqueous PAM was more effective at reducing the turbidity of runoff water than PAM applied in granular form at the same rate. A higher rate of granular PAM performed similarly to the aqueous application.
- The turbidity in runoff from dry PAM treatments started high and tended to decrease with time. Dry PAM may need to be activated by gentle rainfall before it can reduce soil loss.

CHAPTER 3: FIELD EXPERIMENTS

Introduction

Soil erosion is a natural occurrence that, on the geologic timescale, is a pedogenic process. When the rate of soil erosion is increased due to anthropogenic disturbance, however, it is destructive. Soil erosion causes breakdown of aggregate structure, releasing organic carbon into the atmosphere (Lal, 2003); it also reduces effective rooting depth, causes loss of nutrients, and loss of arable land area (Pimental and Kounang, 1998). Eroded soil is ultimately transported to surface waters, resulting in increased total suspended solids and turbidity in affected waters. Sedimentation in streams is associated with declining primary productivity, decreased in-stream habitat, and decreased biodiversity (Allan, 2004). Additionally, fine-grained sediments deliver contaminants and excessive nutrients to streams, resulting in eutrophication and bioaccumulation of heavy metals (Owens et al., 2005).

While a typical erosion rate on farmland may be between 2.25 and 11 ton ha^{-1} yr^{-1}, erosion rates on construction sites may range from 223 ton ha^{-1} yr^{-1} up to 2465 ton ha^{-1} yr^{-1} (Broz et al., 2003). The primary factor that contributes to increased soil erosion on construction sites is the removal of vegetation, leading to increased raindrop impact energy, increased overland flow velocity and volume, and increased soil removal and transport (Owens et al., 2000). Additionally, heavy equipment traffic increases soil bulk density, which also reduces infiltration, increases the volume and velocity of runoff, and increases soil transport capacity (Owens et al., 2000; Broz et al., 2003).

Because vegetation removal is the primary cause of high erosion rates on construction sites, onsite soil erosion may be reduced by the use of temporary groundcover. In studies evaluating mulch or erosion control blankets (ECB's), bare areas frequently have much higher rates of soil loss than areas covered with mulch or ECB's. In several studies evaluating erosion control products (bonded fiber matrix, compost, straw, straw blanket, straw/coconut blanket, wood fiber blanket), covered plots had significantly less soil loss than bare plots (Benik et al., 2003; McLaughlin and Brown, 2006; Bautista et al., 1996; Faucette et al., 2005; Hayes et al., 2005). Plots covered with straw mulch were found to lose one-tenth the soil of the bare control plots but about ten times more soil than any ECB treatment (Benik et al., 2003). McLaughlin and Brown (2006) also found that covered plots had reduced runoff volume and turbidity, and Bautista et al. (1996) found that straw-mulched plots had less runoff, 2-16 times less sediment, and more plant cover than the bare control.

In addition to temporary groundcover, the use of chemical soil stabilizers may further decrease soil erosion. A soil conditioner often used on construction sites is linear, anionic polyacrylamide (PAM). The results of studies involving the use of PAM for either vegetative establishment or erosion control have been somewhat mixed, but the application of PAM to a slope has generally been found to reduce soil erosion. For example, PAM at rates of 20 kg ha^{-1} to 80 kg ha^{-1} has been reported to reduce rilling and to reduce soil loss by half or even ten-fold compared to a bare control (Agassi and Ben-Hur, 1992; Flanagan et al., 2002a; Flanagan et al., 2002b). Polyacrylamide continues to be effective at moderately low rates. Yu et al. (2003) applied 10 kg ha^{-1} and 20 kg ha^{-1} of granular PAM, and soil loss on PAM-treated slopes was 15-30% of the control for two different soil types. Lower rates of PAM do not appear to be as effective as moderate PAM rates. For example, Hayes et al. (2005) found that low PAM rates (0.75 kg ha^{-1} to 10.5 kg ha^{-1}) did not significantly reduce either turbidity or sediment loss, and Soupir et al. (2004) found that PAM in aqueous form at low rates (1.68 to 6.73 kg ha^{-1}) reduced TSS compared to a bare soil control, though the reductions were not statistically significant.

In addition to preventing soil erosion in the short term, groundcover should aide in the establishment of vegetation to decrease long-term soil erosion. A number of studies examine the effect of different mulches on vegetative establishment on slopes (≥ 2.3°). Button and Potharst (1962), under drought conditions, determined that the type and amount of mulch applied to the soil surface had no significant effect on germination or seedling survival. Other studies, however, have found that straw mulch generated better vegetative covering than other erosion control options, including straw/coconut blanket, bonded-fiber matrix (BFM), excelsior blanket, straw blanket (Benik et al., 2003; McLaughlin and Brown, 2006). Benik et al. (2003) found that straw mulch generated 89% vegetative cover on a 20° slope, while the bare control had only 44% coverage, and that variability among the treatments decreased by the second growing season. Ringe and Graves (1987) reported that all mulches tested (excelsior, wood fiber hydromulch, paper mat, hay fiber hydromulch, jute, and straw mat) on a 24.2° slope, though not significantly different from each other, resulted in better vegetative growth than the bare control, but neither McLaughlin and Brown (2006) nor Benik et al. (2003) reported significant differences in vegetative cover during any growing season.

Application of polyacrylamide (PAM) at the time of seeding may result in improved emergence of planted seed and increased vegetative cover over time. Aqueous PAM improved corn emergence in the field compared to granular PAM in June and July, and both

PAM application methods were better than a non-PAM control unless it rained immediately after planting (Cook and Nelson, 1986). Under conditions of frequent watering, PAM resulted in improved water infiltration and increased the rate of emergence of grass seeds (Rubio, 1989). With less frequent watering, all grass had improved emergence with PAM due to less surface crusting (Rubio, 1989).

When PAM is applied along with mulch, erosion control and vegetative establishment may be superior to that of either the mulch or PAM alone. Straw, straw with granular PAM, cotton fiber matrix test product, bonded fiber matrix, excelsior blanket, and straw blanket were evaluated to determine their relative effectiveness for erosion control and vegetative establishment.

Methods and Materials

Description of Study Sites

Vegetative establishment was evaluated at two different sites (sites 1 and 2), and vegetative establishment and water quality were evaluated at one site (site 3). The slope face at site 1 (near Clayton, NC) was oriented in the east-west direction roughly parallel to an adjacent interstate, consisted of bare subsoil with some saprolite, and received mostly direct sunlight during the day. Site 2 (on Davis Drive in Research Triangle Park, NC) had subsoil overlain with imported, organic-rich topsoil and a roughly north-south orientation. Site 3, located at the North Carolina State University Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, NC, was built previously using a mix of fill material from nearby construction sites.

Plot Setup

At sites 1 and 2, slope preparation was performed by the North Carolina Department of Transportation. Slopes were graded to a 26.6° slope and tracked by a bulldozer. At site 3, the slope was tilled using a small, gas-powered tiller to prepare soil for seeding. After slope preparation, plots were delineated. Plot size at sites 1 and 2 was 3.05 m wide and 9.14 m long downslope, and plots were 1.52 m by 6.10 m at site 3.

Plots were seeded, limed, and fertilized by hand according to North Carolina Department of Transportation (NCDOT) guidelines (Table 17). After seeding, treatments were applied in a randomized complete block design. The five treatments at site 1 were each replicated five times and included 3360 kg ha^{-1} bonded fiber matrix (BFM; SoilGuard, Profile Inc., Chicago, IL); excelsior blanket (Curlex I, American Excelsior, Rice Lake, WI); 2240 kg ha^{-1} wheat straw (S); 2240 kg ha^{-1} wheat straw with 37 kg ha^{-1} of granular, linear, anionic polyacrylamide (SP) (PAM; 705, Applied Polymer Systems, Woodstock, GA); and double-sided straw blanket. At site 2, the four treatments were also replicated five times and included 2240 kg ha^{-1} of straw, 2240 kg ha^{-1} of straw with 37 kg ha^{-1} of PAM, 3360 kg ha^{-1} cotton fiber matrix test product (C; Cotton Fiber Matrix, Mulch & Seed Innovations, LLC, Centre, AL), and approximately 4480 kg ha^{-1} of BFM (Soil Guard, Profile Inc., Chicago, IL). The treatments at site 3, replicated four times each, were as follows: 2240 kg ha^{-1} straw (S); 2240 kg ha^{-1} straw with 37 kg ha^{-1} dry, linear, anionic polyacrylamide (SP; APS 705, Applied Polymer Systems, Woodstock, GA); 4480 kg ha^{-1} bonded fiber matrix (BFM: SoilGuard, Profile Inc, Chicago, IL); and 3360 kg ha^{-1} cotton fiber matrix test product (C; Cotton Fiber Matrix, Mulch & Seed Innovations, LLC, Centre, AL). The cotton fiber matrix test product contained PAM; at a rate of 3360 kg ha^{-1} of cotton mulch, the estimated PAM rate was 9.4 kg ha^{-1}. It is important to note that the commercial product using cotton fiber materials is substantially different than the experimental product originally tested.

During hydromulch application at site 3, the area at the top of the plots was scoured by the high pressure stream of water, displacing seed, lime, and fertilizer. To account for this, the top 1.52 m of each plot (including straw plots) were re-seeded with 56 kg ha^{-1} of tall fescue seed. At site 3 only, all plots were watered equally immediately after installation, and subsequent watering using sprinklers was done weekly in the absence of rainfall.

Treatments at all sites were installed according to industry standards or manufacturers guidelines. Seeding and plot setup were completed in mid-March of 2007 for site 1, late July of 2007 for site 2 (Figure 8), and early March for site 3. The granular PAM was applied using hand-held, rotary seed spreaders, and hydromulches were applied using a TurfMaker 420 hydroseeder (TurfMaker Corp., Rowlett, TX) using a mulch to water ratio of 59.9 g L^{-1} for the BFM and 89.9 g L^{-1} for the cotton fiber matrix test product.

<u>Biomass and Vegetative Cover</u>

After about two months of growth at each site, biomass and vegetative cover were assessed. Biomass was determined by taking grass clippings in three (site 1 and site 3) or nine (site 2) 10 cm^2 randomly selected areas within each plot. Grass clippings from a single plot were combined, dried overnight at 105° C, and weighed in order to calculate biomass for each plot. Vegetative cover was assessed by independent ocular estimation from two (site 1, site 3) or four (site 2) observers who estimated the amount of cover (%) on each plot. The independent estimates were averaged to obtain a single cover estimate for each plot

Water Quality

Water quality was only assessed at site 3. Plastic barriers were installed in a v-shape symmetric about a PVC collection pipe in the center of each plot 5.94 m from the top of the plot. The barrier / tube intersection was sealed with expandable foam, ensuring that all runoff from the plot flowed into the pipe. Runoff was collected in five-gallon buckets (Figure 9).

After each rain event, runoff volume, turbidity, and total suspended solids were recorded for each plot. Runoff volume was measured by measuring the depth of water in the bucket in inches, then converting depth to volume of water using the following equation:

$y = 12.261x^2 + 1327.3x - 47.281$, where x is depth of water in inches and y is the runoff volume in mL

Because the bucket was not a perfect cylinder, the volume equation was determined by recording the volume of water added to a similar bucket and then measuring the depth of water in the bucket. The quadratic equation shown above was selected from other possible equations using the method of least squares. Turbidity was measured using a TC-3000e portable turbidity meter (version 1.5, LaMotte, Chestertown, MD). Measured turbidities were corrected with a standard curve based on formazine standards. Following the Standard Methods for the Examination of Water and Wastewater (Clesceri et al., 1998), TSS samples were filtered with 47 mm glass fiber ProWeigh filters from Environmental Express (Mt. Pleasant, SC) and dried overnight at 103-105° C.

Soil Texture

At site 3 only, soil samples were taken from the top, middle, and bottom of each plot using a soil corer and combined to perform particle size analysis. There were clear differences in soil texture and mineralogy across the 16 test plots. Plots 1-6 were loam; plots 7-16 generally had more sand and clay, with most being sandy clay loam. Two plots were clay loam, and one was clay. Based on soil color, soil in the loam plots had mineralogy dominated by hematite, while soil in other plots had mineralogy dominated by goethite.

Data Analysis

Statistical analyses were performed using SAS software (version 9.1, SAS Institute, Cary, NC). Data were log transformed to ensure normality and equality of variance. Analysis of variance was used to analyze treatment effects. For the data from site 3, soil textural class, in addition to treatment, was included in the analysis of variance when modeling turbidity, TSS, and vegetative cover because it was significant. Soil textural class was not included as a factor when modeling runoff volume, erosion rate, or biomass because the term was not significant. Treatment means were separated using Fisher's least significant difference with the Tukey-Kramer adjustment for multiple comparisons. Error rates were controlled at $\alpha = 0.05$ unless otherwise noted.

Results

Site 1

There were significant treatment differences in both biomass ($p=0.0028$, Table 18) and vegetative cover ($p=0.007$, Table 19). The treatment factor explained slightly more variability in vegetative cover ($R^2 = 0.60$) (Table 20) than in biomass ($R^2 = 0.54$) (Table 21). Both the biomass and vegetative cover of BFM were significantly less than all other treatments, but there were no other significant differences among the treatments (Figure 10). Bonded fiber matrix had about 13 times less vegetative cover or biomass than any other treatment, while the remaining treatments were very similar to each other in both biomass and vegetative cover. Biomass and vegetative cover had a strong, positive correlation (Table 22).

The BFM product, while remaining on the slope for the duration of the experiment, appears to have actually inhibited vegetative growth, perhaps because seed, lime, and fertilizer were applied directly onto the soil surface and BFM was applied on top. Although unobserved, it is possible that the seeds rotted before they had a chance to germinate. The other ground cover treatments did not form as complete of a seal over the seedbed, which facilitated increased germination. It is possible that a lower rate of BFM would have improved germination without compromising erosion control.

Other studies have also noted that BFM had significantly less biomass and vegetative cover than other treatments evaluated. Benik et al. (2003) noted that BFM, while providing erosion control superior to that of straw, had significantly lower biomass. In a similar study, straw mulch generated more grass cover than mechanically bonded fiber matrix (McLaughlin and Brown, 2006). Bonded fiber matrix may be superior to other products at preventing erosion because of the cohesive, thick, protective mat that it forms over the soil surface. These properties, while suitable for erosion control, may inhibit the establishment of vegetation.

Although excelsior, straw, straw blanket, and straw with PAM all resulted in increased biomass and vegetative cover relative to BFM, vegetative cover and biomass for all treatments were still relatively low, with a maximum average cover of just over 50% in the plain straw treatment. Coverage of 50% is not aesthetically pleasing because half of the soil surface remains bare. While not ideal, similar amounts of vegetative cover have been shown to reduce soil losses by wind erosion by 95% (Fryrear, 1985) and water erosion by over 81% (Pan and Shangguan, 2006). For all treatments, soil coverage by residual mulch remained high at the time of grass evaluation (57 days after planting), and there was no evidence of excessive erosion. These stands may have improved substantially over a longer period of time than our evaluation.

Site 2

There was not a significant relationship between treatment and vegetative cover at site 2 ($p = 0.077$) (Table 23), and no significant treatment differences existed when the experimentwise error rate was controlled at $\alpha = 0.1$. Additionally, there was not a significant relationship between treatment and biomass ($p = 0.43$) (Table 24).

The mean vegetative cover and mean biomass for each treatment are shown in Figure 11. The treatment with the greatest vegetative cover was cotton hydromulch, with nearly 45% coverage. Straw had the lowest mean vegetative cover at just over 25%. Although BFM at site 1 had extremely low biomass and vegetative cover compared to other treatments, this was not the case at site 2. Bonded fiber matrix had only slightly less biomass and vegetative cover than the cotton hydromulch.

Straw and straw with PAM had similar biomass and vegetative cover. It was expected that adding PAM would result in higher biomass and vegetative cover because adding PAM to the soil surface has been shown to maintain soil structure, improve infiltration, and decrease erosion. It is possible that the PAM, applied in a dry, granular form, may have washed off of the slope in the first storm before becoming activated in water.

At site 2, it is likely that none of the plots had high biomass or vegetative cover because there was an extreme drought and high temperatures (many days at or near 37°C) for the duration of the two-month experiment. The total rainfall was about 8 cm (State Climate Office of North Carolina). The plots received no irrigation, and were not watered after seeding. This likely contributed to poor germination and, ultimately, decreased groundcover during the evaluation period, two months after planting (Figure 12).

<u>Site 3</u>

Runoff volume

There were seven rain events during the experiment (between March 7 and May 8) with a range of intensities (Table 25, State Climate Office of North Carolina). Runoff volume was discarded for three rainfall events because collection buckets overflowed for some plots and volume was unknown. Mean runoff volumes, along with standard deviation and coefficient of variation, for each treatment from the remaining rainfall events are shown in Table 26. The coefficient of variation for runoff volume from cotton plots was 206%. There was evidence of rilling on two of the four cotton plots. The rills delivered runoff and sediment from outside of the plot dimensions, so runoff volume from all cotton treatments was discarded before analysis of the remaining treatment differences.

When runoff volume was modeled using treatment and soil texture, soil texture was not significant ($p=0.38$). Soil texture was removed from the model, and when runoff volume was modeled using only treatment, there were significant differences ($p=0.043$, Table 27). Straw alone had about 1.6 times more runoff than BFM, but neither BFM nor straw were different from straw with PAM.

The cotton fiber matrix product, which was still in testing stages, was largely washed off the plots after two rainfall events. Runoff volumes from cotton plots tended to be 4 or more times greater than the runoff volumes from any other treatment. The increased runoff volume from the cotton test product plots suggests that these plots suffered destruction of surface aggregate structure, resulting in decreased infiltration and increased runoff volume. Destruction of aggregate surface structure may have occurred after the cotton product washed off the slope face, which is further discussed with respect to turbidity and TSS, below.

Although runoff from straw and straw with PAM plots was similar, previous research has indicated that the application of PAM in aqueous form stabilizes surface structure, decreasing surface crusting and increasing infiltration (Zhang et al., 1998; Rapp et al., 2000; Cook and Nelson, 1986; Flanagan et al., 2002a and 2002b; Yu et al., 2003). Stabilization of surface aggregate structure, paired with increased infiltration and decreased runoff volume, was not observed for the straw with PAM treatment. Runoff volumes for straw and straw with PAM were not significantly different, so it is possible that the dry PAM was washed off of the slope face with the first rainfall before it had a chance to become activated.

Turbidity

The soil texture blocking term was significant for turbidity, so turbidity was modeled using both treatment and soil texture as independent variables. As shown in Table 28, differences in turbidity were significant for both treatment ($p=0.0044$) and soil texture ($p<0.0001$).

When the experimentwise error rate was controlled at $\alpha = 0.10$, there were no significant treatment differences for turbidity (Table 29). Although not significantly different, the mean turbidity of runoff from cotton plots was at least 3.6 times greater than the mean turbidity of runoff from any other plot. The cotton product was still under development, and it was evident that most of the cotton test product washed off the slopes into the runoff collection system after only the second rainfall, leaving the soil exposed. Comparing images of two plots, one cotton fiber matrix test product and one bonded fiber matrix, provides evidence of this process. One month after application, it was apparent the most of the cotton test product was gone (Figure 13), while much of the bonded fiber matrix product remained on the plot (Figure 14) Although neither plot had much vegetative cover, the soil on the bonded fiber matrix plot remained protected by the mulch itself. The cotton product was still in the experimental design stage, and significant modifications have been made to it to improve longevity, as will be noted in later tests.

Runoff turbidity from loam plots was significantly greater than runoff turbidity from sandy clay loam and clay loam plots (Table 30); there were no other differences. Table 30 also shows the relative magnitudes of soil erodibility factors as estimated by Stewart et al. (1975) for soils with 2% organic matter. Burroughs et al. (1992) found that the susceptibility of a soil to interrill erosion is related to soil texture. Loam is the most erodible soil texture shown because it is fine textured but lacking in clay, which provides structure and decreases erodibility. Clay is the least erodible because clays tend to stick together and be well-structured. Sandy clay loam is somewhat erodible, but less so than loam because it has more sand, which is not easily eroded due to its large size. Clay loam has moderately low erodibility because, again, the clay provides some degree of structure, decreasing erodibility.

Total Suspended Sediment

Turbidity and TSS had a strong correlation (R=0.83, $p<0.0001$, Table 31) when data was combined across all treatments, and both treatment and soil type were significant for TSS (Table 32). The mean TSS of runoff from cotton plots was significantly greater than the TSS of runoff from both straw and BFM plots (Table 33). On average, the mean TSS of runoff from cotton plots was 6 times greater than that of both straw and BFM. As discussed above, the cotton test product washed off the slope face after the second rainfall, leaving the soil surface exposed on the cotton fiber matrix plots. When the experimentwise error rate was controlled at $\alpha = 0.10$, there were no significant differences in soil texture due to the high variability of TSS within each soil textural class (Table 34).

Neither turbidity nor TSS was significantly different between straw and straw with PAM, indicating that cumulative effect of adding PAM over the seven recorded rainfall events was not significant. At SECREF, the first rainfall event was unusually intense for the area (Table 25). Polyacrylamide may have washed off the slope during the first rainfall event, leading to decreased effectiveness for the rest of the experiment.

One cotton plot developed a rill, which likely delivered substantially more sediment and runoff from the plot compared to other cotton plots. In order to address this possibility, all statistical analyses were re-run with this plot removed from the data. However, this did not change the statistical differences for turbidity, runoff volume, biomass, and total erosion rate. The exception was TSS, which was no longer statistically significant (p=0.33)

Total Sediment Loss

There were significant treatment differences in mean sediment loss per storm event (Table 35). The mean sediment loss for the cotton test product was at least 10 times greater than any other treatment, but only BFM had significantly less sediment loss than cotton. Straw, straw with PAM, and BFM all lost less than 20 kg ha^{-1} of sediment per storm event, indicating that these treatments prevented excessive erosion.

Biomass

Biomass was assessed 63 days after seeding. Treatment means for biomass were not significantly different (p=0.32), even though the biomass of straw, BFM, and straw with PAM were all at least double that of the cotton fiber matrix test product (Figure 15). Straw with PAM, which had the highest mean biomass, had about 3.5 times greater biomass than the cotton fiber matrix test product. The low biomass of cotton may have been related to the increased runoff volumes from cotton plots. Increased runoff volume necessitates decreased infiltration, which has been linked to slower seed emergence and less overall biomass (Rapp et al., 2000; Rubio, 1989). It is also likely that seed washed off the cotton plots along with soil before the seed had a chance to germinate.

Vegetative Cover

There were significant treatment differences for vegetative cover (Table 36). Straw and straw with PAM had significantly higher vegetative cover than cotton; there were no other significant treatment differences (Table 37). The mean vegetative cover for both straw treatments was more than double that of the cotton fiber matrix test product. There was a strong correlation between biomass and vegetative cover (Table 38). Because cotton had the lowest biomass of any treatment, it is not surprising that it also had the lowest vegetative cover. Reasons for low biomass and vegetative cover on the cotton plots were discussed above.

There were also significant soil texture differences for vegetative cover (Table 36). Plots with sandy clay loam and clay loam textures had significantly lower vegetative cover than plots with clay or loam textures (Table 39). Generally, as silt and clay contents in a soil increase, plant available water increases (Brady and Weil, 2002) and biomass and vegetative cover would be expected to increase. There was not a clear relationship between soil textual class, plant available water, and biomass for this experiment; it is likely that differences in biomass and vegetative cover arise from something other than plant available water.

Most of the loam and clay plots were situated on one side of the experimental block, and the sandy clay loam and clay loam plots were situated on the opposite side of the experimental block. It is possible that the two groups of soils were collected from different areas, as the slope was constructed from multiple soils. Even though both soil groups received equal amounts of lime and fertilizer, it may not have been enough to overcome nutrient deficits in the sandy clay loam and clay loam soils.

Conclusions

- At site 1, bonded fiber matrix had significantly less biomass and vegetative cover than excelsior blanket, double-sided straw blanket, straw alone, and straw with PAM under normal rainfall conditions. The remaining treatments produced similar vegetative growth.
- There were no significant differences between biomass for straw alone or straw with

granular PAM at any site.

- Low rainfall during the duration of the experiment at site 2 contributed to low biomass and vegetative cover for all treatments.
- The cotton experimental product had significantly higher turbidity and TSS than both BFM and SP at site 3. The mean turbidity of this product in development was at least double that of any other treatment. The current, commercial product is substantially changed compared to our test product.
- Also at site 3, the experimental cotton product lost significantly more sediment than either S or BFM, and at least ten times more sediment than S, SP, and BFM.
- Bonded fiber matrix and cotton fiber matrix may not always decrease soil erosion relative to less expensive alternatives, such as straw.

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TABLES AND FIGURES

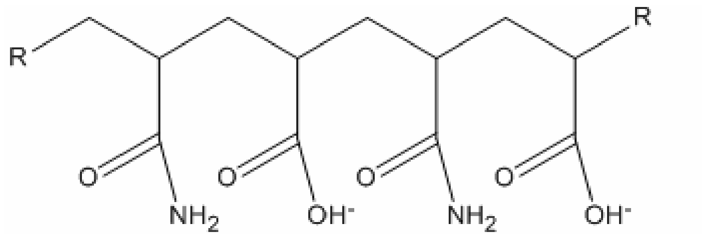

Figure 1. Chemical structure of linear, anionic polyacrylamide.

Table 1. Treatment differences in time to initiate runoff for second rainfall simulator run. Means with same letter are not significantly different at α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	**Mulch Rate**	**PAM Rate (kg ha^{-1})**	**PAM Application Method**	**Mean Time to Runoff Initiation (Mins.)**	
S	low	37	granular	2.1	A
C	low	0	n/a	2.2	A
S	low	0	n/a	2.6	A B
WF	low	0	n/a	3.0	A B
WF	low	37	aqueous	3.2	A B
S	low	37	aqueous	3.3	A B
C	high	37	aqueous	3.8	A B
WF	high	0	n/a	3.9	A B
C	low	37	aqueous	4.0	A B
C	high	0	n/a	4.0	A B
S	low	74	granular	4.3	A B
WF	high	37	aqueous	6.4	B

Table 2. ANOVA models and their significance for simulated rainfall tests. Wood fiber is WF and cotton fiber matrix test product is C.

Dependent Variable	Independent Variable(s)	p-value
time of runoff initiation, second run	presence or absence of PAM, all treatments	0.13
time of runoff initiation, second run	PAM rate, all treatments	0.27
time of runoff initiation, second run	mulch type	0.29
runoff volume, second run	treatment	0.14
runoff volume, second run	presence or absence of PAM	0.74
runoff volume, second run	PAM rate, dry straw treatments only	0.12
runoff volume, second run	mulch type	0.32
runoff turbidity, first run	treatment	0.0005
runoff turbidity, second run	treatment	0.0005
runoff turbidity, first run	presence or absence of PAM for C and WF only	<0.0001
mean turbidity	aqueous or dry PAM application	<0.0001
runoff turbidity, first run	mulch rate with straw treatments removed	0.26
runoff turbidity, second run	mulch rate with straw treatments removed	0.63
runoff turbidity, first run	mulch rate, C only, no PAM	0.0066
runoff turbidity, second run	mulch rate, C only, no PAM	0.79
runoff turbidity, first run	mulch rate, WF only, no PAM	0.62
runoff turbidity, second run	mulch rate, WF only, no PAM	0.45
runoff turbidity, first run	interaction between mulch rate and PAM rate	<0.0001
runoff turbidity, second run	interaction between mulch rate and PAM rate	<0.0001
runoff turbidity, first run	mulch type with dry PAM treatments removed	0.05
runoff turbidity, second run	mulch type with dry PAM treatments removed	0.14
TSS, first run	presence or absence of PAM	0.083
TSS, second run	presence or absence of PAM	0.055
TSS, first run	mulch rate with straw treatments removed	0.44
TSS, second run	mulch rate with straw treatments removed	0.14
TSS, first run	mulch rate, C only, no PAM	0.078
TSS, second run	mulch rate, C only, no PAM	0.42
TSS, first run	mulch rate, WF only, no PAM	0.56
TSS, second run	mulch rate, WF only, no PAM	0.28
TSS, first run	interaction between mulch rate and PAM treatment for C and WF only	0.047
TSS, second run	interaction between mulch rate and PAM treatment for C and WF only	0.0006
TSS, first run	mulch type with dry PAM treatments removed	0.0049
TSS, second run	mulch type with dry PAM treatments removed	0.02
TSS, first run	interaction between mulch type and mulch rate for C and WF only	0.78
TSS, second run	interaction between mulch type and mulch rate for C and WF only	0.29

Table 2. (continued)

Dependent Variable	Independent Variable(s)	p-value
total sediment loss, first run	treatment	0.0041
total sediment loss, second run	treatment	0.0005
total sediment loss, first run	presence or absence of PAM for C and WF only	0.0011
total sediment loss, second run	presence or absence of PAM for C and WF only	0.0007
total sediment loss, first run	mulch rate for C and WF only	0.80
total sediment loss, second run	mulch rate for C and WF only	0.26
total sediment loss, first run	interaction between mulch rate and PAM rate for C and WF only	0.0054
total sediment loss, second run	interaction between mulch rate and PAM rate for C and WF only	0.0042
total sediment loss, first run	mulch type with dry PAM treatments removed	0.0055
total sediment loss, second run	mulch type with dry PAM treatments removed	0.023
total sediment loss, first run	interaction between mulch type and PAM rate with dry PAM treatments removed	0.0003
total sediment loss, second run	interaction between mulch type and PAM rate with dry PAM treatments removed	0.0003

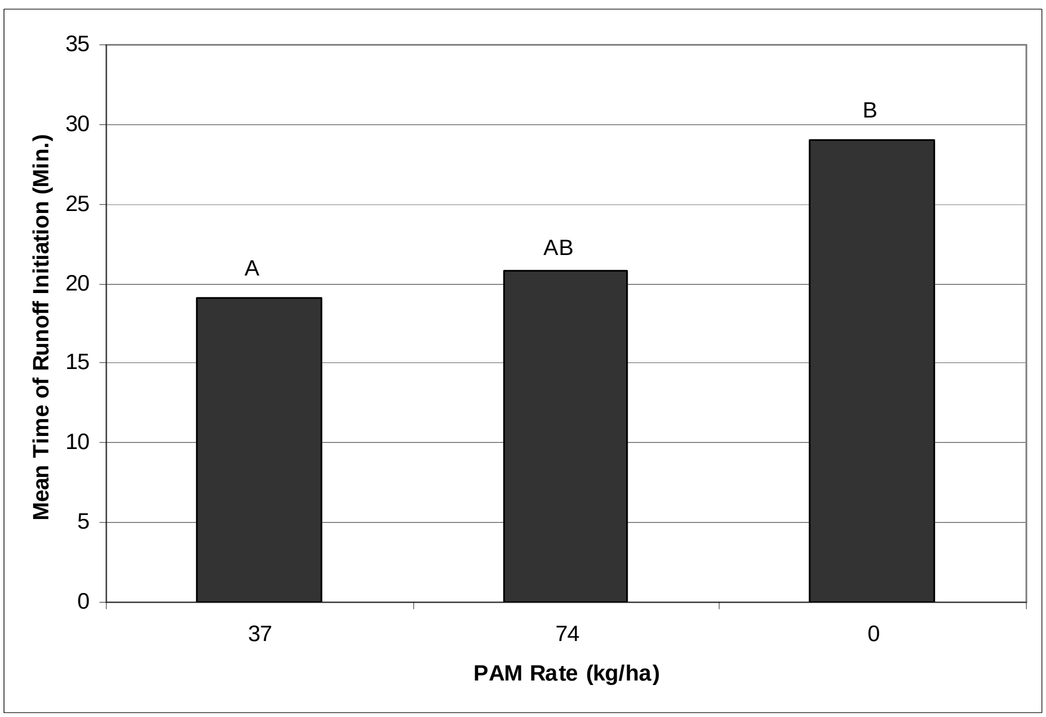

Figure 2. Mean time of runoff initiation for first run, dry straw treatments. Means with same letter are not significantly different at $\alpha = 0.05$.

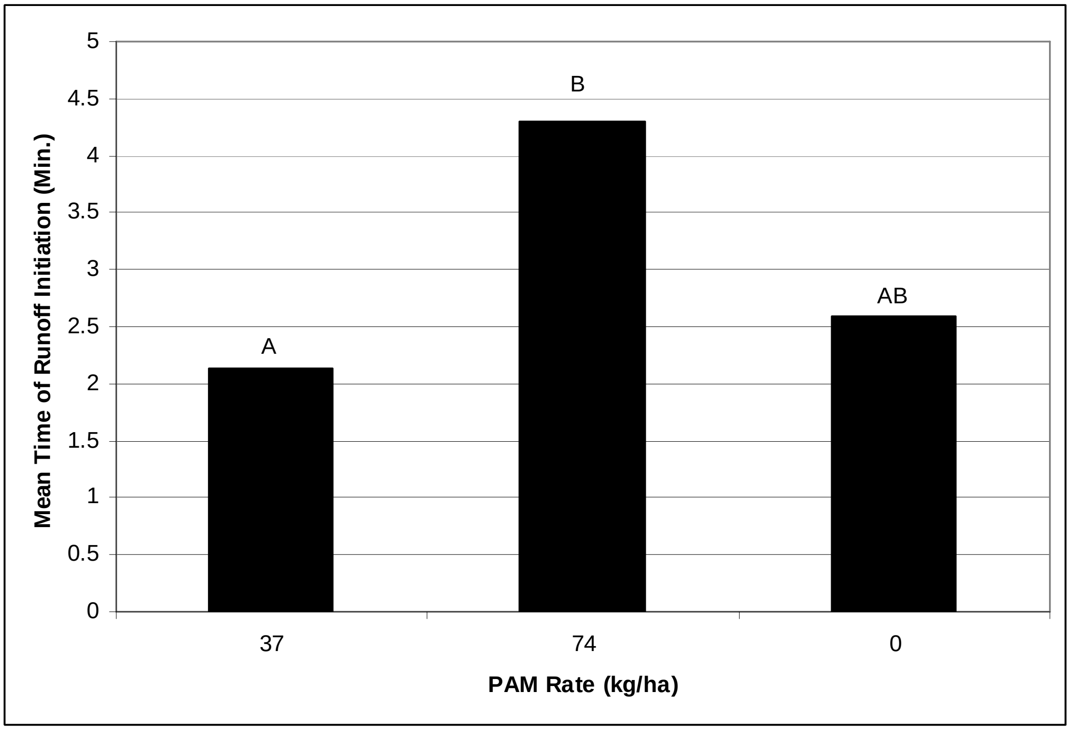

Figure 3. Mean time of runoff initiation for second run, dry straw treatments. Means with same letter are not significantly different at α = 0.10.

Table 3. Mean time of runoff initiation for low and high rates of cotton and wood fiber mulch, second rainfall simulation. Means with different letters are significantly different at α = 0.1.

Mulch Rate	Mean Time of Runoff Initiation (Mins.)	
low	3.3	A
high	4.5	B

Table 4. Pearson correlation coefficients for time of runoff initiation and runoff volume, second rainfall simulation. Top number is Pearson correlation coefficient, bottom is p-value.

	Runoff Volume	Time of Runoff Initiation
Runoff Volume	1	-0.49
		0.0004
Time of Runoff Initiation	-0.49	1
	0.0004	

Table 5. Treatment means for turbidity in first run of rainfall simulator. Means with same letter are not significantly different at α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	**Mulch Rate**	**PAM Rate (kg ha^{-1})**	**PAM Application Method**	**Mean Turbidity (NTU)**	
WF	high	37	aqueous	62	C
C	high	37	aqueous	98	B C
WF	low	37	aqueous	108	B C
C	low	37	aqueous	110	B C
S	low	74	granular	115	B C
C	high	0	n/a	208	A B C
S	low	37	granular	229	A B C
S	low	37	aqueous	288	A B C
WF	high	0	n/a	461	A B C
C	low	0	n/a	565	A B
WF	low	0	n/a	770	A B C
S	low	0	n/a	1495	A

Table 6. Treatment means for turbidity in second run of rainfall simulator. Means with same letter are not significantly different at α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	**Mulch Rate**	**PAM Rate (kg ha^{-1})**	**PAM Application Method**	**Mean Turbidity (NTU)**	
WF	high	37	aqueous	83	B
S	low	74	granular	96	A B
C	low	37	aqueous	102	B
S	low	37	granular	138	A B
WF	low	37	aqueous	152	A B
C	high	37	aqueous	182	A B
C	high	0	n/a	420	A B
S	low	37	aqueous	491	A B
C	low	0	n/a	514	A B
WF	high	0	n/a	935	A B
WF	low	0	n/a	985	A
S	low	0	n/a	1045	A

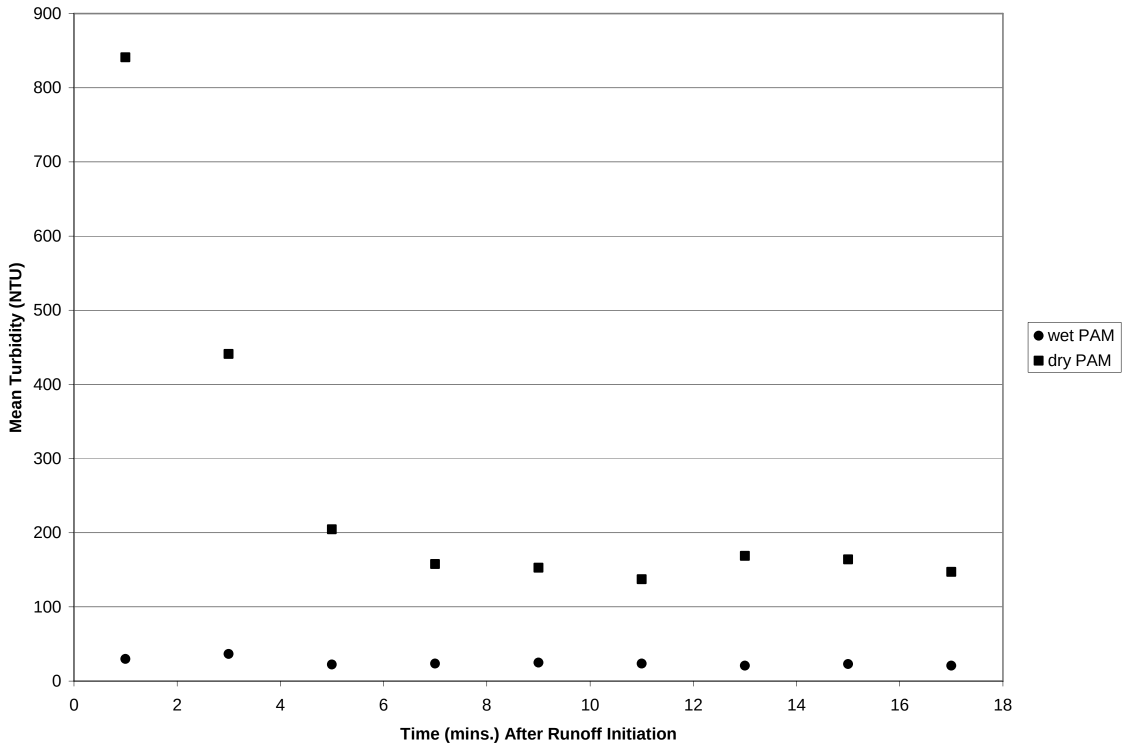

Figure 4. Runoff turbidity as a function of collection time under simulated rainfall.

Table 7. ANOVA results for turbidity of runoff samples as a function of PAM application method.

Time After Runoff (Mins.)	p-value
1	0.032
3	0.051
5	0.0074
7	0.016
9	0.020
11	0.044
13	0.017
15	0.0085
17	0.0084

Table 8. Pearson correlation coefficients for runoff turbidity and time of sample collection. Top number is Pearson correlation coefficient, bottom is p-value.

	Sample Time	Turbidity
Sample Time	1	-0.18
		0.14
Turbidity	-0.18	1
	0.14	

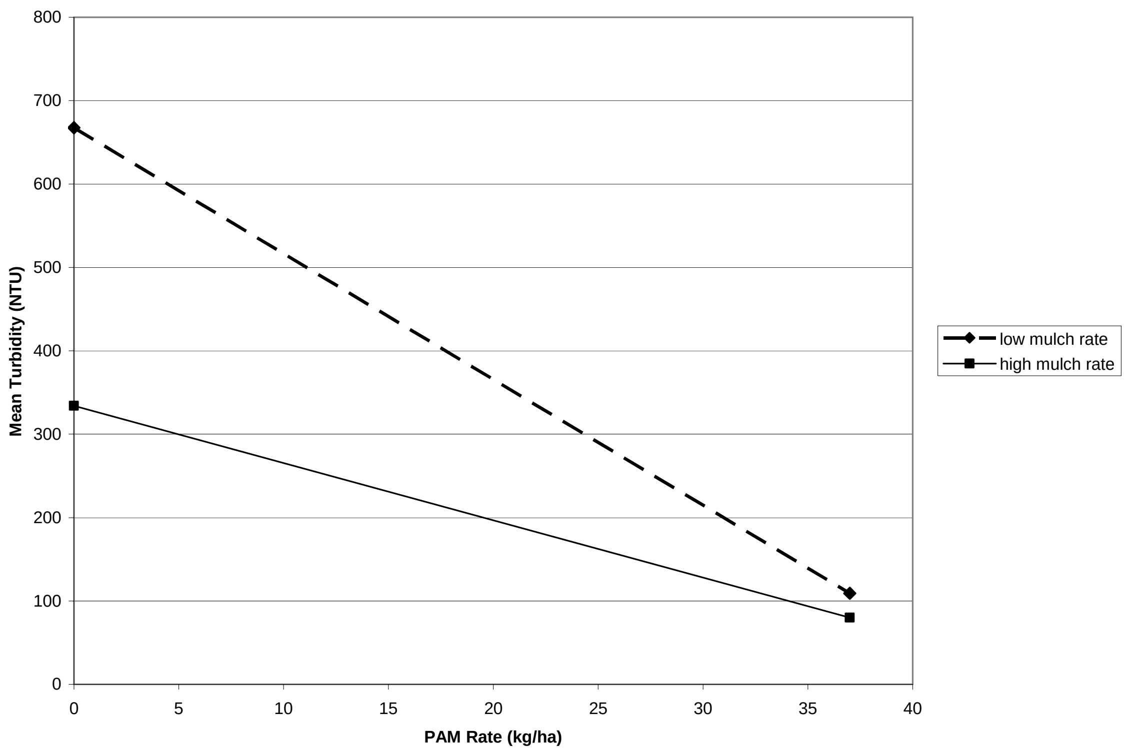

Figure 5. Turbidity was affected by an interaction between PAM rate and mulch rate under simulated rainfall.

Table 9. Mean turbidity for each mulch type, first rainfall simulation. Means with same letter are not significantly different at $\alpha = 0.10$. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	Mean Turbidity (NTU)	
C	245	A
WF	350	A
S	892	B

Table 10. Means and treatment differences for TSS in the first rainfall simulator run. Means with same letter are not significantly different at α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	Mulch Rate	PAM Rate (kg ha^{-1})	PAM Application Method	Mean TSS (mg L^{-1})	
C	low	37	aqueous	394	A
WF	low	37	aqueous	475	A
C	high	37	aqueous	498	A
WF	high	37	aqueous	665	A
C	high	0	n/a	692	A B
C	low	0	n/a	1072	A B
S	low	37	aqueous	1078	A B
S	low	74	granular	1343	A B
WF	low	0	n/a	1580	A B
WF	high	0	n/a	2006	A B
S	low	0	n/a	5938	B
S	low	37	granular	12787	B

Table 11. Means and treatment differences for TSS, second rainfall simulator run. Means with same letter are not significantly different α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	Mulch Rate	PAM Rate (kg ha^{-1})	PAM Application Method	Mean TSS (mg L^{-1})	
WF	high	37	aqueous	298	B
C	low	37	aqueous	370	A B
C	high	37	aqueous	396	A B
WF	low	37	aqueous	464	A B
C	high	0	n/a	505	A B
S	low	37	aqueous	1074	A B
C	low	0	n/a	1092	A B
WF	high	0	n/a	1454	A B
S	low	74	granular	1791	A B
WF	low	0	n/a	2085	A
S	low	0	n/a	2314	A
S	low	37	granular	3804	A

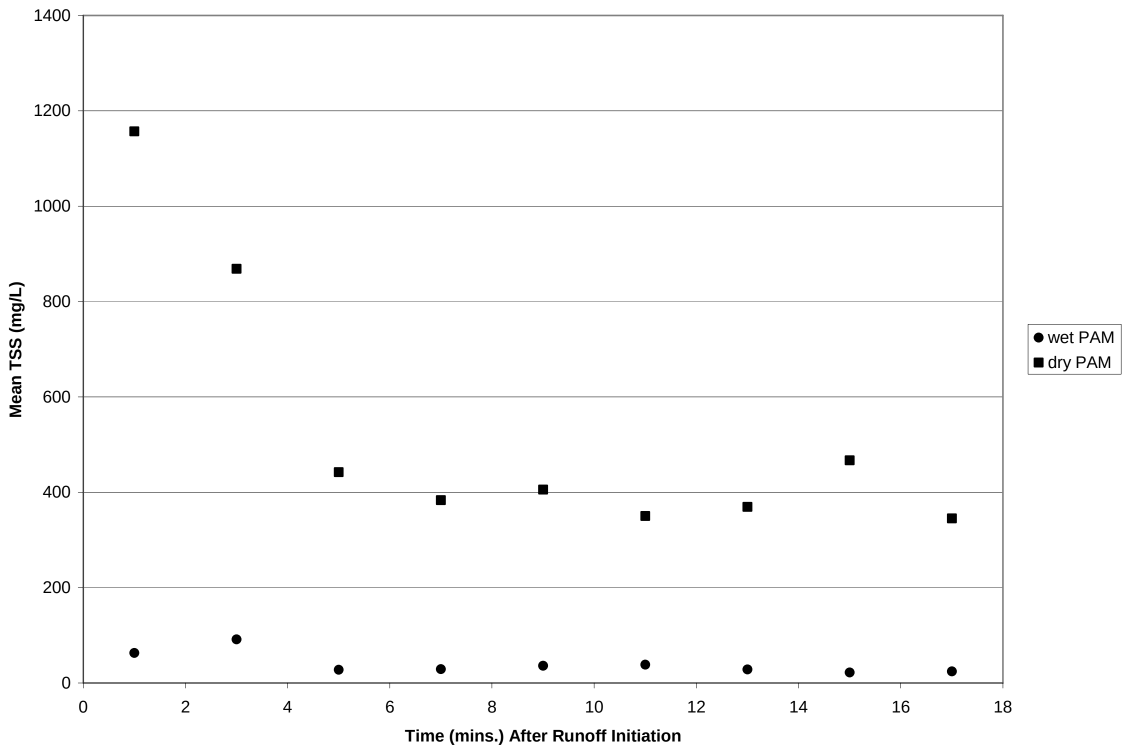

Figure 6. Mean TSS in runoff as a function of time after runoff initiation under simulated rainfall.

Table 12. ANOVA results for differences in TSS of aqueous and granular PAM treatments as a function of time after runoff.

Time After Runoff (Mins.)	p-value
1	0.020
3	0.039
5	0.015
7	0.016
9	0.016
11	0.065
13	0.031
15	0.0080
17	0.0092

Table 13. Means and treatment differences for sediment loss during first rainfall simulation. Means with same letter are not significantly different at α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	**Mulch Rate**	**PAM Rate (kg ha^{-1})**	**PAM Application Method**	**Mean Sediment Loss (kg ha^{-1})**	
C	low	37	aqueous	2	A
WF	low	37	aqueous	4	A B
WF	high	37	aqueous	5	A B
C	high	0	n/a	7	A B
C	high	37	aqueous	7	A B
C	low	0	n/a	15	A B
S	low	74	granular	16	A B
S	low	37	aqueous	28	A B
WF	low	0	n/a	41	A B
WF	high	0	n/a	50	A B
S	low	0	n/a	53	A B
S	low	37	granular	191	B

Table 14. Means and treatment differences for total sediment lost during second rainfall simulation. Means with same letter are not significantly different at α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	**Mulch Rate**	**PAM Rate (kg ha^{-1})**	**PAM Application Method**	**Mean Sediment Loss (kg ha^{-1})**	
WF	high	37	aqueous	0.18	A
C	low	37	aqueous	0.50	A B
WF	low	37	aqueous	1.04	A B C
C	high	0	n/a	1.34	A B C
C	high	37	aqueous	1.62	A B C
C	low	0	n/a	2.19	A B C
S	low	37	aqueous	4.04	B C
WF	high	0	n/a	4.34	A B C
S	low	0	n/a	5.45	B C
S	low	74	granular	6.19	B C
WF	low	0	n/a	6.49	B C
S	low	37	granular	18.73	C

Table 15. Means and differences in sediment loss by mulch type for first rainfall simulation. Means with same letter are not significantly different at α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	Mean Sediment Loss (kg ha^{-1})	
C	7.8	A
WF	25.0	A B
S	40.7	B

Table 16. Means and differences sediment loss by mulch type for second rainfall simulation. Means with same letter are not significantly different at α = 0.05. Straw is S, wood fiber is WF, and cotton fiber matrix test product is C.

Mulch Type	Mean Sediment Loss (kg ha^{-1})	
C	1.4	A
WF	3.0	A
S	4.7	B

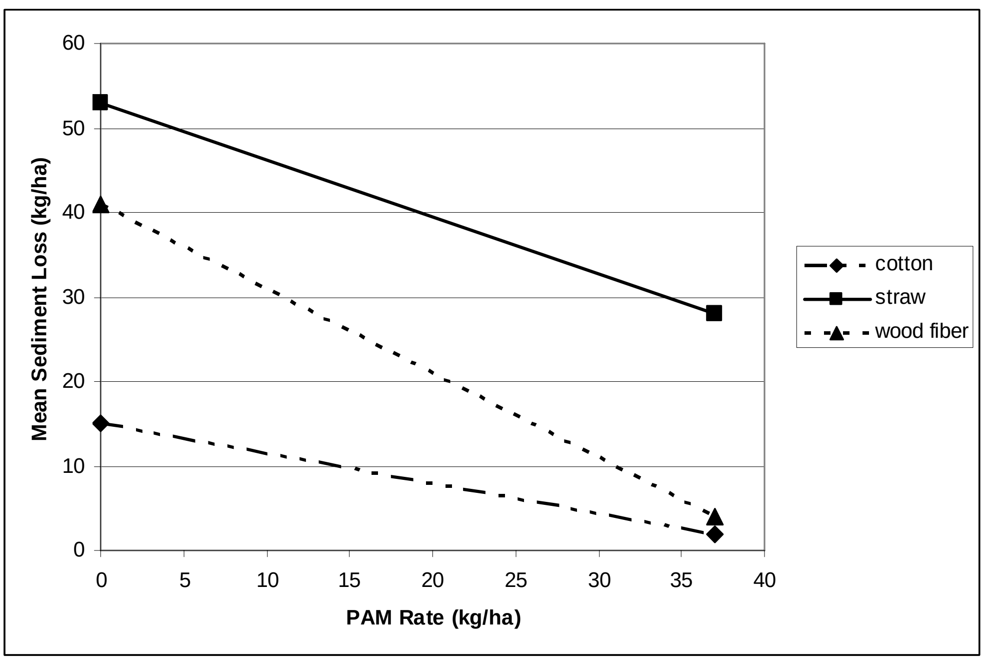

Figure 7. Interaction between mulch type and PAM rate for sediment loss, first rainfall simulation.

Table 17. North Carolina Department of Transportation seed and mulch specifications for eastern North Carolina.

Addition	**Rate (kg ha^{-1})**
Tall Fescue	56
Centipede	5.6
Hulled Bermudagrass	28
10-20-20 Fertilizer	560
Limestone	4479

Figure 8. Completed plot setup of site 2. Treatments pictured from left to right: straw, cotton, straw + PAM, BFM, straw.

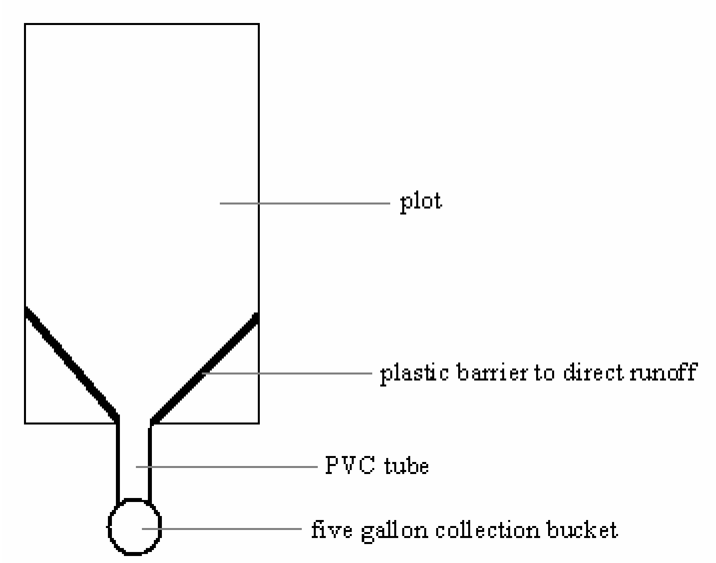

Figure 9. Runoff collection system at site 3.

Table 18. ANOVA model for biomass as a function of treatment at site 1.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	4	335006.12	83751.53	5.81	0.0028
Error	20	288073.85	14403.69		
Corrected Total	24	623079.97			

Table 19. ANOVA model for vegetative cover as a function of treatment at site 1.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	4	7748.66	1937.17	7.60	0.0007
Error	20	5095.30	254.77		
Corrected Total	24	12843.96			

Table 20. Proportion of variability in vegetative cover explained by treatment at site 1.

R-Square	**Coefficient of Variation**	**Root MSE**
0.60	43.68	15.96

Table 21. Proportion of variability in biomass explained by treatment at site 1.

R-Square	**Coeff. Var.**	**Root MSE**
0.54	50.79	120.02

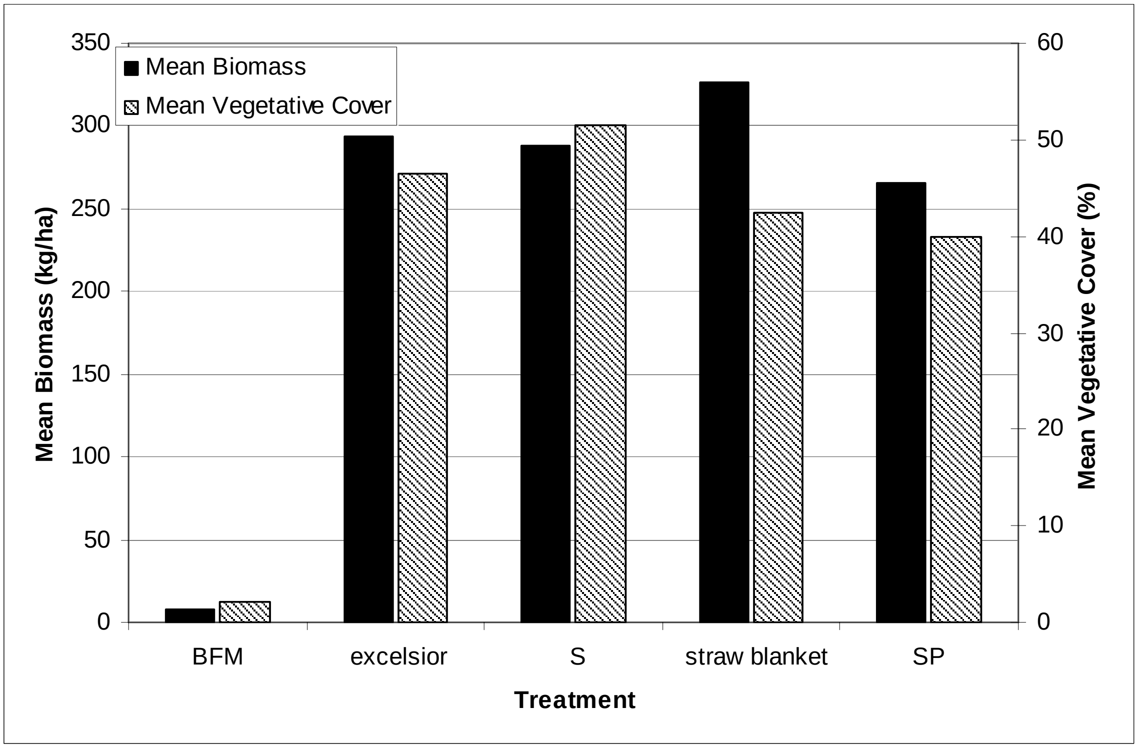

Figure 10. Mean biomass and vegetative cover at site 1. Bonded fiber matrix is BFM, straw is S, straw with PAM is SP.

Table 22. Pearson correlation coefficients for biomass and vegetative cover at site 1. Top number is Pearson correlation coefficient; bottom number is p-value.

	Vegetative Cover	**Biomass**
Vegetative Cover	1	0.84
		<0.0001
Biomass	0.84	1
	<0.0001	

Table 23. ANOVA table for relationship between treatment and vegetative cover at site 2.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	3	997.51	332.50	2.75	0.077
Error	16	1933.80	120.86		
Corrected Total	19	2931.31			

Table 24. ANOVA table for relationship between treatment and biomass at site 2.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	3	169271928	56423976	0.97	0.43
Error	16	934429605	58401850		
Corrected Total	19	1103701533			

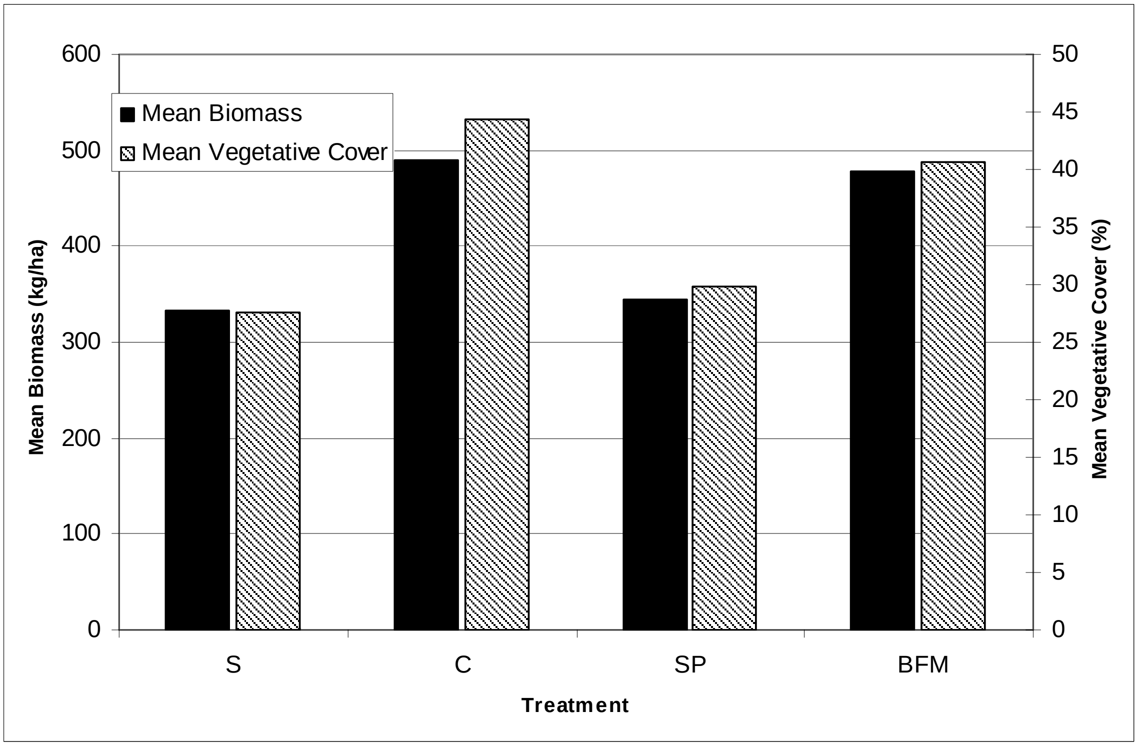

Figure 11. Mean biomass and vegetative cover at site 2.

Figure 12. Straw plot at site 2, two months after planting.

Table 25. Total daily and maximum hourly rainfall intensity for plots at site 3 during the evaluation period.

Date	Total Daily Rainfall (mm)	Maximum Hourly Rainfall (mm hr^{-1})
16-Mar	48.0	8.6
29-Mar	3.30	1.5
11-Apr	28.4	14.7
15-Apr	31.5	5.6
27-Apr	3.81	3.8
4-May	2.54	1.3
8-May	1.8	1.3
total	119.4	

Table 26. Average runoff volume per storm event for each treatment at site 3. Cotton is C, straw is S, straw with PAM is SP, bonded fiber matrix is BFM.

Treatment	Mean Runoff Volume (mL)	Standard Deviation	Coefficient of Variation (%)
C	1975	4072	206
S	483	236	49
SP	401	276	69
BFM	304	216	71

Table 27. ANOVA table for runoff volume as a function of treatment at site 3.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2.693878	1.346939	3.38	0.043
Error	45	17.94949	0.398878		
Corrected Total	47	20.64337			

Table 28. ANOVA table for modeling turbidity using treatment and soil type at site 3.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	3	21.42	7.14	4.63	0.0044
Soil Type	3	52.28	17.43	11.3	<.0001

Table 29. Treatment means and differences for runoff turbidity at site 3. Means with same letter are not significantly different at $\alpha = 0.10$. Cotton is C, straw is S, straw with PAM is SP, bonded fiber matrix is BFM.

Treatment	Mean Turbidity (NTU)	
C	1910	A
SP	530	A
BFM	410	A
S	403	A


Figure 13. Cotton plot at site 3 one month after hydromulch application.


Figure 14. Bonded fiber matrix plot at site 3 one month after hydromulch application.

Table 30. Means and differences for runoff turbidity as a function of soil textural class at site 3.

Soil Type	Number of Observations	Mean Turbidity (NTU)	Estimated Soil Erodibility Factor	
clay loam	14	142	0.13-0.20	A
clay	7	198	0.25	A B
sandy clay loam	49	357	0.25	B
loam	42	1672	0.34	B

Table 31. Pearson correlation coefficients for turbidity and TSS at site 3. Top number is Pearson correlation coefficient, bottom is p-value.

	Turbidity	TSS
Turbidity	1	0.80
		<.0001
TSS	0.80	1
	<.0001	

Table 32. ANOVA table for TSS as a function of treatment and soil texture at site 3.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	3	23.27	7.76	5.05	0.0026
Soil Texture	3	15.21	5.07	3.3	0.023

Table 33. Treatment means and differences for TSS at site 3. Means with same letter are not significantly different at $\alpha = 0.05$ level. Cotton is C, straw is S, straw with PAM is SP, bonded fiber matrix is BFM.

Treatment	Mean TSS (mg L^{-1})	
BFM	1309	A
S	1596	A
SP	2090	A B
C	9746	B

Table 34. Mean TSS by soil type at site 3. Means with same letter are not significantly different at α = 0.1 level.

Soil Texture	Number of Observations	Mean TSS (mg L^{-1})	Standard Deviation	Coefficient of Variation (%)	
loam	42	5855	18650	319	A
sandy clay loam	49	2886	8407	291	A
clay loam	14	1283	1516	118	A
clay	7	1071	663	62	A

Table 35. Means and treatment differences in sediment loss per storm event at site 3. Means with same letter are not significantly different at α = 0.10. Cotton is C, straw is S, straw with PAM is SP, bonded fiber matrix is BFM.

Treatment	Mean Sediment Loss (kg ha^{-1})	
BFM	4	A
S	8	A B
SP	16	A B
C	171	B

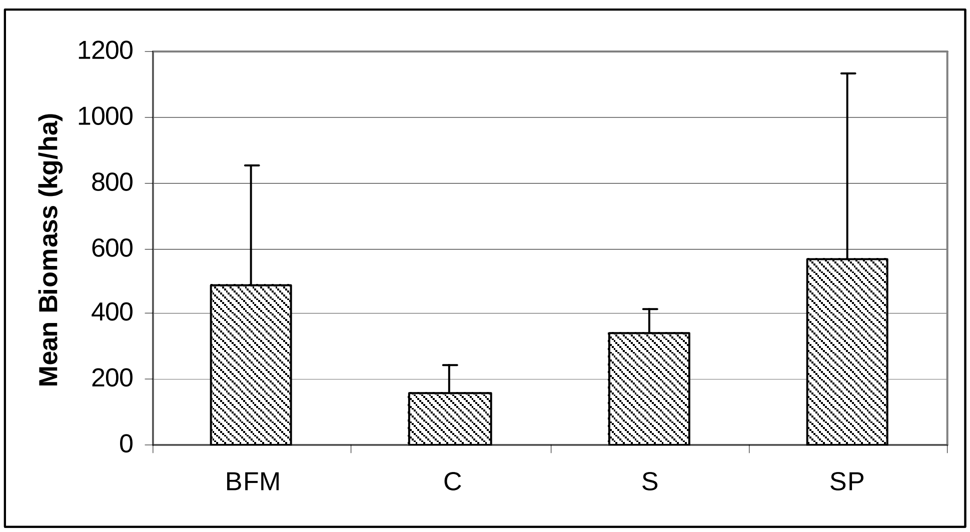

Figure 15. Mean treatment biomass at site 3. Error bars represent one standard deviation. Cotton is C, straw is S, straw with PAM is SP, bonded fiber matrix is BFM.

Table 36. ANOVA table for vegetative cover as a function of treatment and soil texture at site 3.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Treatment	3	1943.20	647.73	7.37	0.0085
Soil Texture	3	7441.90	2480.63	28.23	<.0001

Table 37. Means and treatment differences in vegetative cover at site 3. Means with same letter are not significantly different at α = 0.05. Cotton is C, straw is S, straw with PAM is SP, bonded fiber matrix is BFM.

Treatment	Mean Vegetative Cover (%)	
C	28	A
BFM	46	A B
S	61	B
SP	66	B

Table 38. Pearson correlation coefficients for biomass and vegetative cover at site 3. Top number is Pearson correlation coefficient, bottom is p-value.

	Biomass	Vegetative Cover
Biomass	1	0.84
		<.0001
Vegetative Cover	0.84	1
	<.0001	

Table 39. Means and soil texture differences in vegetative cover at site 3. Means with same letter are not significantly different at α = 0.05.

Soil Texture	Mean Vegetative Cover (%)	
sandy clay loam	29	A
clay loam	30	A
clay	72	B
loam	78	B

Appendices

APPENDIX 1: EXAMPLE SAS CODE

data mulch;
input treatment :$22. Product$ productamt pamamt PAM$ pamtext$ runofft1 runoffamt1 corturb1 tss1 totsed1 runofft2 runoffamt2 corturb2 tss2 totsed2;

**input line is the variable names. "$" denotes categorical variable.;*

logcorturb1=log(corturb1);
logcorturb2=log(corturb2);
logtss1=log(tss1);
logtss2=log(tss2);
logtotsed1=log(totsed1);
logtotsed2=log(totsed2);
logrunofft2=log(runofft2);

**above lines are how to transform variables in SAS.;*

datalines;
**paste data from excel into here. Exclude cells with variable names.;*
;
ods html body= 'mulch.html';
proc print ;
run;

**prints your dataset. Look it over to make sure there were no errors from importing it.;*

/testing all variables for normality and equal variance/;
proc univariate normal plot;
var runofft1;
run;

**Ho is that data is normal. You want high p values. Also examine normal plot and stem and leaf plot to determine the nature and severity of any departures from normality;*

proc glm;
    class treatment;
    model runofft1 = treatment;
    means treatment/hovtest=BF;

**Ho is that data has equal variance..;*

```
*/begin analyzing effects/*;
ods html body = 'turbmeans.html';
proc means;
var runofft1;
class treatment;
run;
```

**gives treatment mean, minimum, maximum, and standard deviation;*

```
title ‘treatmentrunoff ’;
proc glm;
	class treatment;
	model runofft1 = treatment;
	means  treatment/lsd tukey;
	ods html body='mulch.html';
run;
```

**proc glm is an ANOVA. Means statement gives pairwise differences with the experimentwise error rate adjusted at α = 0.05 by default.;*

```
title 'mulch type';
proc glm;
class pamamt productamt;
model corturb1=pamamt*productamt;
means pamamt*productamt/lsd tukey;
ods html body = 'mulch.html';
run;
```

**this is an example of testing the significance of an interaction.;*

APPENDIX 2: WATER STORAGE CALCULATIONS

Assumption:
Total soil volume is comprised of 50% pore volume and 50% soil volume

Volume of soil:
200 cm x 100 cm x 6 cm = 120,000 cm^3 volume of soil and air

Half of total volume is pore space, which is available to hold water.
0.5 (120,000 cm^3) = 60,000 cm^3 volume of pores = maximum volume of water that can be held in soil

24.7 mm of rain over two simulations = 2.47 cm of rain

Volume of rain:
2.47 cm x 200 cm x 100 cm = 49,000 cm^3 of rain

Total volume of rain delivered over two simulations does not exceed potential maximum storage capacity of soil in the soil boxes.