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Application of polyacrylamide (PAM) through lay-flay polyethylene tubing: effects on infiltration, erosion, N and P transport, and corn grain yield

By

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Application of polyacrylamide (PAM) through lay-flat polyethylene tubing: effects on infiltration, erosion, N and P transport, and corn grain yield

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Polyacrylamides (PAMs) are water-soluble, long-chain synthetic organic polymers that, when applied as a soil amendment, purportedly improves infiltration, decreases sediment and agrochemical transport, and improves crop yield. There is a paucity of data, however, on the effect of PAM applied through lay-flat polyethylene tubing on infiltration, erosion, agrochemical transport, and crop yield for Mid-South soils in furrow irrigated environments. The objective of this thesis was to compile and analyze PAM use in agricultural settings in the United States, and to conduct a 2 year field experiment to assess PAM effects on infiltration, erosion, N and P transport, and corn grain yield on a Dundee silt loam and a Forestdale silty clay loam soil located in Stoneville and Tribbett, Mississippi, respectively. Results indicate PAM has utility to improve infiltration and crop yield in Mid-South production systems, but effects on sediment and N and P transport will be variable and site specific.

DEDICATION

I would like to dedicate this thesis to my parents, Mark and Cindy McNeal. Your inescapable love and unending support are the foundation of who I am today.

To my father, who never failed to selflessly put the needs of his family before his own. From baseball to the outdoors, and from college to graduate school and my career, your counsel and example are with me each day. You never missed the forest for the trees in spending time with us, and are the example of sacrificial love and support with which I pray to serve my own family.

To my mother, who has always been a pure and consistent example before me of the love of Christ. In both joy and sorrow your faith has never wavered, and your humble spirit and sacrificial love are continual reminders of the presence of God in my life.

I owe my parents a debt I cannot repay. My prayer is that I am a husband to my wife, a father to my children, a selfless provider for my family, and a servant to others in a way that honors my father and mother. I love you both.

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CHAPTER I

A REVIEW OF POLYACRYLAMIDES IN AGRICULTURE: IMPLICATIONS FOR MID-SOUTH PRODUCTION SYSTEMS

Abstract

A comprehensive review of polyacrylamide (PAM) effects on infiltration, erosion and agrochemical transport on agricultural landscapes does not exist. The objectives of this article were to identify which soil textures agricultural research on PAM has occurred in the United States; denote the PAM formulations, rates and application techniques applied in agricultural settings; determine the parameters influencing PAM efficacy in regards to infiltration, erosion and off-site agrochemical transport and; quantify the effect of PAM on crop yield. Ionic and non-ionic PAM formulations are commercially available, but only anionic PAM formulated as water dispersed granules (WDG), water soluble powders (WSP) and emulsifiable concentrates (EC) are applied in agricultural environments. Current research in the United States suggests that approximately 72% of PAM evaluations have occurred in arid regions west of the Mississippi River. The majority of PAM data describes results for silt loam or coarser soil textures (n=41), with little research on fine textured soils (n=8). The effect of PAM on infiltration and erosion has been evaluated at the micro-plot scale under laboratory conditions and at the meso-plot scale under rain-fed, pivot and furrow irrigated landscapes. Polyacrylamide effects on agrochemical transport have been evaluated only in furrow irrigated environments. Polyacrylamide effects on infiltration, erosion and agrochemical transport are dependent on soil texture, formulation, application rate, and number of subsequent applications. Pooled over all studies and evaluated parameters, PAM increased infiltration 39% (n=135), reduced erosion 60% (n=40), decreased N (n=3) and P off-site transport (n=5) 76%, and improved crop yield 9.4% (n=5). These data indicate potential for PAM applied in Mid-South production systems to improve infiltration, decrease sediment and agrochemical transport, and increase crop yield. Future research should focus on PAM effects on infiltration, erosion, off-site agrochemical transport, and crop yield on various soil textures east of the Mississippi River.

Introduction

Polyacrylamides (PAMs) are water soluble, long chain synthetic organic polymers produced from natural gas (Flanagan et al., 2003) that, when applied as a soil amendment, may promote aggregate stability (Caesar-TonThat et al., 2008; Green et al., 2004; Laird, 1997; Mamedov, 2010), improve irrigation and rainfall infiltration rates (Aase et al., 1998; Ajwa and Trout, 2006; Ben-Hur et al., 1992; Bjorneberg and Aase, 2000; Bjorneberg et al., 2003; Entry and Sojka, 2003; Entry et al., 2002; Gardiner and Sun, 2002; Green et al., 2000; Leib et al., 2005; Lentz and Bjorneberg, 2003; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2002; Mitchell, 1986; Shainberg et al., 1990; Sojka and Entry, 2000; Sojka et al., 1998, 2003; Terry and Nelson, 1986; Zhang and Miller, 1996), reduce erosion (Aase et al., 1998; Ben-Hur et al., 1992; Bjorneberg and Aase, 2000; Entry and Sojka, 2003; Entry et al., 2002; Flanagan et al., 2003; Kornecki et al., 2005; Lentz and Bjorneberg, 2003; Lentz and Sojka, 1994; Leib et al., 2005; Lentz et al., 1992, 1998, 2001, 2002; Lu and Wu, 2003; McLaughlin and Brown, 2006; Orts and Glenn, 1999; Orts et al., 2001; Shrestha et al., 2006; Sojka and Entry, 2000; Sojka et al., 2003; Szogi et al., 2007; Zhang and Miller, 1996), and decrease off-site agrochemical transport (Entry and Sojka, 2003; Entry et al., 2002; Goodson et al., 2006; Krauth et al., 2008; Lentz and Sojka, 1994; Lentz et al., 1998, 2001; Lepore et al., 2009; Sojka et al., 2005, 2006; Szogi et al., 2007).

The Mississippi Alluvial River Valley Aquifer (MARVA) has experienced a precipitous decline over the last 40 years. Declining aquifer levels are primarily due to an increase in the number of irrigated acres for row-crop production and an intensification of water withdrawals to meet demands for higher crop yields. In the mid-southern United States, surface (furrow), sprinkler (pivot), and subsurface drip irrigation are the three irrigation application methods utilized. Irrigation application efficiencies vary primarily as a function of delivery system, with approximate intake values of 30%, 70%, and 88% for furrow, pivot and subsurface drip irrigation systems, respectively (Howell, 2003). Consequently, a means to improve furrow irrigation application efficiency is required for the Mid-South region where 80% of acres are furrow irrigated.

Export of excess nutrients and other associated agrochemicals due to present-day agricultural practices are the most significant contributors to the degradation of surface water quality in the United States (U.S. EPA, 2000; USDA-ARS, 2003). However, profitable and sustainable agronomic practices necessitate nutrient inputs in the form of organic or chemically derived fertilizer materials (Flanagan and Canady, 2006). Fertilizer applications that exceed soil nutrient holding capacity often result in off-site transport and pollution of down-stream water bodies (Brichford et al., 1993).

Consequently, irrigation-induced runoff and sediment transport are major contributors to degradation of surface water quality. A means to maintain current on-farm profitability while reducing off-site sediment and agrochemical transport is required.

Polyacrylamides have utility in Mid-South agricultural ecosystems if they improve irrigation application efficiency and/or reduce erosion and off-site agrochemical transport. There is a paucity of data, however, on the effect of PAM on water, sediment, nutrient transport and crop yield for Mid-South soils and production systems. The objectives of this document were to identify PAM formulations used as soil amendments in row crop agriculture, describe methods employed to study PAM in agricultural settings, and to identify factors that affect PAM's performance as related to infiltration, erosion, and N and P transport.

Materials and Methods

Infiltration, off-site sediment and agrochemical transport, and yield were normalized to the control, that is, no PAM. Box plots for PAM effects on normalized infiltration, erosion, N and P transport and crop yield were created in SigmaPlot 13.0 (Systat Software, Inc., San Jose, California). The boundary of the box plot closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile. Error bars above and below the box indicate the 90th and 10th percentile, and solid dots indicate outliers. Normalized infiltration values were regressed on soil organic matter and fitted to Eqn. [1], a sigmoidal model:

$$y = a/(1+\exp(-(x-x0)/b)) \qquad (1.1)$$

where *a* is the maximum; *x0* is the inflexion point, and *b* is the rate constant.

Normalized N and P transport data were regressed on normalized sediment transport data and fitted to Eqn. [2], a linear regression model:

$$y = y0+a*x \qquad (1.2)$$

where *y0* is the intercept, and *a* is the slope of the line.

Ionic and Non-ionic PAMs and their Commercial Utility

Polyacrylamides are commercially available in non-ionic, cationic and anionic forms (Laird, 1997; McGuire et al., 2006; Figure 1-3). Effects of non-ionic PAM in agricultural settings is not reported in the literature; however, non-ionic PAM is used extensively as a thickening agent in animal feeds, the paper and paperboard industry when in contact with food, and the fruit and vegetable industry to assist with the washing and peeling of food to be packaged (Barvenik, 1994). Cationic PAM has only been evaluated in laboratory settings with no reported use in irrigated agriculture. Although cationic PAMs do exist and flocculate clay molecules regardless of their mineralogy, they are less effective relative to anionic PAMs in basic to neutral systems (Laird, 1997). Only anionic PAM is applied in agricultural landscapes (Sojka et al., 2005; Shrestha et al., 2006). Anionic PAM promotes flocculation by providing charged binding sites for soil colloids in suspension. Polyacrylamide binds with the soil surface to preserve pore space integrity throughout the irrigation event and growing season. This document will deal exclusively with anionic PAMs of various formulations.

Anionic PAM Formulations

Three anionic PAM formulations are referenced in agricultural literature and may have potential utility in Mid-South agricultural settings: dry granular (DG), water soluble powder (WSP) and emulsifiable concentrate (EC). Dry granular PAM is applied directly to the soil surface with a spreader or in bulk at the furrow head and incorporated by furrow irrigation (Entry and Sojka, 2003; Lentz and Bjorneberg, 2003; Leib et al., 2005, Sojka et al., 2006, Szogi et al., 2007). Thus far, DG evaluations are reported only at the meso-scale under furrow irrigated conditions (Entry and Sojka, 2003; Lentz and Bjorneberg, 2003; Leib et al., 2005; Sojka et al., 2006; Szogi et al., 2007). Emulsifiable formulations are sparsely reported in the literature, but can be applied with irrigation water through a pivot (Bjorneberg, 1998; Flanagan et al., 2003) or lay-flat polyethyelene tubing (Lentz et al., 1992, 1998). To date, WSP is the most widely evaluated PAM formulation in agricultural settings (Aase et al., 1998; Ajwa and Trout, 2006; Bjorneberg, 1998; Bjorneberg et al., 2003; Caesar-TonThat et al., 2008; Flanagan et al., 2003; Goodson et al., 2006; Green et al. 2000, 2004; Kay-Shoemake et al., 1998, 2000; Kornecki et al., 2005; Krauth et al., 2008; Lentz and Sojka, 1994; Lentz et al. 2001, 2002; Lepore et al., 2009; Lu and Wu, 2003; Lu et al., 2002; Mamedov et al., 2010; McLaughlin and Brown, 2006; Mitchell, 1986; Orts and Glen, 1999; Orts et al., 2001; Shrestha et al., 2006; Sojka and Entry, 2000; Sojka et al., 1998, 2003, 2006; Zhang and Miller, 1996). Polyacrylamide as a WSP formulation has been applied through a pivot (Bjorneberg, 1998; Bjorneberg et al., 2003; Flanagan et al., 2003; Krauth et al., 2008; Zhang and Miller, 1996), lay-flat polyethyelene tubing (Goodson et al., 2006; Kay-Shoemake et al., 2000; Kornecki et al., 2005; Lentz and Sojka, 1994; Lentz et al., 2001, 2002; Mitchell, 1986; Sojka and Entry, 2000; Sojka et al., 1998, 2003, 2006), and directly to the soil surface (Entry and Sojka, 2003; Lentz and Bjorneberg, 2003; Leib et al., 2005; Sojka et al. 2006; Szogi et al., 2007).

States and Soil Textures where PAM Studies have been conducted

To date, 72% of the cumulative body of PAM data in irrigated agriculture is from regions, soils, and production systems west of the Mississippi River (Figure 4-5). Although soil textures from these regions are similar to those in the Mid-South, cultural practices, particularly tillage and irrigation application methods, vary substantially between regions. Soil physical and chemical properties can impact soil-water relations and, consequently, soil-water-PAM interactions (Bresson and Boiffin, 1990; McIntyre, 1958; Mucher and De Ploey, 1977; Valentin 1991; Valentin and Bresson, 1992).

Evaluation Systems

In the United States, furrow and pivot irrigation are the most utilized irrigation delivery systems, accounting for > 93% (Hutson et al. 2004). However, to understand the chemical nature of PAM and its ability to bind with and flocculate soil colloids in water and on the soil surface, laboratory evaluations are necessary. Polyacrylamides have been evaluated at the micro- and meso-plot scale, that is, under laboratory and field (pivot and furrow irrigated) conditions, respectively.

Factors Evaluated at the Micro-Plot Scale, Laboratory and Field

To date, only WSP (Aase et al., 1998; Ajwa and Trout, 2006; Caesar-TonThat et al., 2008; Dontsova and Norton, 2002; Green et al. 2000, 2004; Orts and Glenn, 1999; Kay-Shoemake et al., 1998; Lepore et al., 2009; Lu and Wu, 2003; Lu et al., 2002;

McLaughin and Brown, 2006; Norton et al., 2006; Orts et al., 2001; Reichart et al., 2009) and EC formulations have been evaluated at the micro-scale, either laboratory or field (Ajwa and Trout, 2006; Lepore et al., 2009). Although DG PAMs have not been evaluated at this scale, the formulation varies from WSP and EC only in the method of application, dry vs dissolved (Bjorneberg, 1998).

Micro-plot (1 to 3-m plots) research on PAM has focused primarily on the compound's ability to affect aggregate stability (Aase et al., 1998; Ajwa and Trout, 2006; Caesar-TonThat et al., 2008; Green et al., 2004; Mamedov et al., 2010), infiltration (Ajwa and Trout, 2006; Bjorneberg and Aase, 2000; Gardiner and Sun, 2002; Green et al., 2000; Lentz, 2003), surface runoff (Aase et al., 1998; Lepore et al., 2009; McLaughlin and Brown, 2006), erosion (Aase et al., 1998; Bjorneberg and Aase, 2000; Lepore et al., 2009; McLaughlin and Brown 2006, Orts and Glenn, 1999; Orts et al., 2001; Shrestha et al., 2006), and off-site agrochemical transport (Lepore et al., 2009). Variables evaluated in PAM infiltration studies include soil texture (Ajwa and Trout, 2006; Busscher et al., 2007, 2009; Green et al., 2000, 2004; Lu and Wu, 2003; Mamedov et al., 2010), formulation (Ajwa and Trout, 2006; Busscher et al., 2009; Lepore et al., 2009; Shrestha et al., 2006), application rate (Aase et al., 1998, Ben-Hur et al., 1992; Buscher et al., 2007, 2009; Caesar-TonThat et al., 2008; Gardiner and Sun, 2002; Lentz, 2003, Lu and Wu, 2003; Orts and Glen, 1999), and number of applications (Ajwa and Trout, 2006; Bjorneberg and Aase, 2000, Bjorneberg et al., 2003; Entry and Sojka, 2003; Green et al., 2000; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2002; Orts et al., 2000).

Factors Evaluated at the Meso-Plot Scale under Pivot Irrigated Conditions

To date, only WSP (Bjorneberg et al., 2003; Flanagan et al., 2003; Krauth et al., 2008; Zhang and Miller, 1996) and EC (Flanagan et al., 2003) formulations have been evaluated in pivot irrigated environments. Polyacrylamide effects on aggregate stability (Shainberg et al., 1990), infiltration (Bjorneberg et al., 2003; Shainberg et al., 1990; Zhang and Miller, 1996), surface runoff (Bjorneberg et al., 2003; Shainberg et al., 1990), erosion (Bjorneberg et al., 2003; Flanagan et al., 2003; Krauth et al., 2008; Zhang and Miller, 1996), and off-site agrochemical transport (Krauth et al., 2008) have been reported. Factors affecting PAM efficacy in pivot irrigated environments include soil texture (Shainberg et al., 1990; Zhang and Miller, 1996), water quality (Flanagan et al., 2003), formulation (Flanagan et al., 2003), application rate (Bjorneberg et al., 2003; Flanagan et al., 2003; Krauth et al., 2008; Shainberg et al., 1990; Zhang and Miller, 1996), and number of subsequent applications (Bjorneberg et al., 2003; Shainberg et al., 1990).

Factors Evaluated at the Meso-Plot Scale under Pivot Irrigated Conditions

Water-soluble powder (Kay-Shoemake et al., 2000; Kornecki et al., 2005, Lentz and Sojka, 1994, 2009; Lentz et al., 1998, 2001, 2002; Mitchell, 1986; Sojka et al., 2003, 2006; Sojka and Entry, 2000), EC (Lentz and Sojka, 2009; Lentz et al., 1992, 1998), and WDG formulations (Entry and Sojka, 2003, Leib et al., 2005; Lentz and Bjorneberg, 2003; Sojka et al., 2006; Szogi et al., 2007) have been evaluated in furrow irrigated environments. These reports focused primarily on PAM effects on infiltration (Entry and Sojka, 2003; Lentz and Sojka, 1994, 2009; Lentz and Bjorneberg, 2003; Lentz et al., 1992, 1998, 2001, 2002; Mitchell 1986, Sojka et al., 2003, Sojka and Entry, 2000), surface runoff (Leib et al., 2005; Lentz and Bjorneberg, 2003; Lentz et al., 1998, 2001, Sojka et al., 2003), erosion (Entry and Sojka, 2003; Kornecki et al., 2005; Leib et al., 2005; Lentz and Bjorneberg, 2003; Lentz and Sojka, 2009; Lentz et al. 1992, 2001, 2002; Sojka and Entry, 2000; Sojka et al., 2003; Szogi et al., 2007), and off-site agrochemical transport (Entry and Sojka, 2003; Lentz et al., 1998, 2001; Lentz and Sojka, 1994; Sojka et al., 2006; Szogi et al. 2007). Factors potentially affecting PAM efficacy with regards to infiltration and agrochemical transport include soil organic matter content (Leib et al., 2005; Lentz and Bjorneberg, 2003), formulation (Lentz and Sojka, 2009; Sojka et al., 2006), application rate (Lentz et al., 1992, 1998, 2000, 2002; Lentz and Sojka, 1994; Mitchell, 1986; Sojka and Entry, 2000), and the number of subsequent PAM applications (Lentz and Bjorneberg, 2003; Lentz et al., 2002; Mitchell, 1986).

Factors Effecting PAM and Soil Infiltration Rates

Our review of the literature indicates that PAM effects on infiltration depends on delivery system, soil texture, formulation, application rate, and number of subsequent applications. Pooled over all parameters, PAM improves infiltration by 60% relative to the control (Figure 6; $P \leq 0.0001$). These data indicate that if PAM is applied as a soil amendment in the Mid-South, infiltration rates should be improved regardless of delivery system, soil texture, formulation, application rate, and number of subsequent applications. However, the box plot for "global" PAM effects on infiltration is skewed indicating that some of the evaluated factors may have a greater influence on PAM effectiveness than others.

Delivery System

The delivery system used to evaluate PAM effectiveness on soil infiltration contributes to the variance observed in the "global" infiltration results. Pooled over existing data, PAM effectiveness decreased in the order of rainfall simulator (95% of control) > pivot irrigated (58% of control) > furrow irrigated (12% of control) (P value $\leq$ 0.0001; Figure 7). Rainfall simulation data are from micro-plots where experimental error associated with "in-field" variability is more controlled than at the meso-plot and field scale. These simulation data are useful for they indicate the potential for PAM to improve soil infiltration relative to the control. The rainfall simulation results are in agreement with the meso-plot pivot data, which indicates PAM applied through pivots in Mid-South production systems should improve soil infiltration rates up to 58%. The least effective delivery system for improving soil infiltration rates in the Mid-South will be when PAM is applied through lay flat-polyethylene tubing. Results indicate, however, that when PAM is applied through lay-flat polyethylene tubing soil infiltration rates should be improved up to 12% relative to current practices.

Soil Texture

Analysis of existing data indicate soil texture and organic matter directly influences PAM effectiveness. Pooled over existing data, PAM effectiveness increased in the order of sandy loam (18% of control) < silt loam (58% of control) < clay (255% of control) ($P \leq 0.0001$; Figure 8). Additionally, infiltration improves as soil organic matter increases up to 8% ($R^2 = 0.9875$; Figure 9). Some variability in the global infiltration data set is attributed to soil texture and organic matter. Soil physio-chemical analysis indicates PAM is more effective on silt loam or finer textured soils, and the effect will increase as a function of soil organic matter up to 8%.

PAM Formulation

Polyacrylamide formulation directly influences PAM effectiveness. Pooled over existing data, PAM efficacy increased in the order of EC (-23% of control) = WDG (-20% of control) < WSP (79% of control) ($P \leq 0.0001$; Figure 10). Some variability in the global infiltration results is attributed to the EC and WDG data sets. This analysis indicates WSP formulations will have a high probability of success in the Mid-South. However, since n for EC and WDG formulations is 22 and 3, respectively, results for these formulations reported in the literature may not reflect their true potential in Mid-South agriculture. Future studies are required to adequately evaluate the effect of all PAM formulations.

PAM Application Rate

Polyacrylamide's effectiveness on infiltration is a function of application rate. Pooled over existing data, infiltration was negatively correlated with application rate ($P \leq 0.0001$; Figure 11). Maximum efficacy was observed at rates ranging from 1-3 mg L^{-1}. At rates > 10 mg L^{-1}, PAM can increase irrigation water viscosity, thereby reducing infiltration rates (Ajwa and Trout, 2006). As PAM is introduced into the Mid-South, rates of 1-3 mg L^{-1} should be applied until further rate response research is conducted to develop economically viable best management practices.

Number of Subsequent PAM Applications

Multiple PAM applications improve soil infiltration rates compared to a single application. Pooled over existing data, the mean improvement in infiltration for multiple vs single applications is 29% and -3%, respectively ($P = 0.0173$; Figure 12). Polyacrylamide effects on infiltration in the Mid-South will be enhanced if multiple applications are made throughout the growing season.

Factors Effecting PAM and Soil Erosion

Our review of the literature indicates that PAM effects on sediment transport depends on delivery system, application rate, and number of subsequent applications. Pooled over all parameters, PAM reduced sediment transport by 68% relative to the control ($P \leq 0.0001$; Figure 13). These data indicate that if PAM is applied as a soil amendment in the Mid-South, sediment transport should be decreased regardless of delivery system, application rate, or number of subsequent applications. However, the box plot for "global" PAM effects on sediment is skewed indicating that some of the evaluated factors may have a greater influence on PAM effectiveness than others.

Delivery System and Soil Texture

The delivery system used to evaluate PAM effectiveness on sediment transport does not contribute to the variance observed in the "global" sediment transport results. Pooled over existing data, PAM effectiveness for furrow and pivot delivery systems was 70% and 65%, respectively, and was not different at $P = 0.2261$ (Figure 14). One can infer from these data that PAM effects on erosion will be similar across the primary delivery systems in the Mid-South, i.e. pivot and furrow. However, PAM effectiveness for sediment transport in agricultural environments has been conducted only on silt loam (n=39) and gravelly clay loam textured soils (n=1). Silt loam textured soils account for approximately less than 20% of the Mid-South hectares in row crop production. Consequently, insufficient data for PAM effects on sediment transport from different soil textures is available for practitioners to make accurate recommendations for Mid-South production systems.

PAM Application Rate

Polyacrylamide effects on sediment transport does not vary between evaluated application rates. Pooled over existing data, sediment transport for PAM applied at 1-3 mg L^{-1} and 5-10 mg L^{-1} was 66% and 73%, respectively ($P \leq 0.2379$; Figure 15). Additionally, Orts et al. (2000) reported that PAM applied at 20 mg L^{-1} reduced off-site sediment transport by > 98%. Linear regression analysis indicates reductions in sediment transport are equivalent for PAM rates ranging from 1-3 mg L^{-1} and 5-10 mg L^{-1} ($P \leq 0.1806$). Polyacrylamide applied at 1-10 mg L^{-1} could reduce sediment transport in Mid-South production systems by 66% relative to current practices. Caution is advised, however, since these analyses were conducted only for silt loam (n=39) and gravelly clay loam textured soils (n=1).

Number of Subsequent PAM Applications

Off-site sediment transport was not different between single and multiple PAM application. Pooled over existing data, the mean reduction in sediment transport for single and multiple applications was 68.4% and 68.7%, respectively ($P = 0.9566$; Figure 16). These data indicate that both single and multiple PAM applications are effective to reduce sediment transport. However, the efficacy of a single PAM diminishes as a function of time elapsed after initial application (Petersen et al., 2007). This would suggest that to achieve maximum reductions in off-site sediment transport from irrigated crop production systems in the Mid-South multiple PAM applications are necessary.

Factors Effecting PAM and Agrochemical Transport

Published data indicate potential for PAM to reduce N and P transport in Mid-South production systems. Pooled over all parameters, PAM reduced N (n=3) and P (n=5) transport by 76% and 82%, respectively ($P \leq 0.0020$; Figure 17). Reductions in N and P transport with PAM were positively correlated with reductions in sediment transport (Figure 19). These data indicate that when PAM decreases off-site sediment transport in Mid-South agricultural settings, N and P transport will be reduced. Analysis of the N and P transport data is only from silt loam textured soils and WDG PAM formulations. As such, additional research is required to ascertain PAM effects on agrochemical transport across delivery systems, soil textures, PAM formulations, application rates and number of subsequent applications.

Factors Effecting PAM and Crop Yield

Polyacrylamide may improve crop yield in Mid-South production systems when applied to silt loam, silty clay loam, and clay loam textured soils. Pooled over all parameters, PAM improved corn, cotton, and soybean yield by 9.4% (Figure 20; $P = 0.0020$). Positive yield response with PAM always occurred on soils with a tendency to form surface crusts. There is potential, therefore, for PAM to improve crop yield in Mid-South production systems when applied to soil textures prone to sealing. Future research with PAM in the Mid-South should be conducted on an array of soil textures and production systems to confirm yield response.

Conclusions

The objectives of this article were to identify on which soil textures agricultural research with PAM has occurred nationally; denote the PAM formulations, rates, and application methods evaluated in agricultural settings; determine the research methods employed for evaluating PAM effects on infiltration, erosion, and agrochemical transport; ascertain the parameters influencing PAM efficacy in regards to infiltration, erosion and off-site agrochemical transport, and; quantify the effect of PAM on crop yield. Pooled over all evaluated parameters, PAM improved infiltration by 60%, decreased off-site sediment and agrochemical transport by 68%, and improve crop yield by 9.4%. PAM effectiveness on a given parameter is dependent on a number of variables. For example, cationic and non-ionic PAM formulations exist, but only anionic PAM formulated as emulsifiable concentrate, water soluble powder, and water dispersed granule have been evaluated in agricultural settings. Of these formulations, PAM effects on infiltration decreased in the order of water soluble powder (79%) > water dispersed granule (-20%) = emulsifiable concentrate (-23%). Formulation effects on erosion are reported only for water soluble formulations on silt loam soils. Polyacrylamide formulation effects on infiltration and erosion indicate greater opportunity for success in the Mid-South if water soluble powder is applied. Polyacrylamide effects on infiltration were greater for pivot (58% improvement) than furrow irrigation delivery systems (12% improvement); conversely, regardless of delivery system, PAM reduced erosion by at least 60%. Multiple in-season applications of PAM at a rate of 1-3 mg L^{-1} delivered through a pivot has the greatest potential to improve infiltration, reduce erosion, and mitigate N and P transport in Mid-South production systems. Polyacrylamides applied to soil textures prone to crusting may improve crop yield in the Mid-South by 9.4%. However, for erosion, agrochemical transport, and crop yield there is a paucity of data for practitioners to make economically viable best management practice recommendations for the use of PAM in Mid-South production systems.

Table 1.1 Summary of research to date on PAM's in agriculture by state, soil, and evaluation method.

State	Soil	Evaluation	Source
AR	Mhoon silt loam	Pivot	Krauth et al., 2008
AR	Dundee silt loam	Pivot	Krauth et al., 2008
CA	Hanford sandy loam	Lab	Ajwa and Trout, 2006
CA	Silty clay	Furrow	Goodson et al., 2006
CA	Silty clay loam	Furrow	Goodson et al., 2006
CA	Hanford sandy loam	Lab	Lu and Wu, 2003
CA	Imperial silty clay	Lab	Lu and Wu, 2003
CA	Linne clay loam	Lab	Lu et al., 2002
CA	Imperial silty clay	Lab	Lu et al., 2002
CA	Imperial silt loam	Lab	Lu et al., 2002
CA	Palouse silt loam	Lab	Lu et al., 2002
CA	Arlington loamy sand	Lab	Lu et al., 2002
CA	Hanford sand	Lab	Lu et al., 2002
CA	Silty clay loam	Furrow	Mitchell 1986
CA	Zacharias gravelly clay loam	Lab	Orts and Glenn, 1999
GA	Cecil sandy loam	Lab	Green et al., 2000
GA	Cecil sandy loam	Lab	Green et al., 2004
GA	Cecil B Clay	Lab	Reichart et al., 2009
GA	Cecil Bt Clay	Lab	Reichart et al., 2009
GA	Cecil	Furrow	Zhang and Miller, 1996
ID	Rad silt loam	Lab	Aase et al., 1998
ID	Rad silt loam	Pivot	Bjorneberg and Aase, 2000
ID	Portneuf silt loam	Pivot	Bjorneberg et al., 2003
ID	Portneuf silt loam	Furrow	Entry and Sojka, 2003
ID	Portneuf silt loam	Furrow	Kay-Shoemake et al., 2000
ID	Portneuf silt loam	Lab	Kay-Shoemake et al., 2000
ID	Portneuf silt loam	Furrow	Lentz and Bjorneberg, 2003
ID	Silt loam	Furrow	Lentz and Sojka, 1994
ID	Portneuf silt loam	Furrow	Lentz and Sojka, 2002

Table 1.1 (continued)

ID	Portneuf silt loam	Furrow	Lentz et al., 1992
ID	Portneuf silt loam	Furrow	Lentz et al., 1998a
ID	Portneuf silt loam	Furrow	Lentz et al., 1998b
ID	Portneuf silt loam	Furrow	Lentz et al., 2001
ID	Portneuf silt loam	Furrow	Orts et al., 2001
ID	Portneuf silt loam	Furrow	Sojka and Entry, 2000
ID	Portneuf silt loam	Furrow	Sojka et al., 2006
IL	Portneuf silt loam	Furrow	Sojka et al., 1998
IN	Catlin silt loam	Lab	Dontson and Norton, 2002
IN	Miami silt loam	Lab	Dontsova and Norton, 2002
IN	Throckmorton silt loam	Lab	Norton et al., 2006
IN	Russel silt loam	Pivot	Flanagan et al. 2003
IN	Fincastle silt loam	Lab	Green et al., 2000
IN	Fincastle silt loam	Lab	Green et al., 2004
IA	Fayette silty clay loam	Lab	Dontsova and Norton, 2002
LA	Commerce silt loam	Furrow	Kornecki et al., 2005
NC	Cecil silt loam	Lab	Mclaughlin and Brown, 2006
OH	Blount loam	Lab	Dontsova and Norton, 2002
OH	Hoytville clay	Lab	Reichart et al., 2009
SC	Norfolk loamy sand	Lab	Caesar-TonThat et al., 2008
TX	Victoria	Lab	Gardiner and Sun, 2002
TX	Willacy	Lab	Gardiner and Sun, 2002
TX	Heiden clay	Lab	Green et al., 2000
TX	Heiden clay	Lab	Green et al., 2004
UT	Timpanogos clay loam	Pivot	Terry and Nelson, 1986
WA	Shano silt loam	Furrow	Leib et al., 2005
WA	Warden very fine sandy loam	Furrow	Leib et al., 2005
WA	Esquatzel fine sandy loam	Furrow	Szogi et al., 2007
WA	Warden very fine sandy loam	Furrow	Szogi et al., 2007
WI	Plano silt loam	Lab	Lepore et al., 2009

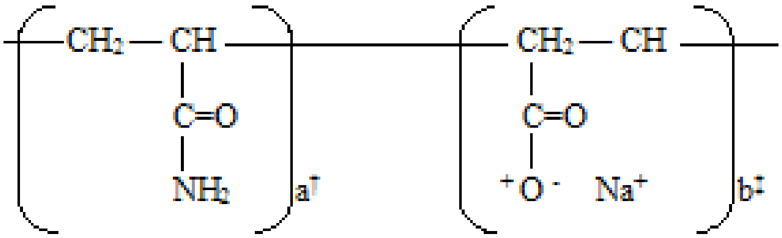

Figure 1.1 Chemical Structure of anionic polyacrylamide.

McGuire et al. 2006.
[†] Acrylamide monomer.
[‡] Anionic acrylic acid monomer.
$a^{\dagger}:b^{\ddagger} = 3:1$.

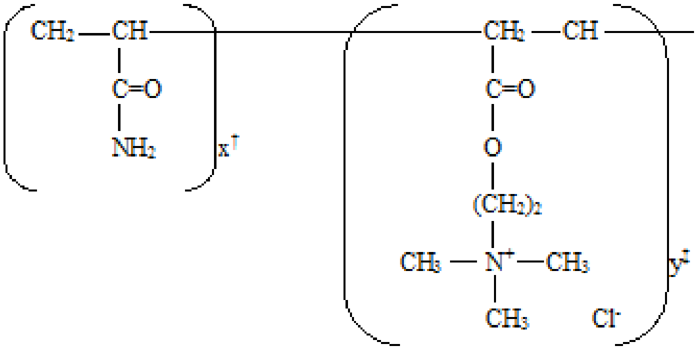

Figure 1.2 Chemical Structure of cationic polyacrylamide.

Laird, 1997.
[†]Acrylamide monomer.
[‡]Acryloxyethyltrimethyl ammonium chloride (DAC) monomer.

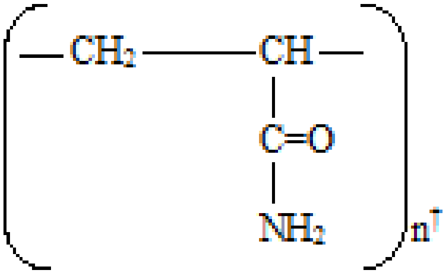

Figure 1.3 Chemical structure of a nonionic polyacrylamide homopolymer.

McGuire et al. 2006.
[†]Non-ionic polyacrylamide homopolymer.

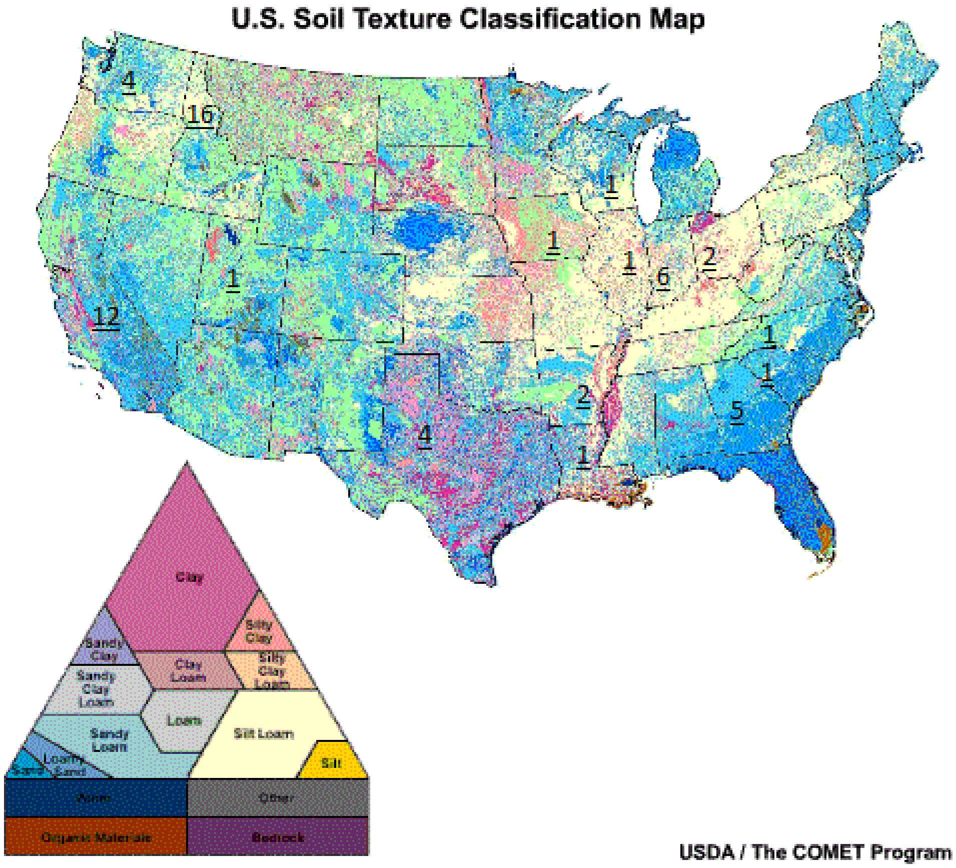

Figure 1.4 Map of the distribution of cumulative PAM research in agricultural environments by state.

[1] Refer to Table 1 for citations.
[2] Numbers represent the total number of PAM studies in agriculture to date for each state.
[3] Dominant soil textures are represented in each state.

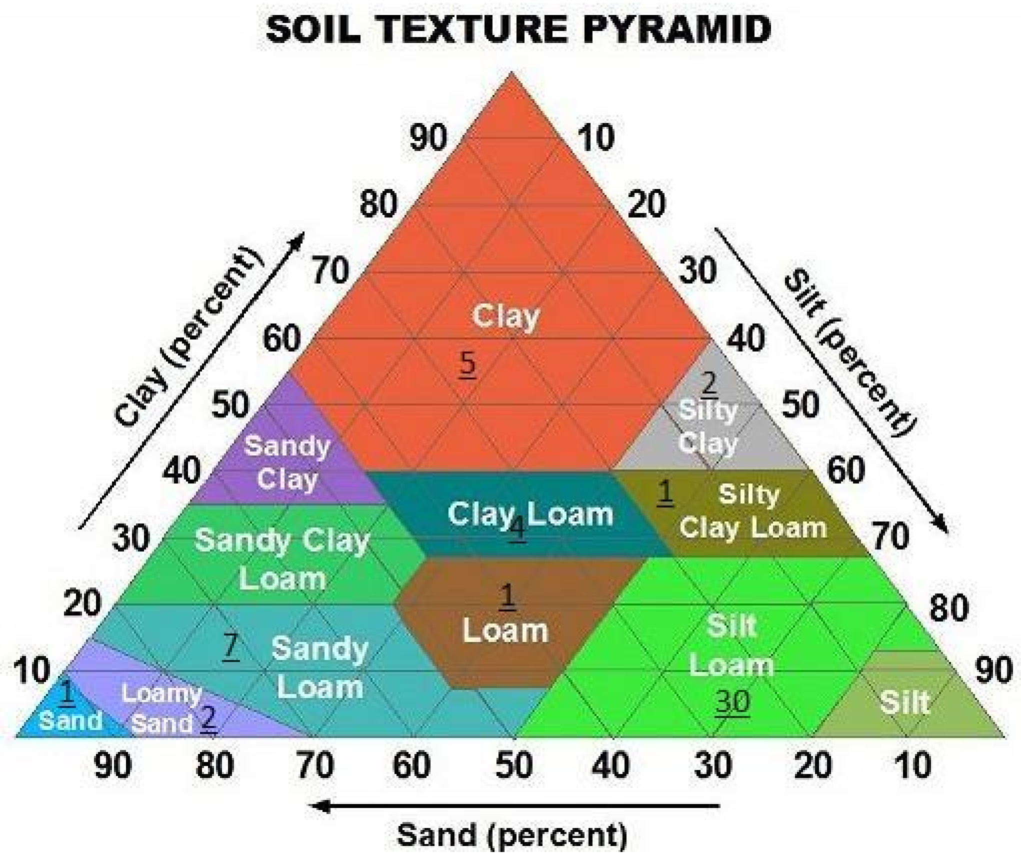

Figure 1.5 Distribution of PAM research by soil textural class.

[1] Refer to Table 1 for citations

[2] Figure represents the total number of PAM studies in the literature by soil texture

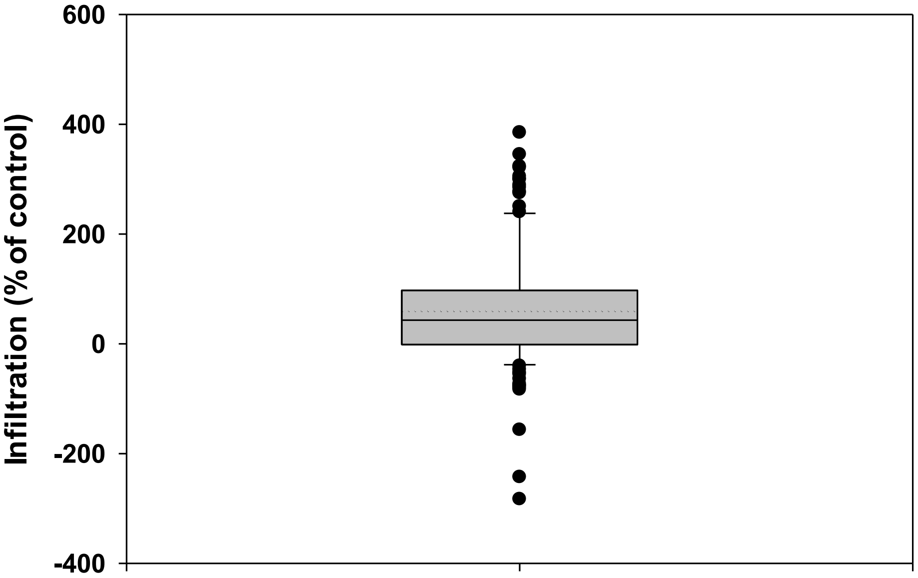

Figure 1.6 Box and whisker plot for PAM effects on infiltration† normalized to the control.

†n=135

[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.

[2] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.

[3] Analysis of variance indicates that pooled over all literature PAM improved infiltration by 60% ($P \leq 0.0001$).

[4] Ajwa and Trout, 2006; Bjorneberg et al., 2003; Entry and Sojka, 2003; Green et al., 2000; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2001.

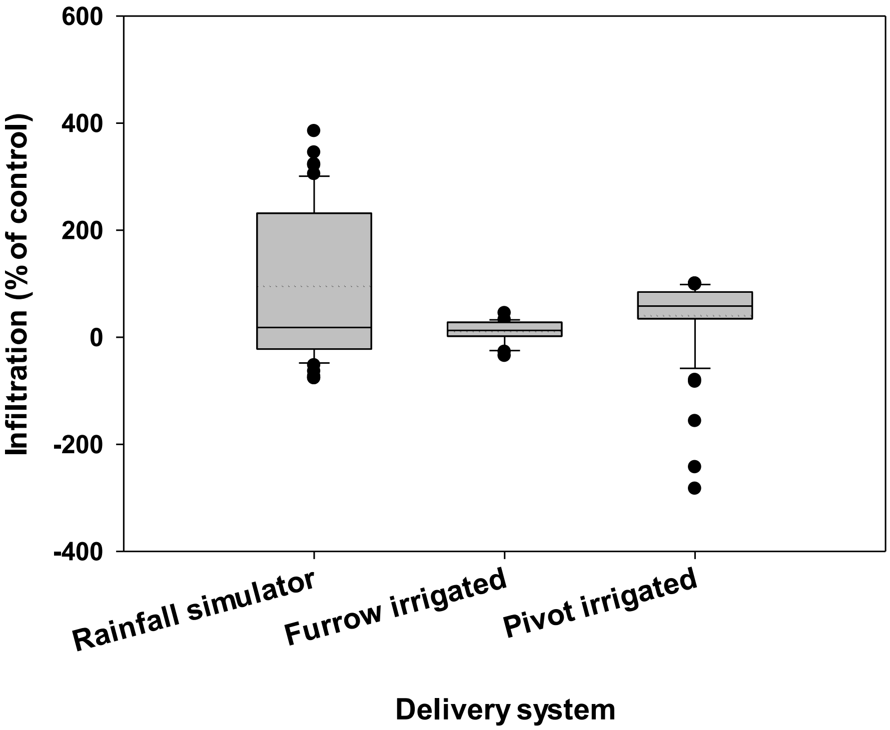

Figure 1.7 Box and whisker plots for PAM effects on infiltration for rainfall simulator[†], furrow irrigated[‡], and pivot irrigated[§] delivery systems normalized to the control.

[†] n=57
[‡] n=20
[§] n=58
[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3] Analysis of variance indicates PAM effects on infiltration decrease in the order of rainfall simulator > pivot irrigated > furrow irrigated ($P \leq 0.0001$).
[4] Ajwa and Trout, 2006; Bjorneberg et al., 2003; Green et al., 2000; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2002.

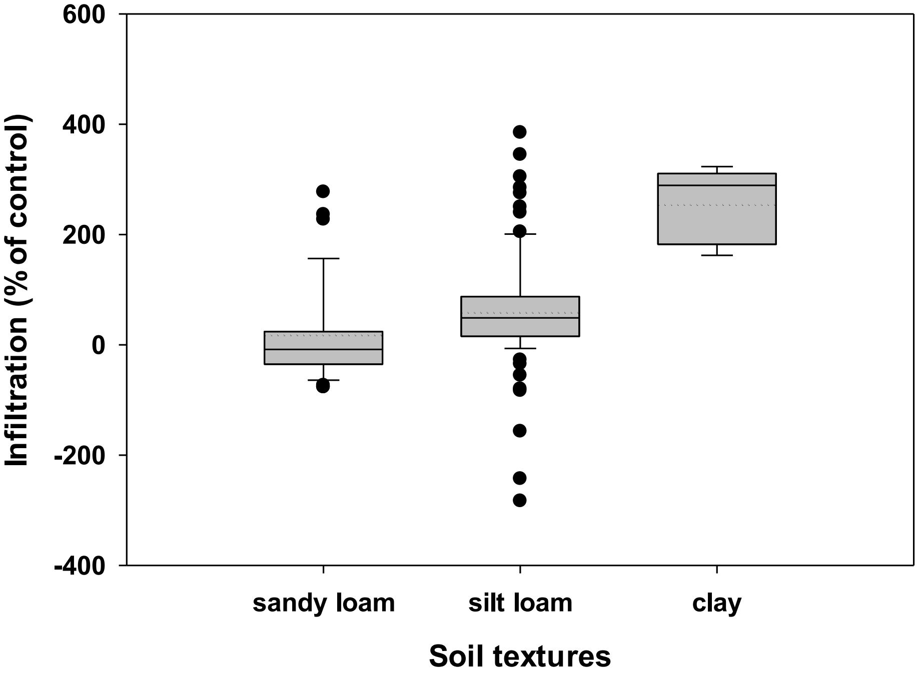

Figure 1.8 Box and whisker plots for PAM effects on infiltration for sandy loam[†], silt loam[‡], and clay[§] textured soils normalized to the control.

[†] n=39
[‡] n=85
[§] n=9
[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3] Analysis of variance indicates PAM effects on infiltration decrease in the order of sandy loam < silt loam < clay ($P \leq 0.0001$).
[4] Ajwa and Trout, 2006; Bjorneberg et al., 2003; Entry and Sojka, 2003; Green et al., 2000; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2002.

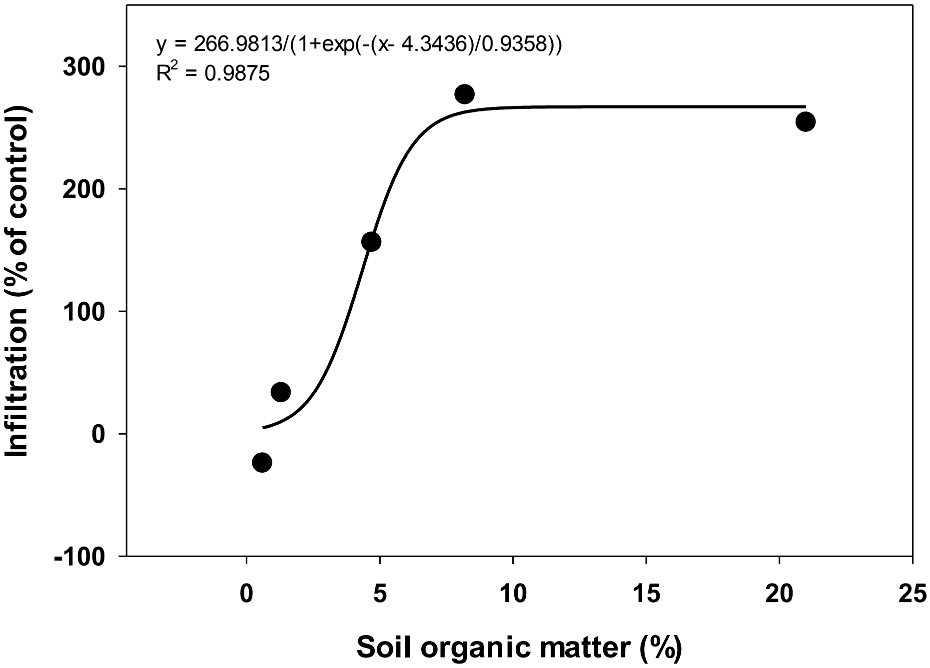

Figure 1.9 Correlation analysis for PAM effects on infiltration as influenced by soil organic matter content pooled over all reviewed literature.

[1] Analysis show PAM effects on infiltration to be directly correlated ($R^2 = 0.9875$) to soil organic matter (n=137) up to approximately 8%.

[2] Ajwa and Trout, 2006; Bjorneberg et al., 2003; Entry and Sojka, 2003; Green et al., 2000; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2000, 2001, 2002; Orts et al., 2000; Szogi et al., 2007.

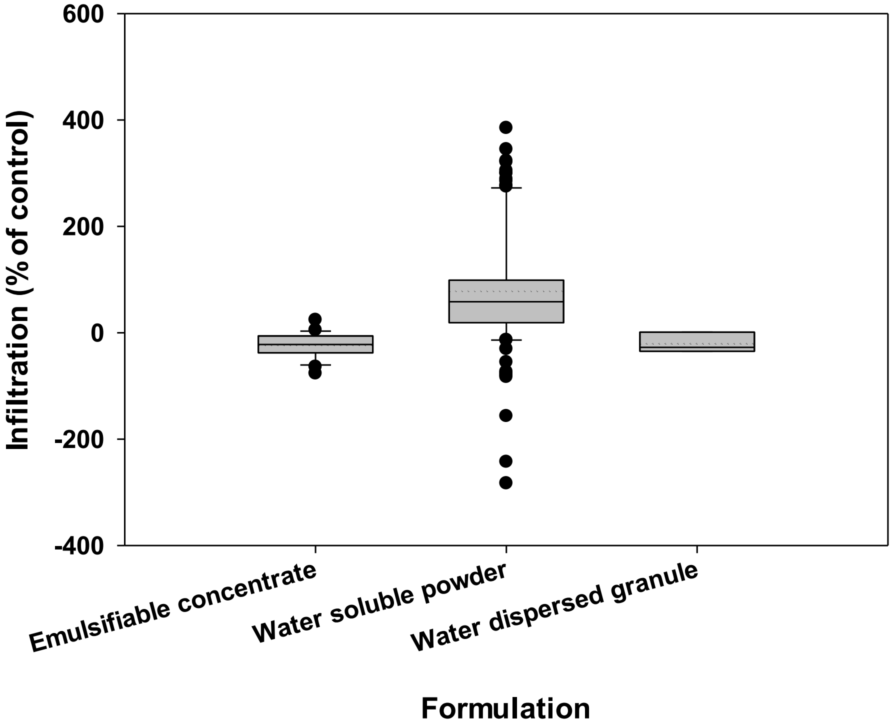

Figure 1.10 Box and whisker plots for PAM formulation effects on infiltration for emulsifiable concentrate[†], water soluble powder[‡], and water dispersed granule[§] normalized to the control.

[†] n=23
[‡] n=110
[§] n=3
[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3] Analysis of variance indicates PAM formulation effects on infiltration decrease in the order of emulsifiable concentrate = water dispersed granule < water soluble powder ($P \leq 0.0001$).
[4] Ajwa and Trout, 2006; Bjorneberg et al., 2003; Green et al., 2000; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2002.

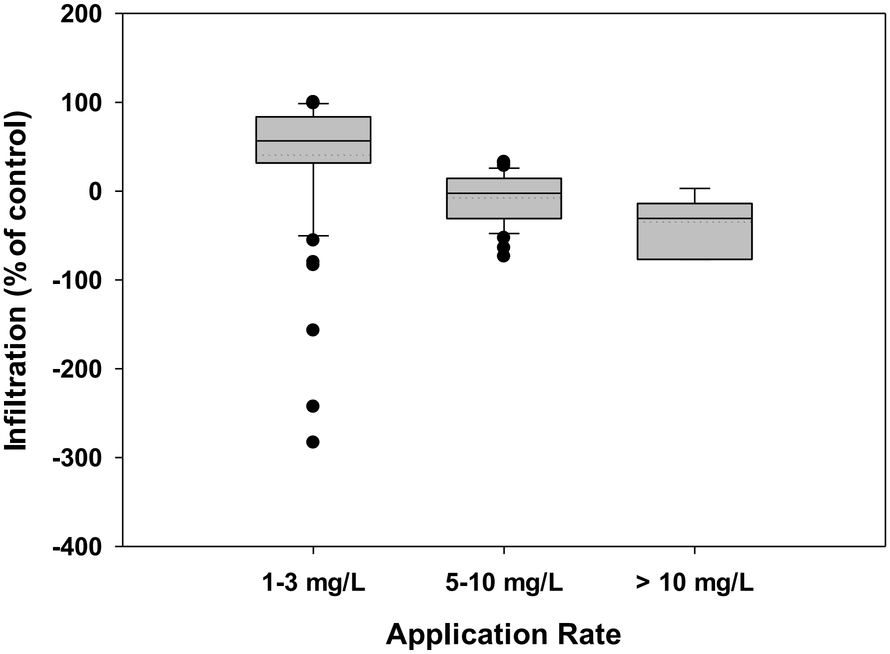

Figure 1.11 Box and whisker plots for PAM application rate effects on infiltration for 1-3 mg $L^{-1\dagger}$, 5-10 mg $L^{-1\ddagger}$, and >10 mg $L^{-1\S}$ normalized to the control.

[†] n=60
[‡] n=38
[§] n=7
[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3] Analysis of variance indicates PAM application rate effects on infiltration increased in the order of > 10 mg L^{-1} < 5-10 mg L^{-1} < 1-3 mg L^{-1} ($P \leq 0.0001$).
[4] Ajwa and Trout, 2006; Bjorneberg et al., 2003; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2002.

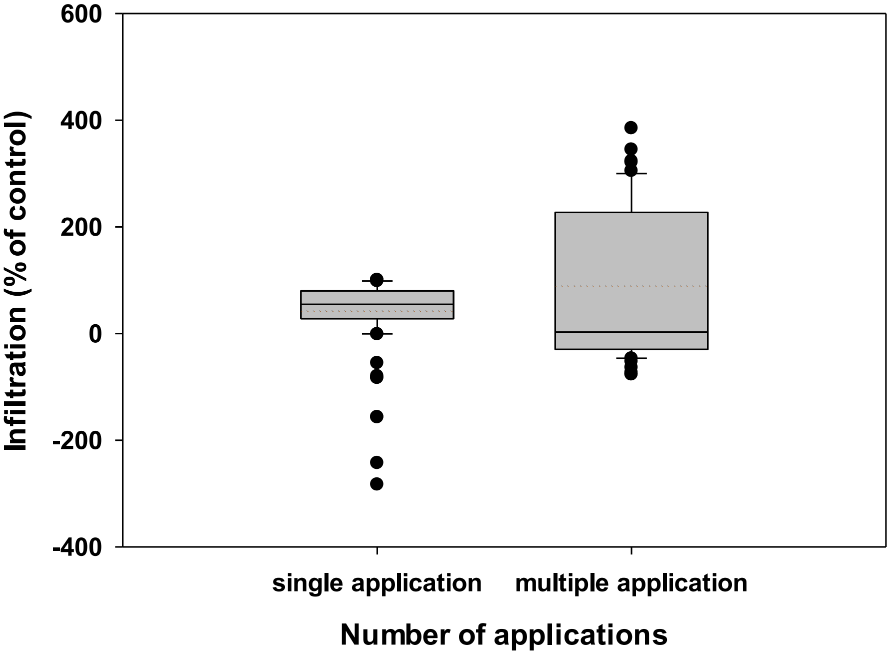

Figure 1.12 Box and whisker plots for number of PAM applications, 1† application vs multiple‡ applications normalized to the control.

†n=62
‡n=43
[1]Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2]Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3]Analysis of variance indicates multiple PAM applications improve infiltration rates (P = 0.0173).
[4]Ajwa and Trout, 2006; Bjorneberg et al., 2003; Entry and Sojka, 2003; Green et al., 2000; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2002; Orts et al., 2000.

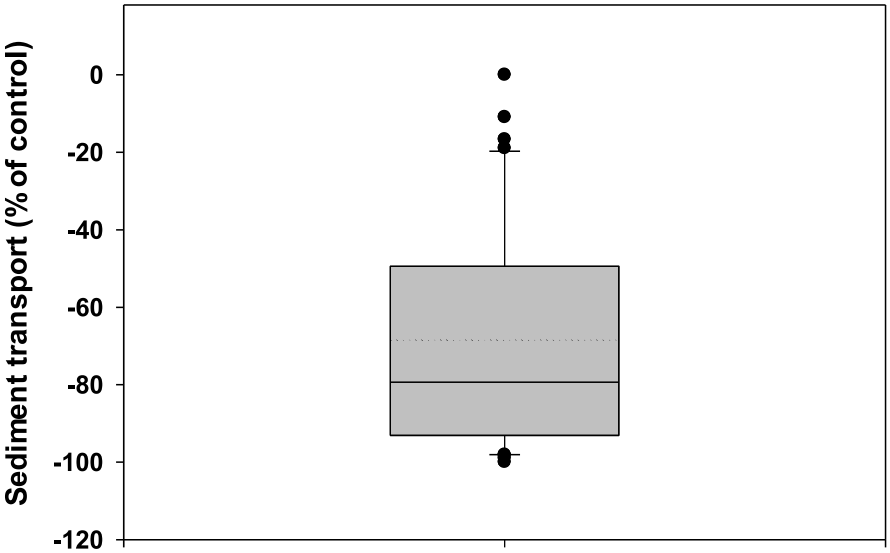

Figure 1.13 Box and whisker plot for PAM effects on sediment transport† normalized to the control.

†n=40

[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.

[2] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.

[3] Analysis of variance indicates that pooled over all literature PAM reduced sediment transport by 68% ($P \leq 0.0001$).

[4] Bjorneberg et al., 2003; Entry and Sojka, 2003; Lentz and Sojka, 1994; Lentz et al., 1992; 1998; 2002; Orts et al., 2000).

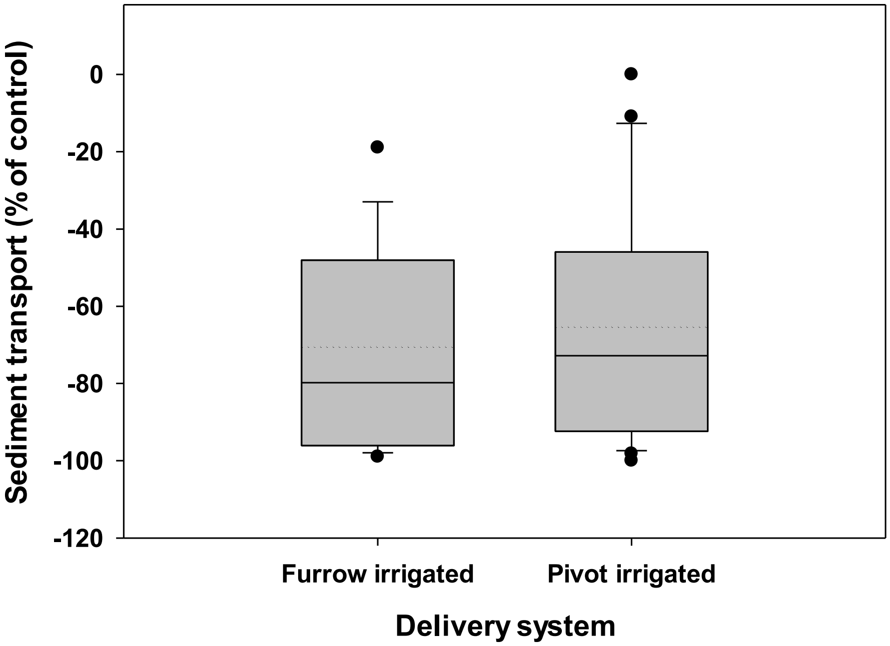

Figure 1.14 Box and whisker plots for PAM effects on sediment transport for furrow† and pivot‡ irrigated systems normalized to the control.

†n=17
‡n=22
[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3] Analysis of variance indicates PAM effectiveness on sediment transport is not different between delivery systems ($P = 0.2261$).
[4] Bjorneberg et al., 2003; Entry and Sojka, 2003; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2002.

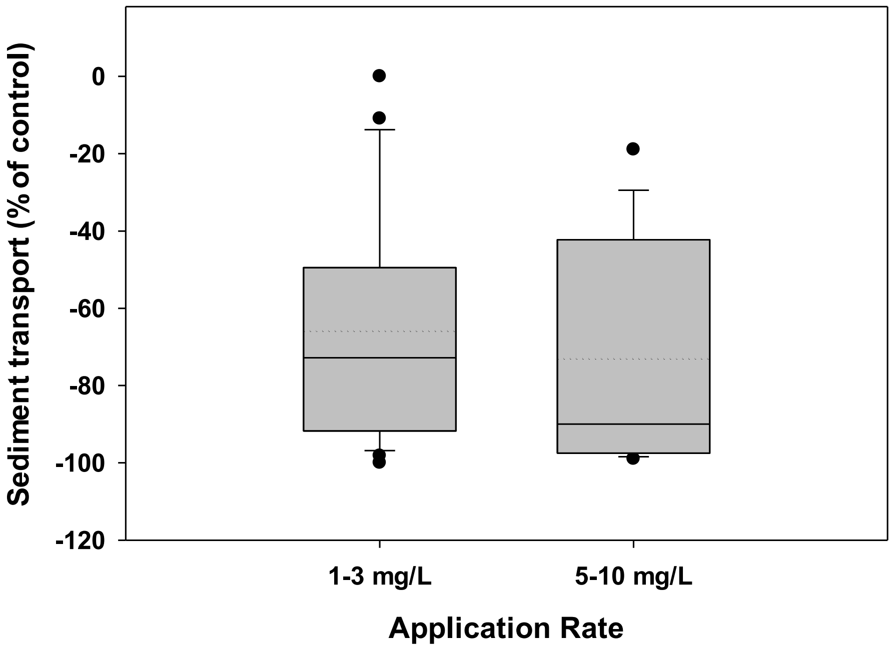

Figure 1.15 Box and whisker plots for PAM application rate effects on sediment transport for 1-3 mg $L^{-1\dagger}$ and 5-10 mg $L^{-1\ddagger}$ normalized to the control.

†n=24
‡n=15
[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3] Analysis of variance indicates PAM effectiveness on sediment transport is not different between rates ($P \leq 0.2379$).
[4] Bjorneberg et al., 2003; Entry and Sojka, 2003; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2002; Orts et al., 2000.

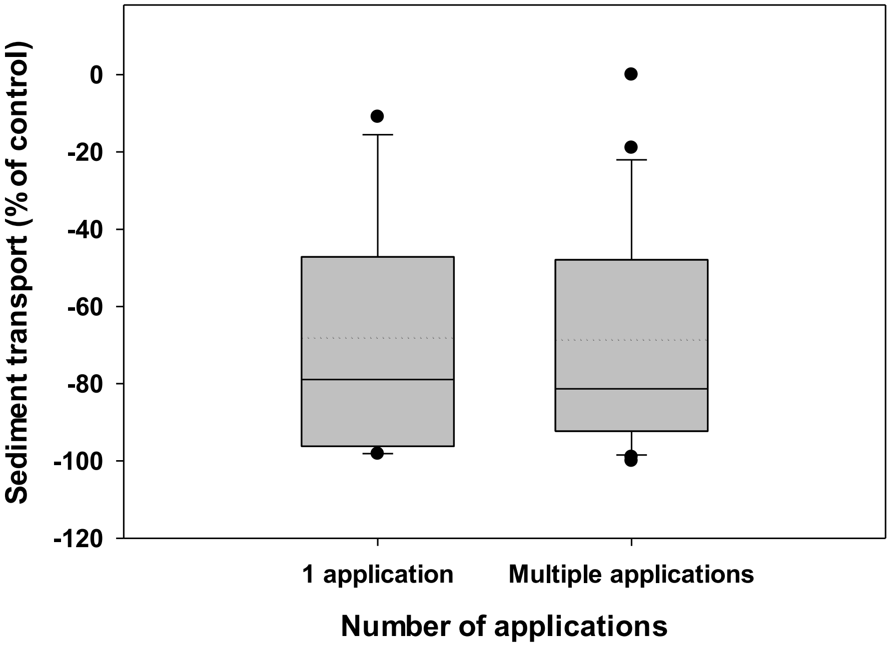

Figure 1.16 Box and whisker plots for number of PAM applications, 1† application vs multiple‡ applications normalized to the control.

†n=17
‡n=23
[1] Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[3] Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3] Analysis of variance indicates PAM effectiveness on sediment transport does not decrease with multiple applications (P = 0.9566).
[4] Bjorneberg et al., 2003; Entry and Sojka, 2003; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2002; Orts et al., 2000.

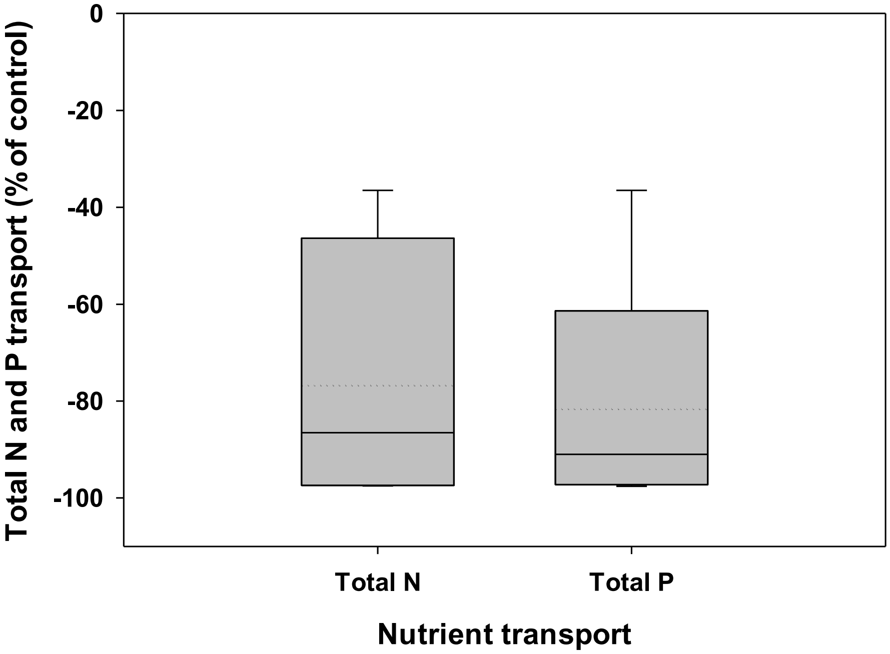

Figure 1.17 Box and whisker plots for PAM effects on total N† and total P‡ transport normalized to the control.

†n=3
‡n=5
[1]Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2]Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3]Analysis of variance indicates that pooled over all literature PAM reduced total N and total P transport by 76% and 82%, respectively % ($P \leq 00020.$).
[4]Entry and Sojka, 2003; Lentz et al., 1998, Szogi et al., 2007.

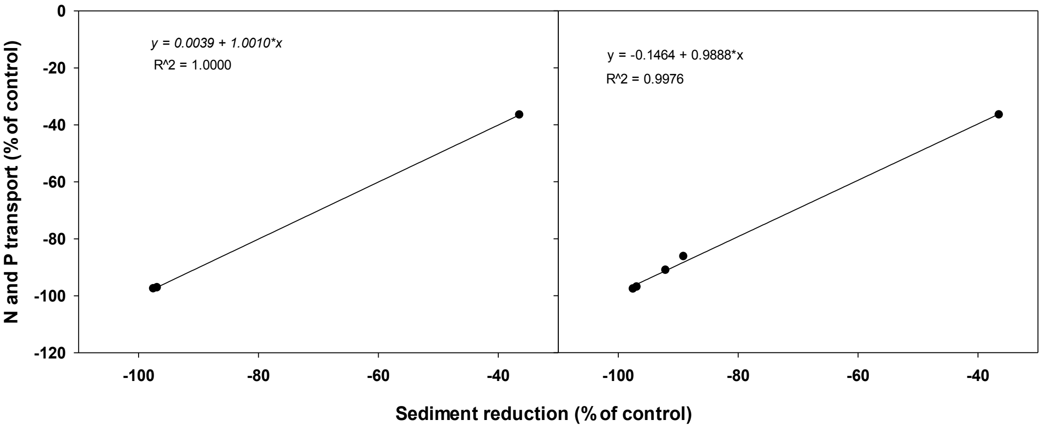

Figure 1.18 Correlation analyses for PAM effects on N and P transport to sediment transport pooled over all reviewed literature

[1]Regression analyses indicate PAM effects on N (n=3) and P (n=5) transport are directly correlated (R^2 = 1.0000 and 0.9976, respectively) to PAM effects on sediment transport.
[2]Entry and Sojka, 2003; Lentz et al., 1998, Szogi et al., 2007.

Figure 1.19 Box and whisker plots for PAM effects on corn, cotton, and soybean yield† normalized to the control.

†n=5
[1]Boundary of the box closest to zero indicates the 25th percentile, a solid line within the box marks the median, a dotted line within the box delineates the mean, and the boundary of the box furthest from zero indicates the 75th percentile.
[2]Error bars above and below the box indicate the 90th and 10th percentile, respectively, and solid dots indicate outliers.
[3]Analysis of variance indicates that pooled over all literature PAM increased crop yield by at least 9.4% ($P \leq 00020.$).
[4]Lentz and Sojka, 2009; Levy et al., 1991; McNeal et al., 2016.

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CHAPTER II

POLYACRYLAMIDE EFFECTS ON SURFACE RUNOFF, INFILTRATION, SEDIMENT TRANSPORT, AND CORN GRAIN YIELD

Abstract

Polyacrylamides (PAMs) are water soluble, long chain synthetic organic polymers that, when applied as a soil amendment, purportedly reduce surface runoff, improve infiltration, and decrease erosion. There is a paucity of data, however, on the effect of PAM applied through lay-flat polyethylene tubing on surface runoff, infiltration, sediment transport, and crop yield for Mid-South soils in furrow irrigated environments. The objective of this study was to assess PAM effects on surface runoff, infiltration, sediment transport and corn grain yield on a Dundee silt loam and a Forestdale silty clay loam soil located in Stoneville and Tribbett, Mississippi, respectively. Each irrigation event delivered 41.5 ha mm at 18.9 L m^{-1} per furrow and runoff was captured in a holding tank on the lower end of each plot. Cumulative runoff was determined by recording water level in the holding tank at 60-s intervals. The initial liter of runoff as well as those at 5, 10, 20, 30 and 40-min intervals were captured in 1-L Nalgene® bottles and stored on prior to analysis. Cumulative infiltration was calculated by the difference between rainfall and runoff (irrigation – runoff) and cumulative sediment transport was determined by multiplying the cumulative runoff value by the average sediment concentration from the 6 water samples collected after runoff inception. For infiltration, the treatment main effect was significant (P = 0.0020). Pooled over year and location, PAM reduced surface runoff and increased infiltration by at least 6%. For total solids, the year x site x treatment interaction was significant (P = 0.0024). PAM had no effect on the transport of total solids in 2014. Conversely, in 2015, PAM reduced the transport of total solids on the Forestdale silty clay loam by 78%, but PAM did not affect the transport of total solids on the Dundee silt loam. For corn grain yield, the treatment main effect was significant (P = 0.0398). Pooled over year and location, PAM increased corn grain yield by 7% relative to the control. These data indicate that PAM applied at 10 mg L^{-1} through lay-flat polyethylene tubing can improve infiltration and corn grain yield on silt loam and silty clay loam textured soils. The effect of PAM on erosion, however, will be site specific, and further study is required to make recommendations for PAM as an erosion control amendment in furrow irrigated environments.

Introduction

Water levels in the Mississippi Alluvial River Valley Aquifer (MARVA) have declined precipitously over the last 40 years. Aquifer decline is primarily due to an increased number of irrigated hectares for row-crop production and intensification of water withdrawals to meet demand for higher crop yields. Depletion of the MARVA was first documented in 1927 (Engler et al., 1963). In Arkansas County, Arkansas, withdrawals increased from 503,459 m3 per day in 1965 to 2.1 million m3 per day in 2000, a 396% increase (Halberg and Stephens, 1966; T.W. Holland, U.S. Geological Survey, written communication 2002). In the Mississippi Delta, approximately 80% of row-crop hectares are furrow irrigated (Dr. L. Jason Krutz, personal communication 2015).

In the mid-southern United States, surface (furrow), sprinkler (pivot), and subsurface drip irrigation are the three primary application methods utilized. Irrigation application efficiencies vary primarily as a function of delivery system: 30, 70, and 88% for furrow, pivot and subsurface drip, respectively (Howell, 2003). Agriculture is the largest user of water in the United States, withdrawing approximately 5.2 million m3 per day as of the year 2000, with furrow and pivot irrigated systems accounting for > 93% of irrigated hectares (Hutson et al., 2004). Consequently, a means to improve furrow irrigation application efficiency in the mid-southern United States is required.

Polyacrylamides are water-soluble, synthetic organic polymers that when applied as a soil amendment improve aggregate stability (Caesar-TonThat et al., 2008; Green et al., 2004; Laird, 1997; Mamedov, 2010), soil infiltration (Aase et al., 1998; Ajwa and Trout, 2006; Ben-Hur et al., 1992; Bjorneberg and Aase, 2000; Bjorneberg et al., 2003; Entry and Sojka, 2003; Entry et al., 2002; Gardiner and Sun, 2002; Green et al., 2000; Leib et al., 2005; Lentz and Bjorneberg, 2003; Lentz and Sojka, 1994; Lentz et al., 1992, 1998, 2001, 2002; Mitchell, 1986; Shainberg et al., 1990; Sojka and Entry, 2000; Sojka et al., 1998, 2003; Terry and Nelson, 1986; Zhang and Miller, 1996), and reduce sediment transport (Aase et al., 1998; Ben-Hur et al., 1992; Bjorneberg and Aase, 2000; Entry and Sojka, 2003; Entry et al., 2002; Flanagan et al., 2003; Kornecki et al., 2005; Lentz and Bjorneberg, 2003; Lentz and Sojka, 1994; Leib et al., 2005; Lentz et al., 1992; 1998; 2001; 2002; Lu and Wu, 2003; McLaughlin and Brown, 2006; Orts and Glenn, 1999; Orts et al., 2001; Shrestha et al., 2006; Sojka and Entry, 2000; Sojka et al., 2003; Szogi et al., 2007; Zhang and Miller, 1996).

To date, 72% of PAM research in irrigated agriculture is from regions, soils, and production systems west of the Mississippi River. As such, there is a lack of data evaluating PAM effects when applied through lay-flat polyethylene tubing on infiltration, sediment transport and yield for Mid-South soils. This lack of information is exacerbated when vast differences in cultural practices among agricultural regions of the United States are considered. The objective of this experiment was to evaluate the effect of PAM applied at 10 mg L^{-1} through lay-flat polyethylene tubing on surface runoff, infiltration, sediment transport and corn grain yield on silt loam and silty clay loam soils.

Materials and Methods

A two-year field study was conducted at the Mississippi State Delta Research and Extension Center, in Stoneville, Mississippi, USA. Experiments were conducted on a Dundee silt loam (fine-silty, mixed, active, thermic Typic Endoaqualfs), with a soil pH of 6.3, 0.95% organic matter, CEC of 11.64 meq/100 g, and 120 kg and 443 kg of P and K ha^{-1}, respectively; and a Forestdale silty clay loam (fine, smectitic, thermic Typic Endoqualfs), with a soil pH of 5.8, 1.04% organic matter, CEC of 14.92 meq/100 g, and 39 kg and 420 kg of P and K ha^{-1}, respectively. Both sites were precision graded to a 2% slope. Raised beds spaced 100-cm apart from the center were formed with disk hippers. Plot dimensions were 7.62 m x 4.06 m. Prior to planting, raised beds were smoothed with a reel and harrow row conditioner, and corn (*Zea mays,* L. 'Pioneer 1498YHR') was planted at 79073 seed ha^{-1}. Both the Dundee silt loam and the Forestdale silty clay loam were treated with 272 kg N ha^{-1} as UAN (32-0-0), applied in a split application, with 137 kg N ha^{-1} being applied after seedling emergence and 135 kg N ha^{-1} applied at the V8 growth stage. On both soil textures the experimental design was a randomized complete block with four replications of each treatment. Treatments included irrigated plus no PAM (control), and irrigated with PAM at a rate of 10 mg L^{-1}, 10.3 kg ha^{-1}. The polyacrylamide product, HM1113, is a 30% active ingredient emulsified concentrate (EC) formulation from Helena Chemical Company (Collierville, Tennessee).

Separate nurse tanks were used for treated (PAM) and untreated (water only) irrigation simulations to avoid cross contamination. A 10-cm diameter schedule 40 PVC pipe delivered irrigation water to experimental units. An EC PAM formulation at 10 mg L^{-1} was applied at a rate of 10.3 kg ha^{-1}. Irrigation flow rates were calibrated to deliver 41.5 ha mm at 18.9 L min^{-1} per furrow, and irrigation were delivered when soil moisture content reached at least a 20.6 ha mm deficit as determined by FAO-56 (Allen et al., 1998). Surface runoff was captured in a holding tank positioned on the down-slope end of the plot. Runoff volume was determined by recording the water height in the tank at 60-second intervals. Cumulative infiltration was calculated by the difference between rainfall and runoff (irrigation – runoff) and cumulative sediment transport was determined by multiplying the cumulative runoff value by the average sediment concentration in runoff. Corn grain yield was determined by harvesting the middle two rows of each plot, and moisture content was corrected to 150 g kg^{-1} H_2O.

The initial liter of runoff and those obtained at 5, 10, 20, 30, and 40 min after runoff inception was collected in 1-L Nalgene® bottles. Bottles were sealed with Teflon® screw caps and immediately placed on prior to analysis. Runoff samples were analyzed in accordance with procedures developed from the American Public Health Association, as similar to those described by Locke et al., (2015). Physical analyses of runoff samples included total solids (TS) and total dissolved solids (DS), that is, all non-aggregated fine solids < 0.45 mm (APHA 1997a, 1997d). To determine TS, 100 mL of well-shaken runoff sample was measured into a tared evaporating dish, and the sample weight was recorded after drying for 48 h at 105°C. Dissolved solids were determined by passing a 100-mL sample through a 0.45-mm glass fiber filter, and the filtrate residue weight measured after oven-drying for 24 h at 105°C. Total suspended solids (SS; solids > 0.45 mm) were calculated by determining the difference between TS and DS.

Cumulative runoff, infiltration, sediment loss and corn grain yield were analyzed as a split-split plot using the Mixed Procedure (SAS version 9.4, SAS Institute Inc., Cary, North Carolina). Year, soil texture, and PAM treatment were considered fixed effects, with year as the whole plot, soil texture as the sub-plot, and PAM treatment as the sub-sub plot. Random effects were replication and interactions among replication and the fixed effects. Least square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS, a macro for converting mean separation output to letter groupings (Saxton, 1998).

Results and Discussion

Surface Runoff and Infiltration

Polyacrylamide applied at 10 mg L^{-1} in furrow via lay-flat polyethylene tubing reduced cumulative runoff and improved infiltration rates on both the silt loam and silty clay loam soil. Treatment main effect was significant for both runoff and infiltration ($P = 0.0020$). Pooled over year and location, PAM reduced runoff and increased infiltration by at least 6% (Table 2.1). Similarly, PAM applied in-furrow improved infiltration and reduced surface runoff on Heiden clay, Cecil sandy loam and Fincastle silt loam by 323%, 277% and 385%, respectively (Green et al., 2000). Additionally, PAM applied at

10 mg L^{-1} in furrow reduced surface runoff and improved infiltration on silt loam soils by at least 2% (Lentz et al., 1992), 10% (Lentz et al., 2002), 14% (Lentz and Sojka, 1994), 15% (Lentz et al., 2001) and 28% (Lentz et al., 1998). Conversely, PAM did not improve infiltration or reduce surface runoff on a Hanford sandy loam when applied in-furrow at 5, 10, and 20 mg L^{-1} (Ajwa and Trout, 2006). These data indicate that PAM's effect on infiltration is site specific, but PAM applied at 10 mg L^{-1} can improve furrow irrigation application efficiency for silt loam and silty clay loam soils. Further research is required, however, to determine PAM effects on other Mid-South soils.

Sediment Transport

The effect of PAM on sediment transport varied across year, soil texture, and particle size fraction transported in runoff. The year x soil texture x treatment interaction was significant for total solids ($P = 0.0024$) and suspended solids ($P = 0.0015$). Polyacrylamide had no effect on the transport of total or suspended solids on either soil texture in 2014. In 2015, no PAM effect on TS or SS was observed on the Dundee silt loam. Conversely, PAM reduced the transport of TS and SS on the Forestdale silty clay loam by at least 78%, primarily by reducing the transport of suspended solids > 0.45 mm (Table 2.2). Independent of year and soil texture, PAM had no effect on dissolved suspended solids ($P = 0.6532$). Others report efficacious effects of PAM on erosion when applied in-furrow to gravelly clay loam and silt loam textured soils, regardless of PAM concentration (1 to 20 mg L-1), furrow flow rate (7.5 to 22.5 L min-1) and furrow slope (0.5 to 3.5%) (Entry and Sojka, 2003; Orts and Glenn, 1999; Orts et al., 2001; Lentz et al., 1992; 1998; 2002; Lentz and Sojka, 1994). Conversely, Bjorneberg et al. (2003) reported that PAM applied in-furrow at 3.5 mg L-1 increased sediment transport from a silt loam textured soil by as much as 100%. These data indicate that PAM can effectively reduce sediment transport but effects will be site specific. Future research is required to delineate sites where PAM can mitigate sediment transport.

Corn Grain Yield

Polyacrylamide applied at 10 mg L^{-1} in furrow increased corn grain yield compared to the control. The treatment main effect was significant for corn grain yield ($P = 0.0398$). Pooled over year and location, PAM increased corn grain yield by 7% compared to the control (Table 2.3). Similarly, Lentz and Sojka (2009) reported anionic EC PAM applied at 10 mg L^{-1} in-furrow to a silt loam soil increased soybean yield by 14.3 % and corn yield by 4.5 % relative to water only. Polyacrylamide effects on grain yield have been attributed to improved infiltration and increased lateral water movement in furrow irrigated environments (Lentz and Sojka, 2009; Lentz et al., 1992; Yoder et al. 1996). Our data indicate that EC anionic PAM applied in-furrow to silt loam and silty clay loam soils can improve corn grain yield relative to conventionally furrow irrigated systems.

Conclusions

The EC PAM formulation evaluated in this study decreased surface runoff and increased infiltration during furrow irrigation events on silt loam and silty clay loam soils by at least 6%. Polyacrylamide had a minimal and inconsistent effect on sediment transport, which varied over year and location. However, PAM increased corn grain yield by 7% compared to the control. Results from this study indicate that PAM can improve infiltration and corn grain yield on silt loam and silty clay loam textured soils across the Mid-South, but PAM effects on erosion will be site specific.

Table 2.1 Polyacrylamide effects on cumulative surface runoff and infiltration pooled over year and soil texture[§].

Treatment	Runoff	Infiltration
	——— $ha\ mm^{-1}$ ———	
Water	30.7 (7.21)[†] a[‡]	10.8 (7.21) b
PAM 10 $mg\ L^{-1}$	28.2 (6.06) b	13.4 (6.06) a

[†] Values in parenthesis denote standard deviation.

[‡] Means followed by the same letter for each parameter are not significantly different at $P \leq 0.05$

[§] Experiment was conducted in 2014 and 2015 on a Dundee silt loam and a Forestdale silty clay loam soil in Stoneville and Tribbett, Mississippi.

Table 2.2 Polyacrylamide effects on total, suspended, and dissolved solids transport in surface runoff[#].

			Solids Concentration in Surface Runoff		
			Kg ha^{-1}		
Year	Site	TRT	Total	Suspended	Dissolved
2014	Dundee	Water	1282.4[§] (895.77)[¶] b[†]	1015.5[§] (876.08) b	266.9[§] (22.15)
		PAM	857.7[§] (310.18) bcd	606.5[§] (328.20) bc	251.2[§] (67.04)
	Forestdale	Water	306.0[‡] (36.33) d	145.6[‡] (32.72) c	160.5[‡] (3.85)
		PAM	481.3[‡] (32.10) bcd	357.0[‡] (66.68) bc	131.7[‡] (34.58)
2015	Dundee	Water	1104.6[§] (172.33) bc	736.8[§] (183.92) bc	367.9[§] (17.08)
		PAM	1091.7[§] (504.23) bc	734.2[§] (491.39) bc	357.5[§] (16.10)
	Forestdale	Water	2278.8[‡] (245.74) a	1992.1[‡] (247.76) a	286.7[‡] (10.92)
		PAM	495.8[‡] (203.15) cd	215.6[‡] (194.53) c	280.3[‡] (12.17)

[†] Means followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.

[‡] Values represent the mean of 3 replicates.

[§] Values represent the mean of 4 replicates.

[¶] Values in parentheses denote standard deviation.

[#] Experiment was conducted in 2014 and 2015 on a Dundee silt loam and a Forestdale silty clay loam soil in Stoneville and Tribbett, Mississippi.

Table 2.3 Polyacrylamide effects on corn grain yield pooled over year and soil texture[§].

Treatment	——— Yield ———
	——— kg ha^{-1} ———
Water	10583 (1643.7)[‡] b[†]
PAM 10 mg L^{-1}	11368 (1489.9) a

[†] Means followed by the same letter are not significantly different at $P \leq 0.05$.

[‡] Values in parenthesis denote standard deviation.

[§] Experiment was conducted in 2014 and 2015 on a Dundee silt loam and a Forestdale silty clay loam soil in Stoneville and Tribbett, Mississippi.

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CHAPTER III

POLYACRYLAMIDE EFFECTS NUTRIENT TRANSPORT IN FURROW IRRIGATED ENVIRONMENTS

Abstract

Polyacrylamides (PAMs) are water soluble, long chain synthetic organic polymers that, when applied as a soil amendment, purportedly reduce surface runoff, improve infiltration, decrease erosion, and off-site nutrient transport. There is a paucity of data, however, on the effect of PAM metered into irrigation water through lay-flat polyethylene tubing on nutrient transport in furrow irrigated environments throughout the Mid-South. The objective of this two-year field experiment was to assess PAM effects on the transport of total Kjeldahl N (TKN), dissolved and sorbed, NO_2^-, NO_3^-, NH_4^+, total ortho P (TOP), dissolved and sorbed, and PO_4^{3-} on a Dundee silt loam and a Forestdale silty clay loam soil located in Stoneville and Tribbett, Mississippi, respectively. Each irrigation event delivered 41.5 ha mm at 18.9 L min^{-1} per furrow, and runoff was captured in a holding tank on the lower end of each plot. Cumulative runoff was determined by recording water level in the holding tank at 60-s intervals. The initial liter of runoff as well as those at 5, 10, 20, 30, and 40-min intervals were captured in 1-L Nalgene® bottles and stored on prior to analysis. Cumulative infiltration was calculated by the difference between rainfall and runoff (irrigation – runoff) and cumulative nutrient transport was determined by multiplying the cumulative runoff value by the average nutrient

concentration from the 6 water samples collected after runoff inception. Independent of year or soil texture, PAM did not reduce the off-site transport of TKN ($P \geq 0.3294$), NO_3^- ($P = 0.4698$) or NH_4^+ ($P = 0.1054$). However, for NO_2^- there was a year x treatment interaction ($P = 0.0157$). Pooled over soil texture, PAM reduced the cumulative transport of NO_2^- in 2014 by 73% relative to the control, but PAM had no effect on NO_2^- transport in 2015. For TOP transport (dissolved + sorbed of all particle size fractions) there was a year x site x treatment interaction ($P = 0.0011$). In 2014 PAM had no effect on TOP loss from the Forestdale silty clay loam, but PAM reduced total P transport from the Dundee silt loam by 78% relative to the control. Conversely, PAM had no effect on TOP transport in 2015. Moreover, regardless of year or location, PAM had no effect on PO_4^{3-} transport ($P = 0.7986$). These data indicate that EC PAM applied at 10 mg L^{-1} through lay-flat polyethylene tubing does not consistently mitigate the off-site transport of N and P on silt loam and silty clay loam soils in Mid-South production systems.

Introduction

Off-site transport of N and P in surface runoff due to present-day agricultural practices is the most significant contributor to the degradation of surface water quality in the United States (U.S. EPA, 2000; USDA-ARS, 2003). Profitable and sustainable agronomic practices necessitate nutrient inputs in the form of organic or chemically derived fertilizer materials (Flanagan and Canady, 2006). In some instances application of N and P in excess of soil nutrient holding capacity facilitates off-site agrochemical transport and the subsequent pollution of down-stream water bodies (Brichford et al., 1993). Moreover, in furrow irrigated environments, irrigation-induced runoff can contribute to off-site N and P transport (Entry and Sojka, 2003; Lentz et al., 1998). A means to maintain current on-farm profitability while reducing the off-site transport of N and P in furrow irrigated environments is required.

The primary carriers for off-site N and P transport in surface runoff are water and sediment. Polyacrylamides are a class of water-soluble, synthetic organic polymers that when applied as a soil amendment may mitigate the off-site transport of N and P in agricultural landscapes by decreasing surface runoff and erosion (Ajwa and Trout, 2006; Entry and Sojka, 2003; Green et al, 2004; Lentz and Sojka, 1994; 2009; Mamedov et al., 2010; Sojka et al., 1998). Polyacrylamide effects on N and P transport in the literature are limited (Entry and Sojka, 2003; Goodson et al., 2006; Lentz et al., 1998; Szogi et al., 2007). Data indicate, however, when PAM improves infiltration and reduces off-site sediment transport by at least 27%, cumulative N and P transport is reduced by at least 31% (Entry and Sojka, 2003; Goodson et al., 2006; Lentz et al., 1998).

To date, 72% of PAM research in irrigated agriculture is from regions, soils, and production systems west of the Mississippi River. There is a paucity of data evaluating PAM effects on N and P transport when applied through lay-flat polyethylene tubing during furrow irrigation events from soil textures and production systems characteristic of the mid-south. The objective of this research, therefore, was to assess PAM effects on the transport of total Kjeldahl N (TKN) (dissolved and sorbed) NO3-, NO2-, NH4+, total ortho-phosphate (TOP) (dissolved and sorbed), and PO43- when applied at 10 mg L-1 in irrigation water through lay-flat polyethylene tubing over two years and two soil textures, a silt loam and a silty clay loam.

Materials and Methods

A two-year field study was conducted at the Mississippi State Delta Research and Extension Center, in Stoneville, Mississippi, USA. Experiments were conducted on a Dundee silt loam (fine-silty, mixed, active, thermic Typic Endoaqualfs), with a soil pH of 6.3, 0.95% organic matter, CEC of 11.64 meq/100 g, and 120 kg and 443 kg of P and K ha^{-1}, respectively; and a Forestdale silty clay loam (fine, smectitic, thermic Typic Endoqualfs), with a soil pH of 5.8, 1.04% organic matter, CEC of 14.92 meq/100 g, and 39 kg and 420 kg of P and K ha^{-1}, respectively. Both sites were precision graded to a 2% slope. Raised beds spaced 100-cm apart from the center were formed with disk hippers. Plot dimensions were 7.62 m x 4.06 m. Prior to planting, raised beds were smoothed with a reel and harrow row conditioner, and corn (*Zea mays,* L. 'Pioneer 1498YHR') was planted at 79073 seed ha^{-1}. Both the Dundee silt loam and the Forestdale silty clay loam were treated with 272 kg N ha^{-1} as UAN (32-0-0) applied in a split application, with 137 kg N ha^{-1} being applied after seedling emergence and 135 kg N ha^{-1} applied at the V8 growth stage. On both soil textures the experimental design was a randomized complete block with four replications of each treatment. Treatments included irrigated plus no PAM (control), and irrigated with PAM at a rate of 10 mg L^{-1}, 10.3 kg ha^{-1}. The polyacrylamide product, HM1113, is a 30% active ingredient emulsified concentrate (EC) formulation from Helena Chemical Company (Collierville, Tennessee).

Separate nurse tanks were used for treated (PAM) and untreated (water only) irrigation simulations to avoid cross contamination. A 10-cm diameter schedule diameter 40 PVC pipe delivered irrigation water to experimental units. An EC PAM formulation at 10 mg L^{-1} was applied at a rate of 10.3 kg ha^{-1}. Irrigation flow rates were calibrated to deliver 41.5 ha mm at 18.9 L min^{-1} per furrow, and irrigation was delivered when soil moisture content reached at least a 20.6 ha mm deficit as determined by FAO-56 (Allen et al., 1998). Surface runoff was captured in a holding tank positioned on the down-slope end of the plot. Runoff volume was determined by recording the water height in the tank at 60-second intervals. Cumulative infiltration was calculated by the difference between rainfall and runoff (irrigation – runoff). The initial liter of runoff and those obtained at 5, 10, 20, 30, and 40-min after runoff inception were collected in 1-L Nalgene® bottles. Bottles were sealed with Teflon® screw caps and immediately stored on ice prior to analyses. Cumulative nutrient transport for TKN (dissolved and sorbed), NO_2^-, NO_3^-, NH_4^+, TOP (dissolved and sorbed), and PO_4^{3-} was calculated as follows:

$$NT = [N]\ x\ R \tag{3.1}$$

where *NT* is the cumulative nutrient transport; *N* is the mean nutrient transport; and *R* is the cumulative runoff.

Water, sediment, and nutrient analyses were conducted by USDA-ARS NSL water quality laboratories (Oxford, Mississippi). Runoff samples were analyzed in accordance with procedures developed from the American Public Health Association, as similar to those described by Locke et al., (2015). Physical analyses of runoff samples included total solids (TS) and total dissolved solids (DS), that is, all non-aggregated fine solids < 0.45 mm (APHA 1997a, 1997d). To determine TS, 100 mL of well-shaken runoff sample was measured into a tared evaporating dish, and the sample weight was recorded after drying for 48 h at 105°C. Dissolved solids were determined by passing a 100-mL sample through a 0.45-mm glass fiber filter, and the filtrate residue weight measured after oven-drying for 24 h at 105°C. Total suspended solids (SS; solids > 0.45 mm) were calculated by determining the difference between TS and DS.

All nutrient samples were analyzed on a Lachat QuickChem 8559 autoanalyzer (Lachat Instruments, Loveland, Colorado). Runoff samples were vacuum filtered (0.45 mm), and the filtrate analyzed for NH_4^+, NO_3^-, NO_2^-, and PO_4^{3-}, i.e. orthophosphate, according to the American Public Health Association (1997b, 1997c, 2000a, 2000b). Total orthophosphate (TOP) was determined by digesting unfiltered samples in H_2SO_4 with ammonium persulfate (American Public Health Association 1997c). Analyses for filtered and digested samples were performed using a ThermoSpectronic GenesysTM 10 ultraviolet spectrophotometer (Spectronic Instruments, Rochester, New York) with a detection limit of 0.01 mg L^{-1}. Unfiltered runoff samples were processed for total Kjeldahl N (TKN) by digesting unfiltered samples on a micro-Kjeldahl block digester (H_2SO_4 with HgO and K_2SO_4) followed by analyses with a Lachat QuickChem 8500 Series II autoanalyzer (Lachat Instruments, Loveland, Colorado) using Lachat Method 10-107-06-2-E.

Cumulative TKN (dissolved and sorbed), NO_3^-, NO_2^-, NH_4^+, total P (dissolved and sorbed) and PO_4^{3-} transport were analyzed as a split-split plot using the Mixed Procedure (SAS version 9.4, SAS Institute Inc., Cary, North Carolina. Year, soil texture, and PAM treatment were considered fixed effects, with year as the whole plot, soil texture as the sub-plot and PAM treatment as the sub-sub plot. Random effects were replication and interactions among replication and the fixed effects. Least square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS, a macro for converting mean separation output to letter groupings (Saxton, 1998).

Results and Discussion

Nitrogen Transport in Surface Runoff

With the exception of NO_2^-, PAM applied at 10 mg L^{-1} in furrow via lay-flat polyethylene tubing had no effect on the off-site transport of TKN or specific N species in surface runoff. For example, independent of year, soil texture, or particle size fraction, PAM had no effect on TKN ($P \geq 0.3294$; Table 3.1), NO_3^- ($P = 0.4698$; Table 3.3) or NH_4^+ ($P = 0.1054$; Table 3.3) losses in surface runoff. For NO_2^-, however, a year × PAM interaction was observed ($P = 0.0157$; Table 3.2). Pooled over soil texture, PAM reduced cumulative NO_2^- transport by 73% in 2014; however, PAM had no effect on NO_2^- transport in 2015. These data indicate that PAM did not significantly or consistently mitigate the off-site transport of N in Mid-South furrow irrigated environments on silt loam or silty clay loam soil textures.

The minimal and inconsistent effects of PAM on the off-site transport of TKN and specific N species under the conditions of this experiment are likely linked to PAM's nominal improvement on infiltration and inconsistent effects on cumulative sediment loss across years and soil textures (Table 2.1-2.2). For example, Szogi et al., (2007) noted that PAM did not significantly improve infiltration or reduce erosion when applied using the dry patch method to a sandy loam textured soil and, consequently, PAM did not effectively mitigate the off-site transport of total N or N species in surface runoff. Conversely, others observed that when PAM increased infiltration and reduced off-site sediment transport by at least 27%, total N transport decreased by at least 33% (Entry and Sojka, 2003; Goodson et al., 2006; Lentz et al., 1998). When compared to data from other experiments, one can conclude that for PAM to mitigate the off-site transport of dissolved and sorbed N species entrained in surface runoff, PAM must improve infiltration and reduce off-site sediment transport at levels greater than those observed under the conditions of this study.

Phosphorus Transport in Surface Runoff

The effect of PAM on P transport varied across year, soil textures, soluble versus sorbed phases, and particle size fractions entrained in runoff. Regardless of year or soil texture, PAM had no effect on the transport of PO_4^{3-} ($P = 0.7986$; Table 3.4). The year × soil texture × PAM interaction was significant for TOP (soluble + all sorbed PO_4^{3-}; $P = 0.0011$; Table 3.4) and sorbed P (PO_4^{3-} removed from particle size fraction > 0.25 µm; $P = 0.0015$; Table 3.4). PAM reduced the transport of total and sorbed P by at least 78% on the Dundee silt loam in 2014, but PAM had no effect on the transport of total or sorbed P on the Forestdale silty clay loam. Conversely, in 2015, regardless of soil texture, PAM had no effect on the transport of total or sorbed P. These data indicate that PAM did not consistently reduce the off-site transport of P in mid-south furrow irrigated environments on silt loam or silty clay loam soil textures.

These data stand in contrast to PAM effects on P transport reported in the literature, where PAM consistently reduced the transport of dissolved and sorbed P in proportion to reductions in surface runoff and sediment transport, respectively. For example, similar to PAM effects on cumulative N transport, cumulative P transport decreased by at least 33% when infiltration was improved and off-site sediment transport reduced by at least 27% (Entry and Sojka, 2003; Goodson et al., 2006; Lentz et al., 1998). These data indicate that to achieve consistent and significant reductions in dissolved and sorbed P species entrained in surface runoff, PAM must improve infiltration and reduce off-site sediment transport at levels greater than those observed under the conditions of this study.

Conclusions

The objective of this study was to assess EC PAM (HM1113) applied at 10 mg L^{-1} in furrow on the off-site transport of total N (dissolved and sorbed), NO_3^-, NO_2^-, NH_4^+, TOP (dissolved and sorbed) and PO_4^{3-} on a Dundee silt loam and Forestdale silty clay loam soil. Our data indicate that PAM applied via lay-flat polyethylene tubing at 10 mg L^{-1} does not consistently reduce the off-site transport of N or P in either the dissolved or sorbed phase on silt loam and silty clay loam soils under furrow irrigated conditions in Mid-South agricultural environments. In this experiment PAM effects on surface runoff and infiltration did not meet thresholds required to impact N and P transport as established in previous literature. Further research is required to determine PAM best management practices needed to effect N and P transport on Mid-South soil textures and landscapes.

Table 3.1 Cumulative total[¶], dissolved[#], and sorbed[††] Kjeldahl N (TKN) transported in surface runoff[‡‡].

			Total Kjeldahl Nitrogen Transport in Surface Runoff		
Year	Site	TRT	g ha^{-1}		
			Total	Dissolved	Sorbed
2014	Dundee	Water	587.9[†] (139.03)[§]	287.8[†] (65.99)	300.1[†] (125.37)
		PAM	389.3[†] (106.98)	233.1[†] (53.35)	156.2[†] (110.68)
	Forestdale	Water	434.6[‡] (79.40)	269.6[‡] (100.94)	165.0[‡] (43.15)
		PAM	322.1[‡] (61.38)	166.3[‡] (42.43)	155.7[‡] (103.66)
2015	Dundee	Water	956.6[†] (313.83)	607.9[†] (42.75)	348.6[†] (276.29)
		PAM	938.9[†] (272.56)	593.9[†] (101.10)	344.9[†] (199.13)
	Forestdale	Water	838.5[‡] (189.96)	405.9[‡] (229.59)	432.7[‡] (136.85)
		PAM	1193.1[‡] (210.64)	596.9[‡] (188.06)	596.1[‡] (181.38)

[†] Values represent the mean of 4 replicates.

[‡] Values represent the mean of 3 replicates.

[§] Values in parentheses denote standard deviation.

[¶] Dissolved and sorbed nitrogen.

[#] Dissolved nitrogen species and nitrogen species sorbed to sediment < 0.25 µm.

[††] Nitrogen species sorbed to sediment > 0.25 µm.

[‡‡] Experiment conducted in 2014 and 2015 on a Dundee silt loam and a Forestdale silty clay loam soil in Stoneville and Tribbett, Mississippi.

Table 3.2 Cumulative NO_2^- transport in surface runoff pooled over soil texture[#].

Year	TRT	NO_2^- Concentration in Surface Runoff
		g ha^{-1}
2014	Water	11.3[§] (8.57)[‡] a[†]
	PAM	3.1[¶] (1.62) b
2015	Water	3.1[§] (1.67) b
	PAM	2.2[§] (0.15) b

[†] Means followed by the same letter and are not significantly different at $P \leq 0.05$.

[‡] Values in parentheses denote standard deviation.

[§] Denote the mean of 7 replicates.

[¶] Denote the mean of 6 replicates.

[#] Experiment conducted in 2014 and 2015 on a Dundee silt loam and a Forestdale silty clay loam soil in Stoneville and Tribbett, Mississippi.

Table 3.3 Cumulative NO_3^- and NH_4^+ transport in surface runoff[¶].

Year	Site	TRT	Nitrogen Species in Surface Runoff	
			g ha^{-1}	
			NO_3^-	NH_4^+
2014	Dundee	Water	61.5[†] (40.10)[§]	132.1[†] (11.88)
		PAM	19.7[†] (6.22)	73.4[†] (11.62)
	Forestdale	Water	96.0[‡] (81.26)	36.3[‡] (29.01)
		PAM	19.9[‡] (6.43)	20.9[‡] (20.44)
2015	Dundee	Water	73.6[†] (10.02)	168.9[†] (18.24)
		PAM	73.9[†] (34.64)	174.8[†] (7.35)
	Forestdale	Water	194.6[‡] (52.47)	208.5[‡] (132.00)
		PAM	214.7[‡] (81.93)	135.0[‡] (37.45)

[†] Values represent the mean of 4 replicates.

[‡] Values represent the mean of 3 replicates.

[§] Values in parentheses denote standard deviation.

[¶] Experiment conducted in 2014 and 2015 on a Dundee silt loam and a Forestdale silty clay loam soil in Stoneville and Tribbett, Mississippi.

Table 3.4 Cumulative total[#], dissolved[††], sorbed[‡‡], and soluble reactive ortho-P[§§] transported in surface runoff[¶¶].

			Cumulative TOP Transport in Surface Water			
Year	Site	TRT	$g\ ha^{-1}$			
			Total	Dissolved	Sorbed	PO_4^{3-}
2014	Dundee	Water	392.4[‡] (159.46)[¶] a[†]	32.0[‡] (5.63)	360.4[‡] (154.60) a	8.4[‡] (8.60)
		PAM	88.0[‡] (63.94) c	26.4[‡] (1.27)	61.6[‡] (64.87) c	5.3[‡] (3.02)
	Forestdale	Water	59.9[§] (48.54) c	17.1[§] (5.75)	42.8[§] (54.30) c	4.8[‡] (1.75)
		PAM	61.3[§] (36.13) c	18.9[§] (6.01)	42.4[§] (42.14) c	4.0[‡] (1.20)
2015	Dundee	Water	128.3[‡] (70.07) bc	12.9[‡] (15.23)	115.4[‡] (60.47) bc	3.6[‡] (2.17)
		PAM	230.5[‡] (147.93) b	13.7[‡] (11.51)	216.9[‡] (158.23) ab	4.7[‡] (2.05)
	Forestdale	Water	131.8[§] (18.51) bc	23.8[§] (18.06)	108.1[§] (12.20) bc	7.1[‡] (1.59)
		PAM	68.6[§] (24.90) c	36.1[§] (16.87)	32.5[§] (14.85) c	11.7[‡] (2.31)

[†] Means followed by the same letter for each parameter in each column are not significantly different at $P \leq 0.05$.

[‡] Values represent the mean of 4 replicates.

[§] Values represent the mean of 3 replicates.

[¶] Values in parentheses denote standard deviation.

[#] Dissolved and sorbed phosphorus.

[††] Dissolved phosphorus species and phosphorus species sorbed to sediment < 0.25 µm.

[§§] Phosphorus species sorbed to sediment > 0.25 µm.

[¶¶] Experiment conducted in 2014 and 2015 on a Dundee silt loam and a Forestdale silty clay loam soil in Stoneville and Tribbett, Mississippi.

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