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16. Abstract
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17. Key Words
mulches, sediments, sedimentation, turbidity, erosion, polyacrylamide

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Measures to Control Erosion and Turbidity in Construction Site Runoff

Final Report

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June 2002

Disclaimer

The contents of this report reflect the views of the author and not necessarily the views of the University. The author is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

Executive Summary

Applying PAM to bare soil surfaces to reduce erosion appears to have two limitations. One is the slope steepness, since we found no evidence of PAM effects on a 2:1 slope but some erosion and turbidity reductions on a 4:1 slope. Since PAM is known to only influence the surface 1-2 mm of soil by maintaining structure, the erosive forces on steep slopes apparently remove this layer relatively quickly during the first storm. Exactly where the breaking point is for PAM to be effective will likely be site specific. The second limitation is in the longevity of treatment effects. There is some evidence that these disappeared in the field after several rainfall events. This was further corroborated in our rainfall simulation tests. Again, the longevity of PAM effectiveness will be specific to the application, site characteristics, and rainfall patterns. Higher rates of PAM may be more effective for longer periods. In most cases, the mulch and seed treatment was usually so effective in reducing erosion and turbidity that the PAM treatments did not provide any additional benefit to water quality.

PAM was found to be effective in reducing turbidity produced from a wide range of sediment sources. A number of reactions were observed, including several sediment sources which did not respond to the PAMs in our tests. However, most of the sediments had relatively straightforward, linear reductions in turbidity with increasing PAM concentrations. In most cases, 0.5-1.0 mg/L was sufficient to achieve maximum turbidity reduction. It appears that PAM is effective for turbidity caused by a majority of sediments from around North Carolina.

We have not developed clear relationships between sediment and PAM properties and turbidity reduction at this point. Work will continue on this topic with the goal to develop a guide to PAM selection based on one or more sediment properties.

Recommendations

- **Mulching and seeding is extremely effective in stopping erosion – this practice should be implemented after soil disturbance as quickly as feasible.**
- **PAM use for erosion control on bare soil has potential, but may be limited to low slopes for short periods.**
- **PAM is effective in reducing turbidity caused by most sediment sources tested and should be included as part of sediment control systems in the future.**
- **PAMs will need to be selected for site-specific conditions. However, some PAMs are useful for a wider array of sediments than others.**
- **PAMs may not be effective in some cases and may need to be augmented or substituted with inorganic salts, coagulants, or other materials.**
- **Flocs formed after PAM applications may require filtration or relatively calm water in order to settle. Where pumping is already in place, such as at borrow pits, filtering systems would be relatively simple to devise or obtain.**

Measures to Control Erosion and Turbidity in Construction Site Runoff

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Abstract

An evaluation of polyacrylamides (PAM) for both erosion and turbidity control for construction sites was conducted in both the laboratory and the field. A laboratory screening was conducted for 11 PAMs on 13 sediment sources from North Carolina Department of Transportation (NC DOT) construction sites around North Carolina. In addition, a field test of two PAMs at two rates, with and without straw mulch and seeding, on a 2:1 fill slope, a 4:1 cut slope, and a 4:1 fill slope were performed. The results indicate that there is no one PAM that is effective for turbidity reduction on all sediment sources, but several are promising for many soils. Superfloc A-100 ranked among the top three flocculants for 10 of 13 sediment sources. Some PAMs are equally effective but at different doses, some as low as .075 mg/L, or a few grams per 1,000 ft^3 of water. The differences between PAMs in reducing turbidity was clearest shortly after mixing the PAM and soil (30 sec). These turbidity differences were usually maintained 30-60 minutes after mixing, but allowing the soil/water mix to settle for 24 hours reduced or eliminated the differences. Tests of PAM with and without mulching on 2:1 slopes at NC DOT construction sites failed to show a significant reduction in turbidity or erosion. Erosion rates were 20 times greater on bare soil plots after the first seven events, with or without PAM, compared to those mulched with straw and seeded to grass. During the eighth and last event, in which over 6 cm of rain was recorded, rates of over 50 tons/ha were recorded for a single, intense storm event for the bare soil plots compared to 3-9 tons/ha on the mulched/seeded plots. PAM at the highest rate (11 kg/ha) was effective in reducing erosion and turbidity on the 4:1 cut slope with a clay loam texture but the effect declined with each storm event. On the sandy 4:1 fill slope, there was no evidence of PAM effects, even at 20 kg/ha. PAM was effective in flocculating turbid water pumped from a borrow pit but turbulence within the basin tended to keep the flocs from settling.

Key Words: polyacrylamides (PAM), construction, turbidity, erosion control, sediment

Introduction

The U.S. Environmental Protection Agency has documented that sediment is the major pollutant of streams and rivers in the United States (USEPA, 2000). Sediment impairs 13% of the assessed streams and contributes to 38% of the water quality problems. The control of erosion is imperative to keeping our farmland productive. More than one-third of the cropland in the U.S. is in danger of having severe erosion, to the point of lost crop productivity (Havlin et al., 1999). In addition to the loss of topsoil, the erosion of soil into surface water leads to sedimentation of streams and eutrophication (McCutchan, 1993). Much of this sediment is due to agriculture, but an increasing amount of sediment, particularly in urbanizing areas, is due to construction practices.

Erosion and sediment control on construction sites is an increasingly important aspect of project management. Most erosion control practices that are currently implemented as part of a sediment and erosion control plan are intended to prevent erosion through diversions, mulching, and seeding. Sediment control is designed to slow runoff to allow entrained soil to settle. This combination may be effective in retaining a large portion of potential sediment within the construction site, but runoff is likely to remain highly turbid. The suspended solids in the discharge water have adverse impacts on the receiving waters and may result in complaints from the public.

The use of polyacrylamide (PAM) to reduce soil erosion has been receiving increasing attention in recent years. One of the most widely published uses is in furrow irrigation systems, in which PAM is added to the irrigation water to prevent erosion of the furrows (Lentz et al., 1992; Lentz et al., 1998). By adding PAM to the irrigation water, furrow erosion was reduced by up to 94%. This has become a standard practice among growers in many states in the western U.S. PAM has also been shown to reduce erosion when introduced through a sprinkler irrigation system (Bjorneberg and Aase, 2000).

Numerous private firms are selling various products containing PAM to be added to seed/mulch mixes when they are applied to construction sites. It is important to understand the effectiveness of these materials. Recent testing of PAM to control erosion on exposed soil surfaces has demonstrated reductions in sediment loss. Erosion was reduced on average 93% compared to a bare soil when a PAM/mulch/seeding treatment was added to dry soil (Roa-Espinosa et al., 1999). Tobiason et al. (2000) found in testing different application methods of PAM on construction sites, a treatment of PAM plus hydromulch reduced turbidity 94-99%, and a PAM only treatment reduced turbidity 88-90% compared to bare soil after 5-7 storms. PAM application rates were also tested showing up to 82% reductions in turbidity.

Clarifying runoff water before discharging it from a construction site is another approach to meeting regulatory guidelines. Przepiora et al. (1997,1998) found that calcium sulfate in the form of molding plaster could successfully reduce turbidity in sediment basins to meet the 50 nephelometric turbidity units (NTU) requirement in North Carolina, although retention times could be up to two days. The plaster was added to the basins by hand. Turbidities of less than 10 NTU have been achieved when the runoff was stored and treated with PAM (Minton and Benedict, 1999). Their system was essentially a water treatment plant system, with pumps and multiple settling basins. The estimated cost of the treatment system was up to 1.5% of the total construction costs for a large project.

There has been some concern about the potential for PAM to be toxic to aquatic species. PAM can be synthesized to be cationic, non-ionic, or anionic. The cationic form is known to be somewhat toxic to fish due to binding to their gills (Biesinger et al., 1976; Goodrich et al., 1991), so most tests of PAM in erosion and sediment control have been of the anionic variety. It is important to note, however, that the toxicity of the cationic PAMs tested was reduced by at least an order of magnitude when fish food or humic acid were introduced into the test water. A detailed study of neutral and anionic PAMs in many animal species found them to be non-toxic at doses much greater (>100 mg/L) than would be used for erosion or turbidity control (McCollister et al., 1965). They found that the anionic PAM was only toxic to fish when the concentration was high enough to make the water viscous. Tobiason et al. (2000) reported that the anionic PAM used at their test sites was not toxic to test species. The building block of PAM, the acrylamide monomer, is a neurotoxin but PAM itself is regulated in the U.S. to contain < 0.05% by weight of the acrylamide monomer. PAM will not regenerate the acrylamide monomer in the environment (Bologna, 1999).

As part of an effort to begin to determine how PAM can be most effectively used in North Carolina, we initiated laboratory and field studies of PAM/soil interactions. We conducted controlled, laboratory evaluations of PAM and soil combinations to determine relationships and develop preliminary recommendations. The practical outcome will be the use of flocculants to reduce turbidity in sediment basins or stormwater ponds. We also conducted field evaluations of the use of PAM alone or in combination with standard practices to control erosion and runoff turbidity to determine effective applications under various conditions. Presented here are the results of the first of these field tests.

Materials and Methods

Field Studies

The initial field evaluation was conducted on a 2:1 fill slope at an active construction site (I-540) in Raleigh, NC (Figure 1). The soil texture was determined using the hydrometer method and was a loam. Thirty plots, each 6 m long, were established by installing 15 cm plastic landscape edging up and down the slope every 1.5 meters. A plastic sheet was trenched into the soil at the bottom of each plot and laid on top of a V-shaped berm to channel run off into a 10 cm diameter pipe., A silt fence was installed to intercept the heavy sediment at the widest point of the V. The end of each pipe had a splitter constructed from a 30 x 10 cm landscape drain laid on its side. The drain had 9 slots, one of which was fitted with a narrow conduit to a 20 L bucket. The water in the remaining 8 slots was allowed to drain onto the ground and away from the bucket. Tests of the improvised splitter indicated that it performed relatively well in obtaining the 1/9 split. This allowed us to calculate the total runoff for storms of < 2.5 cm of rain.

Runoff in the bucket was measured for volume and then subsampled for laboratory analysis for turbidity and total suspended solids (TSS). Sediment on the plastic sheet and in the silt fence was collected, weighed in the field, and then subsampled for dry weight determination. Rainfall was recorded using a tipping-bucket rain gauge with a datalogger.

The field study involved two PAM products, Soilfix from Ciba Specialty Chemicals (Suffolk, VA) and Silt Stop 705 from Applied Polymer Systems (Norcross, GA) at two application rates (a manufacturer's recommended rate and one/half this rate), with and without straw mulch and seeding, straw mulch and seed only, and bare soil. The seed used was a sorghum/sudangrass hybrid called sudax. Each treatment was replicated three times. Table 1 lists the soil treatments used in the field study.

Lime, fertilizer, seed, and straw mulch were applied by hand at the recommended rates to all plots receiving the mulch/seed treatment. The PAM treatments were applied on June 19, 2001 using conventional hand-pumped spray applicators. Samples were collected after rain events until a 6 cm storm event on July 27, 2001 severely eroded the bare plots.

This study design was replicated at an adjacent site with a 4:1 cut slope. We made one modification in that we kept all plots separated by one foot and used individual silt fences for each plot. This was to prevent movement of sediment across the silt fence as occurred during the last event in the first site. We used a standard NCDOT grass mixture of fescue and bahiagrass. The soil at this site was a silty clay loam. We completed installation of the plots on September 14, 2001.

A third site was located at the I-95 loop project near Fayetteville in Cumberland County. This site also had a 4:1 fill slope comprised of a sandy loam with very little clay. We dropped the lower rate of both PAMs because these did not appear to be effective in our previous tests. The plot installation was completed November 29, 2001. After seven rainfall events, we reapplied Soilfix at the rate of 20 kg/ha to the three bare soil plots which had the original 1.68 kg/ha. These plots, and three controls, were manually leveled and smoothed prior to the application. We collected samples from these six plots for three additional runoff events.

We also conducted limited testing of PAM effects using a rainfall simulator and tilted soil beds. The rainfall simulator was designed at Purdue University and is being used by 20 institutions for a large study of phosphorus losses from animal waste. It consists of a VeeJet nozzle which produces droplet sizes and velocities similar to natural rainfall. The nozzle is elevated 4 m above the test beds and the rainfall amount is adjusted using an actuated valved to turn the flow on or off. The nominal rate is 7.4 cm/h if the flow is uninterrupted. We used 5 seconds on/5 seconds off for a 3.7 cm/h rate for 15-16 minutes. The soil beds were constructed of wood and were 1 m x 2 m x 0.09 m deep. They were packed with a local subsoil to a depth of 0.07 cm and tilted to a 5% slope lengthwise. Runoff passed through a series of holes in the lower lip into a gutter and finally into a bucket. PAM was applied in a volume of 11 L water after mixing for several hours with a sump pump. The pump was used to apply the treatment through a garden hose and nozzle. The time of runoff initiation, volume, and total suspended solids (TSS) were measured for each test. The data presented here are averages of two replications for each treatment.

We also conducted tests of flocculation in a stilling basin (10 m x 30 m) at the Fayetteville site. This was installed at a pump which was dewatering a borrow pit. Turbidity levels had been persistent even with the stilling basin. We first gathered water samples to determine the best PAM to use at this site. We then constructed a corrugated pipe system containing PAM (APS 740) through which the borrow pit water was pumped at approximately 100-200 L/min. Two baffle fences of burlap were hung across the stilling basin near the rock dam in the middle. Samplers were installed at the pipe outlet and at the stilling basin outlet and set to take samples every six hours.

Laboratory Studies

Laboratory experiments were conducted to evaluate combinations of PAM and soils to determine relative effectiveness for flocculation. Thirteen North Carolina soils provided by NC DOT were used in the flocculation study. Each soil came from a different part of the state, representing 13 of 14 of the NC DOT Divisions. This was our approach to attempting to obtain a representative array of potential sediment sources from around the state. In initial flocculation testing, 11 different types of PAM were used, each ranging in molecular weight and charge density (Table 2). The PAM was provided by different companies, which included: Applied Polymer Systems (APS), Ciba Specialty Chemicals, Cytec, and Chemtall. Of these, we are aware of only APS selling PAM for erosion and turbidity control.

The flocculation test setup involved suspending soil in water, adding PAM at various concentrations, and then measuring the turbidity of the soil solution after a short amount of time. Five grams of soil were weighed out and placed into a 100 ml container. 100 ml of Distilled water were then poured into each container. Each PAM was then added to the soil solution at rates ranging from 0 to 10 mg/L PAM. The PAM used in this experiment was granular but was dissolved in distilled water and diluted appropriately prior to adding it to the test containers. For each PAM, we mixed a series of 100 ml solutions consisting of 0, 0.0125, 0.025, 0.05, 0.075, 0.125, 0.25, 0.5, 1.0, and 2.0 mg/L. In each vessel we added 5 g of air dried soil, covered it, and then thoroughly mixed it by shaking. The turbidity was measured 30 seconds after shaking stopped. The nephelometer (Analite Nephelometer Model 152, McVan Instruments) was calibrated with standard formazin solutions before and after each test and the values were adjusted to the standardized curve. To compare different PAMs for a particular soil, we compared both the response curve slopes and the average turbidity. PAMs with steeper response curve slopes were considered more effective since incremental doses reduced turbidity more rapidly.

Initial flocculation testing was done on each soil using all 11 PAM’s. Results from each PAM used were compared for each soil, and the four best flocculants were chosen for replicate testing for each soil. The above method of testing was then used on each of the soils combined with the four best PAM's for the specific soils.

Each soil was analyzed for characteristics that relate to PAM interactions. The analyses performed were: pH, exchangeable cations, texture, mineralogy, and SAR. Each soil property was then compared to the amount of soil flocculation using SAS statistical tools.

Results

Literature Review

There are many methods used to decrease soil erosion, these include: cover crops, tillage practices, mulch, riparian strips, and polyacrylamide. Polyacrylamide has been used to control erosion for the last few decades. In the 1950's extensive research was conducted on polymer's use as a soil amendment. Even though significant research had been done, few farmers used polymers as erosion control due to the high cost. During the last 10 to 15 years advances in the chemistry of synthetic polymers has lead to a lower price and renewed interest in polymers as soil amendments. Research involving polyacrylamide has shown positive results in controlling soil erosion and stabilizing the physical condition of the soil (Seybold, 1994). This review focuses on the use of polyacrylamide to decrease erosion and improve surface water quality.

Polyacrylamide (PAM)

Polyacrylamide (PAM) is a water-soluble synthetic polymer. It is made by the polymerization of acrylamide. It can vary in molecular weight and charge by varying the manufacturing process. PAM used in soil erosion control has a range of molecular weights (MW) between 0.1 Mg mol^{-1} and 15 Mg mol^{-1}. PAM can be manufactured as a cationic, nonionic or anionic polymer. Cationic PAM may have adverse effects on aquatic life and presently is not used in erosion control (Seybold, 1994). The degree of negative charge that anionic PAM has is controlled by the charge density. The charge density is the percentage of OH^- groups substituted for NH_2 groups on the polymer (hydrolysis) (Green et al., 2000).

Nonionic PAM tends to coil in aqueous systems rather than form a chain, but intramolecular electrostatic repulsion extends the molecules of anionic polymers. Therefore anionic polymers are generally more effective for flocculation and stabilization of soil particles than nonionic polymers. Polymers with charge densities 40% or greater tend to coil around cations in solution (Laird, 1997; Malik, 1991).

PAM is typically purchased as a dry powder. Dry PAM typically has active polymer concentrations of 75-90%, the remainder being water, processing aids, and buffers (Barvenik, 1994). PAM is most often dissolved in water before application. The water must be rapidly agitated for dry granular PAM to be thoroughly dissolved. It is soluble in cold water, and heating does not significantly increase the rate of dissolution

(Montgomery, 1968). High concentration liquid PAM solutions tend to mix with irrigation water more effectively than granular PAM. Pumping liquid solutions is not recommended because it may shear PAM molecules, reducing its viscosity and reducing the effectiveness to stabilize the soil surface. Liquid solutions mix more uniformly with irrigation water than dry PAM, but are very viscous. PAM solution viscosity increased 5% relative to water for every 10 ppm increase in PAM concentration for a PAM with MW 12-15 Mg mol^{-1} and an 18% charge density (Bjorneberg, 1998).

Soil-Polyacrylamide Interactions

One cause of increased erosion and decreased infiltration in fields is surface seal formation. Seal formation in soils exposed to drop impact is caused by two mechanisms. First, the raindrops disintegrate soil aggregates. Second, clay particles migrate into a region 0.1-0.2 mm below the surface. This layer decreases the water infiltration and hence increases runoff (Levy et al., 1992). Soils with clay content above 20% with low organic material and moderate exchangeable sodium percentages will form surface seals when exposed to rain (Smith et al., 1990; Green et al., 2000). PAM treated soils result in preserved aggregation, lower bulk density (in treated regions), less soil surface sealing, and reduced penetrometer resistance in the surface soil (Zang and Miller, 1996).

Polyacrylamide is a soil amendment that stabilizes soil structure, but does not remediate poor soil structure (Green et al., 2000; Lentz and Sojka, 1994). PAM application has been shown to increase the percentage of stable aggregates from 10% in control soil to 78% in treated soils (Shainberg et al., 1992). Polymers promote flocculation of soil particles in suspensions and stabilize preexisting soil aggregates through adsorption of PAM to aggregate surfaces. The stabilizing effect increases with higher molecular weight, as the large polymers have more polymer units that can adsorb to soil (Laird, 1997).

Negatively charged PAM would be expected to be repulsed from negatively charged clay surfaces, but through a phenomenon known as cation-bridging they are attracted (Green et al., 2000; Laird, 1997). Soil adsorption of PAM occurs when the negative charge is screened by high electrolyte concentrations or when multivalent cations are present on the clay surfaces. The multivalent cations act as bridges between the anionic groups of the polymer and the negative clay surfaces. In the presence of electrolytes, the negative charge and the thickness of the diffuse double layer at the clay and polymer surfaces is suppressed, resulting in decreased repulsion forces and greater adsorption soil particles to anionic polymer (Shainberg and Levy, 1994). Anionic polymers may also adsorb on the broken edges of clay by attraction between the negative groups of the polymer and the positive aluminum ions exposed on broken clay edges (Ben-Hur et al., 1992). Low pH, low organic matter, and the presence of multivalent cations in the system also enhance polymer adsorption to soil (Helalia and Letey, 1988; Nadler and Letey, 1989).

Shainberg et al. (1990) hypothesized that there are two different types of cation-bridging between polymers and soil. The first type is an interaction between anionic groups of the polymer with an exchangeable cation through a water molecule to yield an “outer-sphere” complex. This mode of interaction happens in aqueous solutions. The second type is the cation-bridging between anionic groups of the polymer in direct association with exchangeable cations in the soil to form an “inner-sphere” complex. The drying of a soil induces inner-sphere complex formation and van der Waals interactions. This explains why drying of the soil leads to better water stable soil aggregates (Shainberg et al, 1990). The adsorption of PAM onto soil constituents is irreversible when the system is allowed to dry because the short-range van der Waals force holds them together (Zang and Miller, 1996; Laird, 1997; Letey, 1994). If PAM is used for a soil application there is evidence that a drying period is needed for the PAM to be most effective in stabilizing soil aggregates (Flanagan et al., 1997; Shainberg et al., 1990).

Treatment of a soil with PAM + gypsum is very effective in controlling seal formation and runoff, because it slows both the physical disintegration of surface aggregates and the chemical dispersion (Levin et al., 1991; Shainberg et al., 1990). The effectiveness of preserving soil aggregates can be improved with the presence of salts such as gypsum (Zang and Miller, 1996; Levy et al., 1992; Shainberg et al, 1990). Increasing the electrolyte concentration results in compression of the electric diffuse double layer at the clay surface and allows better adsorption of negatively charge PAM to negatively charged clay (Letey, 1994). Treatment with gypsum is done by broadcasting it onto the soil surface. It dissolves during wetting and releases enough Ca^{2+} ions to prevent clay dispersion (Smith et al., 1990).

PAM Interactions with Soil as a Function of Soil Properties

High molecular weight PAM does not penetrate into soil aggregates. The strong adsorption of PAM limits its effectiveness below the soil surface (Nadler et al., 1994). Adsorption is related to soil aggregate size and not to molecular confirmation or electrostatic charge interactions. (Letey, 1994). The results of many experiments suggest this hypothesis, that PAM adsorption occurs mainly on the external surface of the clay packages and not on internal surfaces (Nadler and Letey, 1989; Malik and Letey, 1991; Lentz and Sojka, 1994). The results of these experiments show that polymers do not penetrate into soil aggregates. Testing how soils interact with PAM is more closely related to field interactions than clay-PAM interactions (Letey, 1994).

In contrast to the majority of views dealing with PAM adsorption on the exterior of aggregates, Levy and Miller (1999), hypothesize that large aggregates have internal adsorption. PAM adsorption occur both on outer and inner aggregate surfaces, even though it has been postulated by many that it only stabilizes outer surfaces. If PAM only stabilizes outside surfaces, once an aggregate is broken, dispersion takes place. A study done by Miller et al. (1998) tested soil ground to small aggregates compared to natural aggregates. They found the amount of adsorption did not significantly differ between the two. The fact that similar rates of PAM were adsorbed on small aggregates and on large aggregates suggests that PAM adsorption occurs both on inner and outer aggregate surfaces. Pores in large aggregates were big enough to enable high molecular weight PAM to penetrate into the soil. Levy and Miller (1999), suggest that coarser textured soils have deeper PAM penetration (into soil pores) than clayey soils.

In one study, the larger specific adsorption by illite than by montmorillonite of the PAM shows that the majority of adsorption takes place on the external surface of the clay packages adsorption (Ben-Hur et al., 1992). The interlayer surface area of montmorillonite, which makes up the majority of the measured surface area, was not available for PAM. They also found that the efficacy of anionic PAM for clay flocculation varies with mineralogy (Kaolinite > illite >> quartz), and solution treatment conditions (acid > salt > H_2O > base). Anionic PAM is highly effective in the acid Kaolinite and acid illite systems. (Laird, 1997).

Two studies suggest that PAM efficacy, as a soil conditioner, may not depend on soil mineralogy, but on soil clay content. Research has shown that MW is a key factor on the effectiveness of PAM on coarse textured soils, but not on fine textured soils (Green et al., 2000). PAM efficacy as a soil conditioner may depend on soil texture rather than on soil clay mineralogy (Miller et al., 1998). Green et al. (2000) concluded that the interaction between soil type and PAM formulations appears to be significant and warrants further investigation. The possible use of polymers in soils from humid regions has received very little attention, despite the fact that these soils are susceptible to seal formation and often show poor aggregate stability (Miller et al., 1998).

PAM is also used as a settling agent. When PAM is present in water, it flocculates clay and silt particles dispersed in the water and causes them to settle to the bottom of the solution. The use of PAM will reduce turbidity in stream bottoms (Sojka and Lentz, 1997). Anionic polymers are repelled by the similarly charged clay surfaces and little adsorption occurs in suspension unless an electrolyte source is present (Ben-Hur et al., 1992).

Trout et al., (1995) showed that a large amount of sediment initially carried in irrigation water eventually settled out and deposited in the furrow beds. Once the sediment went into suspension the particles flocculated into larger particles, which eventually deposited on the ground. Shainberg and Singer (1985) found that these deposited particles form a more permeable surface than unflocculated primary particles and microaggregates.

Environmental Issues

PAM has proven to be nontoxic in the environment, and the only concern is its residual monomer acrylamide. PAM exhibits low orders of toxicity to mammalian systems and in studies with humans PAM has shown no association with tumors. Cationic PAMs have been reported as being much more toxic to fish than anionic PAMs, although the addition of food reduced cationic PAM toxicity an order of magnitude (Biesinger et al., 1976). Cationic PAM toxicity was also greatly reduced by constituents in natural waters (Goodrich et al., 1991). Anionic PAM is much less toxic to fish, except when concentrations actually begin to create viscous conditions (McCollister et al., 1965; Seybold, 1994). The toxicities reported for cationic PAMs is in the 1 mg/L range while those for anionic PAMs are 100-1000 times greater, which provides a good safety margin for typical applications.

PAM degradation in soil systems has been shown to be approximately 10% per year and does not lead to the release of acrylamide. Though PAM does not degrade to acrylamide, it is still the major source of acrylamide release into the environment. Residual acrylamide due to polyacrylamide processing is the source of the pollutant. By US law the concentration of acrylamide in PAM cannot exceed 0.05%. Acrylamide is a known neurotoxin to humans and has an LD50 between 110 and 280 mg/kg body weight. It is also biodegradable and does not accumulate in soils (Seybold, 1994). In studies, concentrations of 500 mg acrylamide kg^{-1} soil were reduced to undetectable levels in 5 days. PAM has not been shown to have any negative effects on plant growth or nutrition and is safe to use as a soil amendment (Barvenik, 1994; Sojka and Lentz, 1997).

There are many environmental benefits linked with the use of PAM. Lentz and Sojka, (1994) showed that PAM treatment generally improved the water quality of furrow discharge, or the tailwater from fields. It had lower levels of total phosphorus, nitrates, BOD and sediment compared with controls. Compared with the controls, the PAM treatment reduced losses of ortho-phosphate, nitrates, and BOD by 30%, total-phosphorus by 47% and total sediment by 58%. Decrease in soil erosion from fields increases the retention of valuable fertilizer and pesticide amendments, and maintains the sustainability of the soil. In addition, PAM was found to reduce the movement of microorganisms in runoff water within irrigated furrows (Sojka and Entry, 2000). This finding has implications for movement of harmful microorganisms in many settings, including animal waste and wastewater applications to fields.

Field Tests

At the first test site (I-540 #1), we recorded seven rain events during the 5 week testing period with total rainfall for each event varying from 0.08 to 2.2 cm (Figure 2). Samples were collected and measured for runoff volume and turbidity for the first seven events. Sediment was collected and measured for five rain events, with the two remaining producing insufficient runoff for sampling. The last event on July 27 exceeded 6 cm of rainfall mostly over an eight hour period, resulting in more sediment eroding from the bare plots than the sediment fence could contain within the plot. We did attempt to estimate the erosion rates for that event, however.

Runoff volume, turbidity, and sediment eroded were not affected by the PAM treatments at this site (Figures 3-22). The main effect was the mulch/seed treatment, which substantially reduced runoff and soil erosion. Runoff volumes were reduced by about 25% over the course of the seven events (Fig. 23). The average turbidity level was reduced from 1638 to 634 NTU with the mulch/seed treatment, roughly a 60% decrease (Fig. 24). The turbidities measured were always far greater than the 50 NTU standard currently in place in North Carolina. This suggests that additional treatments will be required even for areas that have been mulched and seeded.

The reductions in sediment losses were quite dramatic, with the bare soil plots having 10 to 20 times the total losses of the mulch/seed plots (Figure 25). The PAM treatments at the higher rates (705) on the bare soil plots may have reduced sediment losses somewhat, but the effect was minor compared to the ground cover treatment. During the testing period the bare plots developed visible channels on the soil surface earlier than the PAM treated plots.

The 6 cm rain received on July 27 overwhelmed the silt fence below the PAM-only plots and the bare plots, causing cross contamination of sediment and runoff between the plots. Plots from both treatments were severely eroded with deep rills. However, since the sediment loads from the bare plots were more than 20 times that of the mulch/seed plots during the previous events, we collected the sediment to estimate losses from those plots. We estimated up to 50 metric or 22 English tons of sediment per hectare was eroded from some of the plots during that single storm (Figs. 26-27). It should be noted that this high intensity rainfall event occurred less than 30 working days after grading, which was the time interval allowed for temporary stabilization to be installed until this year in North Carolina. Current regulations require that temporary stabilization occur within 15 working days. The sediment losses at 15 days, 30 days, and the July 27 event were plotted as an illustration of the impact of these intervals in out specific situation (Fig. 28).

The second I-540 site (I-540 #2) received six rainfall events during our study, ranging from 0.8 cm to 4.2 cm (Fig. 29). Most of the runoff generated at this site occurred during the first storm event on September 24, 2001 (Fig. 30). The amount of runoff during this storm did not follow any expected treatment pattern. In fact, the highest average runoff on this date was from the bare soil plots treated with APS 705 at the high rate. However, this is due to the extremely high runoff from one plot, totaling 3800 m^3/ha. Leaving this plot out brings the average down to 320 m^3/ha, much lower than the untreated bare soil plots. The bare soil plots receiving the high rate of 705 averaged the lowest amount of runoff for the next three events (Figs. 31-33). There were no obvious differences among PAM treatments in the last two events (Figs. 34-35). The total runoff volume for these plots was largely controlled by the first event, which accounted for 50-95% of the total volume for all six events (Fig. 36). As was found at the first site, the mulch/seed treatment resulted in significant reductions in runoff volume, averaging less than one-third as much water.

Among the bare soil plots, turbidity was reduced with the 705 treatments for most of the storm events, particularly for the 11.2 kg/ha rate (Figs. 37-42). The mulch/seed treatment plots did not appear to respond to the PAM treatments in any discernable pattern. The average turbidity was reduced roughly 50% with the 11.2 kg 705/ha treatment compared to the untreated control in the bare soil plots (Fig. 43). The effectiveness of this treatment appeared to decline over time, with very little difference between the control and the treated plots after the third event (Fig. 44). However, the turbidity levels were quite high even in the best bare soil treatment, averaging over 1300 NTU. The mulch/seed treatment reduced average turbidity from 2272 NTU on the bare soil plots to 182 NTU. This is still considerably higher than the maximum of 50 NTU allowable under current regulations, but a >90% reduction is still a considerable achievement through conventional mulch and seed treatment.

Sediment losses over the first three events were collected after the October 14 event. There were no effects apparent with the PAM treatments on the bare soil plots through the first three events (Fig. 45). The Soilfix treatments on the mulch/seed plots did reduce sediment losses during this same time period, with the high rate reducing losses from 2445 kg/ha on the control plots to 138 kg/ha for the 1.68 kg Soilfix/ha treatment plots. The bare soil plots treated with 705 had much less sediment loss during the November 25 event, but no PAM effects were evident after the next two events (Figs. 46-48). By this time, the ground cover had become established and the resulting sediment losses were very small or impossible to measure. The December 11 event of 4.0 cm produced >4,000 kg/ha on the bare soil plots but only 0-25 kg/ha on the mulch/seed plots.

The total sediment loss among the bare soil treatments did not reflect substantial differences with either PAM at either rate (Fig. 49). The Soilfix treatments did reduce total sediment losses in the mulch/seed plots when compared to the untreated control. The mulch/seed treatment did reduce total sediment loss by 90% compared to the bare soil average.

We dropped the low PAM rates when we established the Fayetteville site since we had seen little response to these in the previous work. We had seven rainfall events ranging from 0.5 cm to 3.4 cm (Fig. 50). Runoff volumes were considerably lower at this site compared to the I-540 sites, most likely due to the relatively sandy soil and high infiltration rates (Figs. 51-57). The only treatment that appeared to result in less runoff was the 705 + mulch seed treatment, which had the least runoff for six of seven events. The differences between the bare soil and mulch/seed treatments was not as dramatic as prior tests, with the bare soil plots averaging 39 m^3/ha and the mulch/seed plots averaging 33 m^3/ha (Fig. 58).

The turbidity levels were also much lower at the Fayetteville site compared to the Raleigh site. There was no clear treatment pattern for the first two events (Fig. 59-60), but the mulch/seed treatment reduced turbidity substantially for the remaining events (Figs. 61-65). As the ground cover became established the differences between bare soil and mulch/seed treatments widened. The average turbidity was substantially lower with the mulch/seed treatment compared to bare soil, but there was no effect of either PAM treatments (Fig. 66).

Sediment losses at the Fayetteville site closely followed the patterns of the turbidity levels. Initial losses did not follow any treatment pattern (Figs 67-68), but the mulch/seed treatment steadily decreased losses compared to bare soil as the ground cover became established (Figs. 69-72). The total amount of sediment from the bare soil plots was roughly 20 times that of the mulch/seed plots (Fig. 73). These losses were an order of magnitude lower than were measured at the Raleigh site.

We also tested Soilfix at a much higher rate (20 kg/ha) applied onto plots leveled and smoothed after the last storm even on February 8, 2002. In comparison to untreated bare soil plots, the turbidity from the treated plots was actually higher for two of three events monitored (Figs. 74-76). This was likely the result of differences between the soil properties rather than actual treatment effects, but certainly indicated that this PAM treatment was ineffective on this soil.

After collecting data from the three test sites, we decided to further study some of the effects we discovered under the more controlled conditions of a rainfall simulator. In particular, we were interested in the effects of PAM on infiltration and in the longevity of PAM treatment effects. One measure of the infiltration rate is the time between rainfall simulation initiation and when runoff first begins. Both PAM treatments delayed runoff initiation compared to the control during the first event of 16 minutes at 3.7 cm/hour (Fig. 77, solid bar). However, there were no differences between time of runoff initiation when the test was conducted again the next day. This suggested that the effect of the PAM treatment was removed during the first event. We then reapplied the PAM treatments to the same soil boxes and ran a third test. This resulted in a delay in runoff initiation again compared to the untreated soil, although the times were lower than the first test because the soil was much wetter.

The volume of runoff was also reduced with the PAM treatments during the first event after application and was then similar during the second rainfall simulation (Fig. 78). The reapplication of PAM reduced runoff volume for the Soilfix treatment but not the 705 treatment. TSS was reduced after the first application and showed no response to PAM treatment during the second rainfall simulation (Fig. 79). However, the reapplication of PAM dramatically reduced TSS in the runoff.

We repeated these tests using the same treatments and soil, although we did not do a second PAM application. The first 15-minute rainfall simulation resulted in no runoff from either of the Soilfix-treated soils and from one of the 705-treated soils. As a result, the 705 results are an average of 0 and the remaining soil box. The Soilfix treatment increased the time to runoff initiation even during the second rainfall simulation, suggesting that it was still effective during this test (Fig. 80). 705 reduced volume during the first event but much less so during the second event (Fig 81). Less than half of the volume ran off the Soilfix-treated soil after the second event compared to the untreated control. TSS was also reduced by both treatments after the second event (Fig. 82).

This site also had a borrow pit which was being dewatered by pumping into a stilling basin. The turbidity levels in the stilling basin were not dropping significantly by the time the water exited the rock dam. We conducted preliminary tests of flocculants on this water and determined that the APS 740 polyacrylamide was suitable for this sediment source. The polyacrylamide was applied to the inside of 8” corrugated pipe as a dispensing mechanism as the pumped water was routed through the pipe. A small rock pad was constructed at the pipe exit to protect the basin walls as well as to mix the flocculent and water.

The turbidity levels at the pipe exit remained quite high for several weeks after initiating this test, with little difference between the pipe exit and the basin outlet (Fig. 83). This site is usually quite windy and we examined potential relationships between wind speed at a weather station in Clinton and turbidity, but there was no apparent relationship. The turbidity levels dropped to below 100 NTU for about a week and then began to rise again. The erratic nature of the turbidity was likely a reflection of the location of the pump inlet, which floated freely. At the end of this study, it had lodged on the side of the borrow pit and pulled up large amounts of sand, burying our sampler intake.

There was clear evidence of flocs in the sample bottles, so we started taking measurements prior to shaking the bottles. We normally shake a sample from field sites prior to measuring turbidity to avoid any settling which occurred after sampling. The turbidity levels in the non-shaken bottles were very low for about a two-week period (Fig. 84). This was a considerable reduction compared to the non-shaken borrow pit samples from the same time period, taken when we recovered the samplers from the automatic sampler. The turbidity levels in the pit and in the basin begin to converge toward the end, likely because the flocculent in the pipe had fully dissolved.

PAM/Sediment Interactions

Our preliminary screening tests were performed using a range of 0.5, 1.0, and 2.0 mg/L (0.03, 0.06, and 0.12 lb/1,000 ft^3) with turbidity measurements taken at 0, 30, and 60 minutes plus 24 hours (Fig. 85). After evaluating the initial data, we concluded that these concentrations did not capture the responses at lower doses, so we greatly expanded the number of tests at concentrations below 0.5 mg/L. We also concluded that the initial readings taken at 30 s after mixing provided a greater indication of turbidity reductions than any later readings. In fact, for many sediment sources, the turbidity at 24 h was similar regardless of treatment. Because there is virtually no turbulence in the sample container, these readings do not reflect typical field situations. It does point out the influence of turbulence in keeping sediment suspended under field conditions.

The screening results for the 11 PAMs and 13 sediment sources can be evaluated in a number of ways. The simplest approach is to select the PAM which resulted in the greatest decrease in turbidity across all concentrations tested (Table 4). For some sediment sources, the best PAM reduced turbidity by up to 99% at the optimal concentration. However, the Coastal Plain soils were somewhat recalcitrant to PAM treatment, with less than a 50% reduction in some cases. Overall, the A-100 material was the top performer in five sediment sources.

When the actual averages for each PAM are presented for each sediment source, it becomes obvious that often several of the PAMs performed similarly (Table 5). The few percentage points difference is not significant in practical applications. The A-100 material was either the most effective or nearly so in all but the 1279S sediment source. This PAM has the lowest charge density, 7%, among those for which we have information.

Another measure of PAM/sediment interactions is the relationship between PAM concentration and turbidity reduction. For most PAM/sediment source combinations, the turbidity dropped consistently with increasing concentrations (Fig. 86). In the case of 1337B, for example, some of the PAMs did not reduce turbidity until the concentrations of 0.25-0.5 mg/L. Others had a linear response and appeared to have the potential for further turbidity reductions at higher concentrations, judging by the continuing drop up to the highest concentration (2 mg/L). The 923 VHM material may have reached the highest optimal dose at 1 mg/L, since there was no decrease at the 2 mg/L dose.

The slope of the dose response curve was determined for each PAM/sediment combination as an indication of the rate of decline with increasing dose (Table 6). This does not measure efficiency or optimal dose, but is an indicator that the PAM is interacting significantly with the sediment source. Ideally, the PAM concentration range would extend to the point of no response (flattening) for all of the PAMs, but we did not achieve this on many of the tests.

The best PAMs for each sediment source were selected from the initial screening to conduct further, replicated tests. The responses of each sediment source followed different patterns as the PAM concentrations were increased. Seven of the sources had a general decline in turbidity as the concentration increased (Figs. 87-93). Some of these responded similarly to the PAMs in the tests (0540, 0977, 1279, 1337, 1495), while others had a wider variation in turbidity reductions (0326, 0644). The concentrations tested exceeded the level needed for maximum turbidity reduction for four of the sediment sources (0326, 0644, 0977, 1279, 1495). It is possible further turbidity reductions could have been achieved on the remaining two, although the turbidity levels in the 0540 samples was already well below 50 NTU.

Two of the sediment sources, 0111 and 0434, had little turbidity reduction with increasing PAM concentrations (Figs. 94-95). There is no obvious relationship between these two soils, having widely different Ca concentrations, pH, and SAR (Table 7). It is possible other PAMs not included in our testing may have been more effective.

Three of the sediment sources (0215, 0749, 1177) produced a marked increase in turbidity when the concentration of PAM exceeded 0.5 mg/L (Figs. 96-98). There appears to be a reaction in these systems in which the PAM begins to react to itself instead of the sediment, reducing its effectiveness. This suggests that the use of PAM with these sediment sources would require careful dosing to obtain the optimal turbidity control.

The 0858 sediment was somewhat different than the others in that there was little response to the PAMs until the highest concentrations were used (Fig 99). Once those concentrations were exceeded, the reduction in turbidity was rapid and then leveled off above 1 mg/L. Testing above that concentration may have revealed an increase in turbidity, but we did not conduct those tests.

Overall, the turbidities at 30 s for the optimal concentration of PAM were usually much higher than the 50 NTU maximum currently targeted. This does not mean that this level cannot be achieved in the field, since mixing and contact time as well as physical barriers can enhance PAM effectiveness. It is clear that PAM can substantially reduce turbidity below current levels in discharged runoff.

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Figure 39. Turbidity of runoff from the treatment plots, from the October 7 event on Site #2 of I-540.

Figure 40. Turbidity of runoff from the treatment plots, from the October 14 event on Site #2 of I-540.

Figure 41. Turbidity of runoff from the treatment plots, from the November 25 event on Site #2 of I-540.

Figure 42. Turbidity of runoff from the treatment plots, from the December 11 event on Site #2 of I-540.

Figure 43. Turbidity of runoff from the treatment plots, from the December 17 event on Site #2 of I-540.

Figure 44. Average turbidity of runoff collected between September 24 and December 17 on Site #2 of I-540.

Figure 45. Turbidity of runoff taken between events of September 24 to December 17 on plots of soil that are bare in comparison to those that have had flocculent applied to them on Site #2 of I-540.

Figure 46. Sediment losses on each plot in kg/ha from October 14 event on Site #2 of I-540.

Figure 47. Sediment losses on each plot in kg/ha from November 25 event on Site #2 of I-540.

Figure 48. Sediment losses on each plot in kg/ha from December 11 event on Site #2 of I-540.

Figure 49. Sediment losses on each plot in kg/ha from December 17 event on Site #2 of I-540.

Figure 50. Total sediment losses on each plot in kg/ha between September 24 and December 17 on Site #2 of I-540.

Figure 51. Applying PAM at highest rate (20 kg/ha) at the Fayetteville I-95 site.

Figure 52. Seven precipitation events that occurred between December 17 and February 7 on the Fayetteville I-95 loop site.

Figure 53. Runoff collected from the treatment plots on I-95, from the December 17 event.

Figure 54. Runoff collected from the treatment plots on I-95, from the January 9 event.

Figure 55. Runoff collected from the treatment plots on I-95, from the January 14 event.

Figure 56. Runoff collected from the treatment plots on I-95, from the January 21 event.

Figure 57. Runoff collected from the treatment plots on I-95, from the January 23 event.

Figure 58. Runoff collected from the treatment plots on I-95, from the January 25 event.

Figure 59. Runoff collected from the treatment plots on I-95, from the February 8 event.

Figure 60. Total runoff collected from the treatment plots on I-95, between December 17 and February 8.

Figure 61. Turbidity of runoff from the treatment plots, from the December 17 event on I-95 Fayetteville.

Figure 62. Turbidity of runoff from the treatment plots, from the January 9 event on I-95 Fayetteville.

Figure 63. Turbidity of runoff from the treatment plots, from the January 14 event on I-95 Fayetteville.

Figure 64. Turbidity of runoff from the treatment plots, from the January 21 event on I-95 Fayetteville.

Figure 65. Turbidity of runoff from the treatment plots, from the January 23 event on I-95 Fayetteville.

Figure 66. Turbidity of runoff from the treatment plots, from the January 25 event on I-95 Fayetteville.

Figure 67. Turbidity of runoff from the treatment plots, from the February 8 event on I-95 Fayetteville.

Figure 68. Average turbidity of runoff collected between December 17 and February 8 on I-95 Fayetteville.

Figure 69. Sediment losses on each plot in kg/ha from December 17 event on I-95 Fayetteville.

Figure 70. Sediment losses on each plot in kg/ha from January 14 event on I-95 Fayetteville.

Figure 71. Sediment losses on each plot in kg/ha from January 21 event on I-95 Fayetteville.

Figure 72. Sediment losses on each plot in kg/ha from January 23 event on I-95 Fayetteville.

Figure 73. Sediment losses on each plot in kg/ha from January 25 event on I-95 Fayetteville.

Figure 74. Sediment losses on each plot in kg/ha from February 8 event on I-95 Fayetteville.

Figure 75. Total sediment losses on each plot in kg/ha between December 17 and February 8 on I-95 Fayetteville.

Figure 76. After first storm on March 3 after the second application of PAM was applied to the Fayetteville I-95 site.

Figure 77. After second storm on March 21 after the second application of PAM was applied to the Fayetteville I-95 site.

Figure 78. After third storm on March 31 after the second application of PAM was applied to the Fayetteville I-95 site.

Figure 79. Minutes after initiation of rain that runoff began with rainfall simulation tests of 3.7 cm of rain per hour for 15 to 16 minutes on March 27 and 28, and April 5.

Figure 80. Total runoff volume measured from each plot after rainfall simulation tests were run on March 27 and 28, and April 5.

Figure 81. Total suspended solids in runoff calculated from each plot after rainfall simulation tests were run on March 27 and 28, and April 5.

Figure 82. Time before runoff occurred once the rainfall simulation test started on each plot on April 12 and April 15.

Figure 83. Total runoff volume measured from each plot after rainfall simulation tests were run on April 12 and April 15.

Figure 84. Total suspended solids in runoff calculated from each plot after rainfall simulation tests were run on April 12 and April 15.

Figure 85. Turbidity in stilling basin after PAM treatment, samples were shaken before the readings were taken.

Figure 86. Turbidity in stilling basin after PAM treatment, samples were not shaken before the readings were taken.

Figure 87. Effects of time on differences between PAM concentrations of A-100 applied to soil 0749.

Figure 88. PAM concentration effects on the sediment source 1337b.

Figure 89. PAM concentration effects on the sediment source 0326b.

Figure 90. PAM concentration effects on the sediment source 0540p.

Figure 91. PAM concentration effects on the sediment source 0644s.

Figure 92. PAM concentration effects on the sediment source 0977p.

Figure 93. PAM concentration effects on the sediment source 1279s.

Figure 94. PAM concentration effects on the sediment source 1337b.

Figure 95. PAM concentration effects on the sediment source 1495s.

Figure 96. PAM concentration effects on the sediment source 0111t.

Figure 97. PAM concentration effects on the sediment source 0434b.

Figure 98. PAM concentration effects on the sediment source 0215b.

Figure 99. PAM concentration effects on the sediment source 0749b.

Figure 100. PAM concentration effects on the sediment source 1177p.

Figure 101. PAM concentration effects on the sediment source 0858b.

Table 1. Treatments for I-540 Sites #1 and #2.

PAM	Rate, kg/ha (lbs/ac)	Straw mulch/seed
Soilfix	0.84 (0.75)	No
Soilfix	0.84 (0.75)	Yes
Soilfix	1.68 (1.5)	No
Soilfix	1.68 (1.5)	Yes
Silt Stop 705	5.6 (5)	No
Silt Stop 705	5.6 (5)	Yes
Silt Stop 705	11.2 (10)	No
Silt Stop 705	11.2 (10)	Yes
None	n/a	No
None	n/a	Yes

Table 2. PAMs used in laboratory screening study.

Source	Name	Available Description
Applied Polymer Systems	702aa	Anionic
Applied Polymer Systems	730b	Anionic
Applied Polymer Systems	702b	Anionic
Applied Polymer Systems	702c	Anionic
Cytec	SF-1606	Anionic, 30% c.d., very high m.w.*
Cytec	A-150 HMW	Anionic, 50% c.d., very high m.w.
Chemtall	923-VHM	Anionic, 20% c.d., very high m.w.
Cytec	A-150	Anionic, 50% c.d., very high m.w.
Cytec	A-100	Anionic, 7% c.d., high m.w.
Cytec	N-300	Neutral , high m.w.
Ciba Specialty Chemicals	Soilfix	Anionic, 30% charge, med. m.w.

***c.d.= charge density, m.w.=molecular weight**

Table 3. Characteristics of the 13 sediments used in this study.

Soil	Texture	Mineralogy*	Ca (ppm)	Mg (ppm)	pH	SAR[+]
0111t	sand		3.82	2.4	6.59	0.82
0215b	sandy loam		121.7	24.4	4.41	0.33
0326b	sand		19.8	11	6.47	0.40
0434b	loamy sand	mixed (kaolinite, vermiculite)	268.5	3.6	3.55	0.16
0540p	clay	kaolinte	28.3	6.9	3.92	0.47
0644s	sandy clay loam		32	12.4	2.79	0.38
0749b	sandy loam	mixed (kaolinite, vermiculite)	6.7	2.8	4.49	0.87
0858b	sandy loam		14.9	5	3.53	1.56
0977p	sandy loam	mixed (kaolinite, mica)	13.2	5.3	4.57	0.46
1177p	sandy loam		4.7	1.4	3.96	1.87
1279s	clay loam		128.4	4.5	4.22	0.46
1337b	clay loam	kaolinte	5.9	2.1	3.76	0.71
1495s	clay loam		3.82	2.4	3.88	0.82

*****Test completed on 5 soils only.
+Sodium Absorption Ratio (Na/(Ca+Mg))

Table 4. Summary of PAM/Sediment screening tests.

Sediment Source (North Carolina)	Designation	Initial Turbidity (30 sec)	Best Flocculent*(avg. reduction %)	Range Across Rates (% reduction)
SW Mountains	1495S	1691	A-100 (64%)	12-95%
Central Mountains	1337B	1596	A-100 (57)	17-94
Southern Foothills	1279S	1429	1606 (56)	25-99
NW Mountains	1177P	3449	A-100 (82)	51-91
NW Piedmont	0977P	1401	A-100 (75)	59-98
Southern Piedmont	0858B	1712	923 VHM (46)	1-93
Northern Piedmont	0749B	3075	Soilfix (86)	68-91
Southern Coastal Plain	0644S	3978	A-100 (44)	6-97
NE Piedmont	0540P	1745	1606 (62)	24-99
Upper Coastal Plain	0434B	1508	A-100 (49)	14-48
Southern Coastal Plain	0326B	265	923 VHM (45)	15-62
Central Coastal Plain	0215B	818	A-100 (53)	29-65
Northern Coastal Plain	0111T	247	1606 (32)	17-38

* Reduction rates are an average of all rates tested for a given flocculent

Table 5. Average turbidity reduction of 11 PAMs on 13 sediment sources. Averages are for all concentration levels tested. The greatest reductions within each sediment source is bolded.

% Reduction	**1495S**	**1337B**	**1279S**	**1177P**	**0977P**	**0858B**	**0749B**	**0644S**	**0540P**	**0434B**	**0326B**	**0215B**	**0111T**
702aa	36	8	18	28	47	13	48	16	41	13	-2	20	15
702b	18	33	47	35	46	34	41	15	34	36	19	35	10
702c	16	-11	25	51	59	23	36	5	24	22	30	18	-37
730b	30	27	40	53	53	6	38	3	1	18	31	-2	7
923 VHM	32	6	49	80	69	**46**	79	31	11	22	**45**	26	3
Soilfix	58	41	**69**	53	**75**	29	**86**	30	52	16	-13	27	21
Superfloc 1606	52	37	56	81	46	26	75	28	**62**	10	38	49	**33**
Superfloc A-100	**64**	**57**	36	80	68	40	78	**44**	53	**49**	42	**53**	28
Superfloc A-150	44	45	44	**82**	42	28	50	-11	21	6	18	7	6
Superfloc A-150 HMW	47	34	43	50	30	8	58	2	40	9	18	45	6
Superfloc N-300	40	40	42	48	48	37	40	20	49	29	7	28	26

Table 6. Slope values for turbidity responses to increasing concentration for 11 PAMs and 13 sediment sources. The steepest slopes, or most responsive PAM, for each sediment source is bolded.

SLOPE	**1495S**	**1337B**	**1279S**	**1177P**	**0977P**	**0858B**	**0749B**	**0644S**	**0540P**	**0434B**	**0326B**	**0215B**	**0111T**
702aa	-29	-42	-32	-47	-32	-43	-33	-32	-42	-31	-20	-31	-17
702b	-46	-33	-25	**-49**	-39	-49	-44	-49	-41	**-38**	-25	-44	-16
702c	-49	-67	-41	-46	-37	-41	-55	-58	-44	-30	-23	-38	**-36**
730b	-53	-36	-37	-43	-40	-33	**-57**	-14	-68	-7	-21	-10	-5
923 VHM	**-55**	**-90**	-42	-6	-35	-47	-20	-55	**-74**	-24	-20	-40	-17
Soilfix	-40	-46	**-69**	-35	-51	-47	-14	**-57**	-42	-26	-31	-24	-10
Superfloc 1606	-41	-53	-40	-10	**-65**	**-58**	-22	-56	-38	-27	-16	-18	-9
Superfloc A-100	-36	-37	-46	-3	-26	-46	-26	-53	-39	-12	**-33**	-39	-15
Superfloc A-150	-48	-47	-49	-20	-53	-54	-45	-19	-64	-18	-27	-14	-11
Superfloc A-150 HMW	-48	-54	-51	-34	-35	-44	-33	-53	-53	-37	-22	**-48**	-11
Superfloc N-300	-41	-44	-43	-48	-51	-46	-47	-53	-40	-37	-21	-31	-32

Table 7. Ranking of PAMs for average turbidity reduction for each sediment.

Rank	1495S	1337B	1279S	1177P	0977P	0858B	0749B
1	A-100	A-100	Soilfix	A-150	Soilfix	923 VHM	Soilfix
2	Soilfix	A-150	1606	1606	923 VHM	A-100	923 VHM
3	1606	Soilfix	923 VHM	923 VHM	A-100	N-300	A-100
4	A-150 HMW	N-300	702b	A-100	702c	702b	1606
5	A-150	1606	A-150	730b	730b	Soilfix	A-150 HMW
6	N-300	A-150 HMW	A-150 HMW	Soilfix	N-300	A-150	A-150
7	702aa	702b	N-300	702c	702aa	1606	702aa
8	923 VHM	730b	730b	A-150 HMW	1606	702c	702b
9	730b	702aa	A-100	N-300	702b	702aa	N-300
10	702b	923 VHM	702c	702b	A-150	A-150 HMW	730b
11	702c	702c	702aa	702aa	A-150 HMW	730b	702c

	0644S	0540P	0434B	0326B	0215B	0111T
1	A-100	1606	A-100	923 VHM	A-100	1606
2	923 VHM	A-100	702b	A-100	1606	A-100
3	Soilfix	Soilfix	N-300	1606	A-150 HMW	N-300
4	1606	N-300	923 VHM	730b	702b	Soilfix
5	N-300	702aa	702c	702c	N-300	702aa
6	702aa	A-150 HMW	730b	702b	Soilfix	702b
7	702b	702b	Soilfix	A-150 HMW	923 VHM	730b
8	702c	702c	702aa	A-150	702aa	A-150 HMW
9	730b	A-150	1606	N-300	702c	A-150
10	A-150 HMW	923 VHM	A-150 HMW	702aa	A-150	923 VHM
11	A-150	730b	A-150	Soilfix	730b	702c

Figure 1. Plot layout at the Raleigh I-540 Site #1

Figure 2: Rain Events - I-540 #1

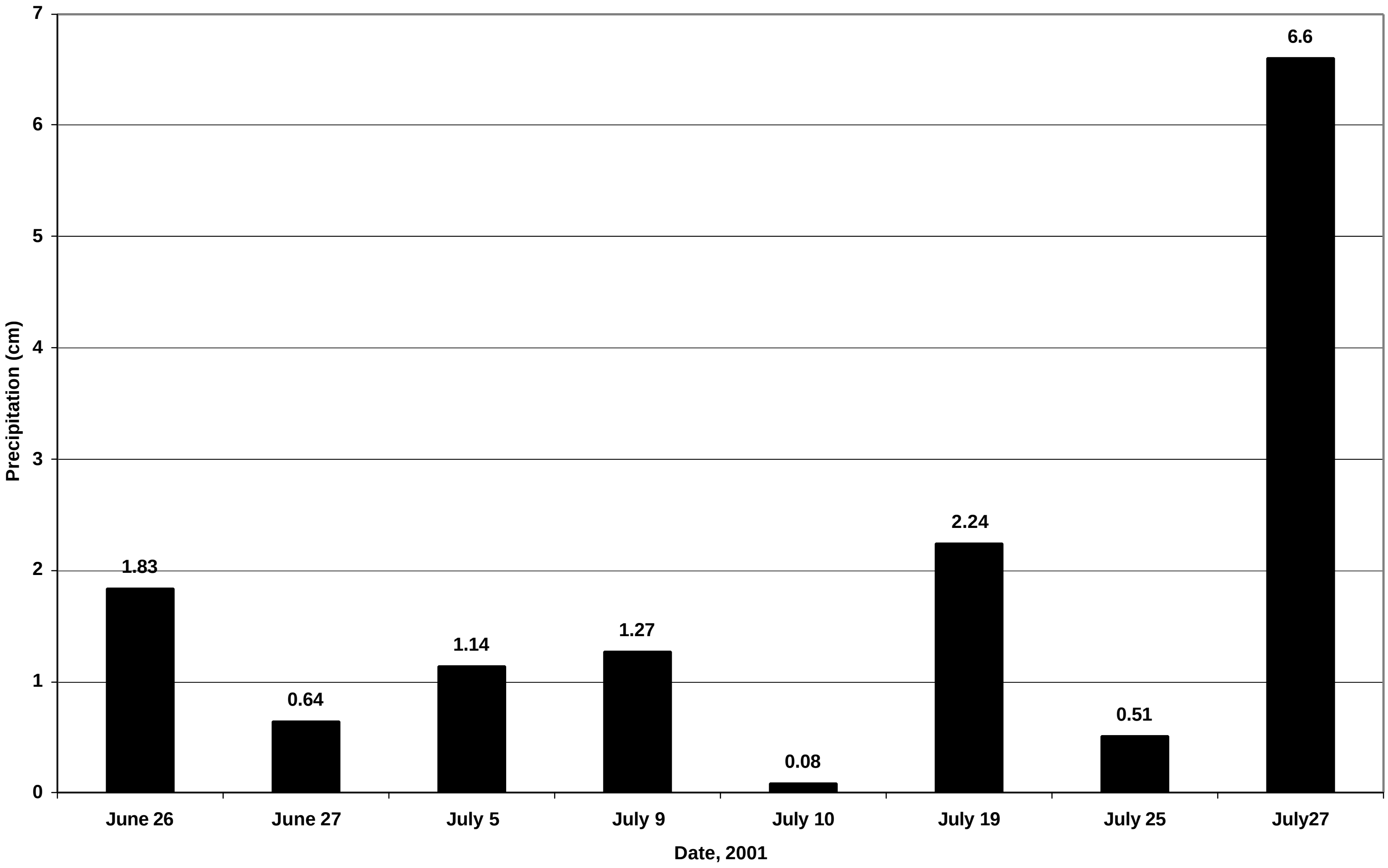


Figure 3: June 26 Runoff
I-540 #1

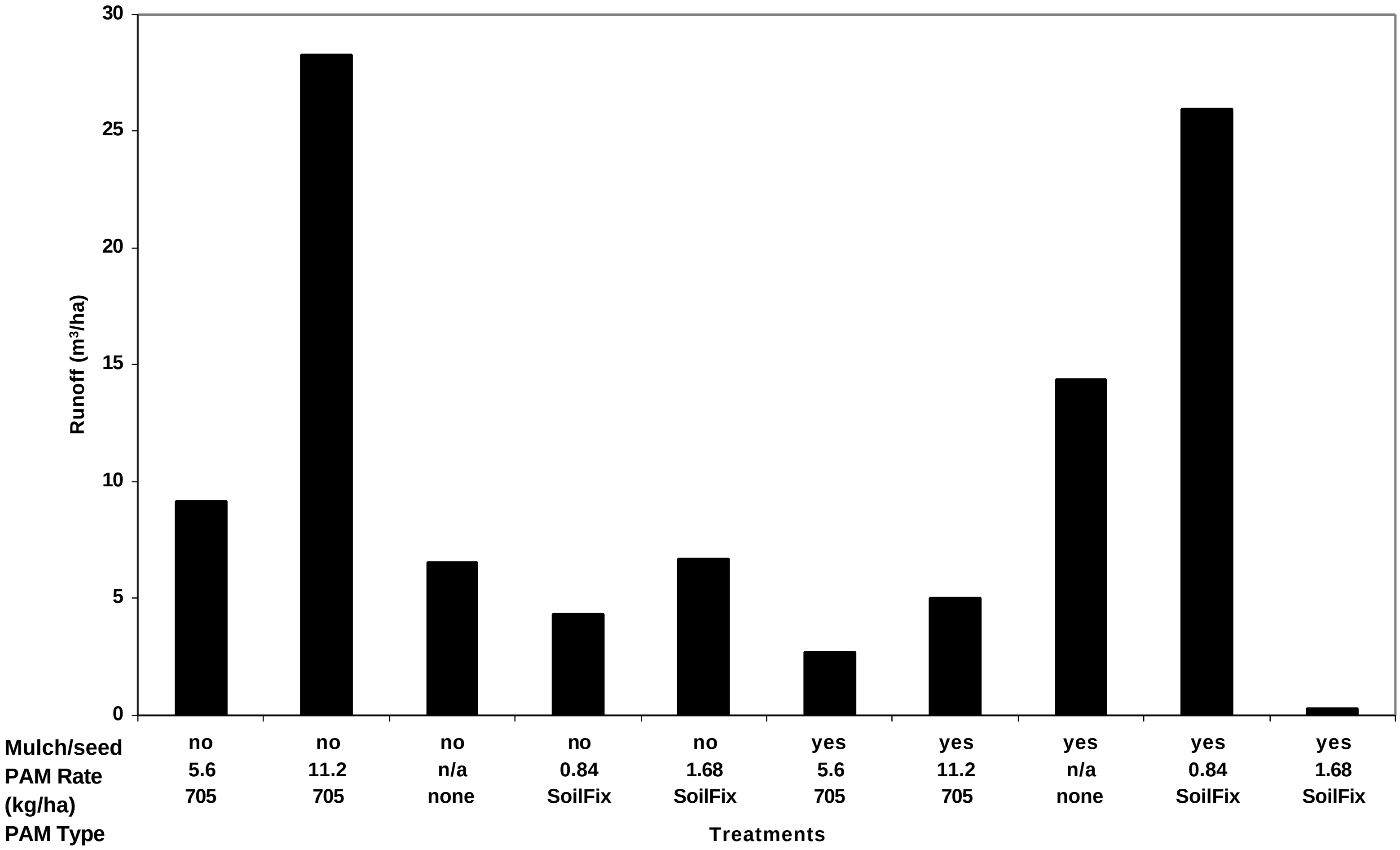


Figure 4: June 27 Runoff
I-540 #1

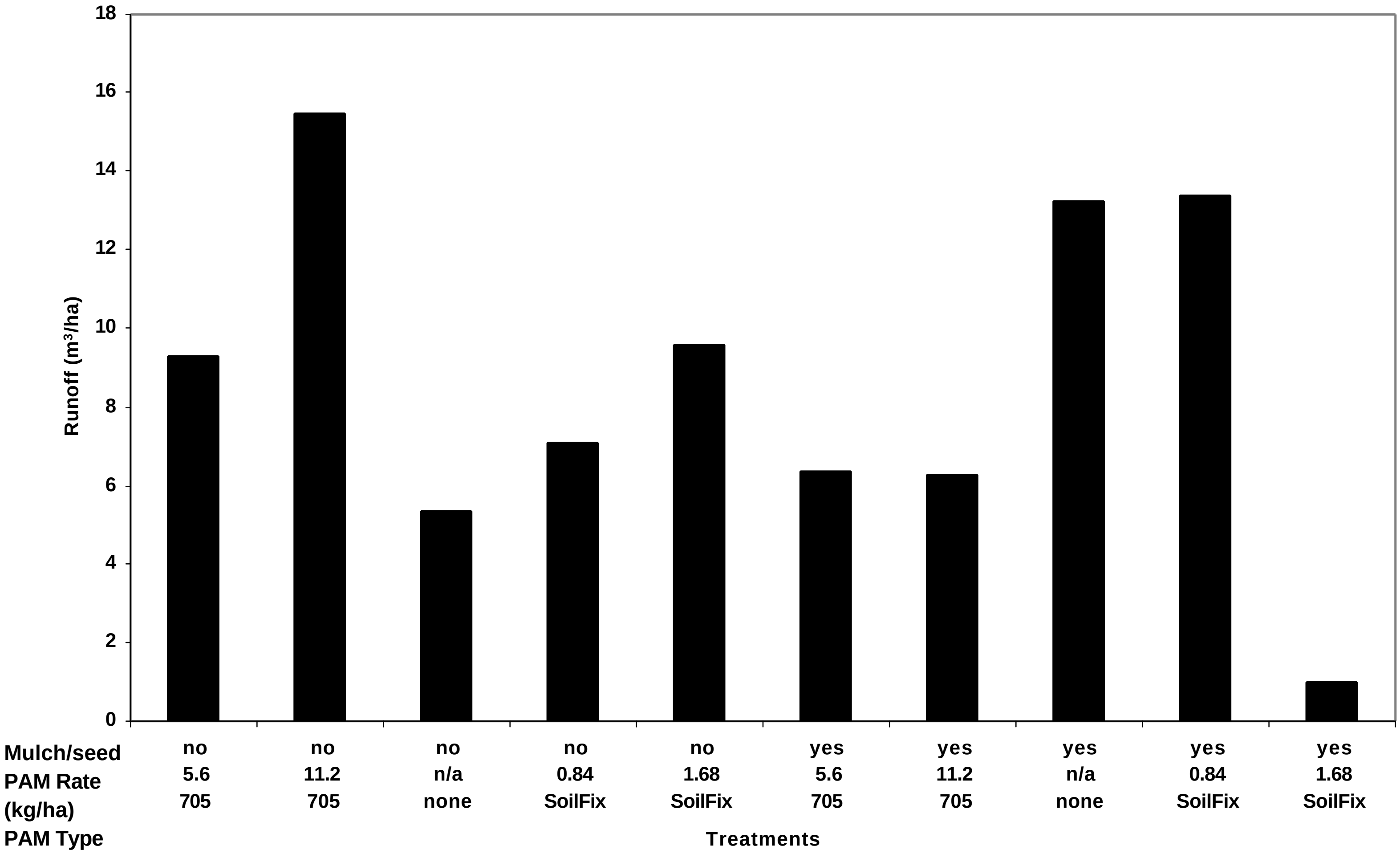


Figure 5: July 5 Runoff
I-540 #1

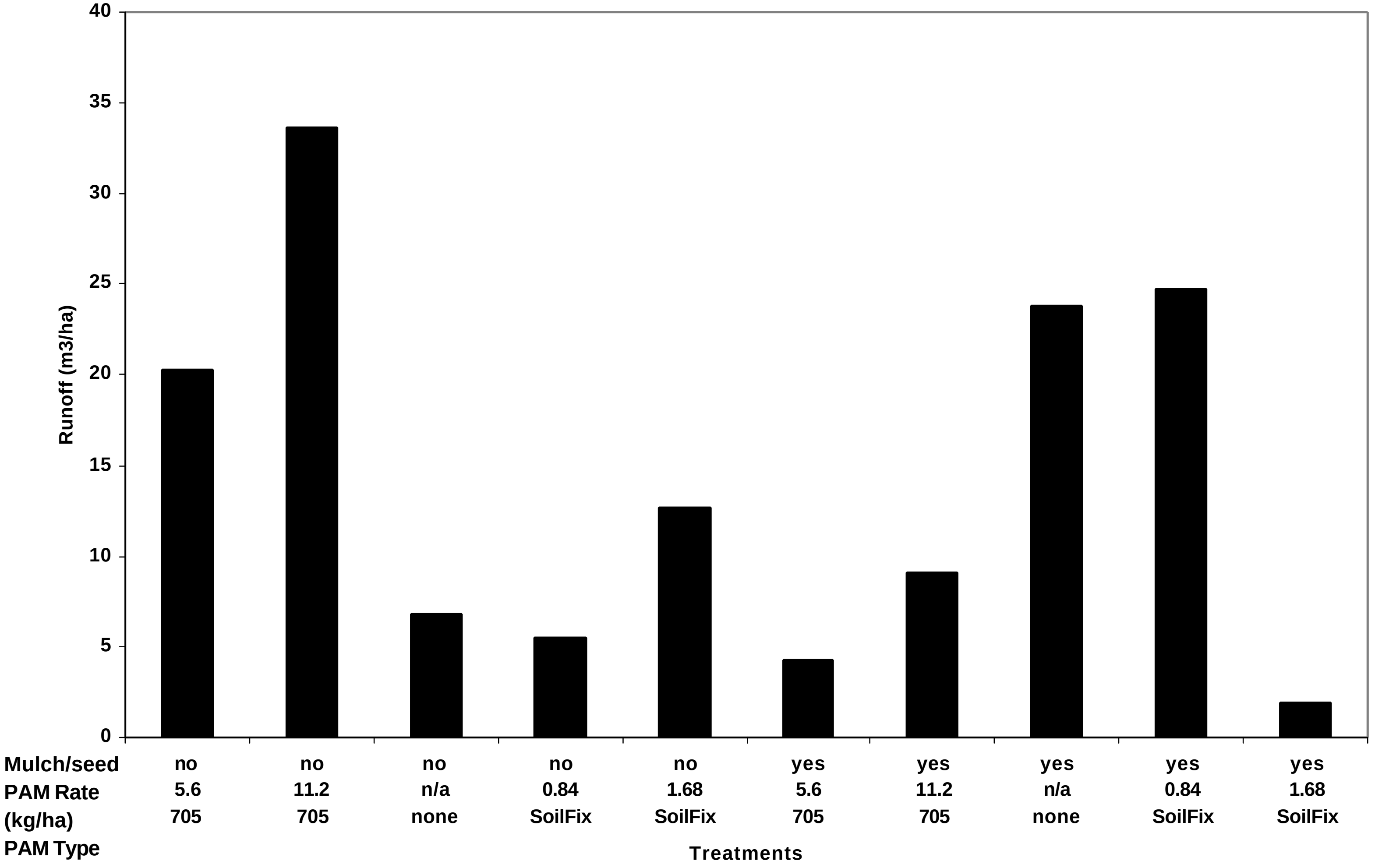
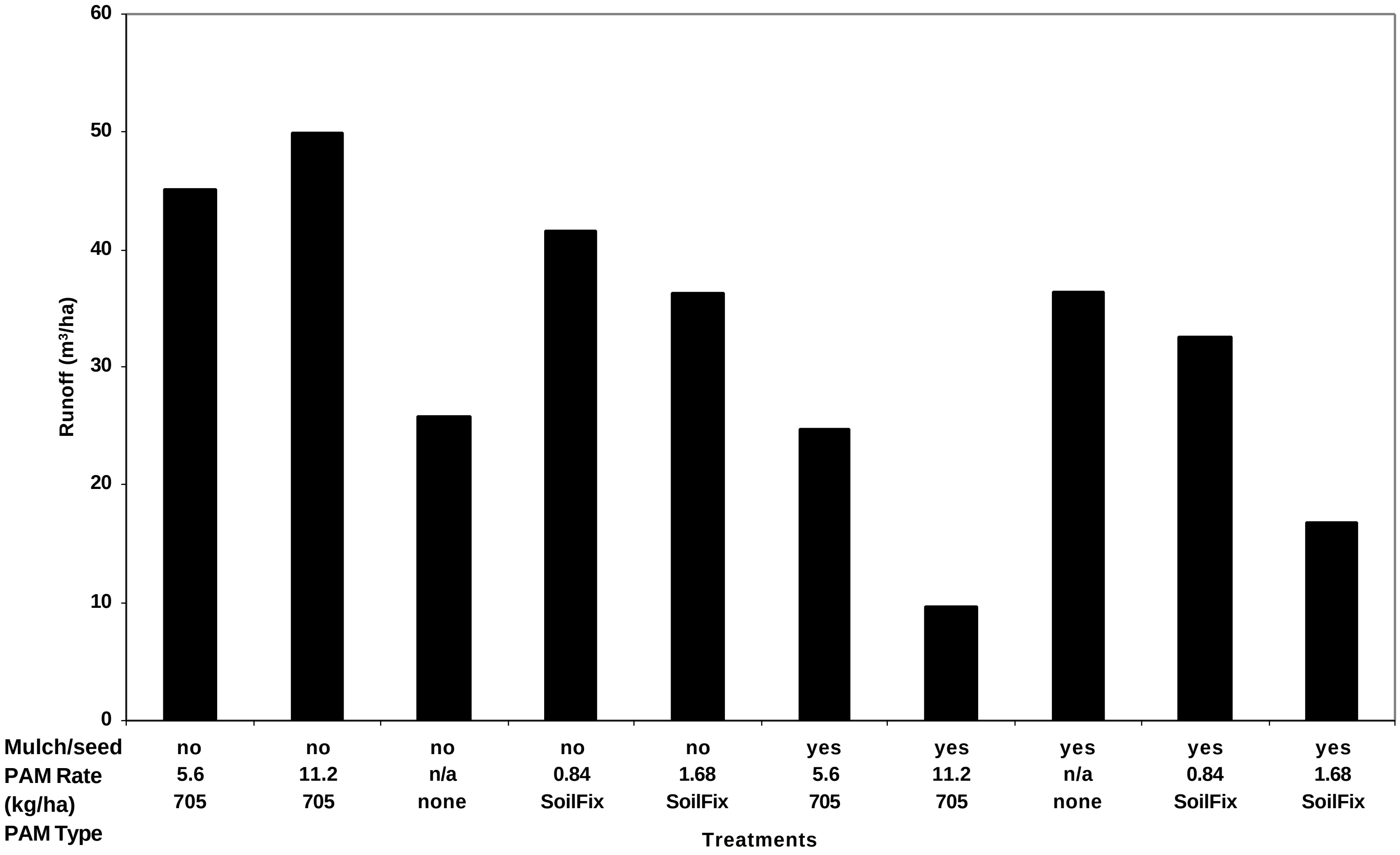


Figure 6: July 9 Runoff
I-540 #1



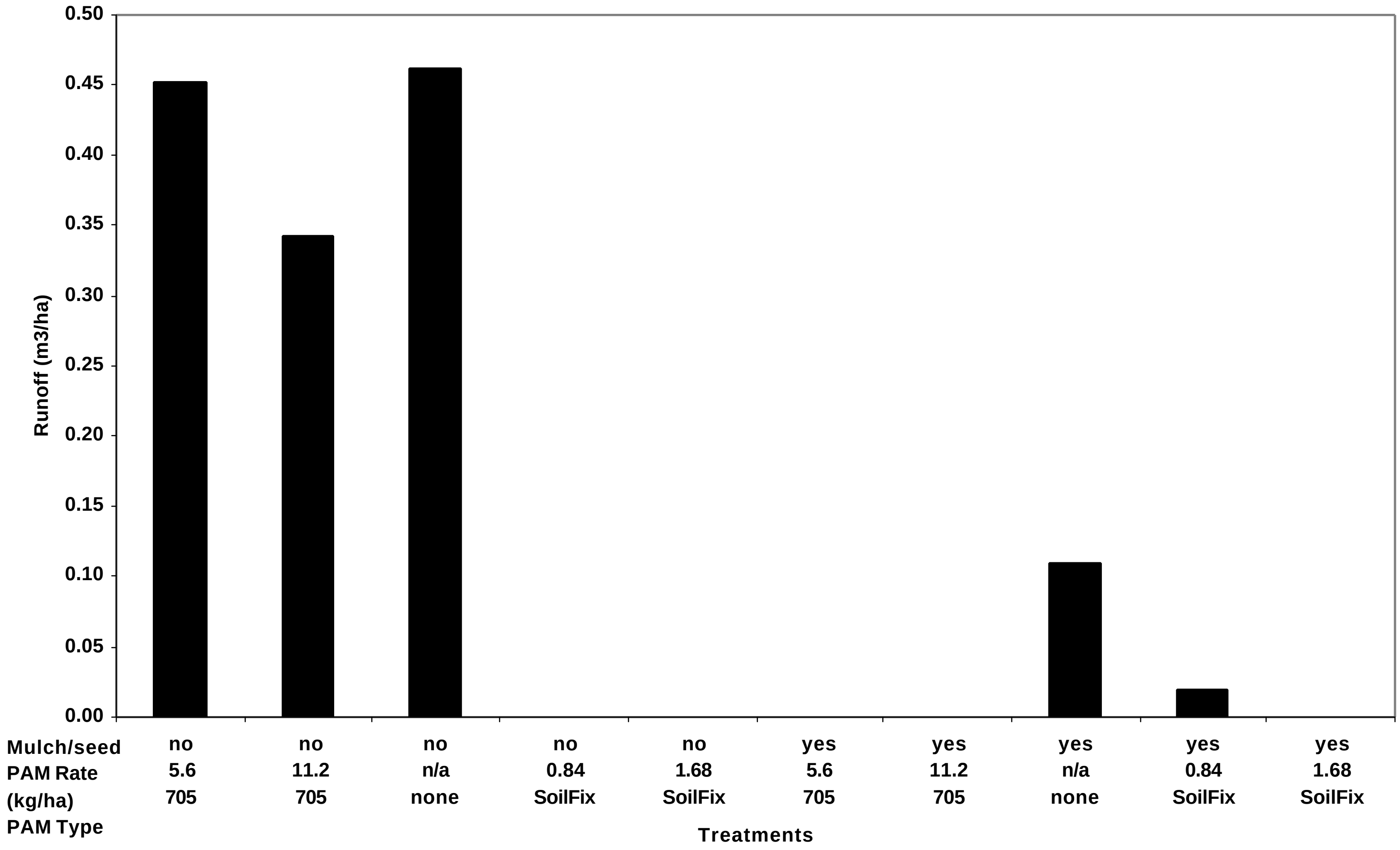
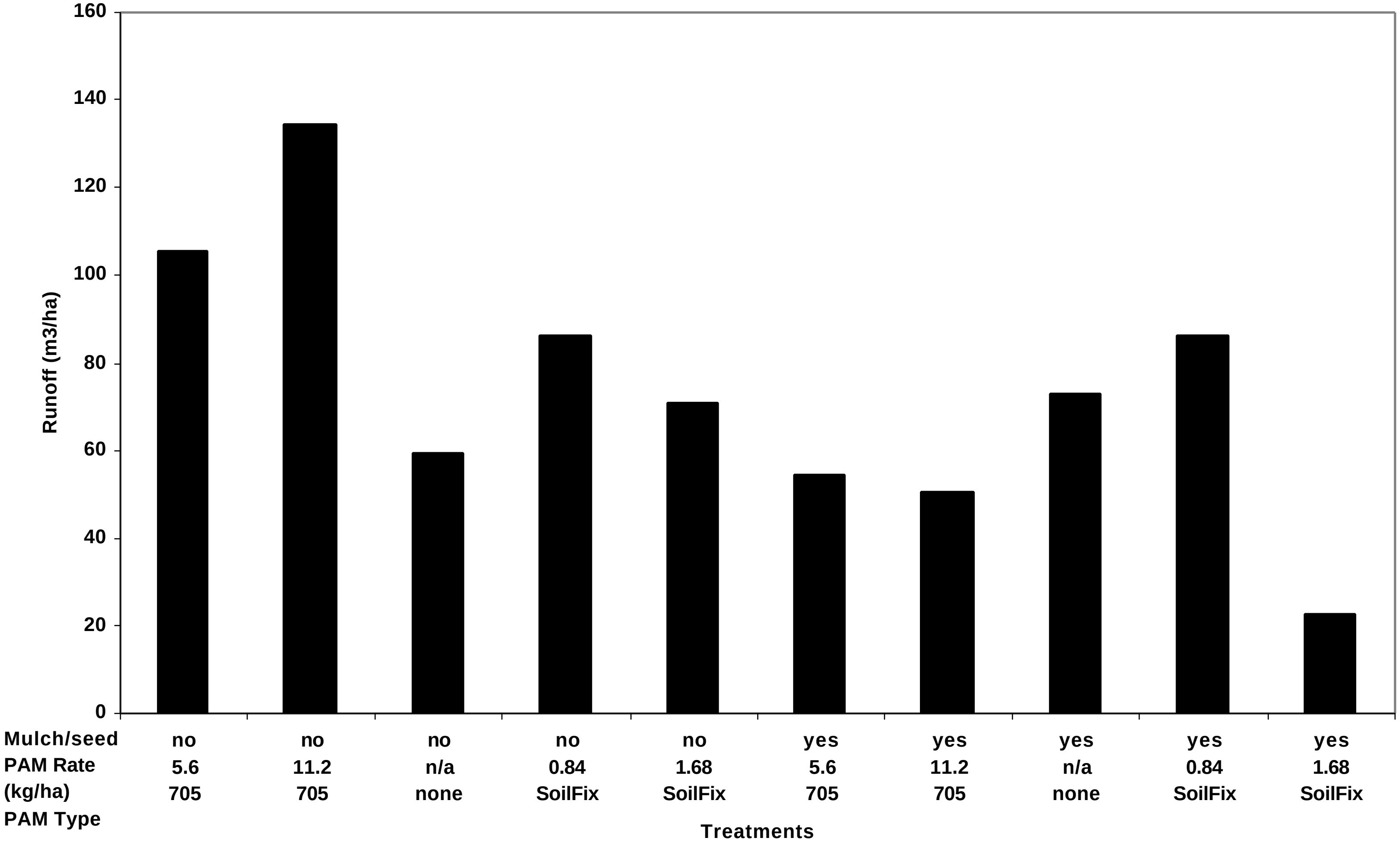


Figure 7: July 10 Runoff
I-540 #1

Figure 8: July 19 Runoff
I-540 #1



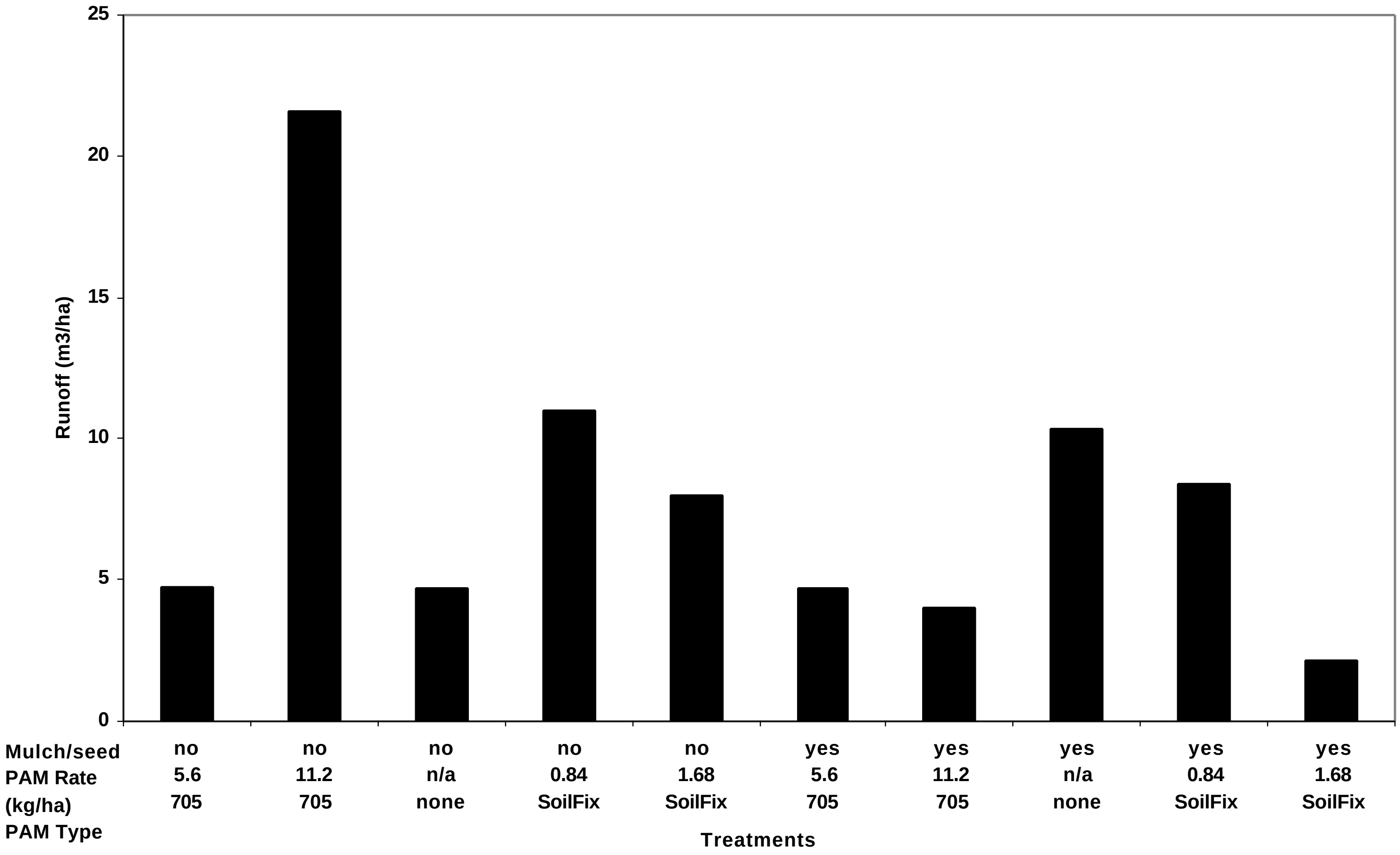
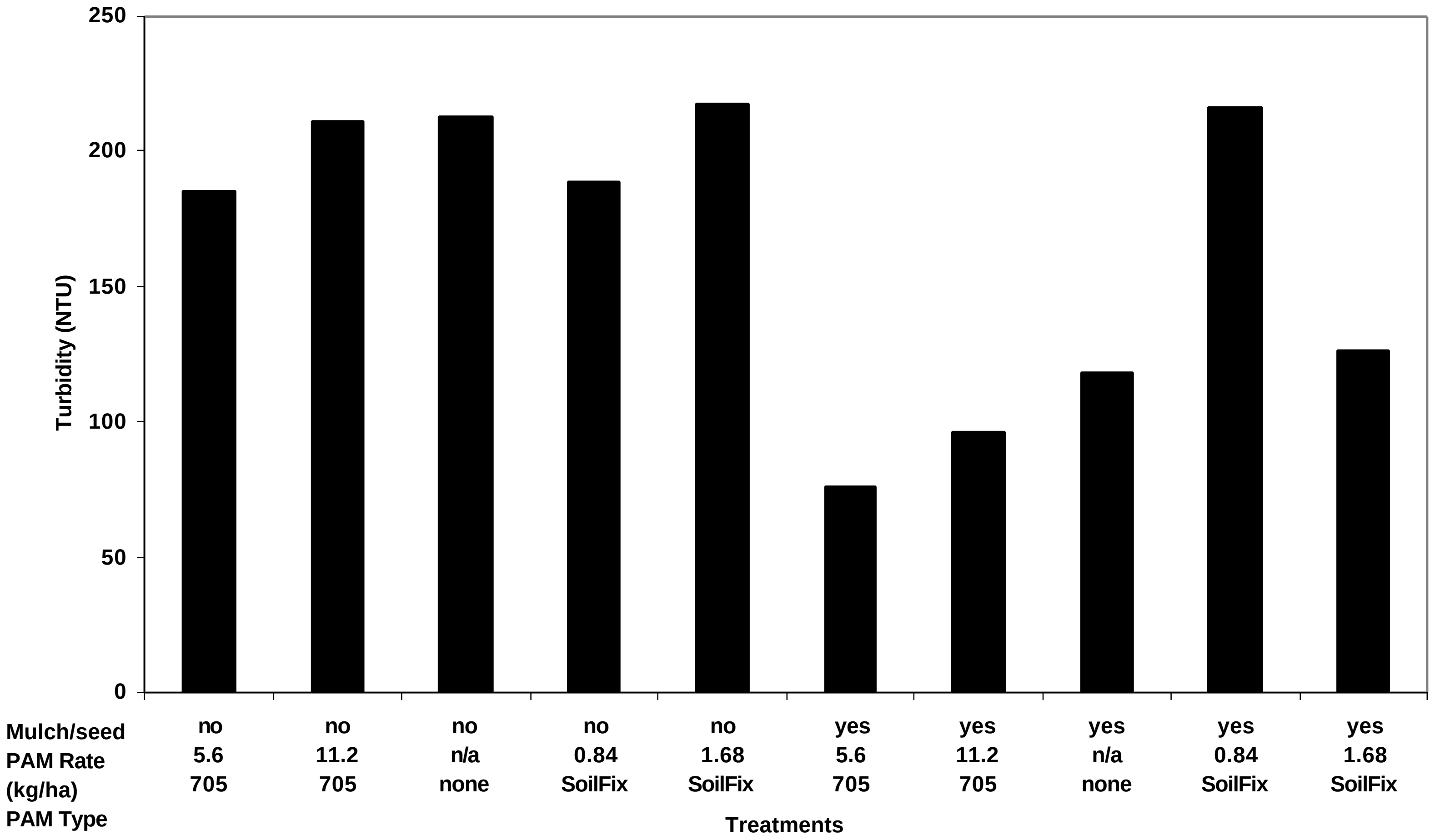


Figure 9: July 25 Runoff
I-540 #1

Figure 10: June 26 Turbidity
I-540 #1



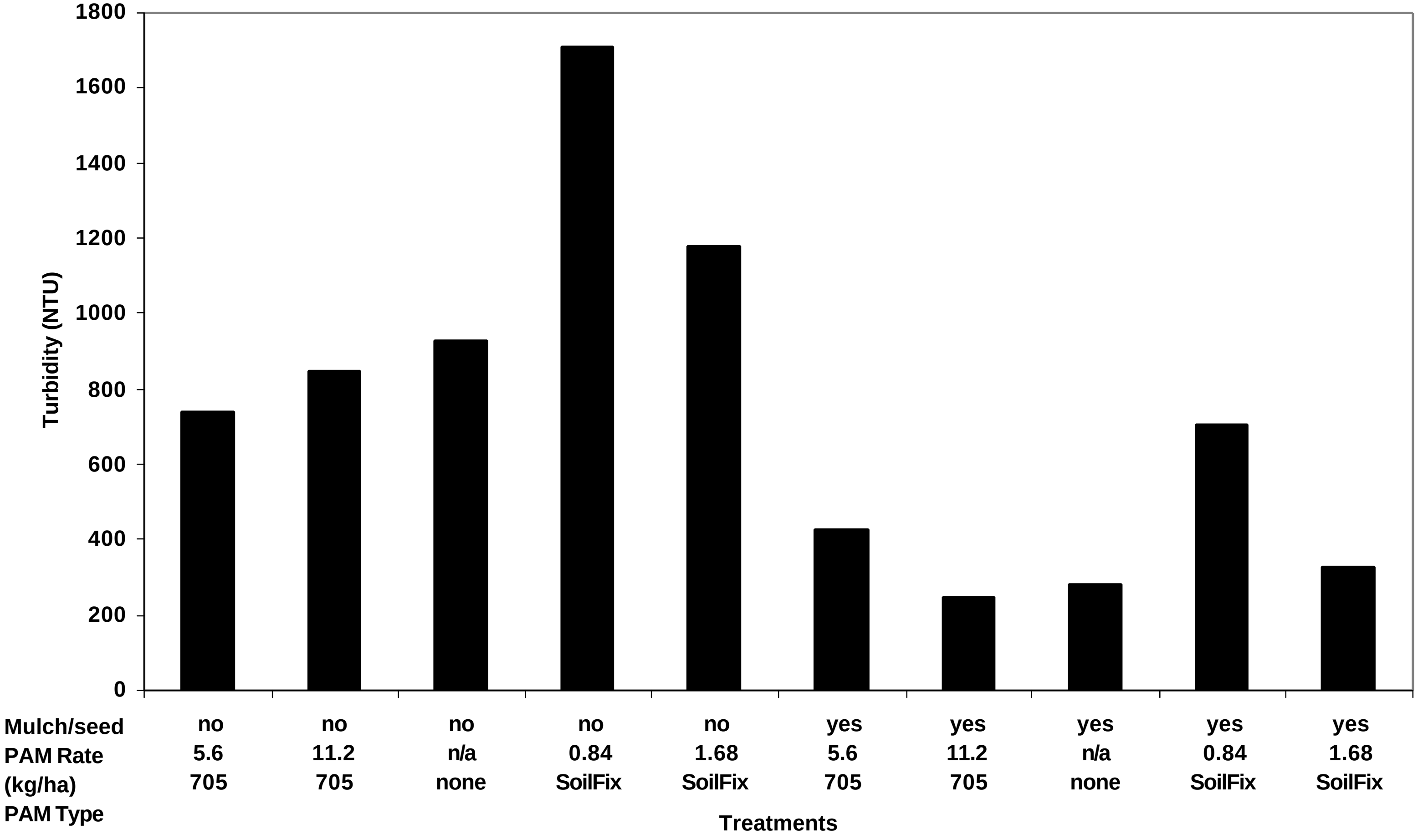


Figure 11: June 27 Turbidity
I-540 #1

Figure 12: July 5 Turbidity
I-540 #1

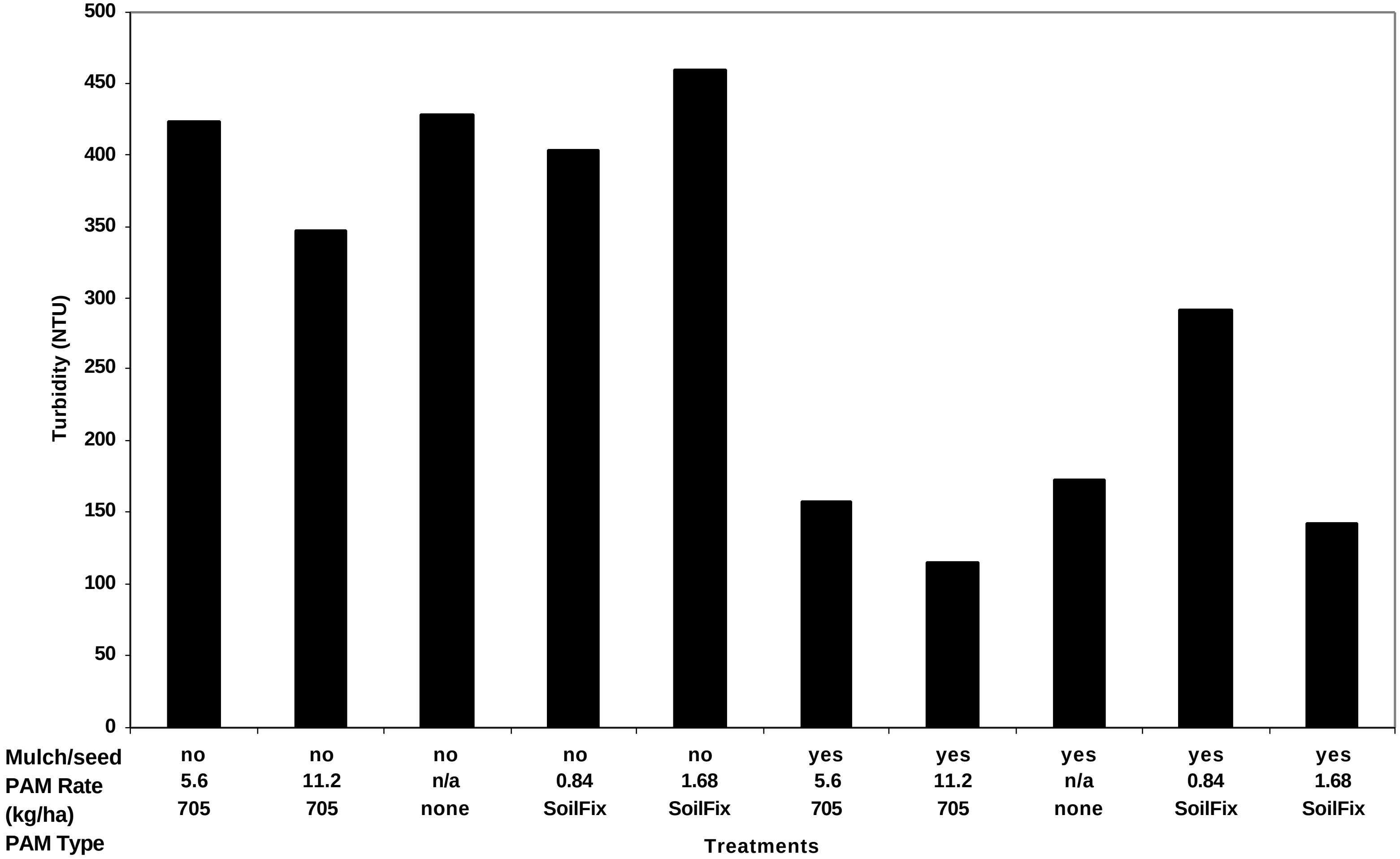


Figure 13: July 9 Turbidity
I-540 #1

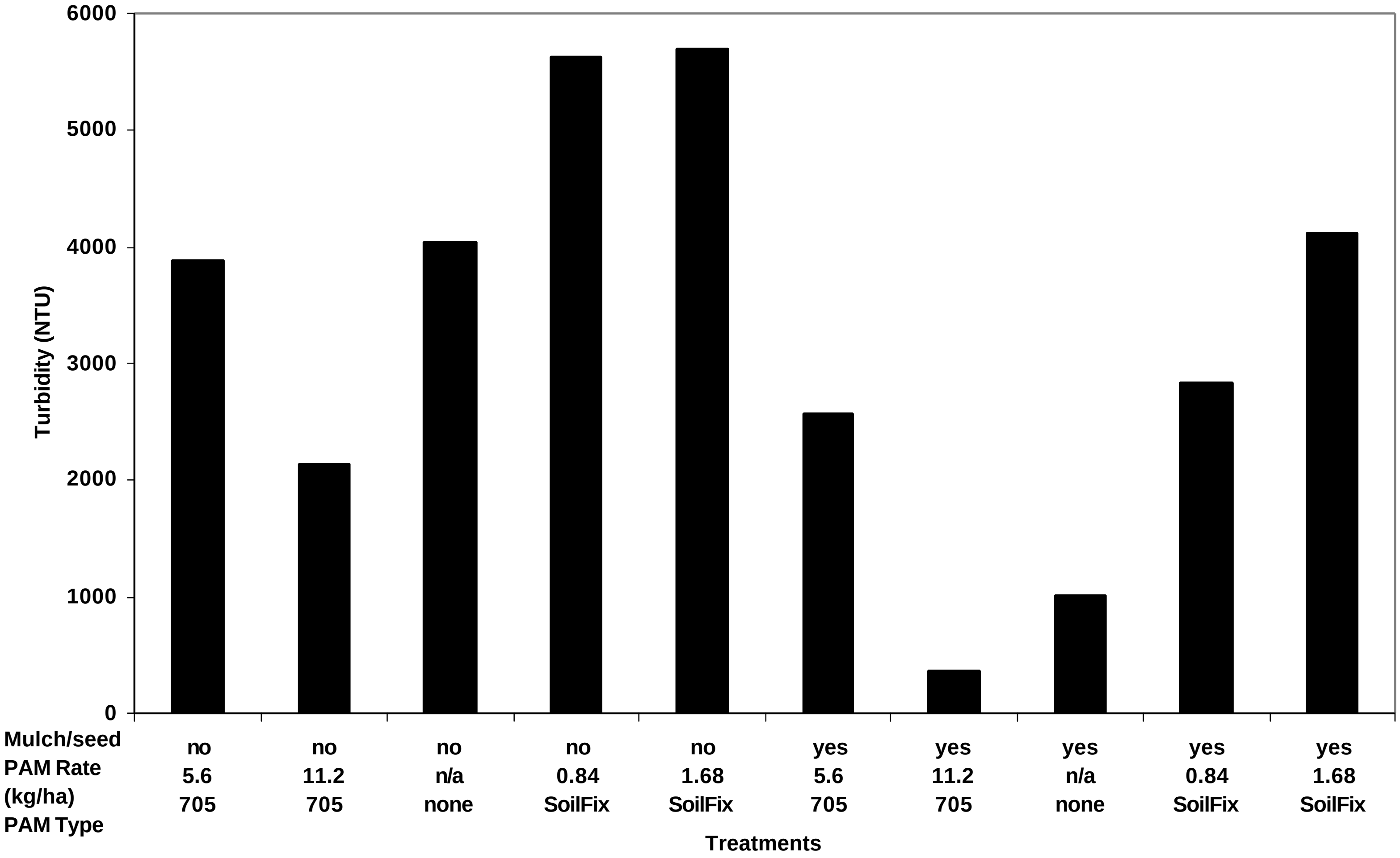


Figure 14: July 10 Turbidity
I-540 #1

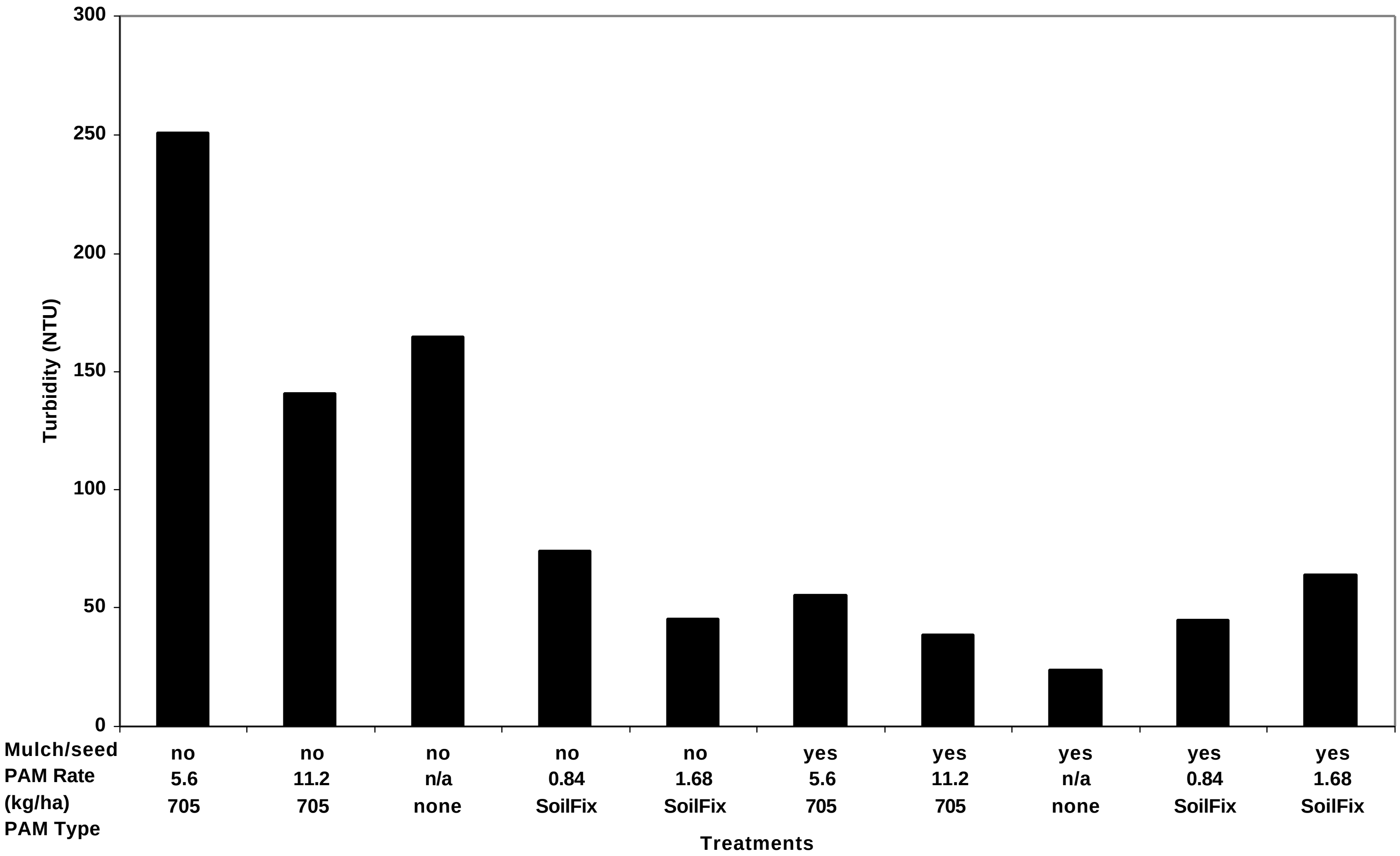


Figure 15: July 19 Turbidity
I-540 #1

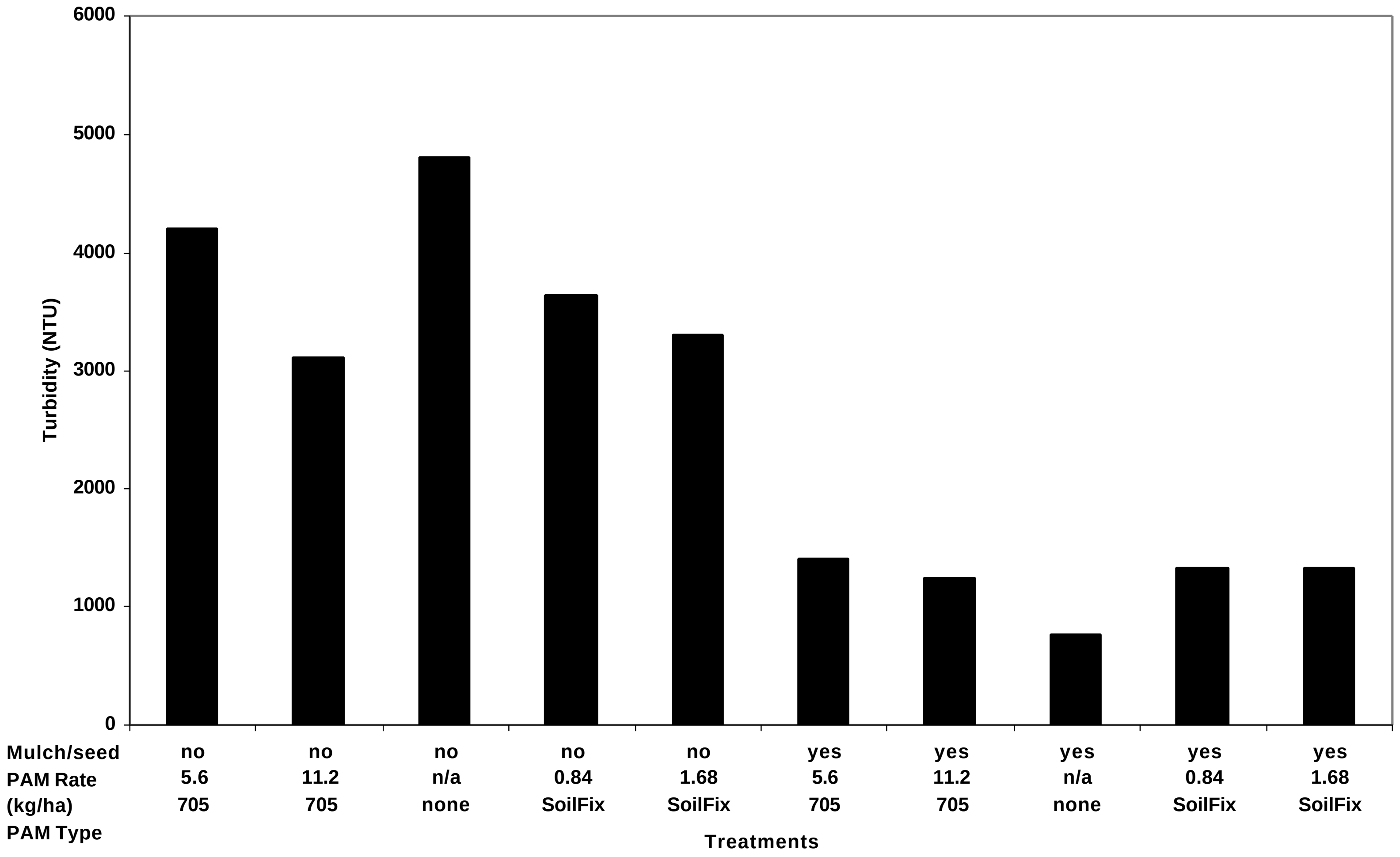
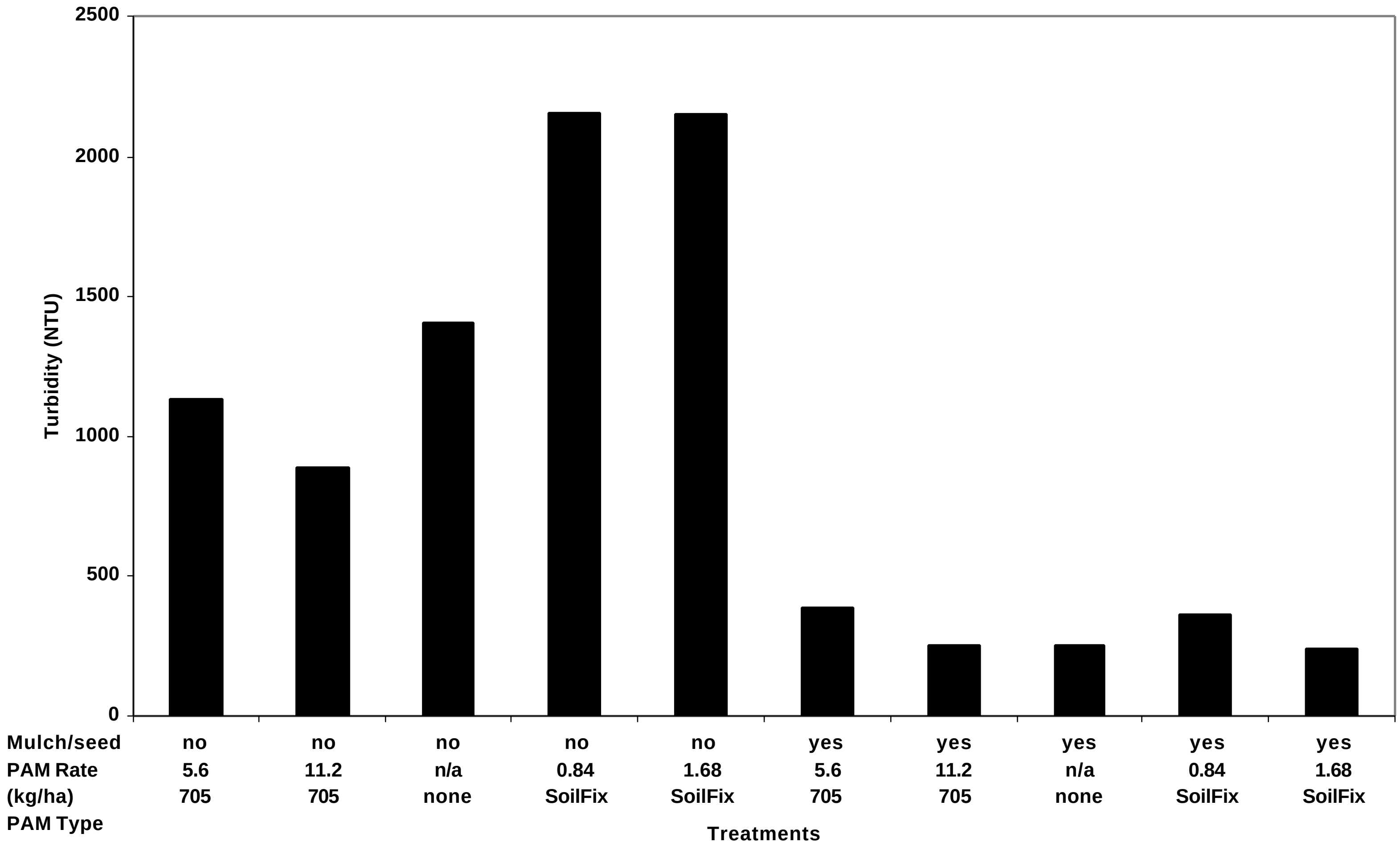


Figure 16: July 25 Turbidity
I-540 #1



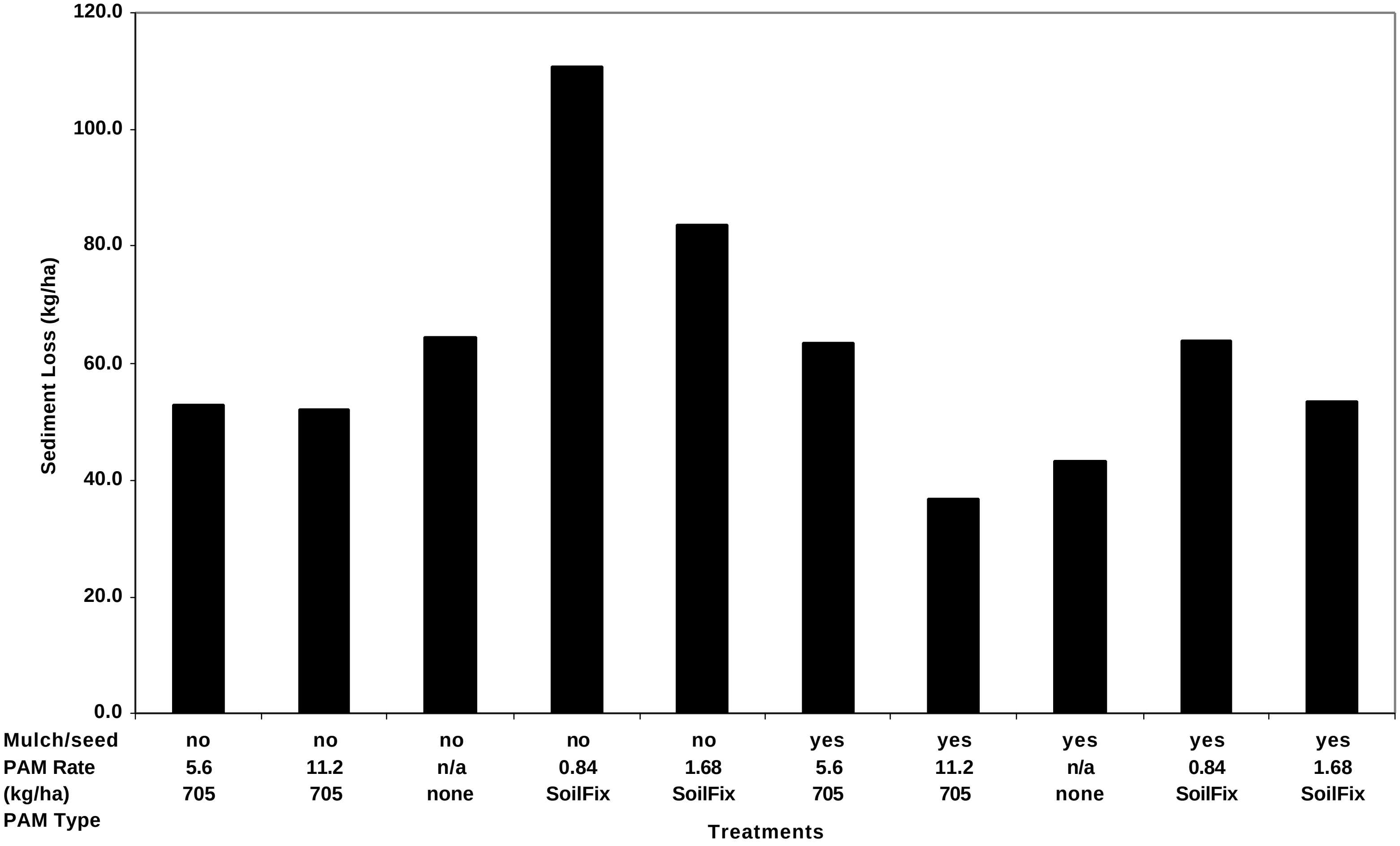


Figure 17: June 26 Sediment Loss
I-540 #1

Figure 18: June 27 Sediment Loss
I-540 #1

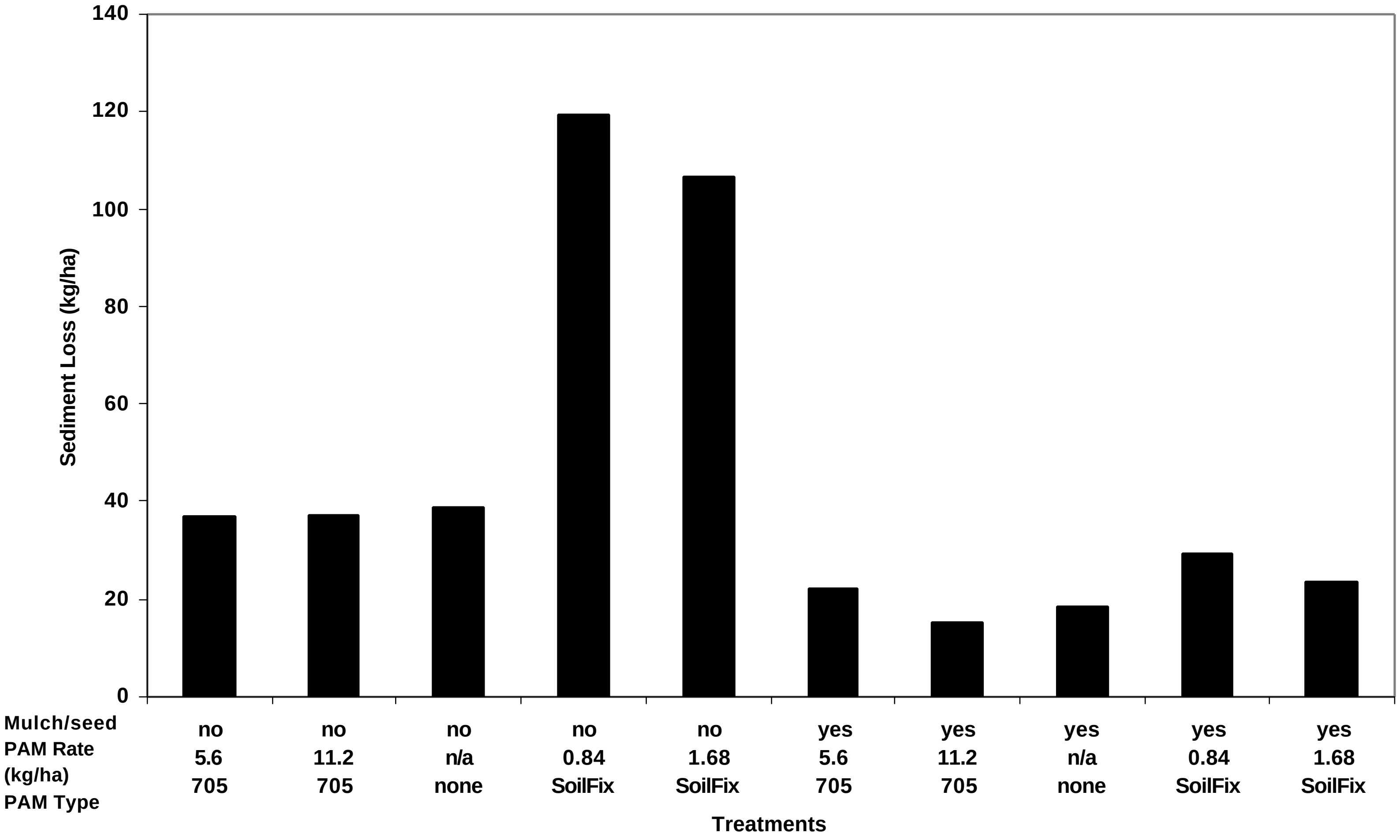
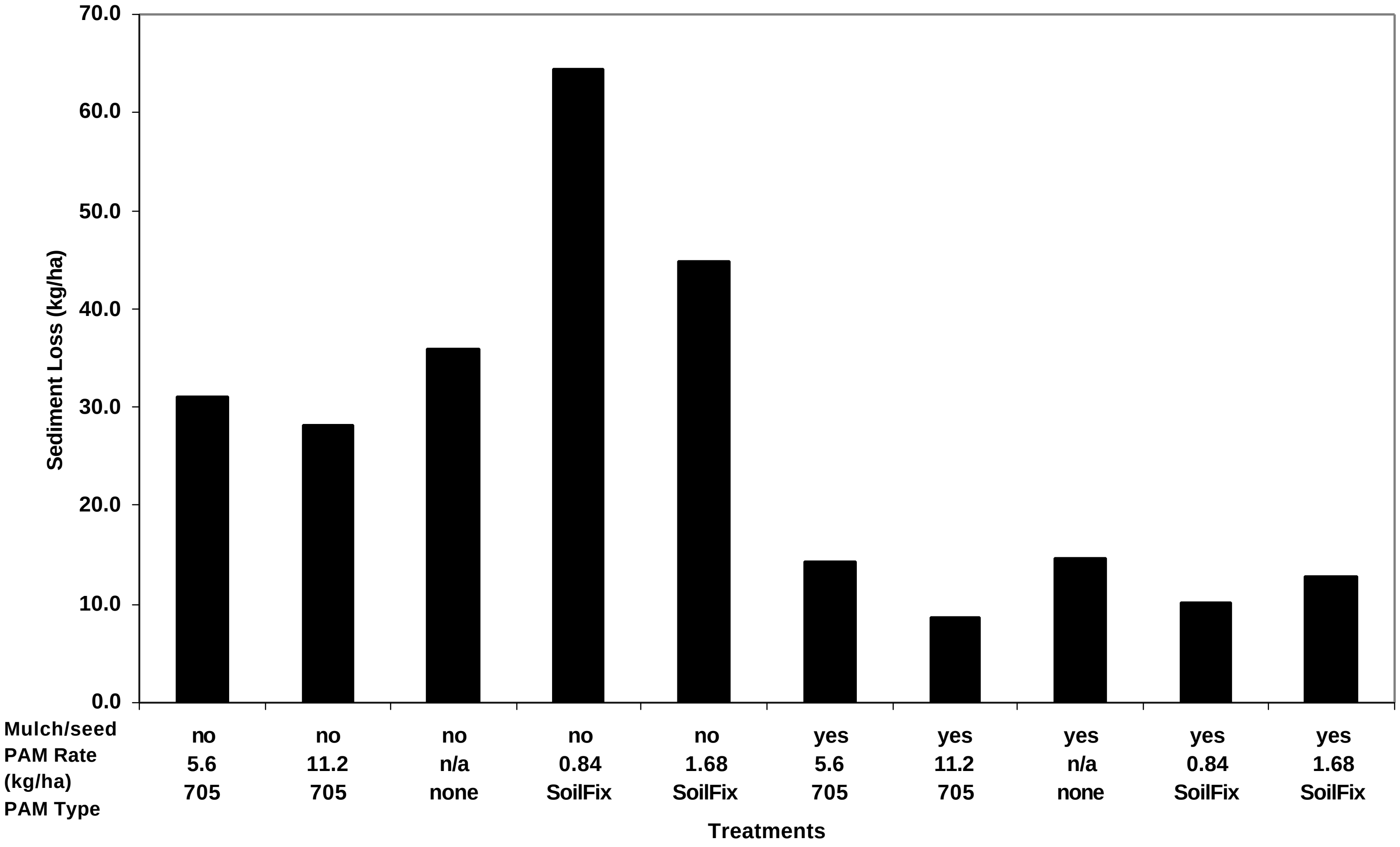


Figure 19: July 5 Sediment Loss
I-540 #1



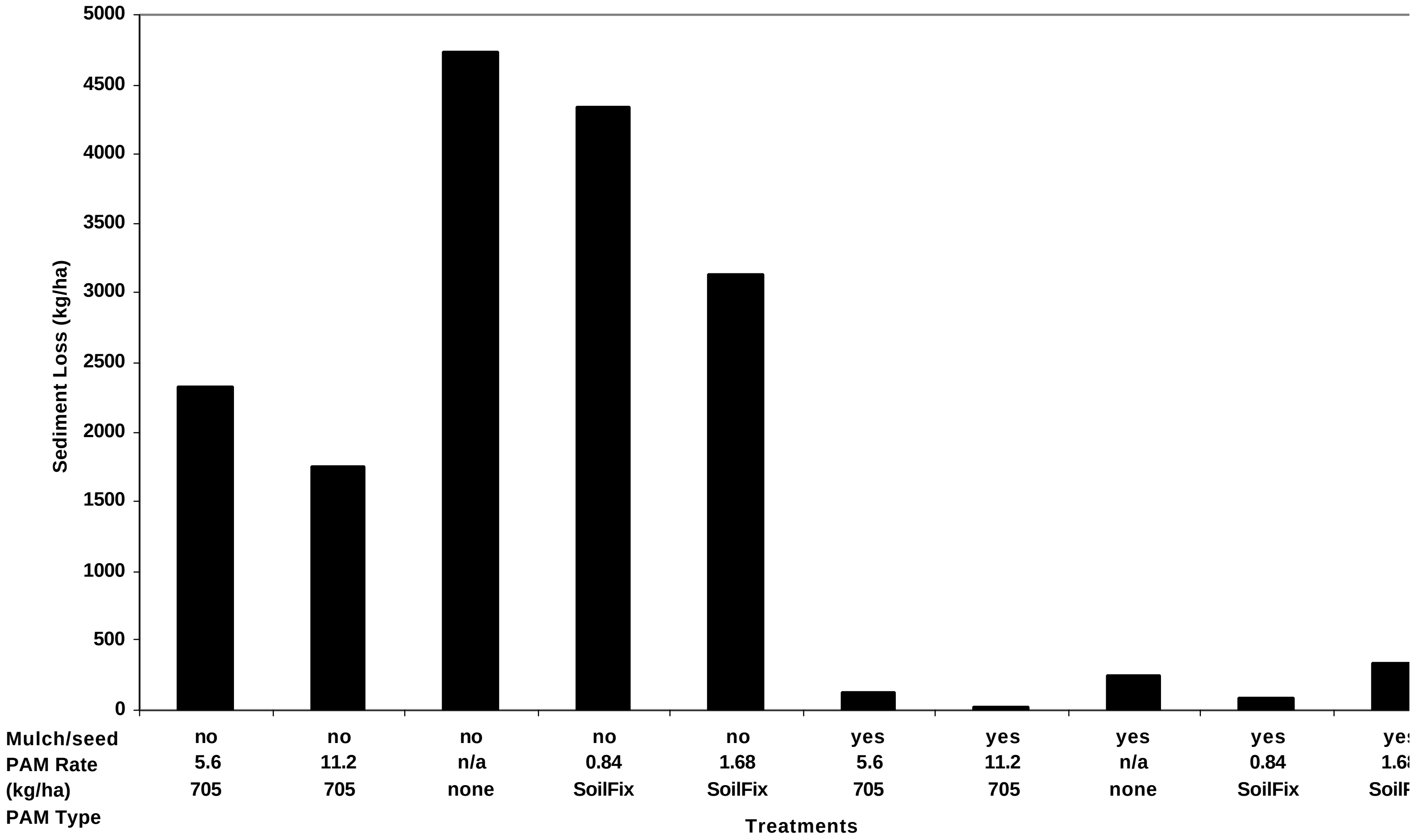


Figure 20: July 9 Sediment Loss
I-540 #1

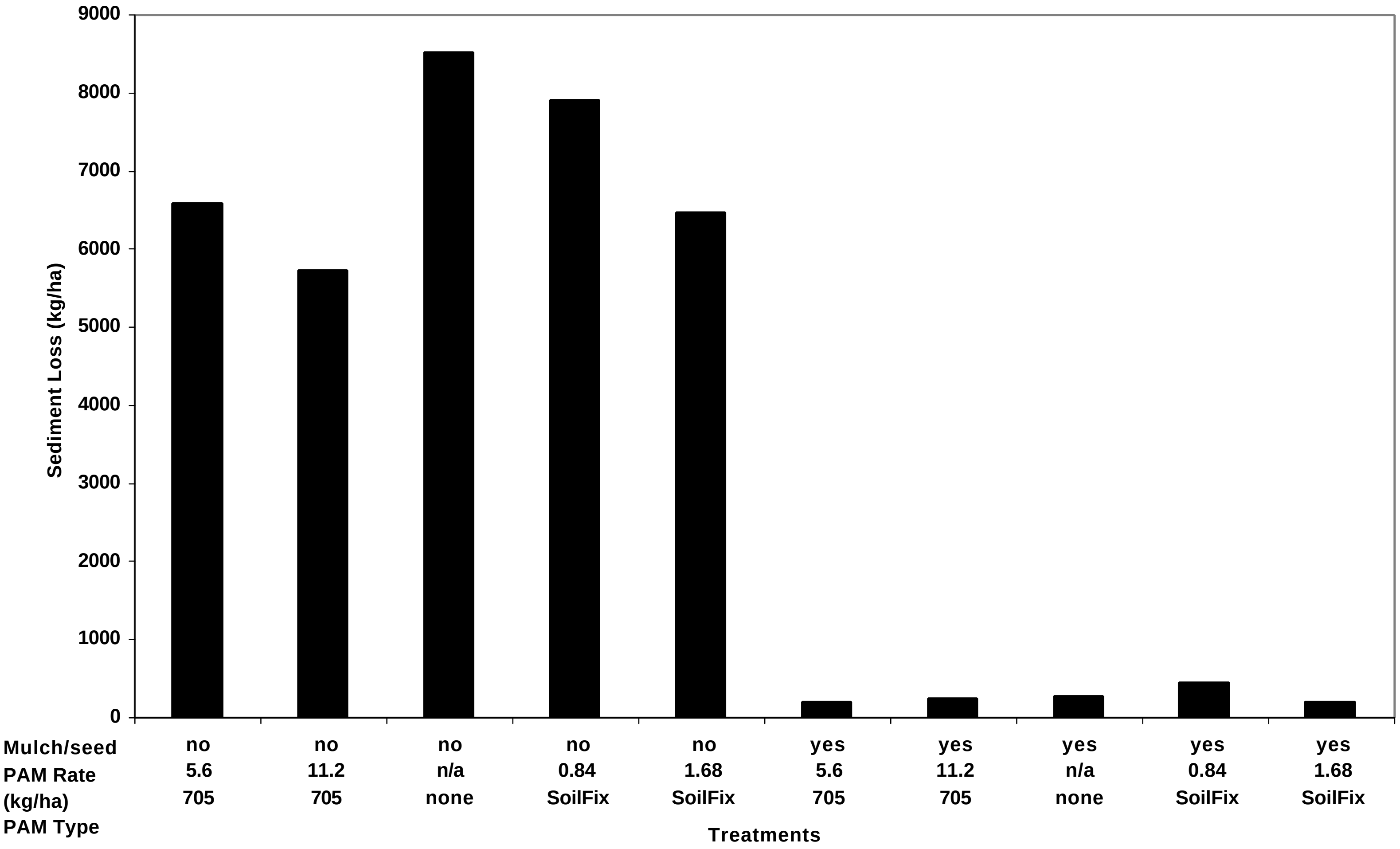


Figure 21: July 19 Sediment Loss
I-540 #1

Figure 22: July 25 Sediment Loss
I-540 #1

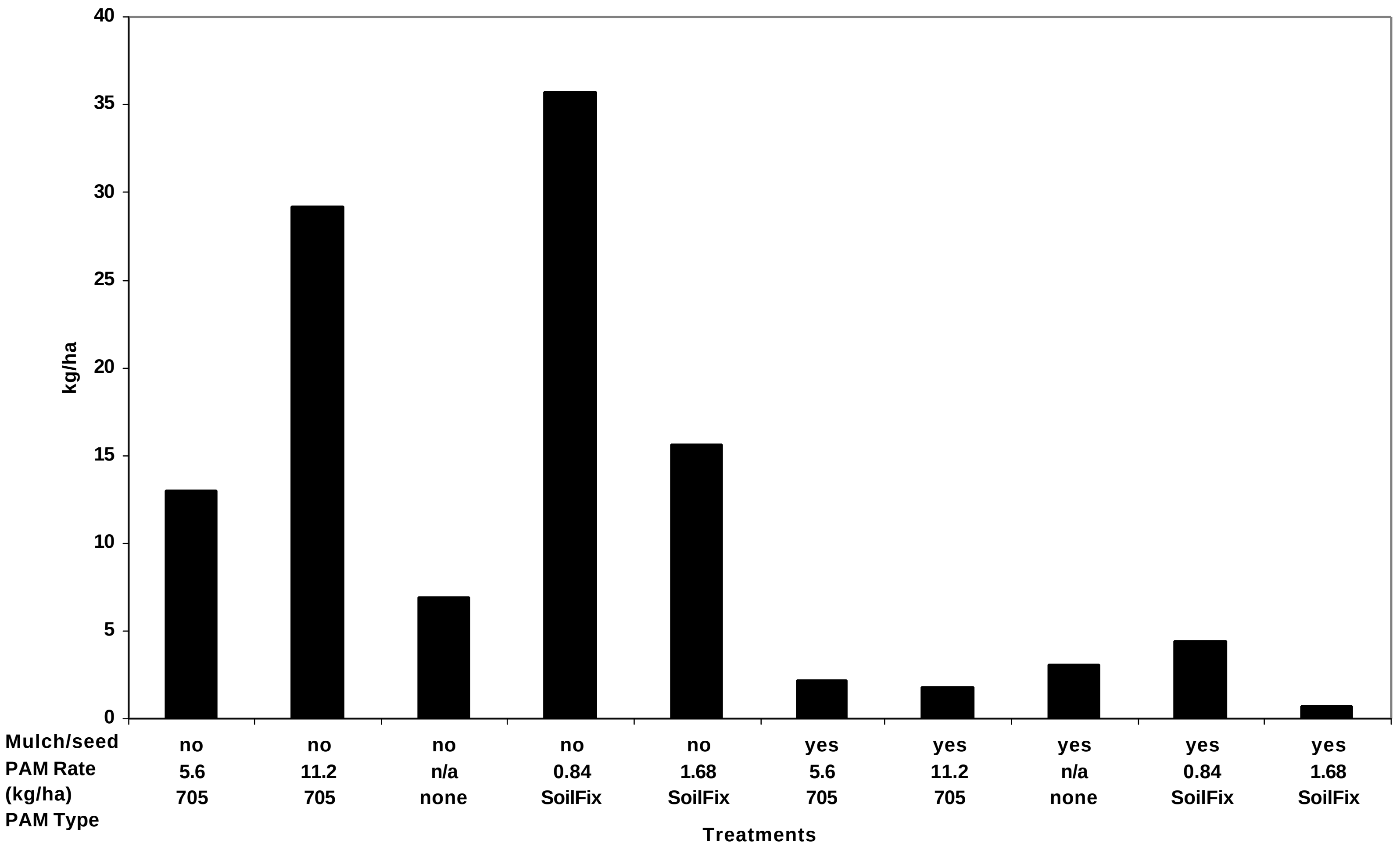
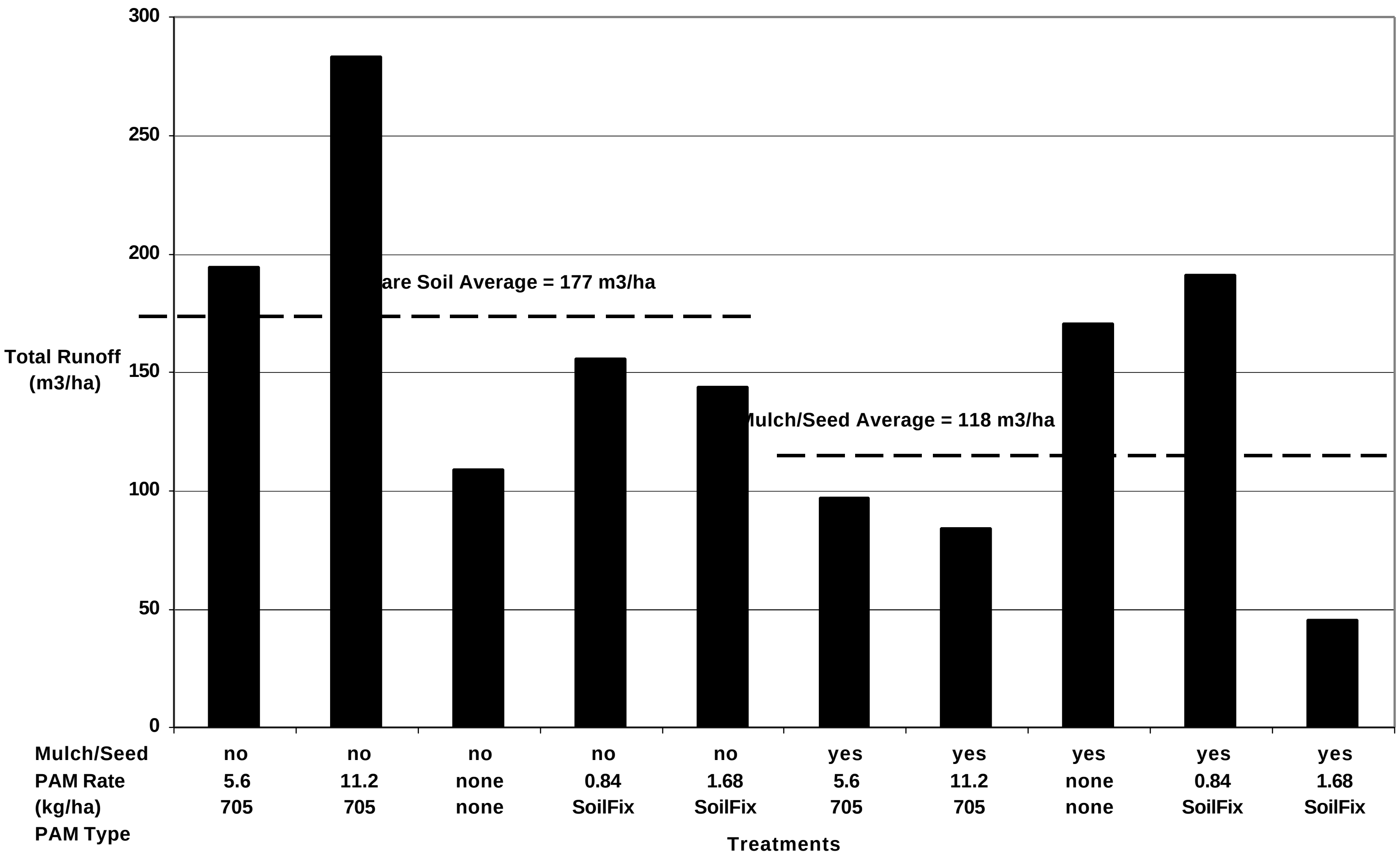


Figure 23: Total Runoff Volume
I-540 #1



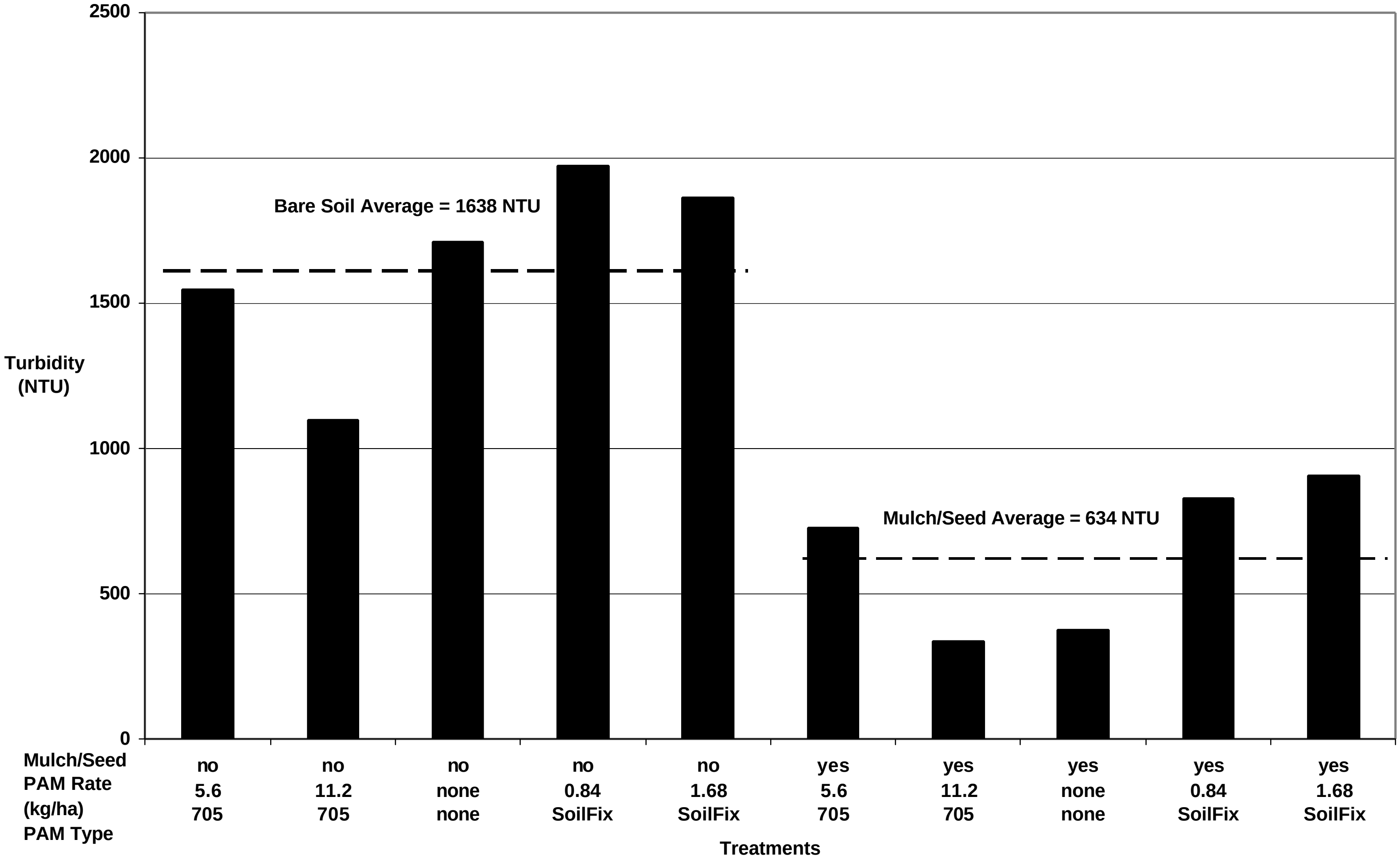


Figure 24: Average Turbidity
I-540 #1

Figure 25: Total Sediment Loss
I-540 #1

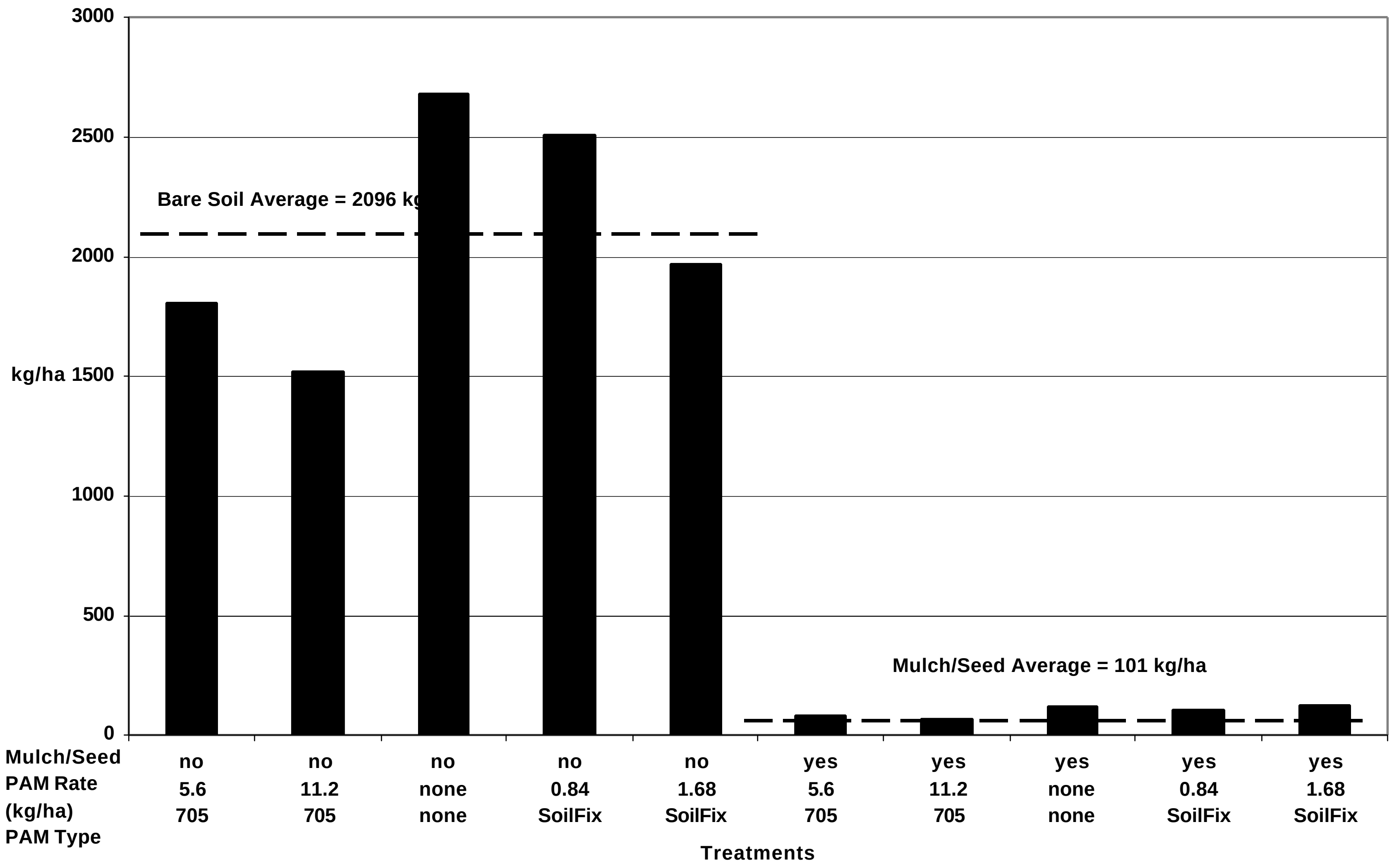


Figure 26: July 27 Estimated Sediment Loss
I-540 #1

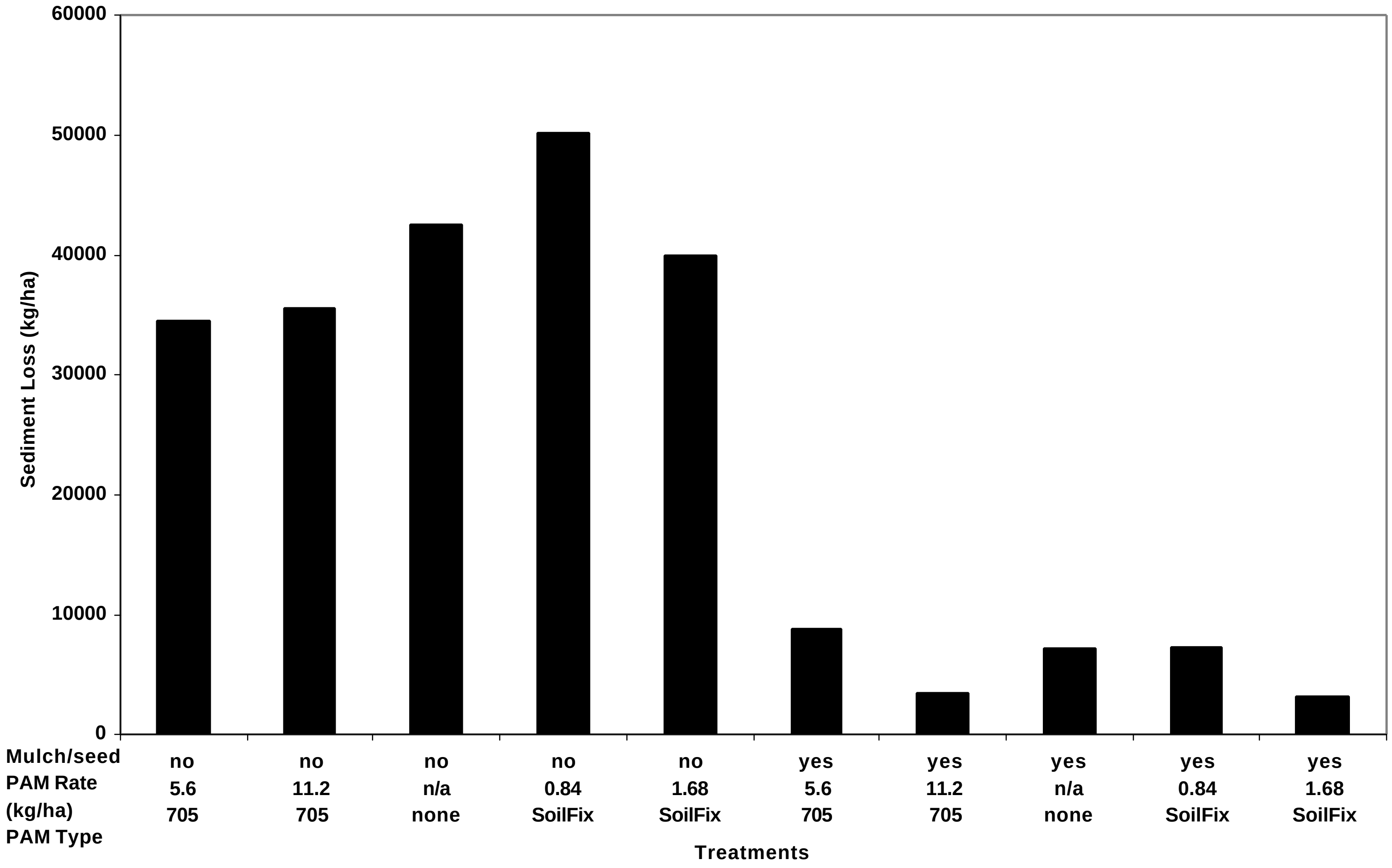


Figure 27: July 27 Estimated Sediment Loss
I-540 #1

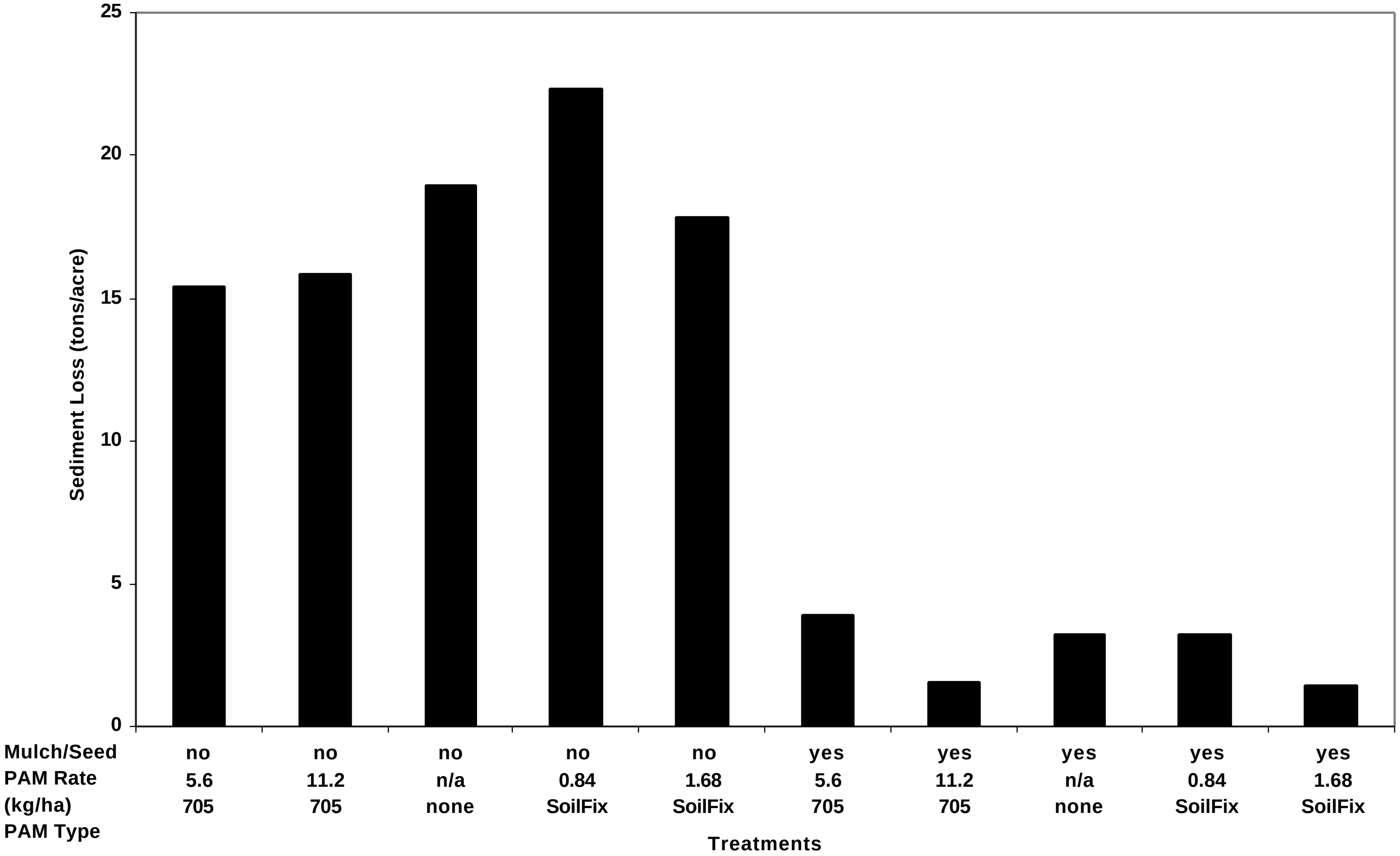


Figure 28: Sediment Losses at Different Time Intervals
I-540 #1

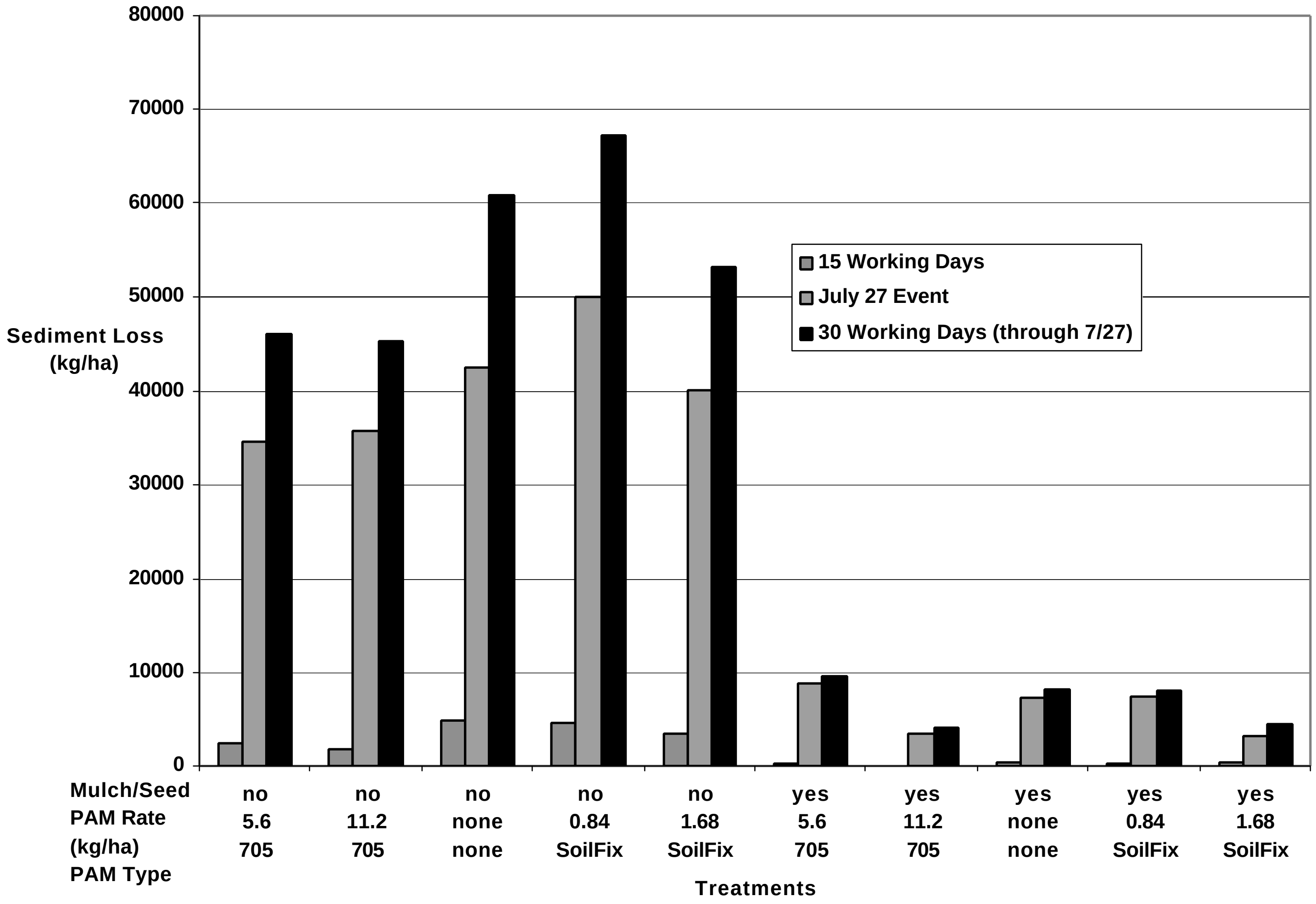


Figure 29. Plot layout at Raleigh I-540 Site #2.

Figure 30: Precipitation Events
I-540 #2

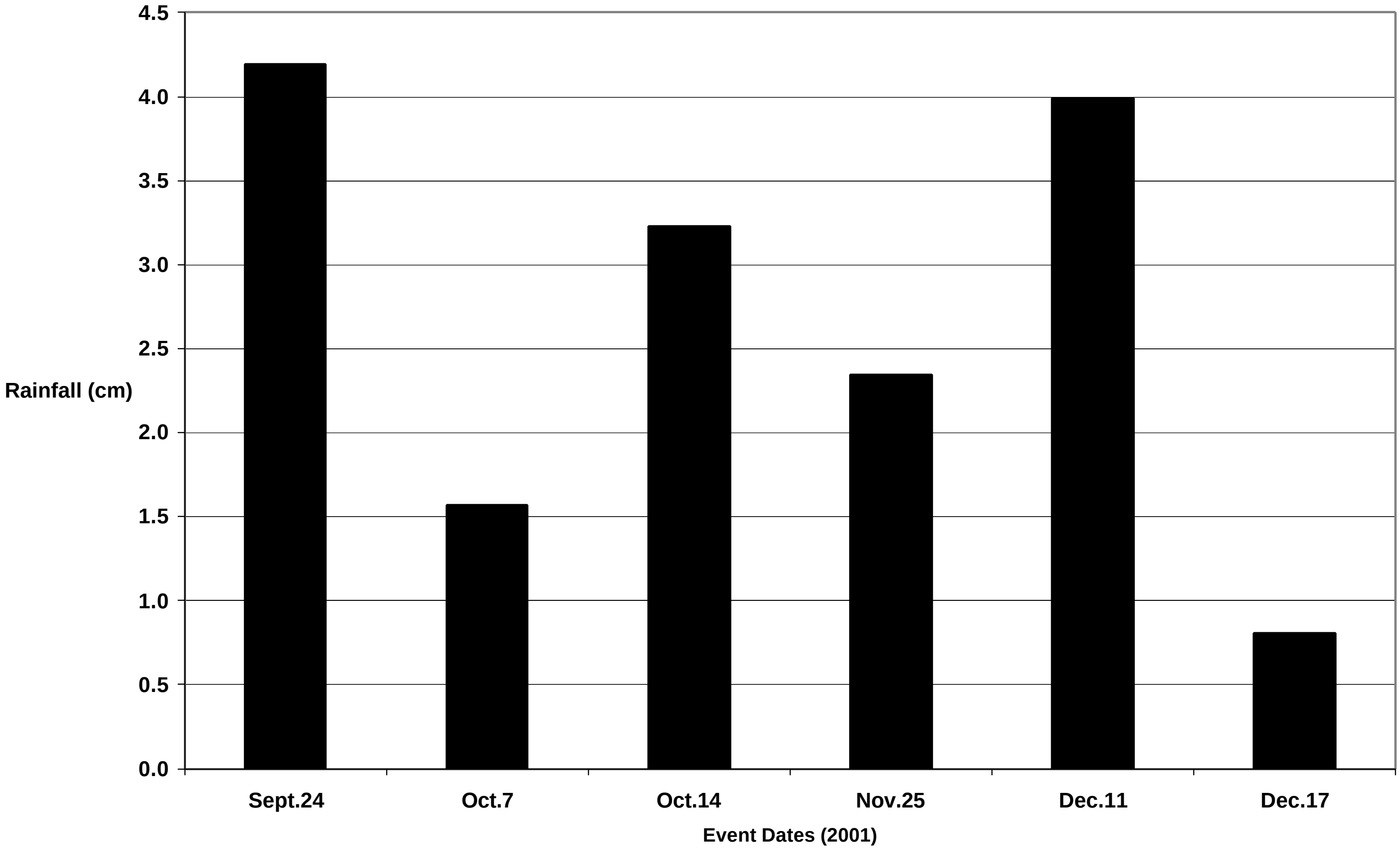


Figure 31: September 24 Runoff
I-540 #2

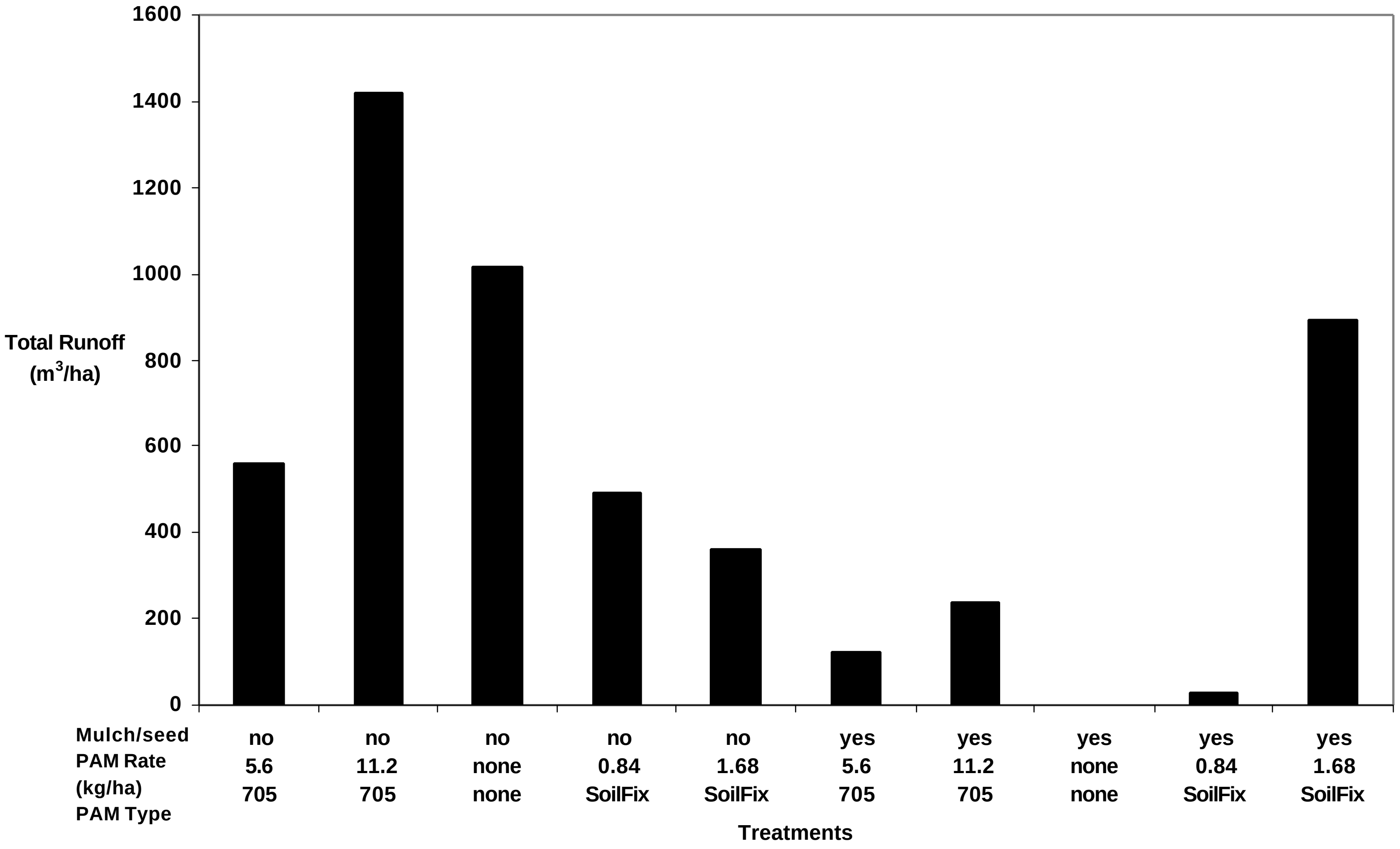
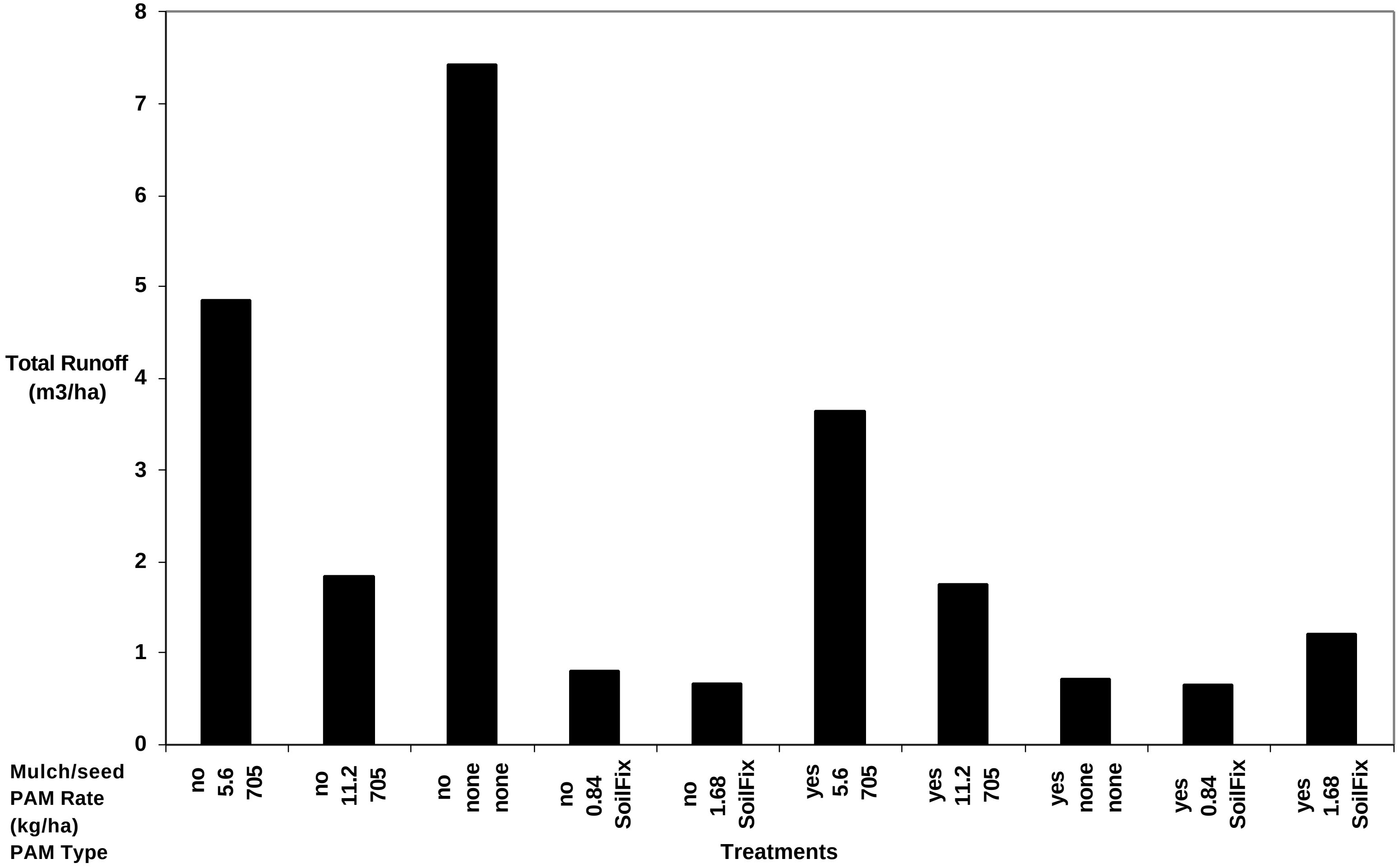


Figure 32: October 7 Runoff
I-540 #2



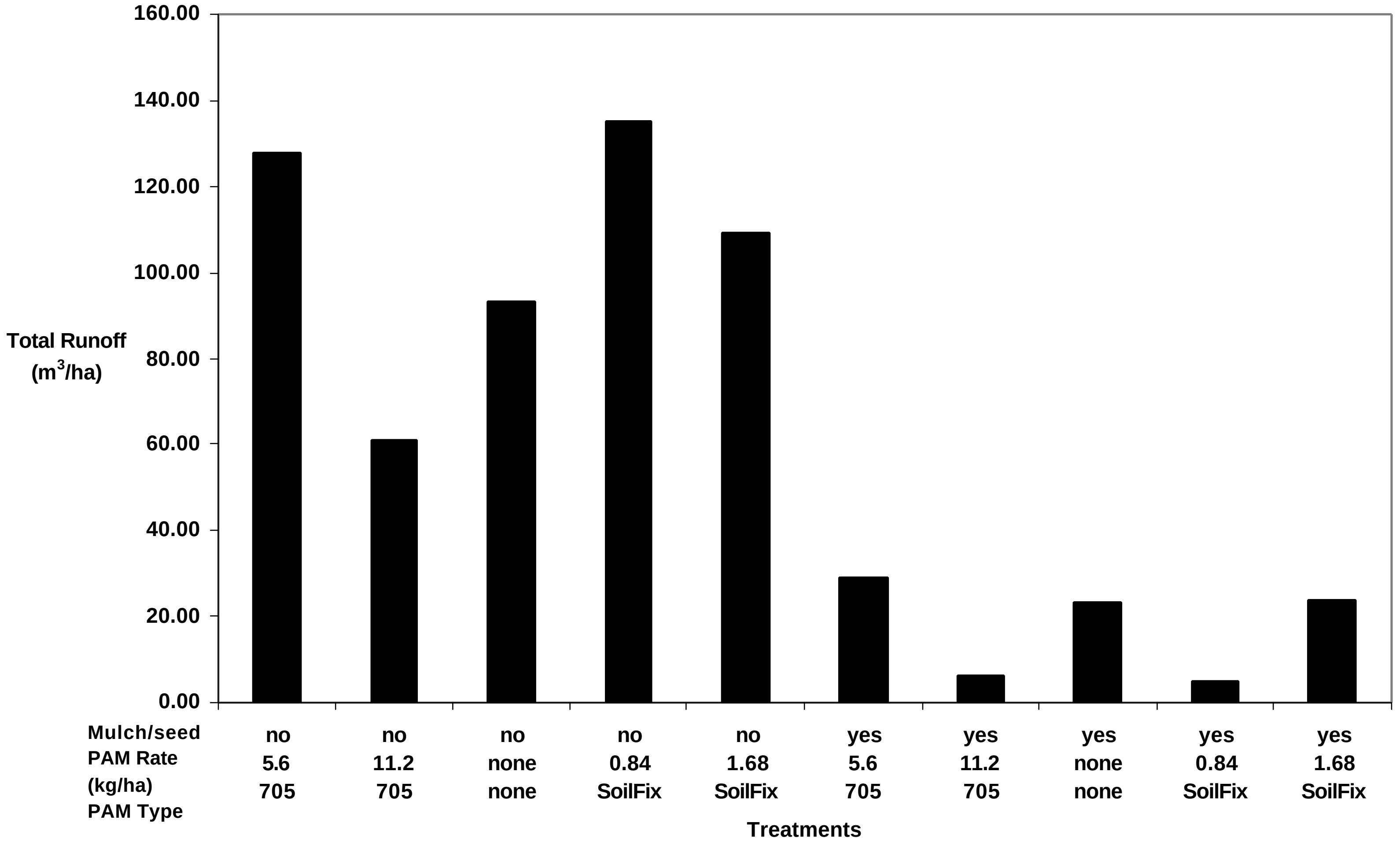
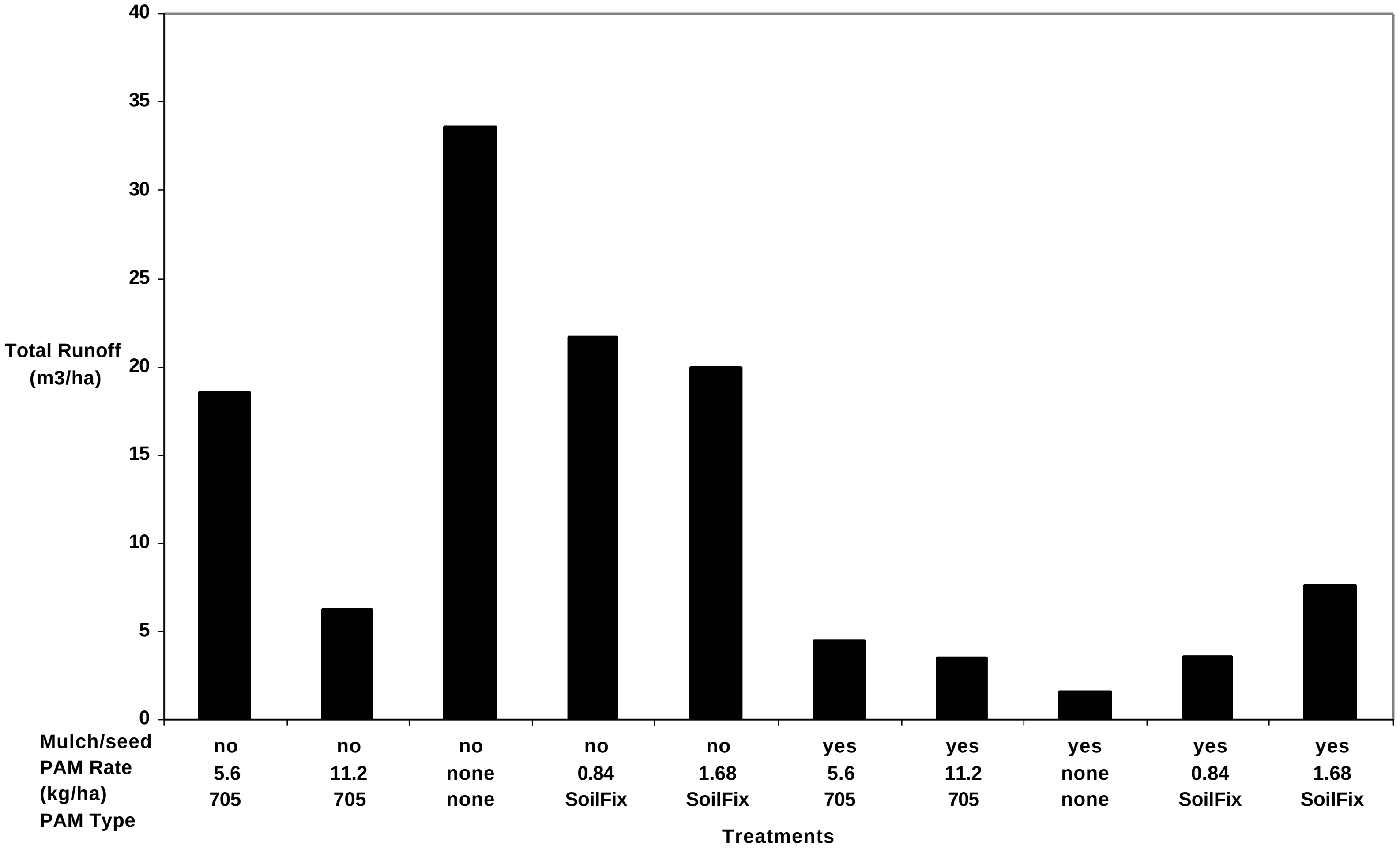


Figure 33: October 14 Runoff
I-540 #2

Figure 34: November 25 Runoff
I-540 #2



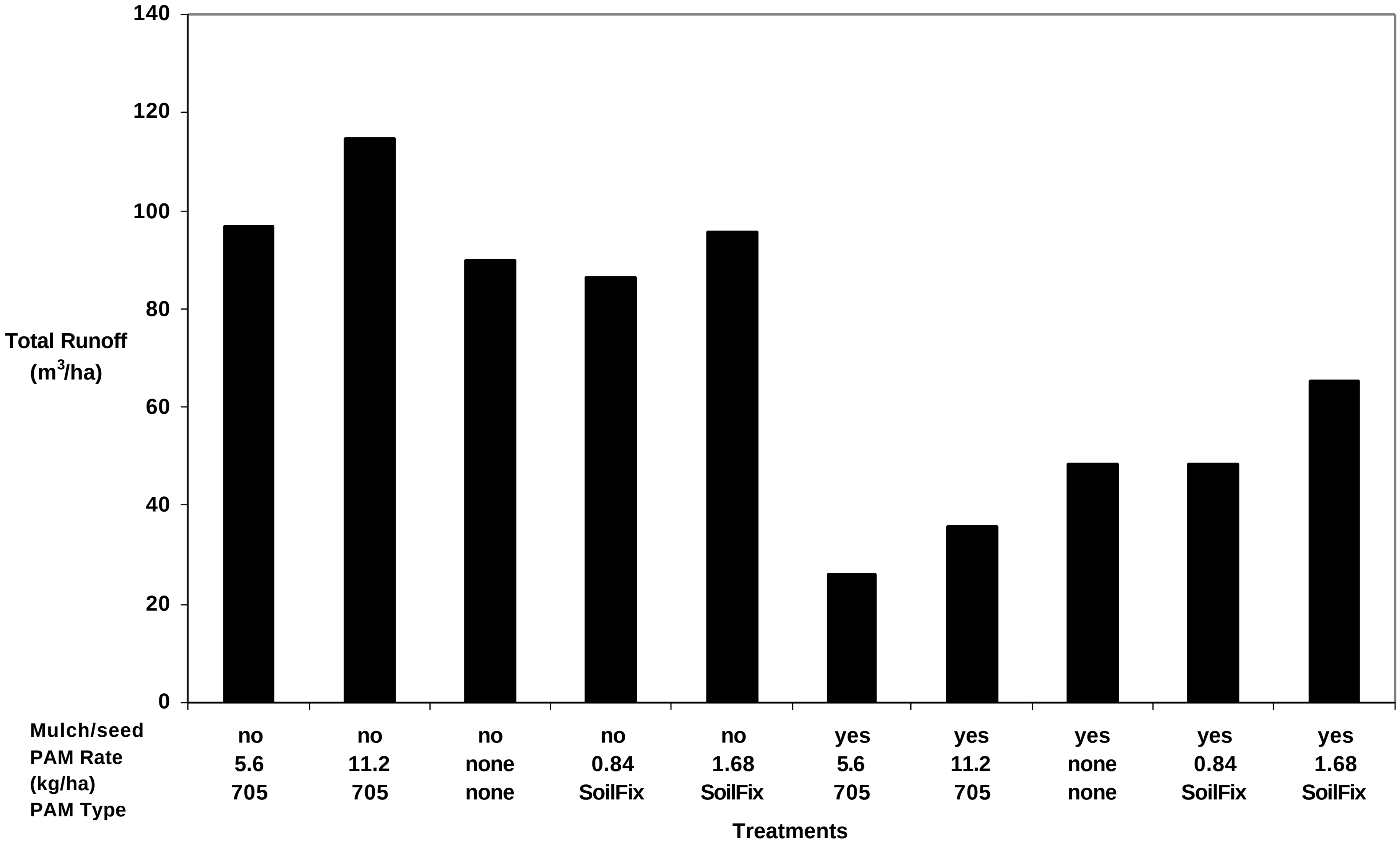
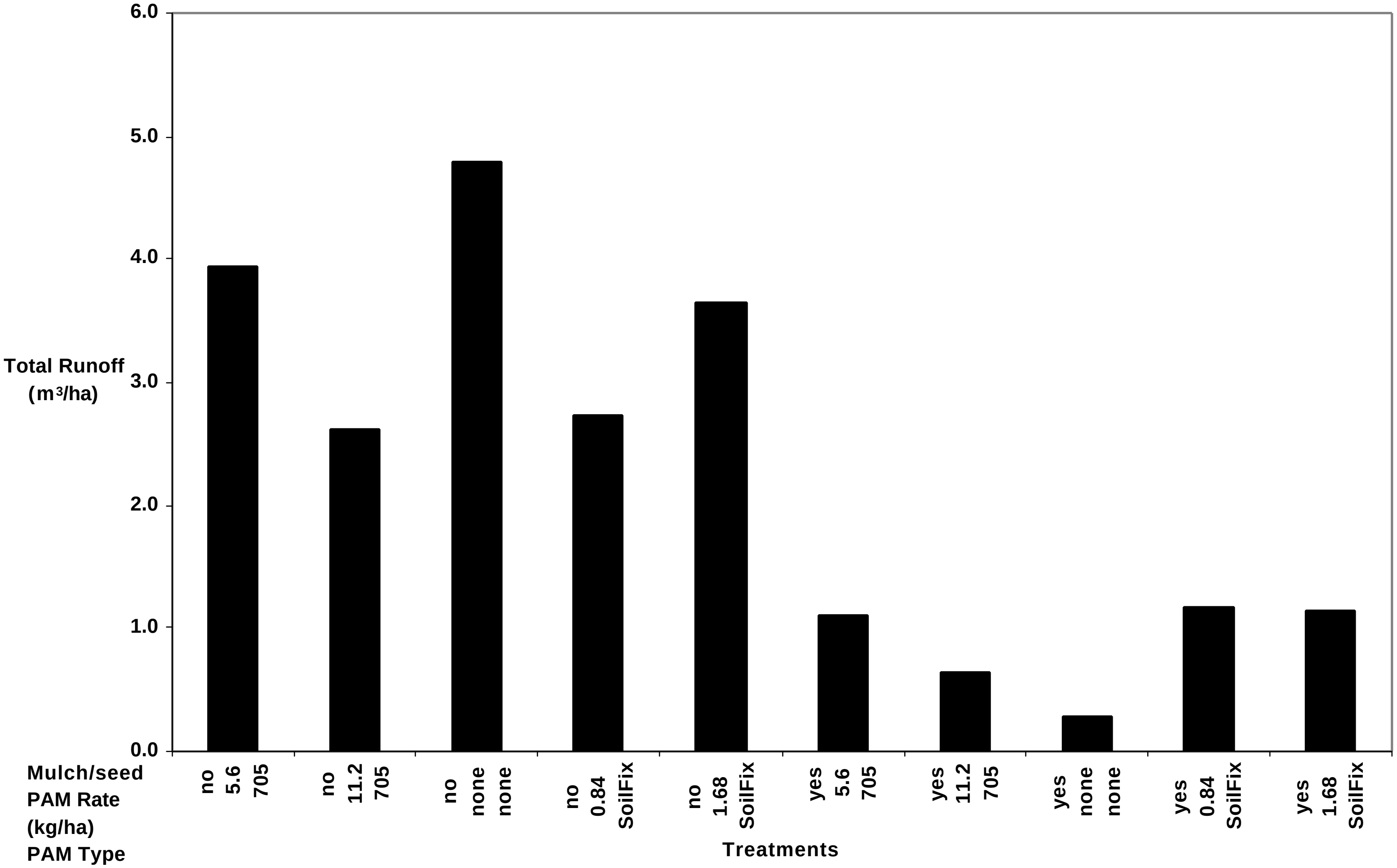


Figure 35: December 11 Runoff
I-540 #2

Figure 36: December 17 Runoff
I-540 #2



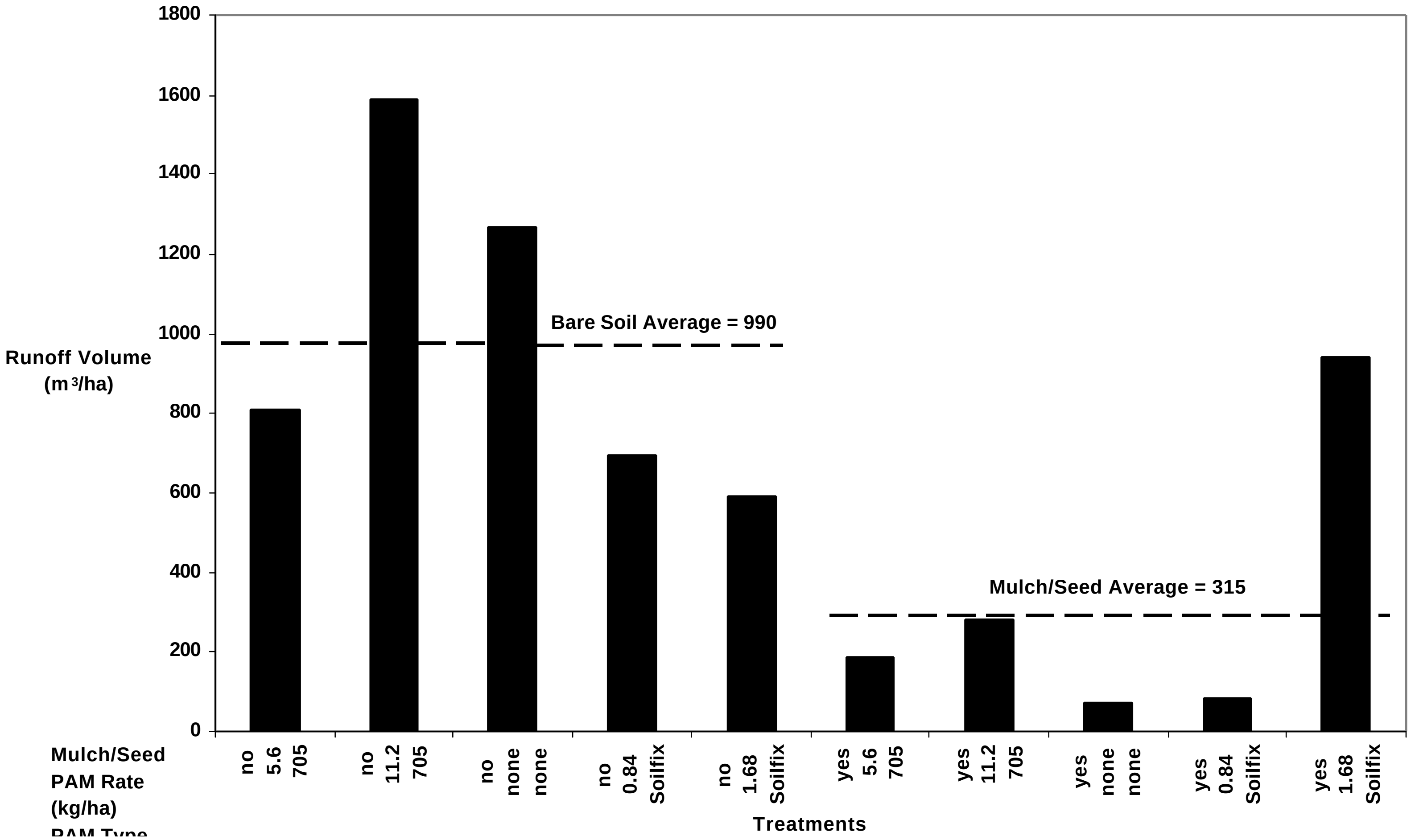


Figure 37: Total Runoff Volume
I-540 #2

Figure 38: September 24 Turbidity
I-540 #2

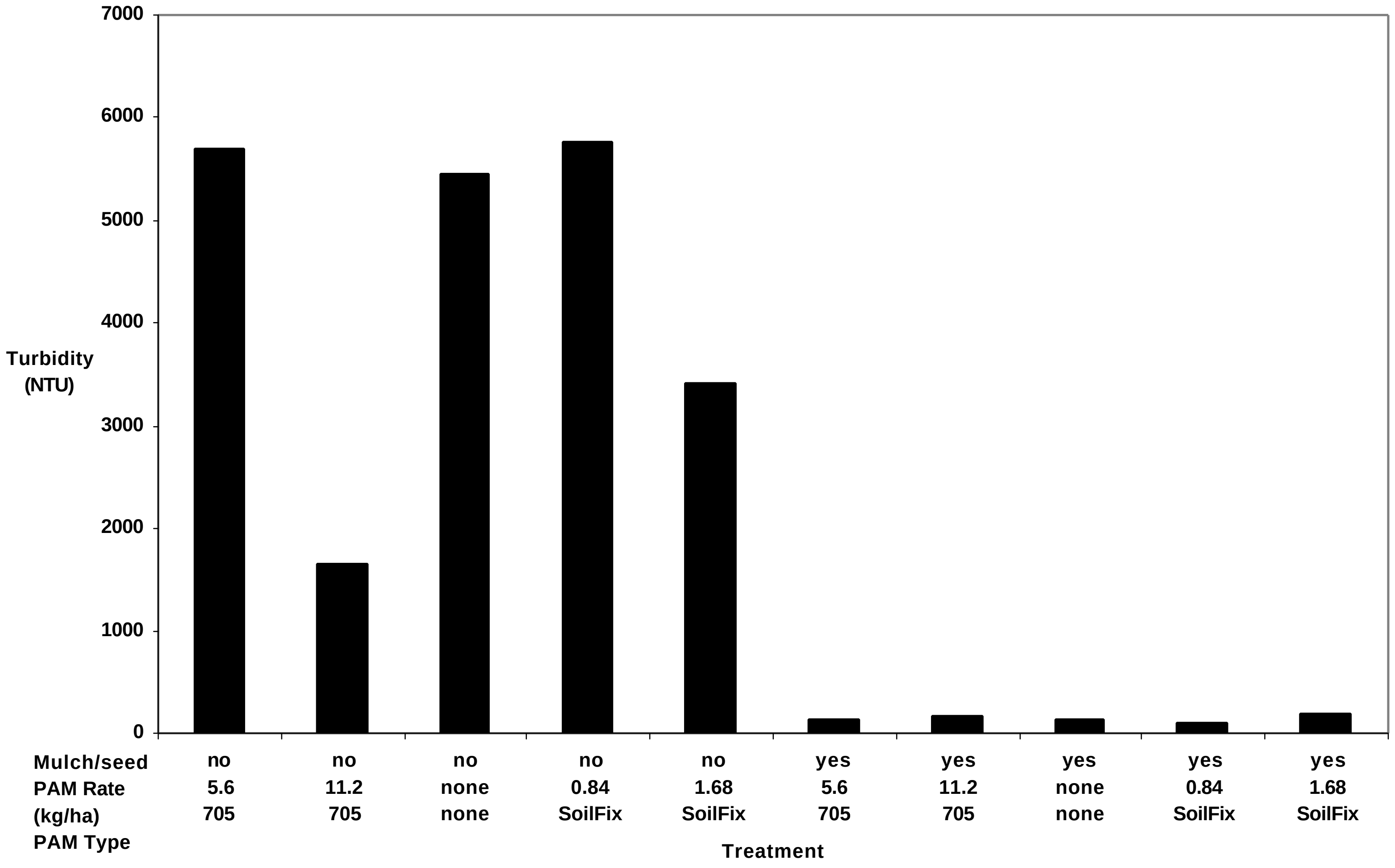


Figure 39: October 7 Turbidity
I-540 #2

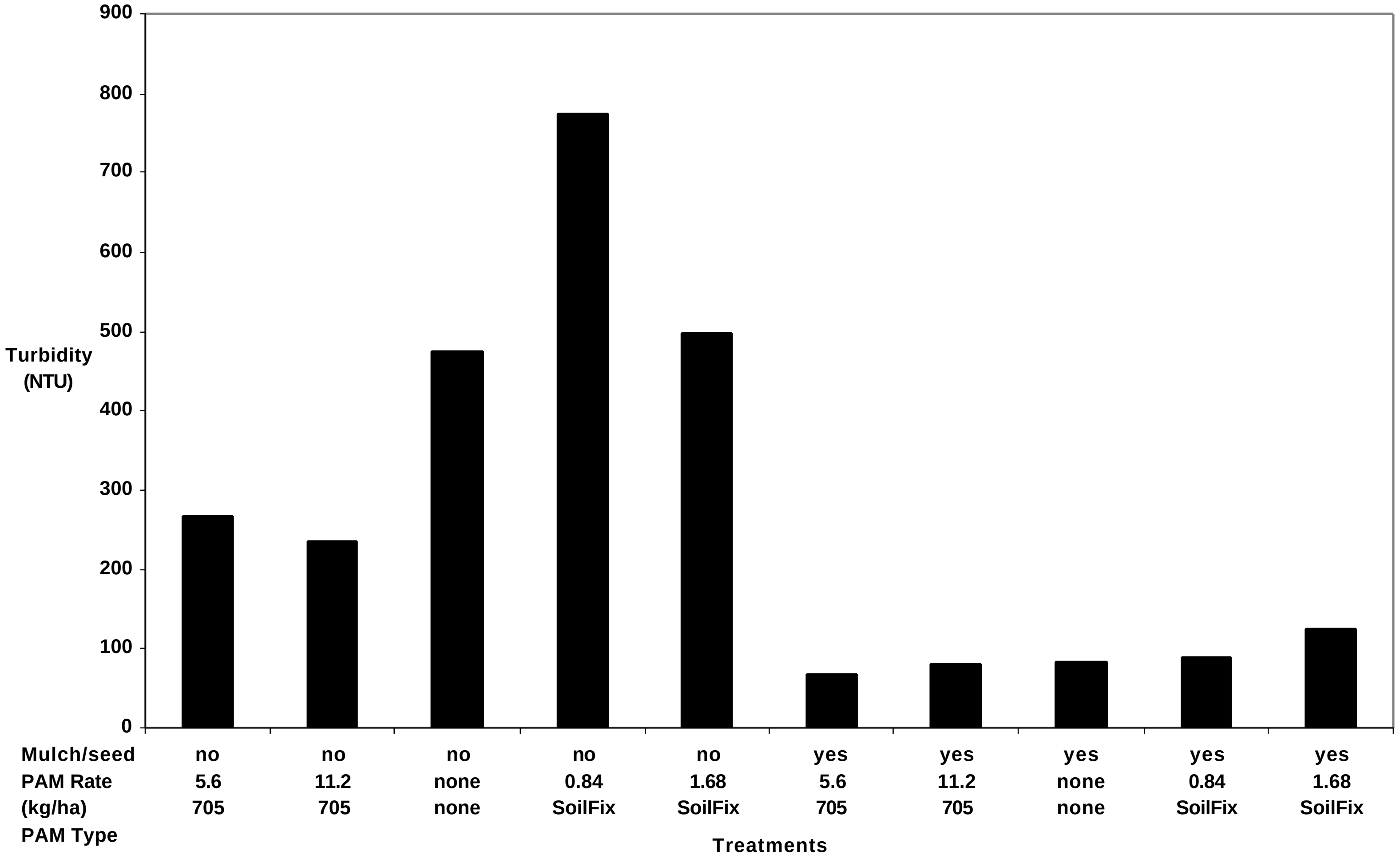


Figure 40: October 14 Turbidity
I-540 #2

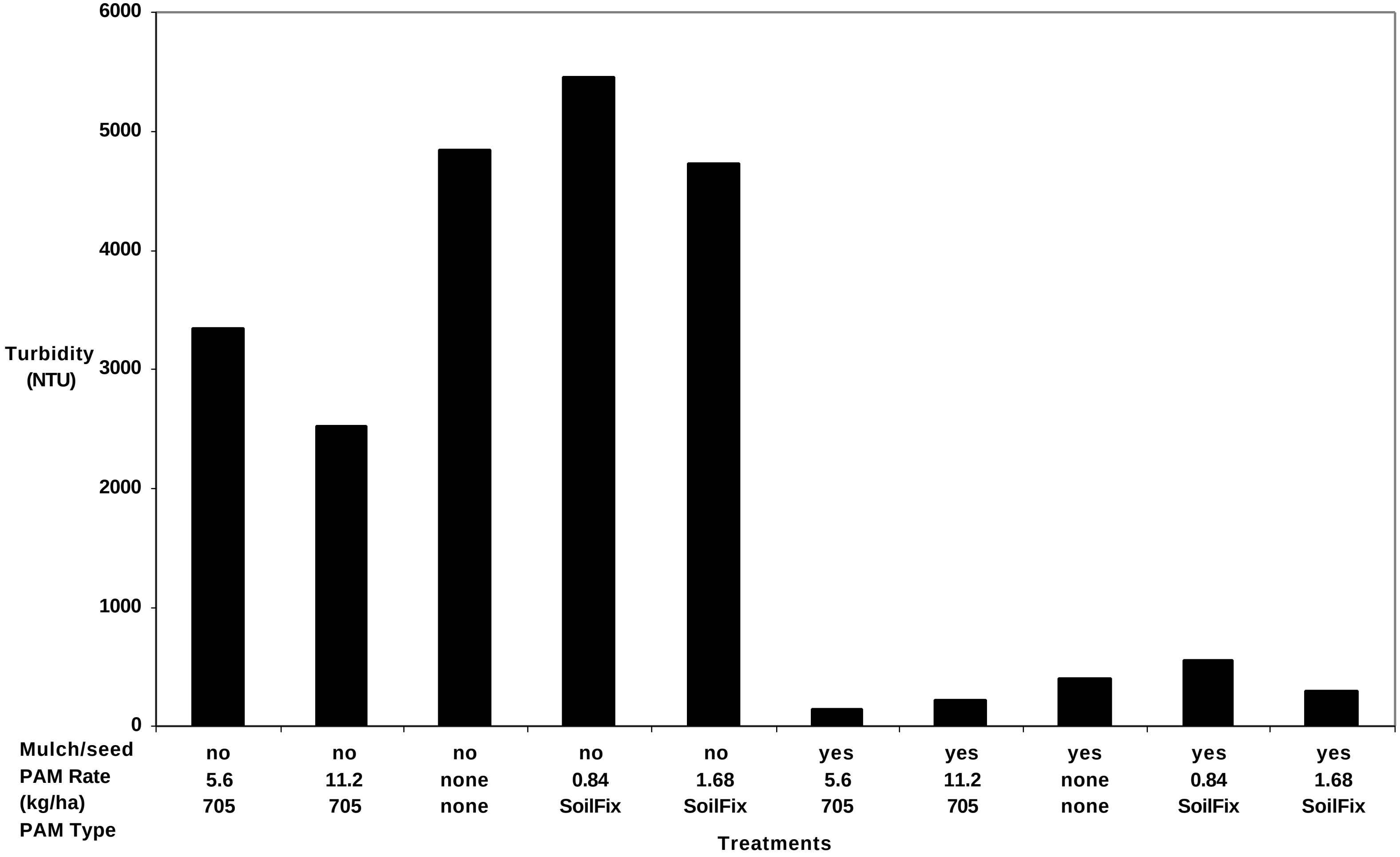


Figure 41: November 25 Turbidity
I-540 #2

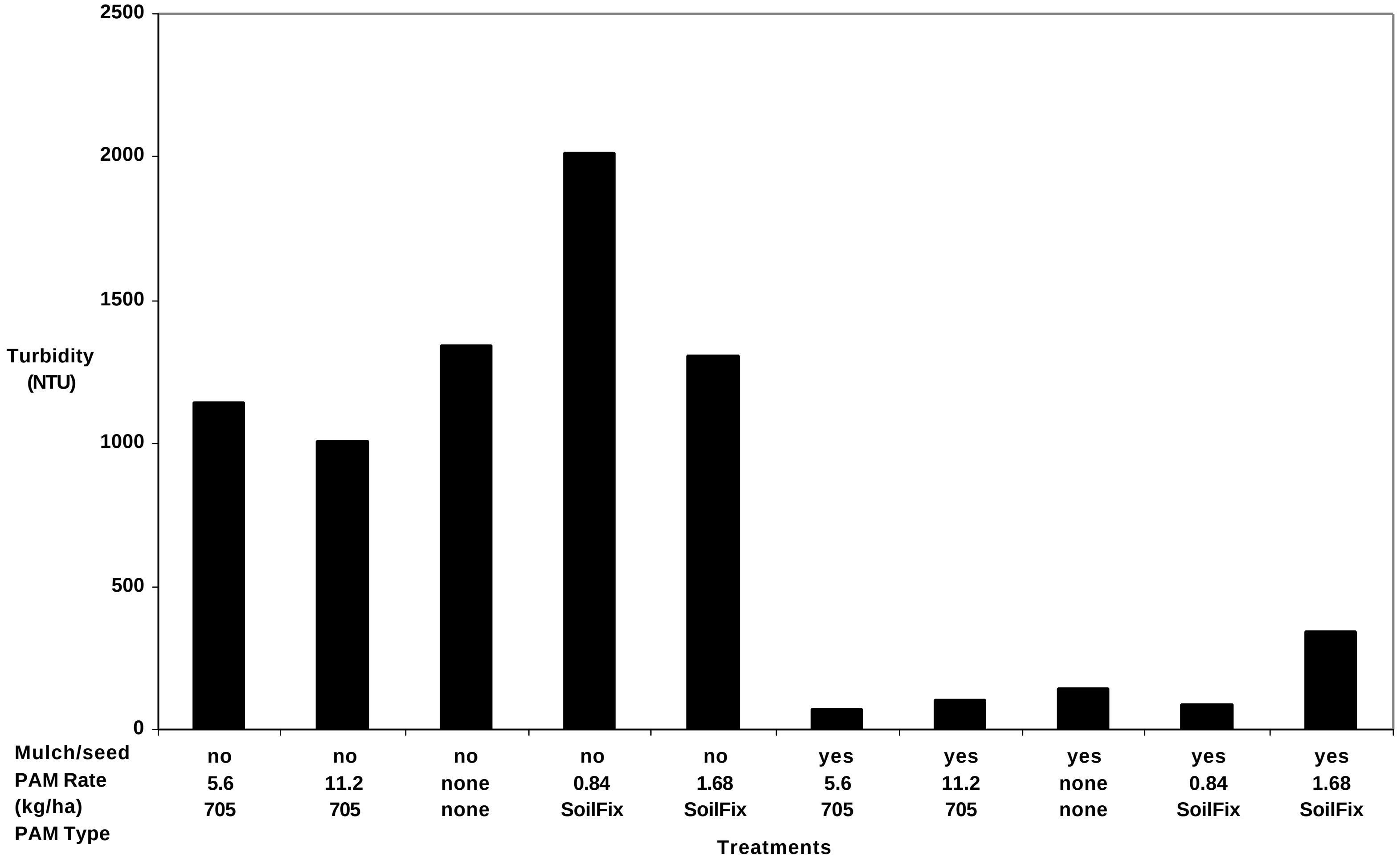


Figure 42: December 11 Turbidity
I-540 #2

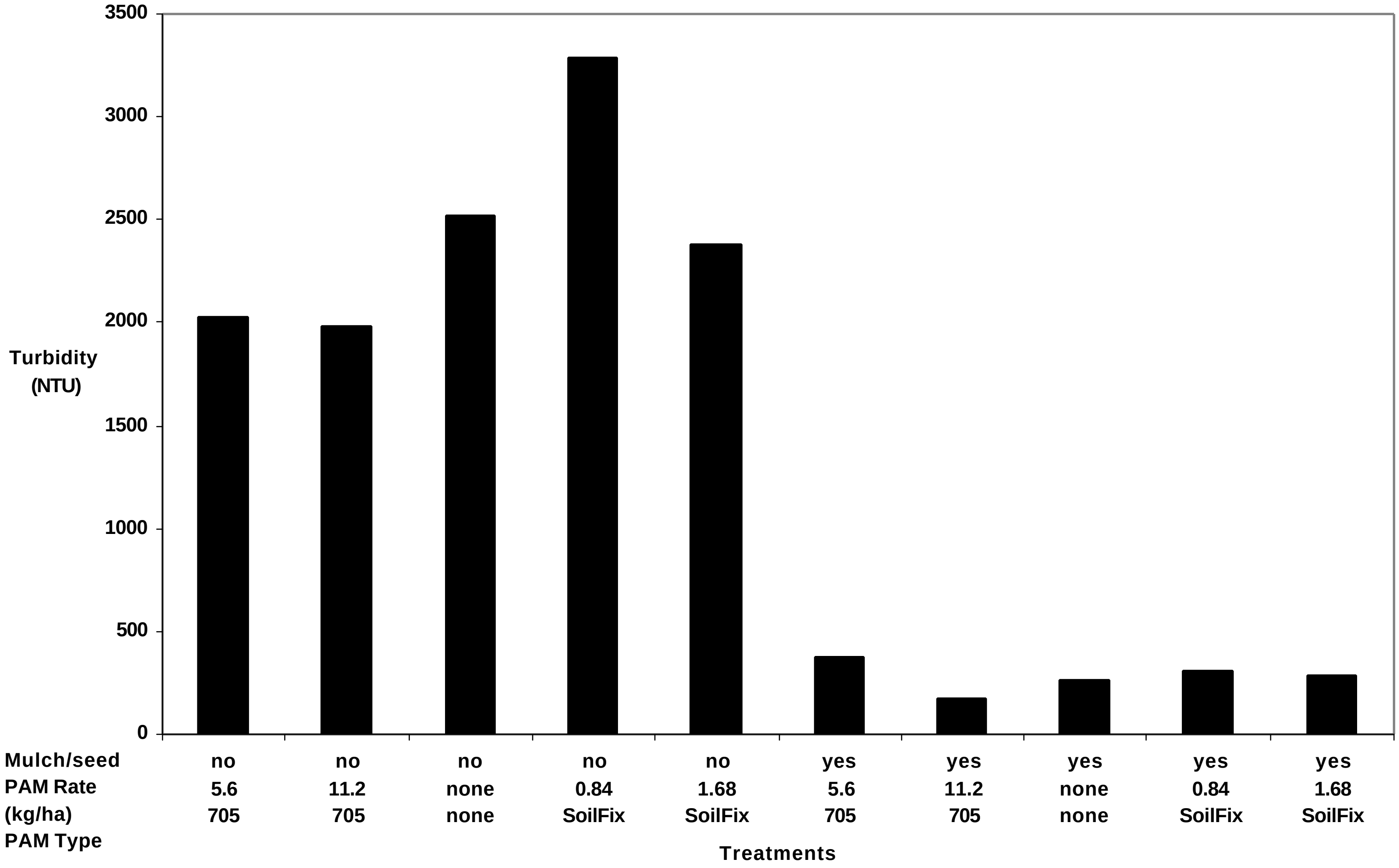


Figure 43: December 17 Turbidity
I-540 #2

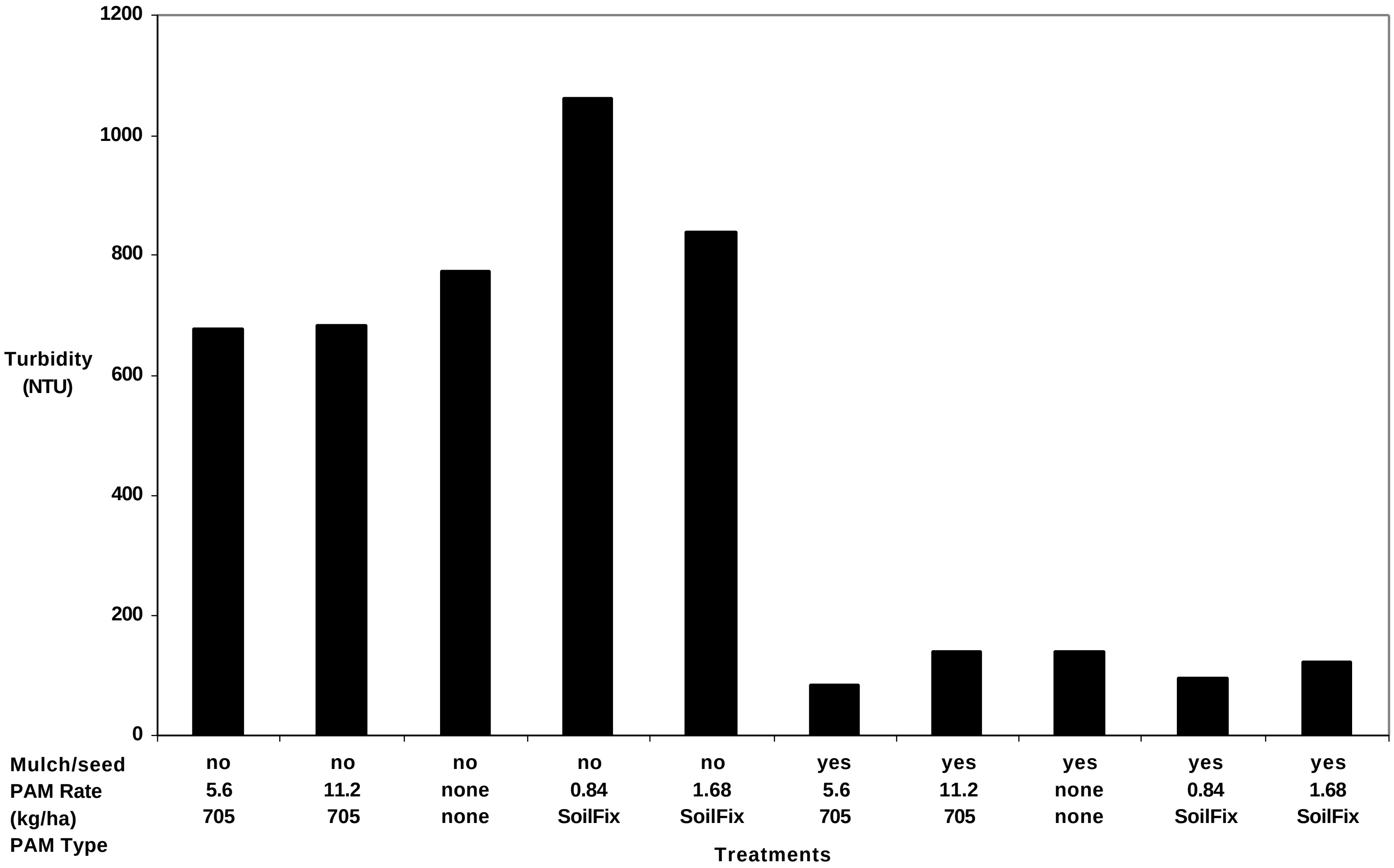


Figure 44: Average Turbidity
I-540 #2

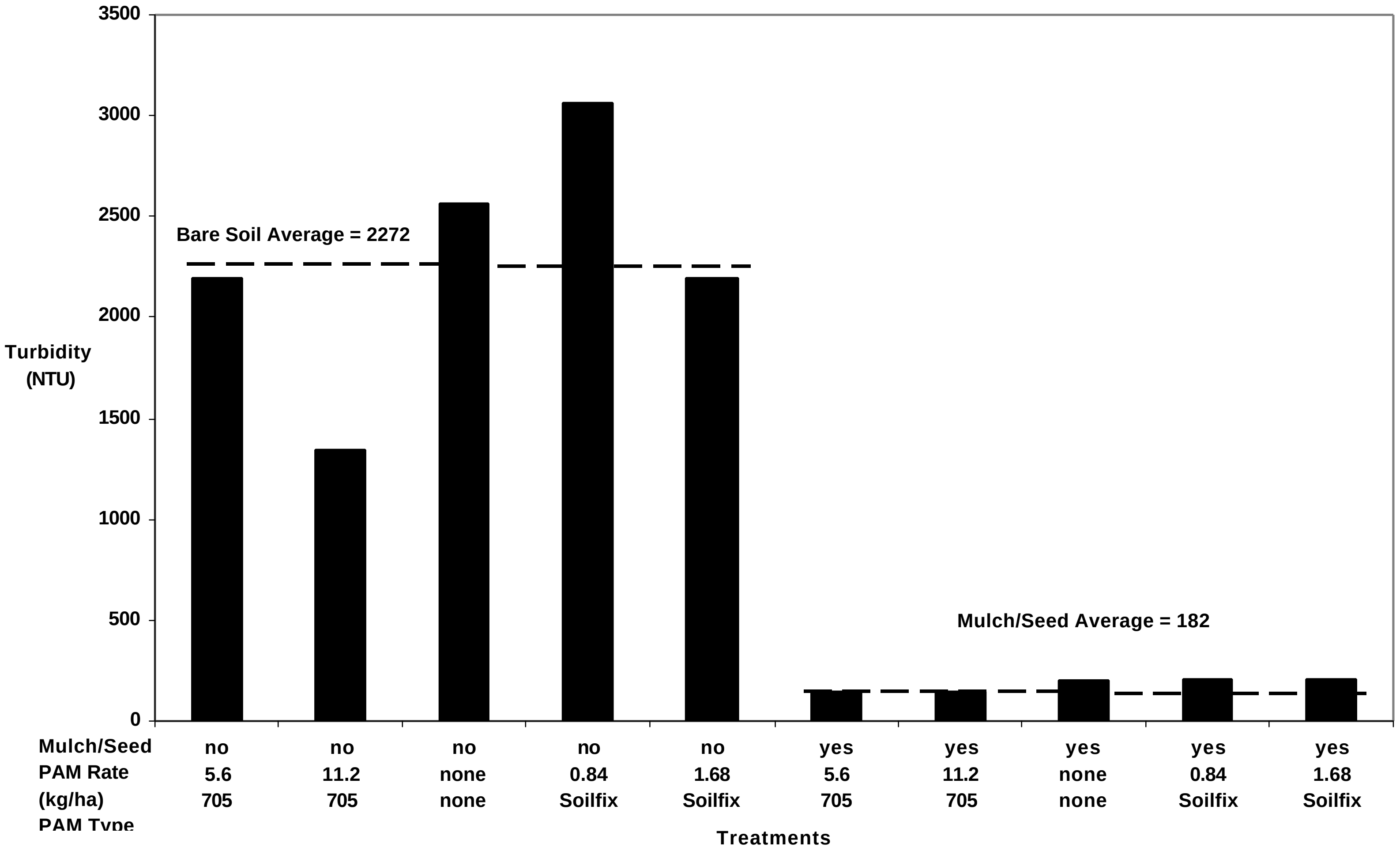


Figure 45: Bare Soil With/Without Flocculant
I-540 #2

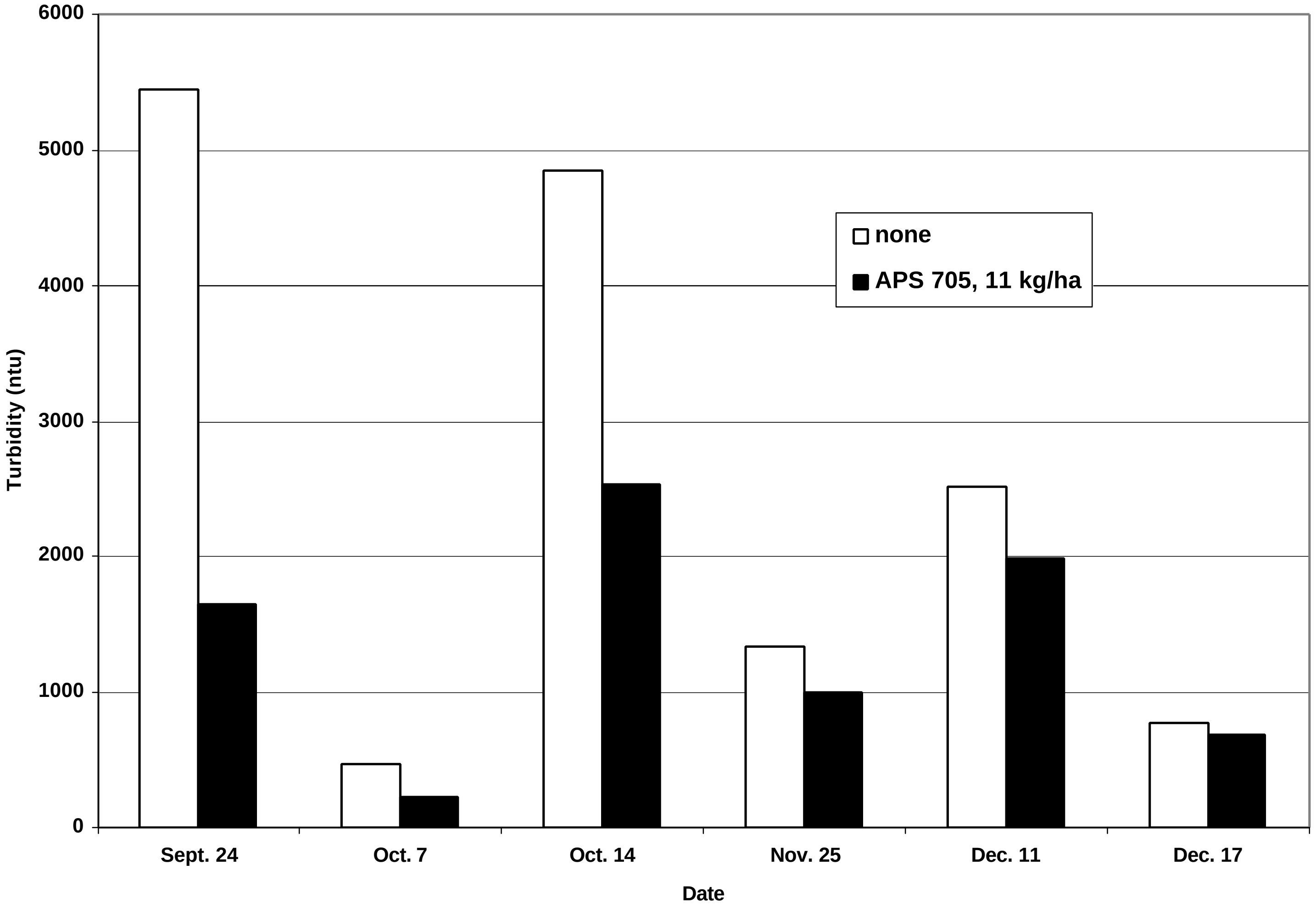
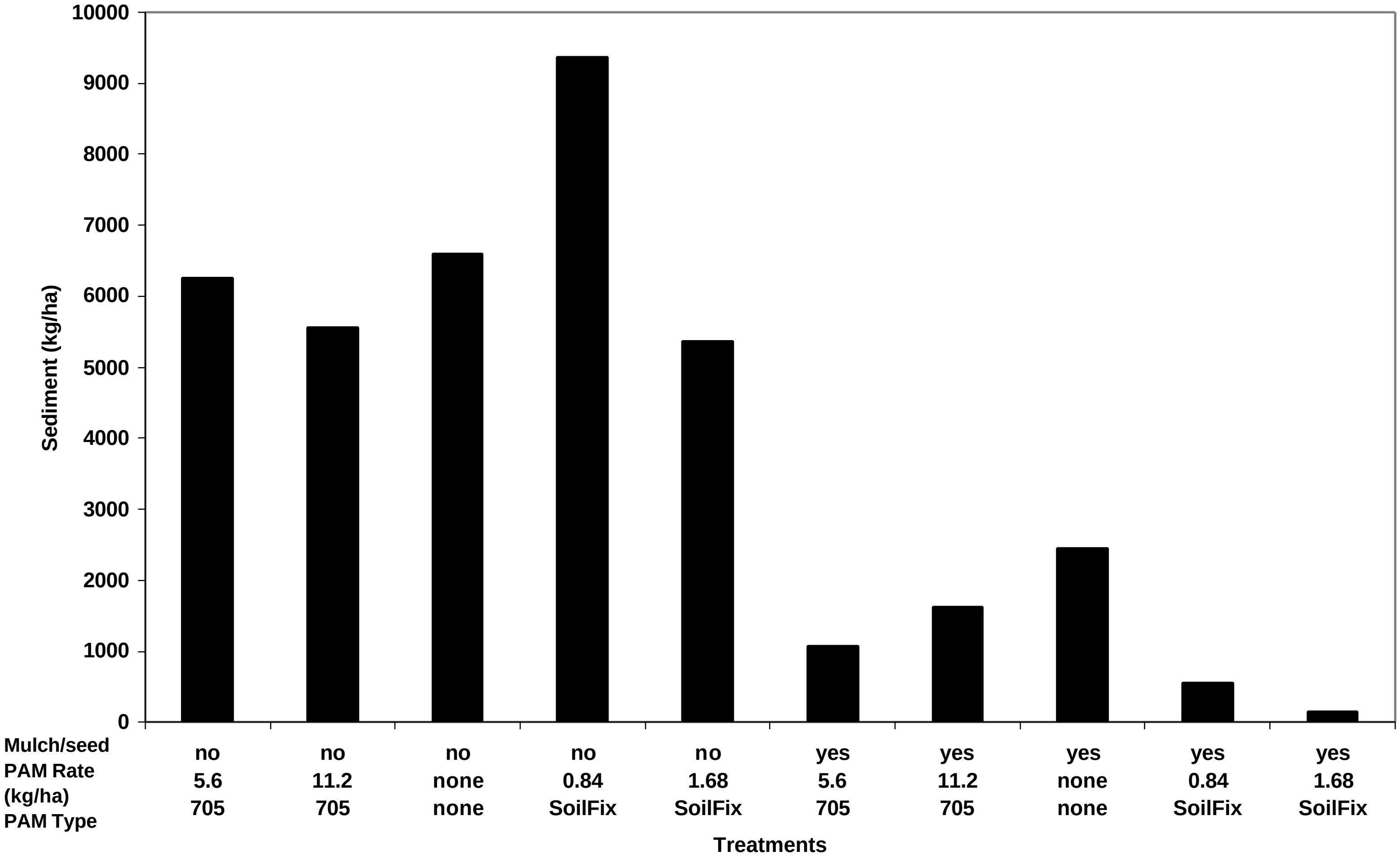


Figure 46: October 14 Sediment
I-540 #2



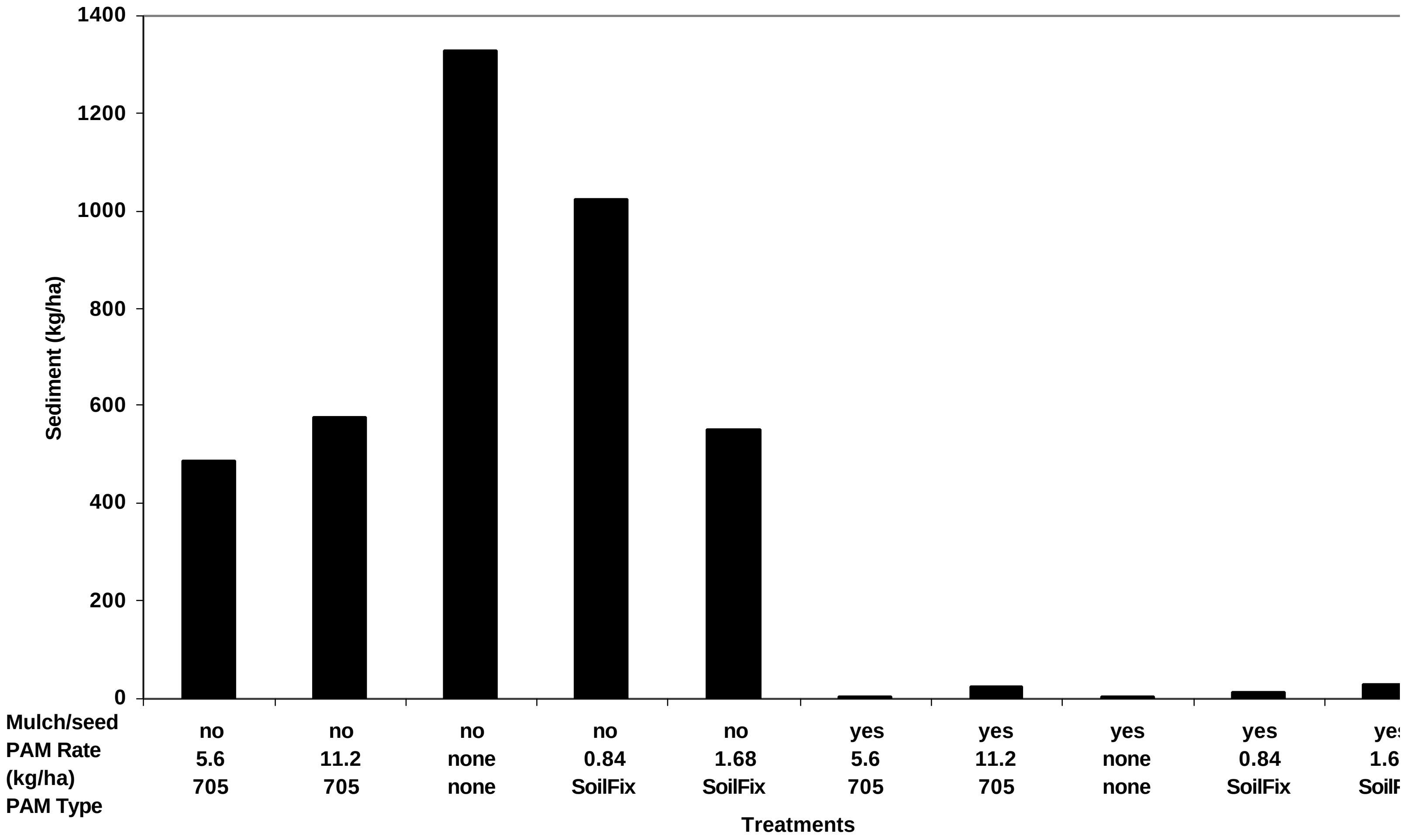
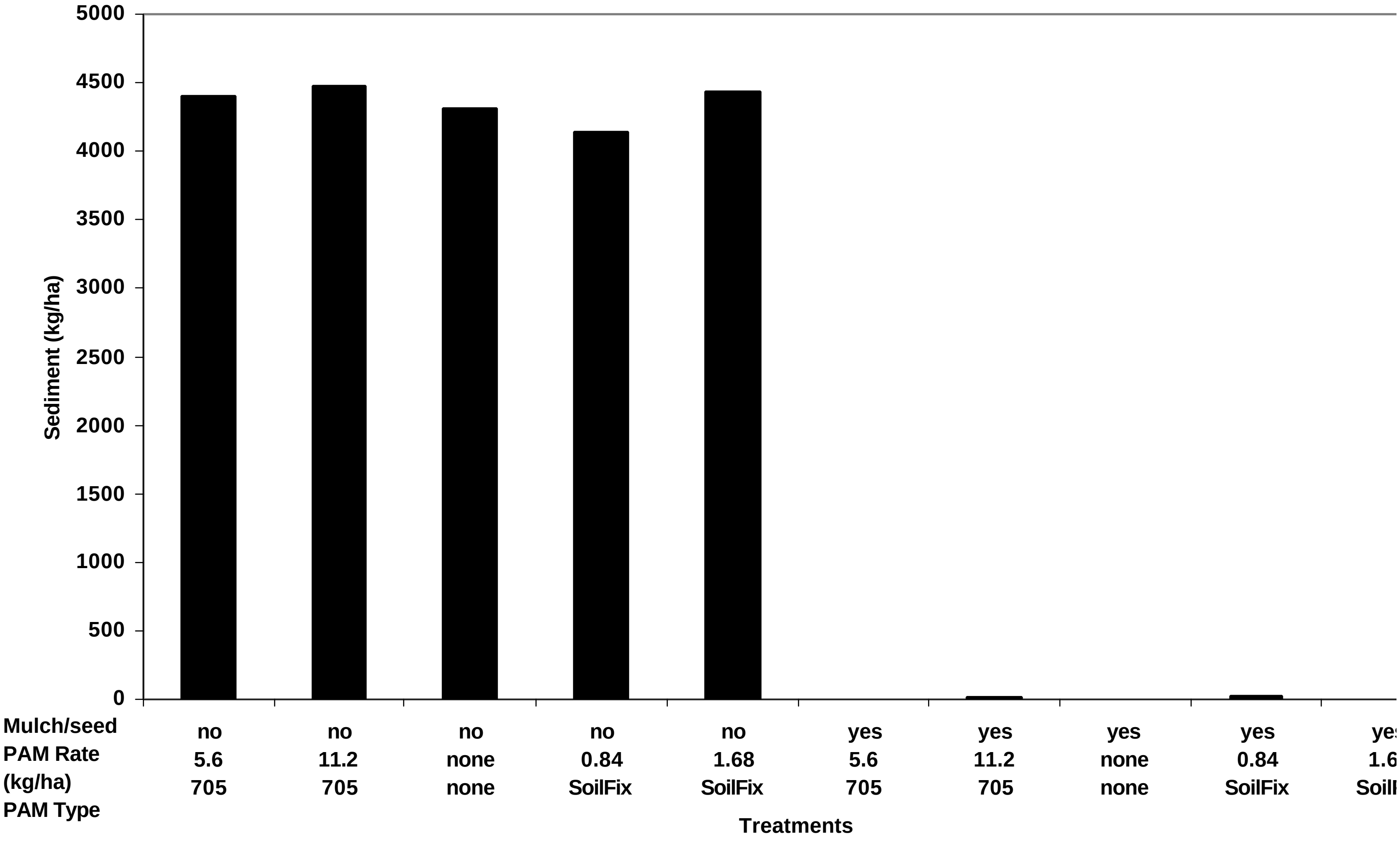


Figure 47: November 25 Sediment
I-540 #2

Fiure 48: December 11 Sediment
I-540 #2



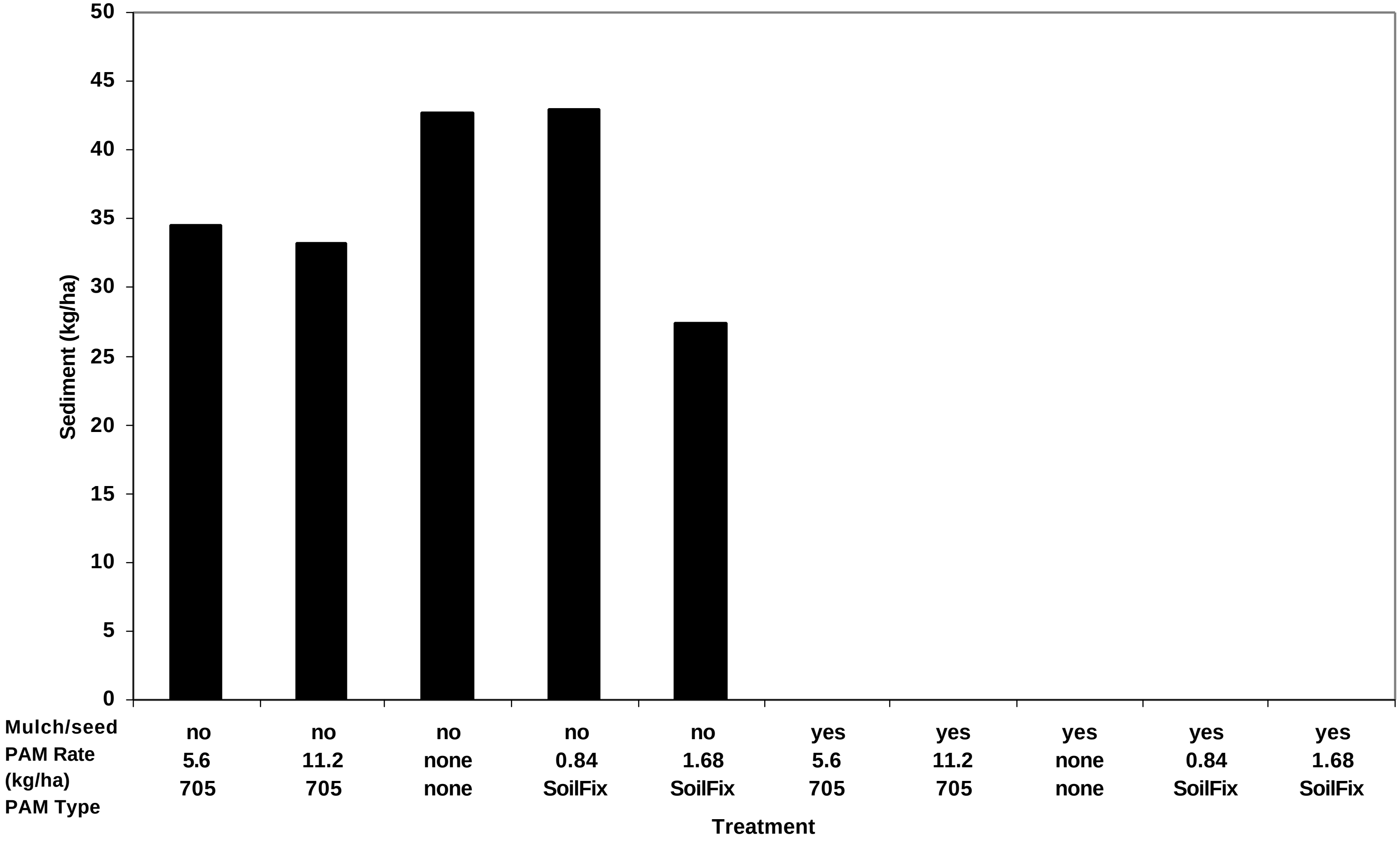


Figure 49: December 17 Sediment
I-540 #2

Figure 50: Total Sediment Loss
I-540 #2

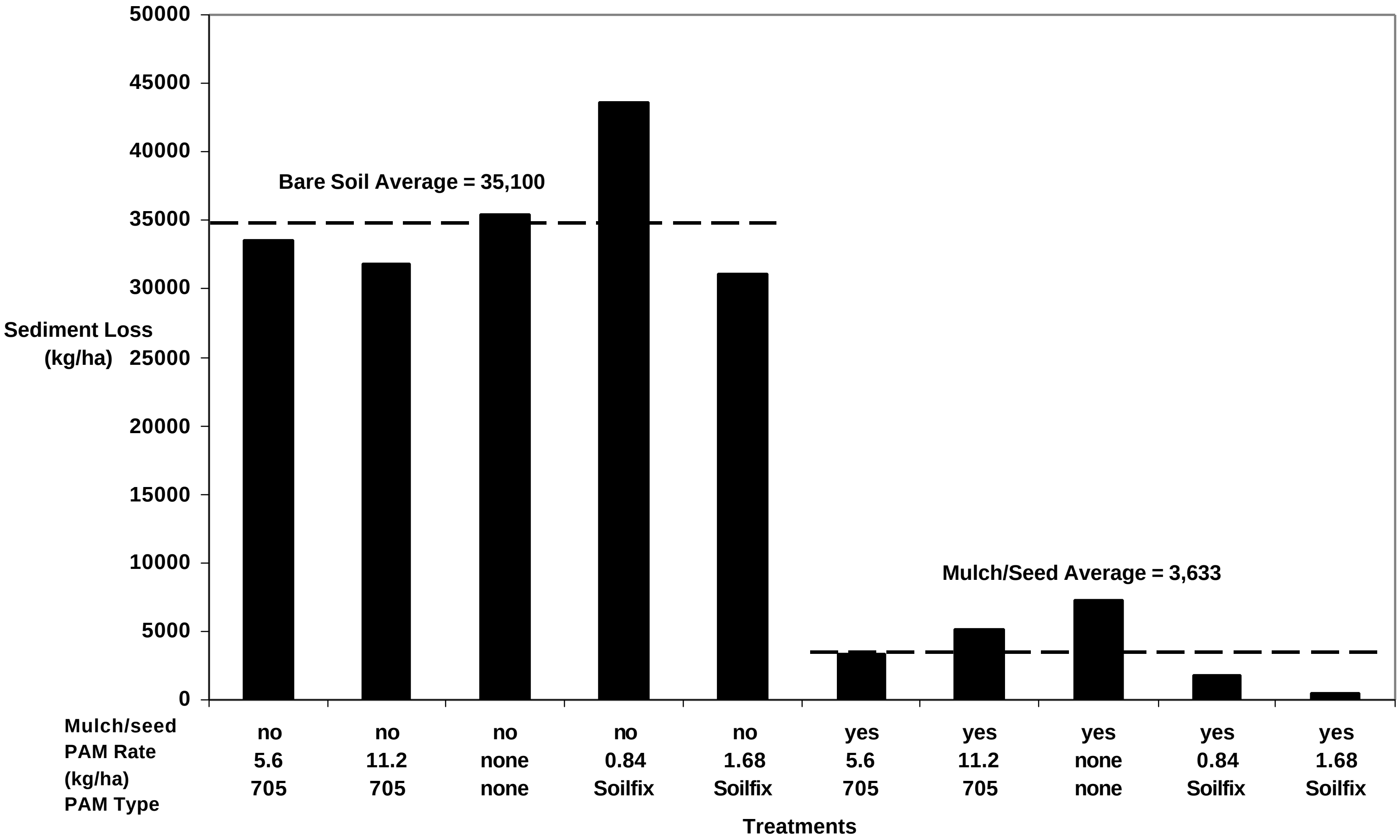


Figure 51. Applying PAM at highest rate (20 kg/ha) at the Fayetteville I-95 site.

Figure 52: Precipitation Events, Fayetteville I-95 Loop

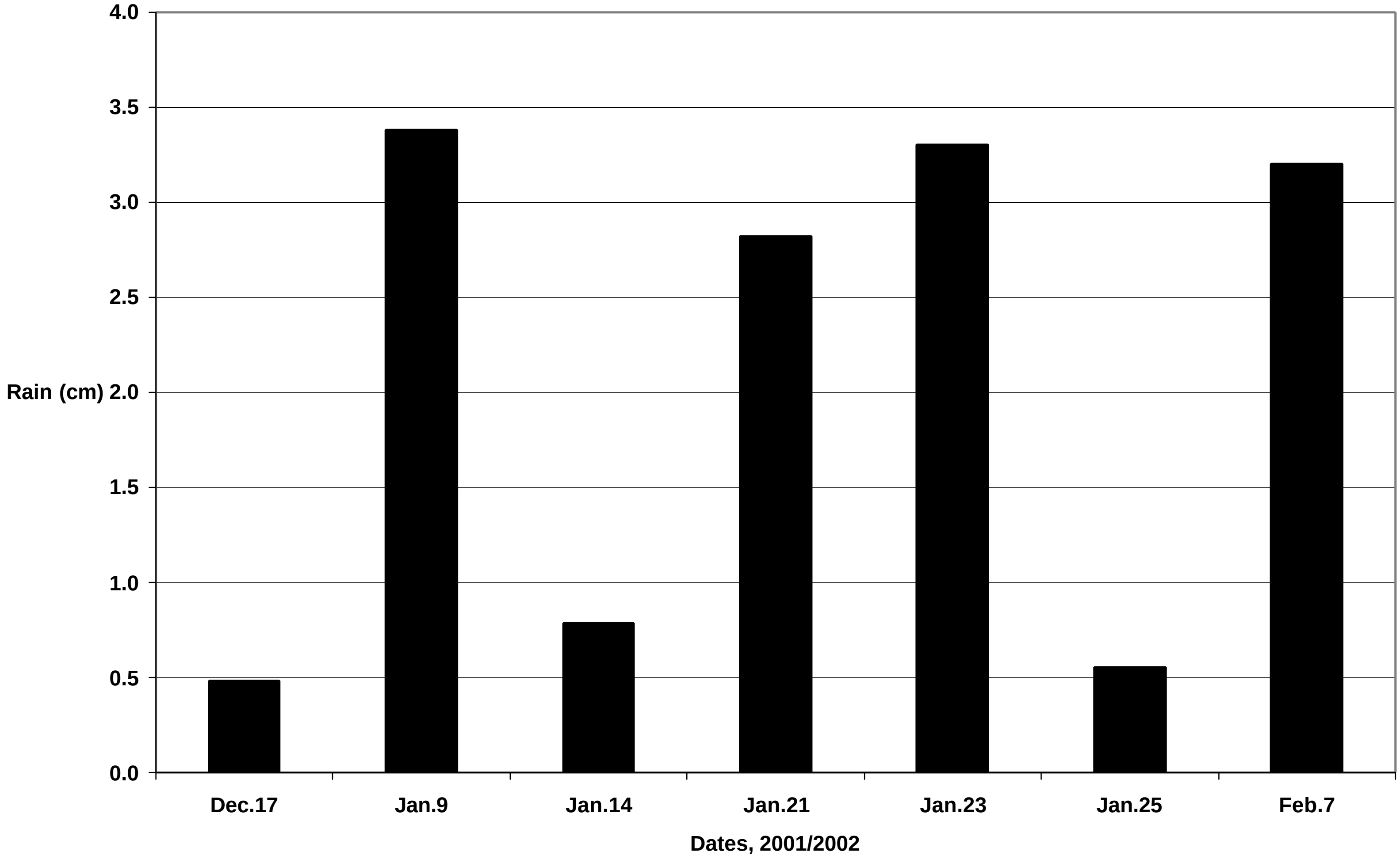
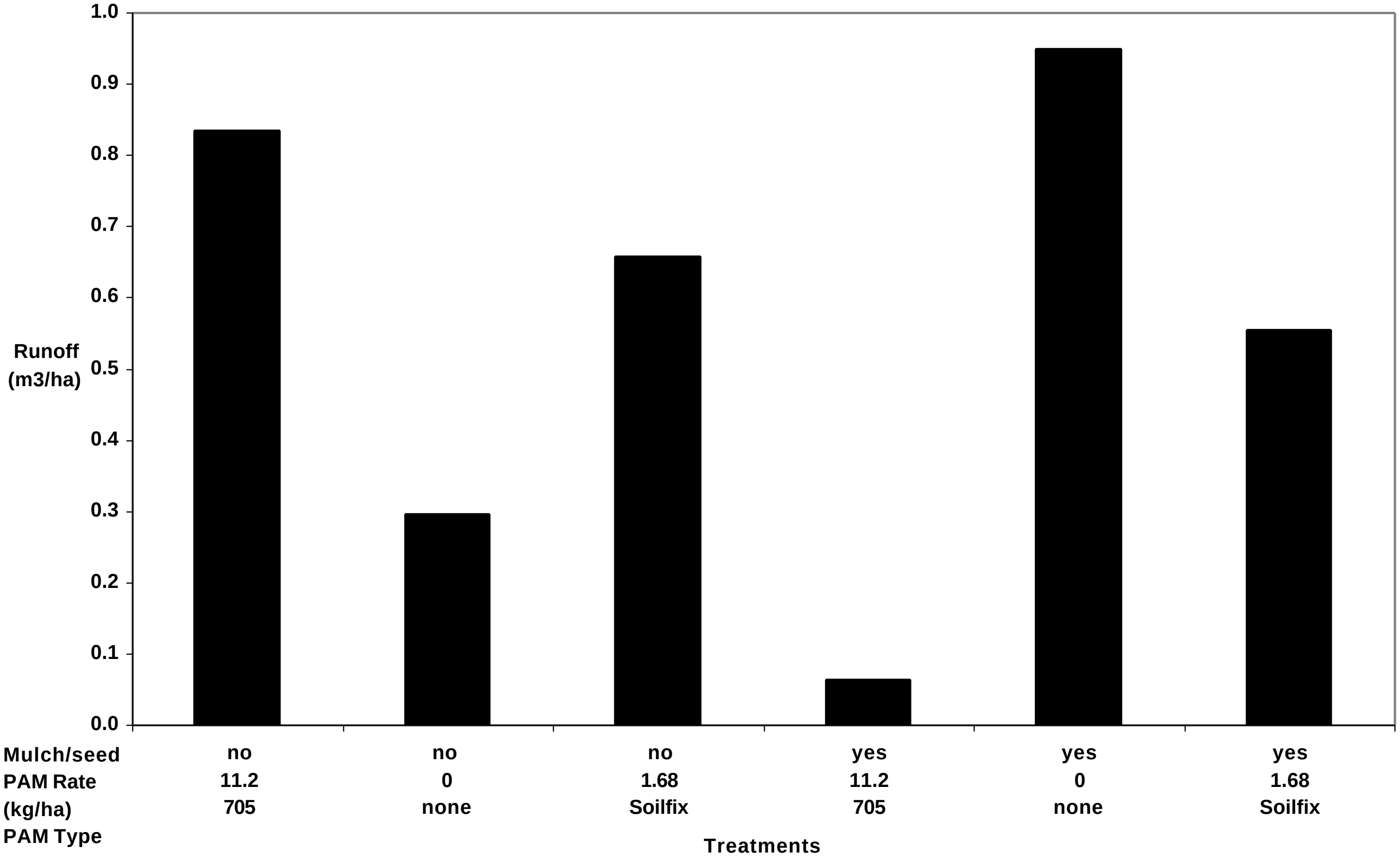


Figure 53: December 17 Runoff
Fayetteville I-95



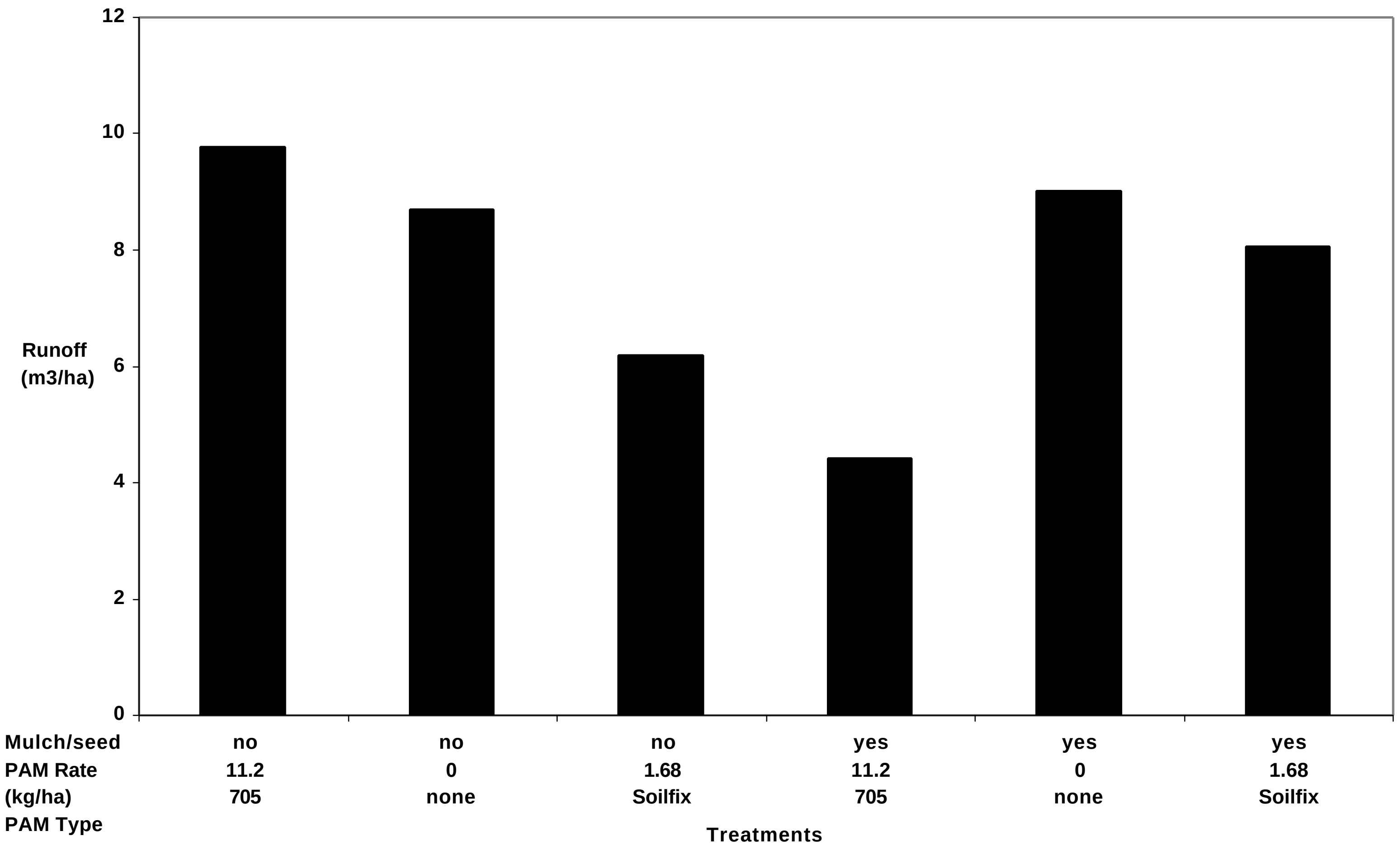


Figure 54: January 9 Runoff
Fayetteville I-95

Figure 55: January 14 Runoff
Fayetteville I-95

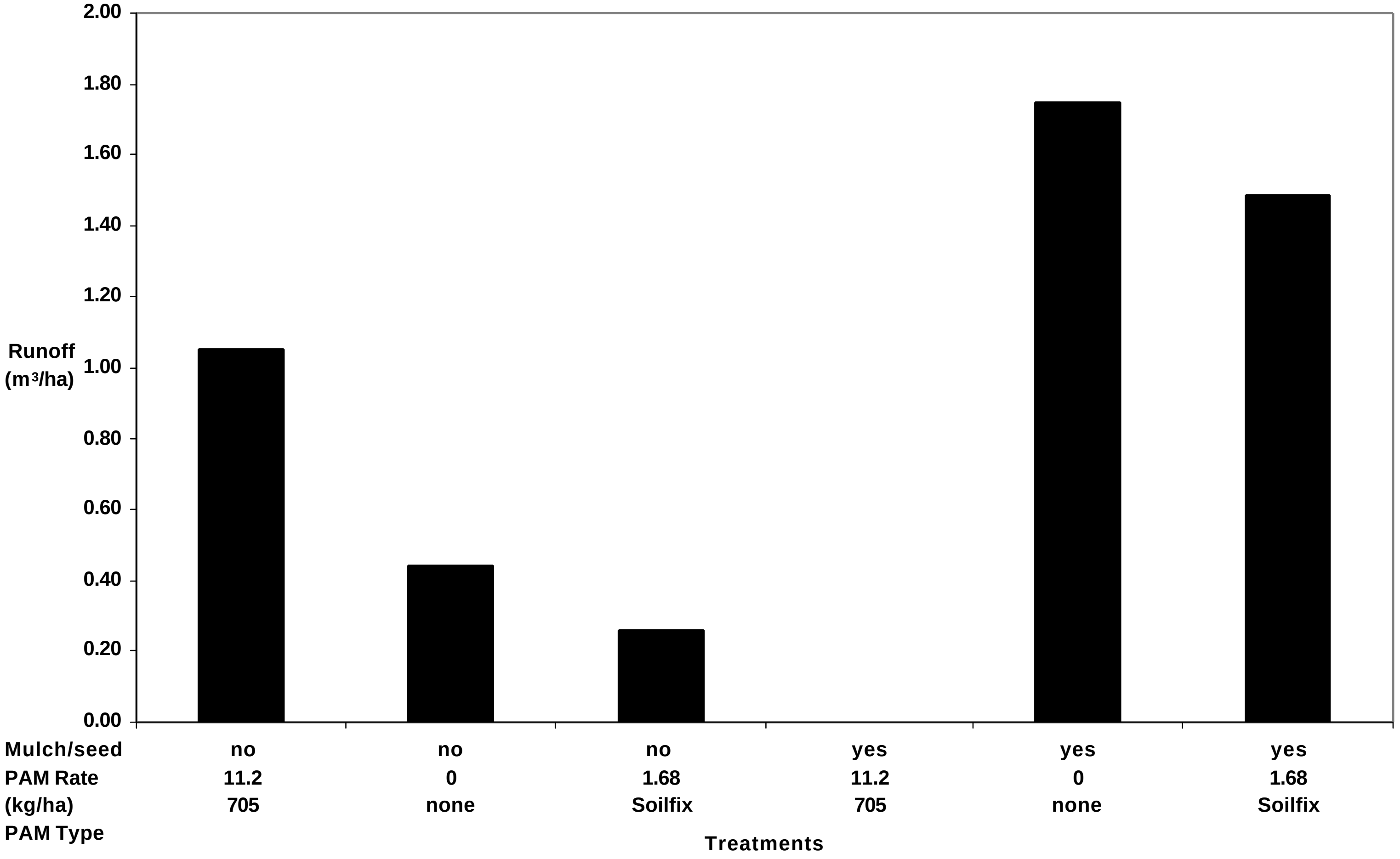


Figure 56: January 21 Runoff
Fayetteville I-95

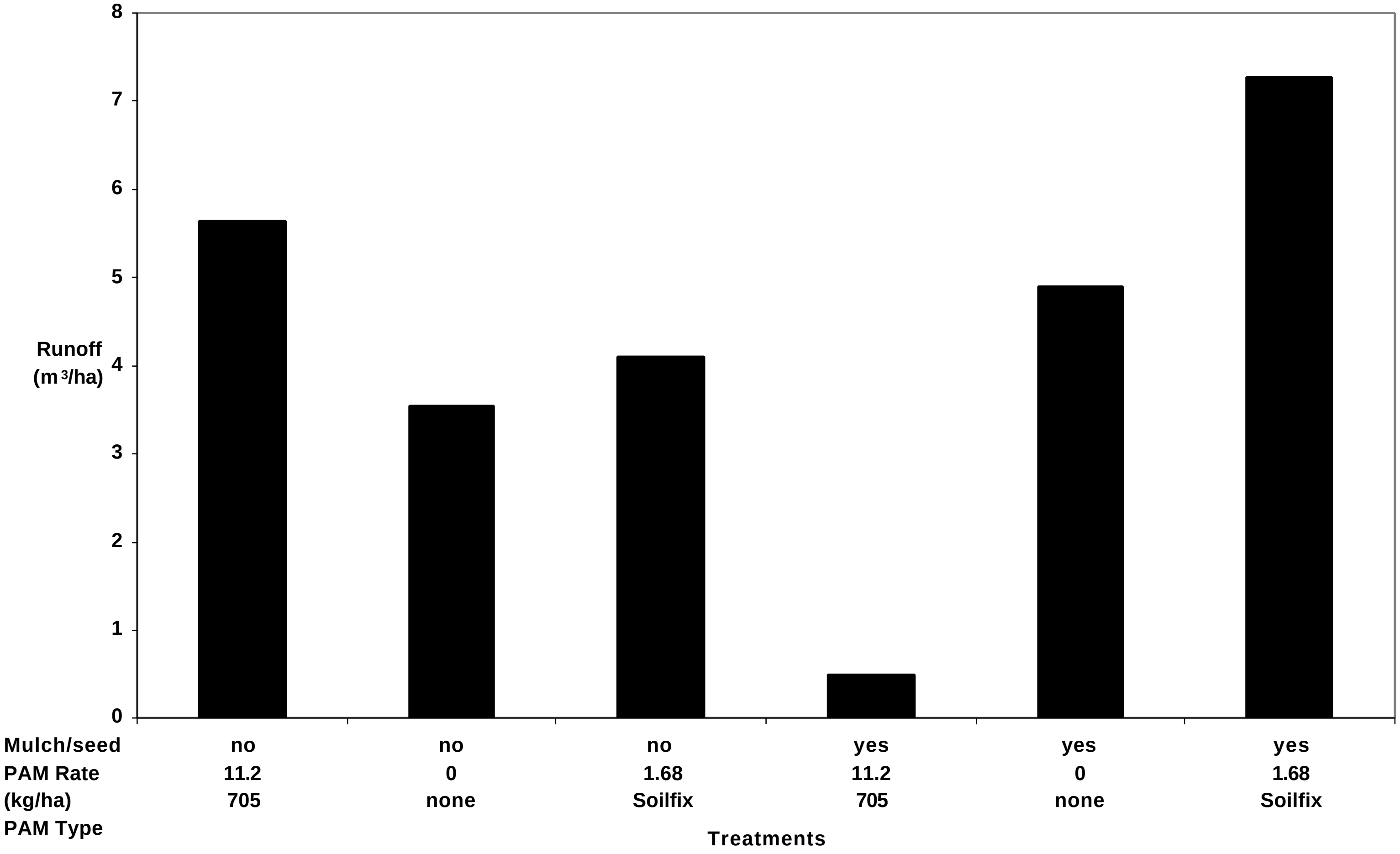


Figure 57: January 23 Runoff
Fayetteville I-95

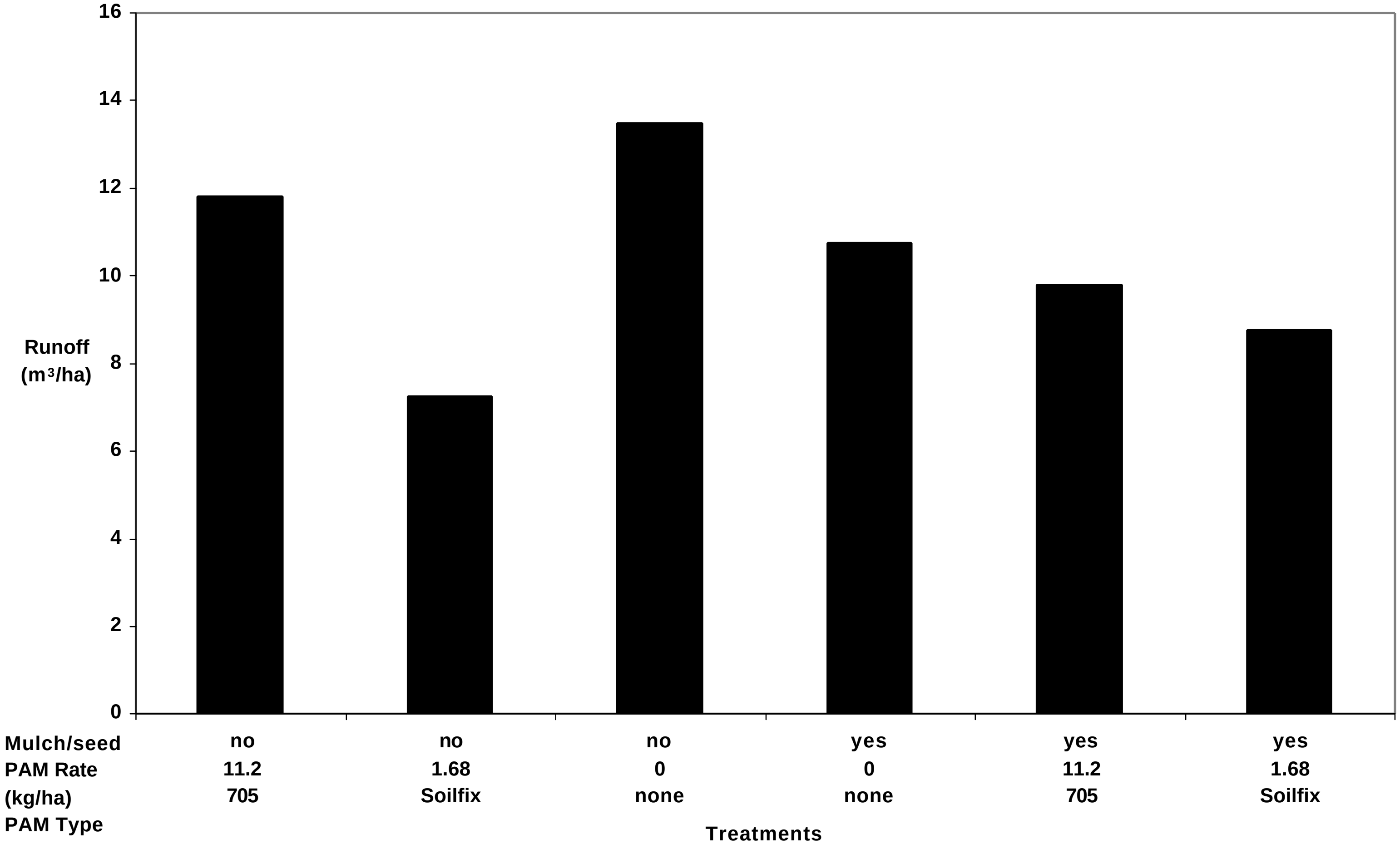


Figure 58: January 25 Runoff Volumes
Fayetteville I-95

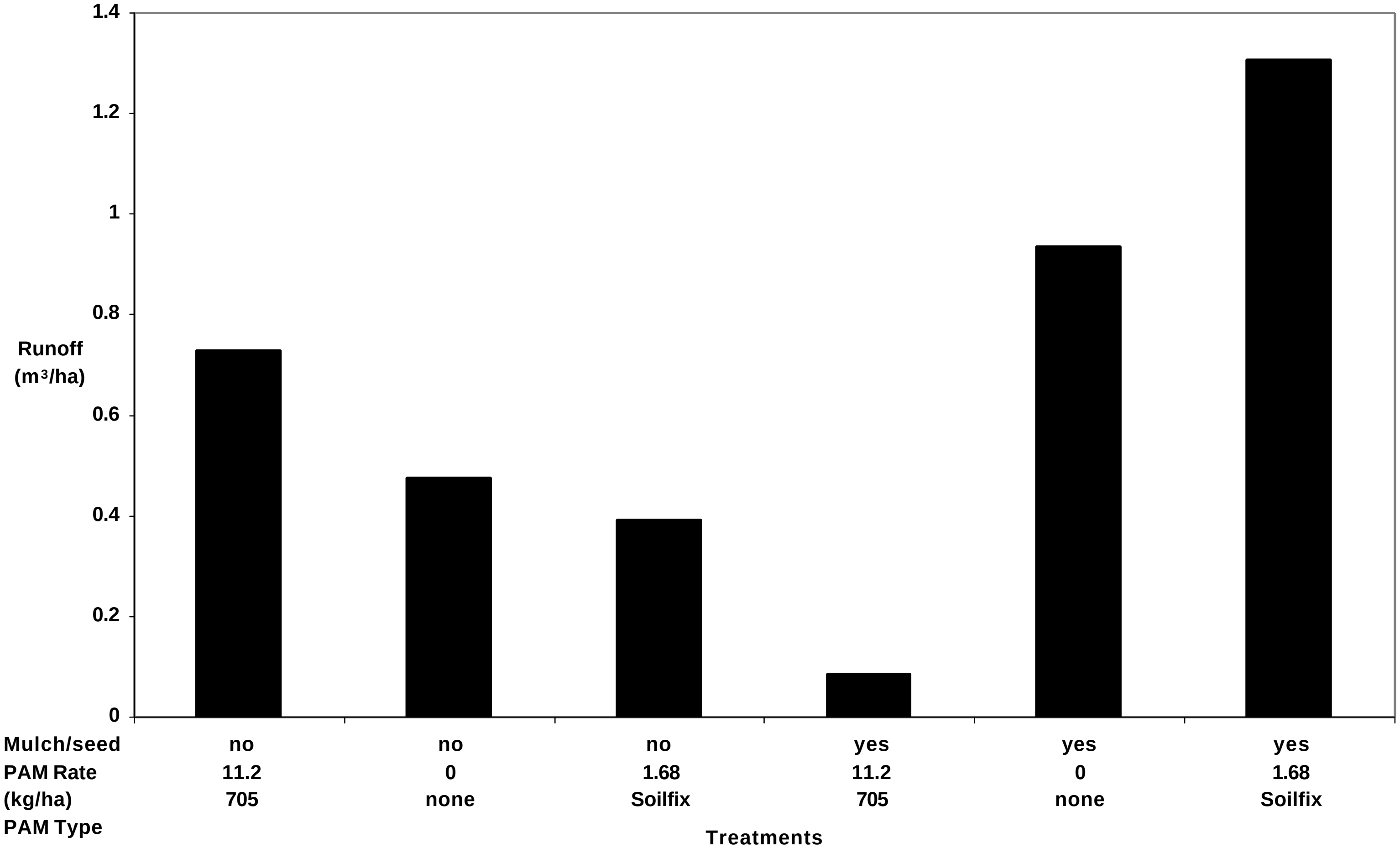


Figure 59: February 8 Runoff
Fayetteville I-95

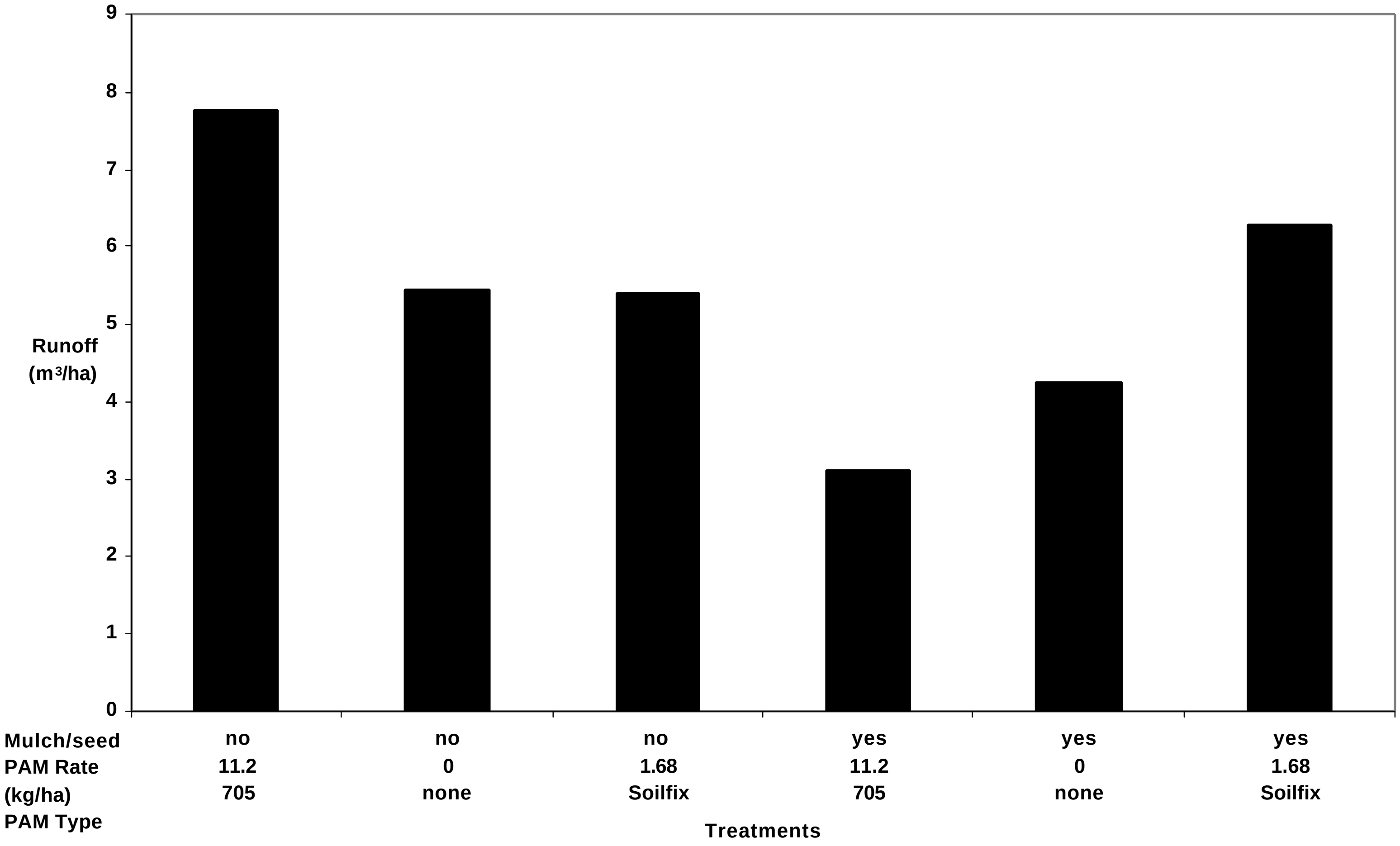


Figure 60: Total Runoff Volume
Fayetteville I-95

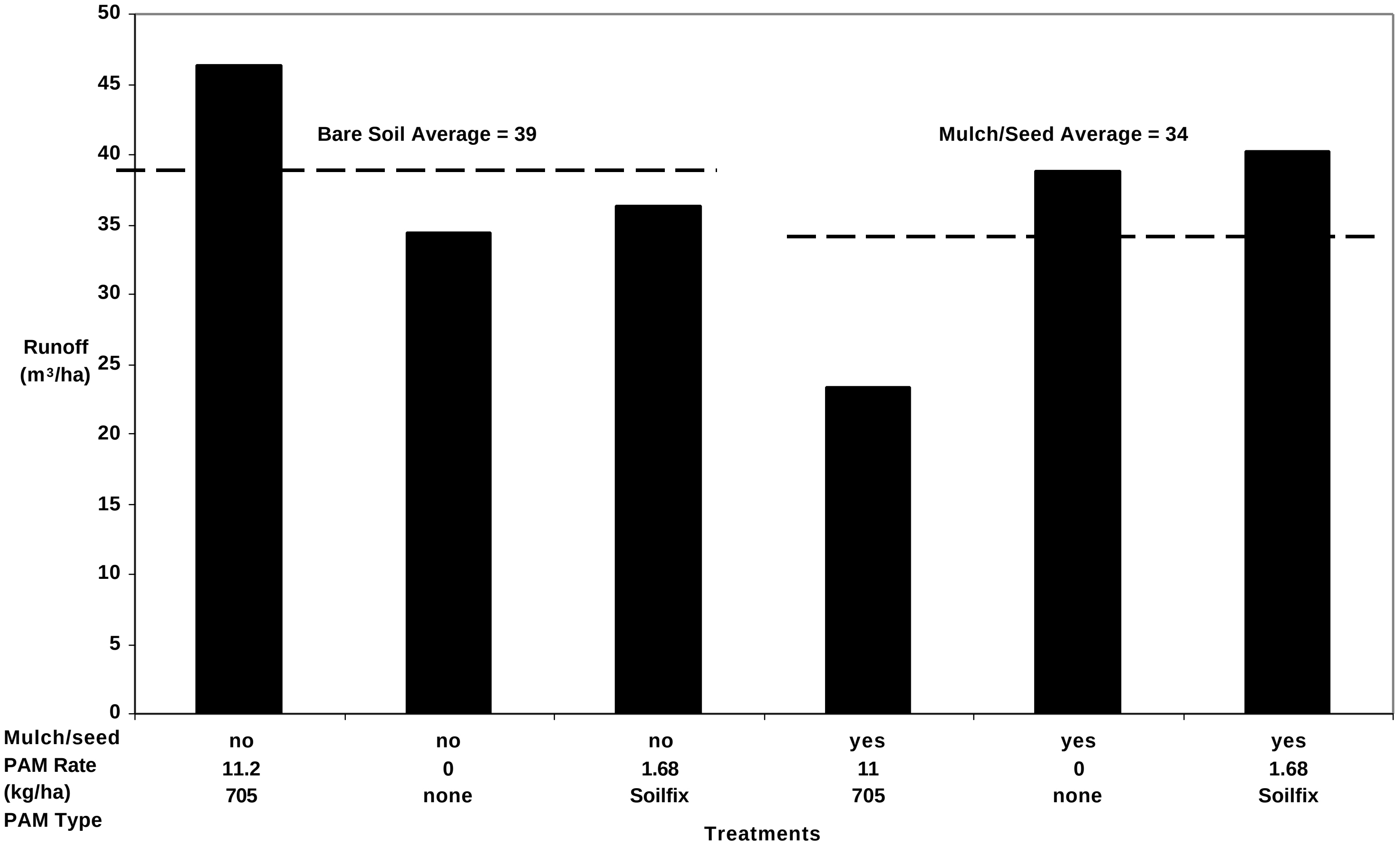


Figure 61: December 17 Turbidity
Fayetteville I-95

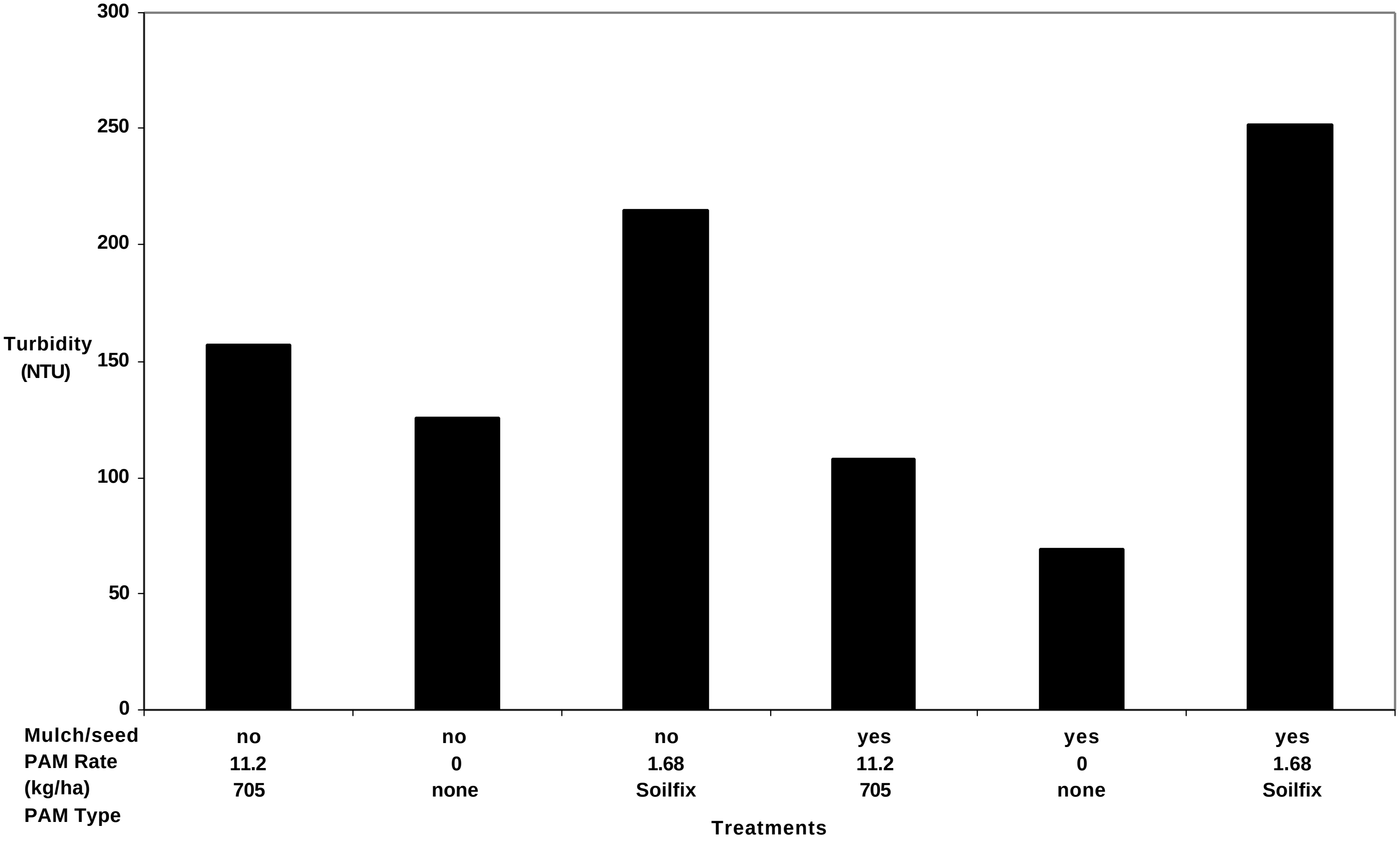


Figure 62: January 9 Turbidity
Fayetteville I-95

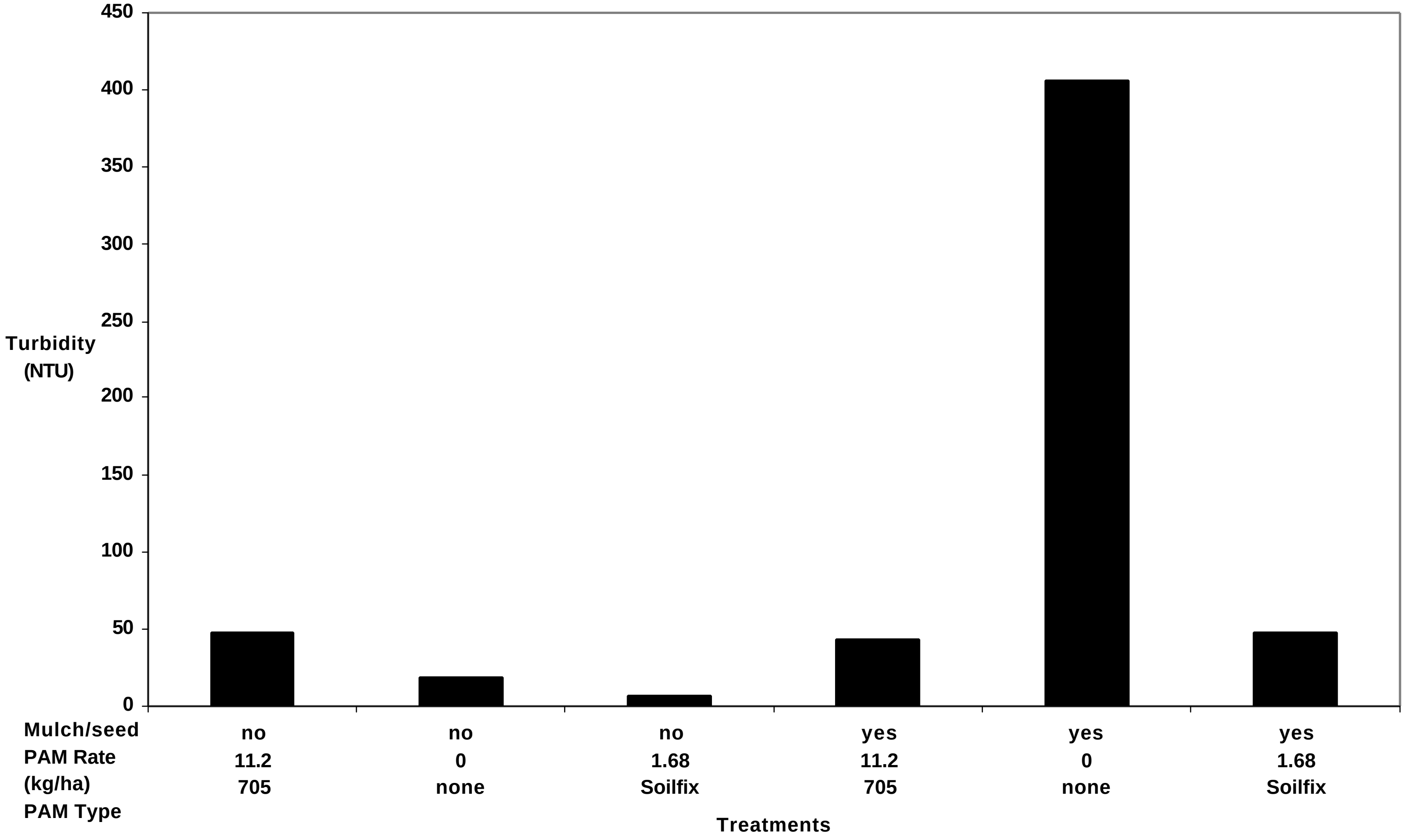


Figure 63: January 14 Runoff
Fayetteville I-95

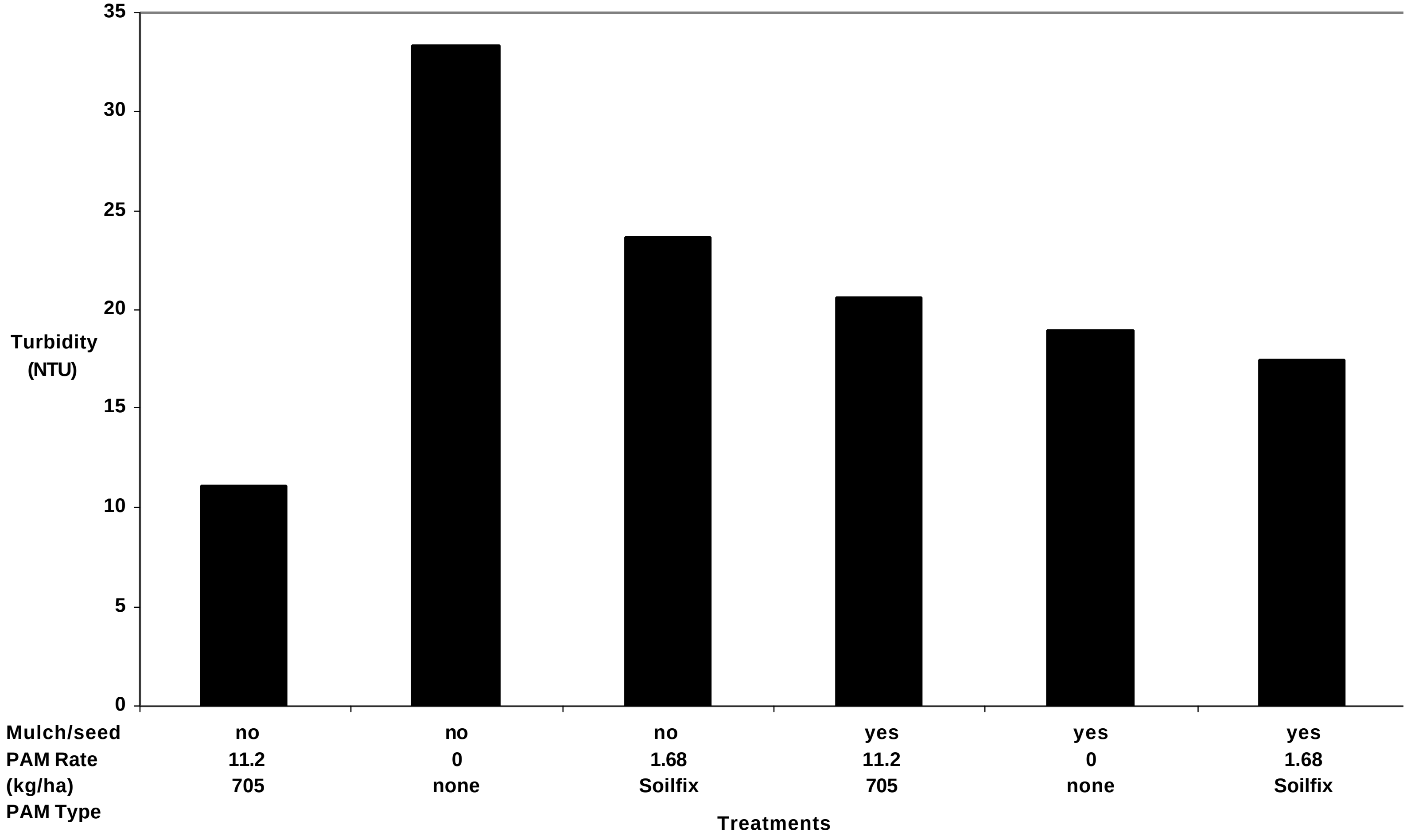


Figure 64: January 21 Turbidity
Fayetteville I-95

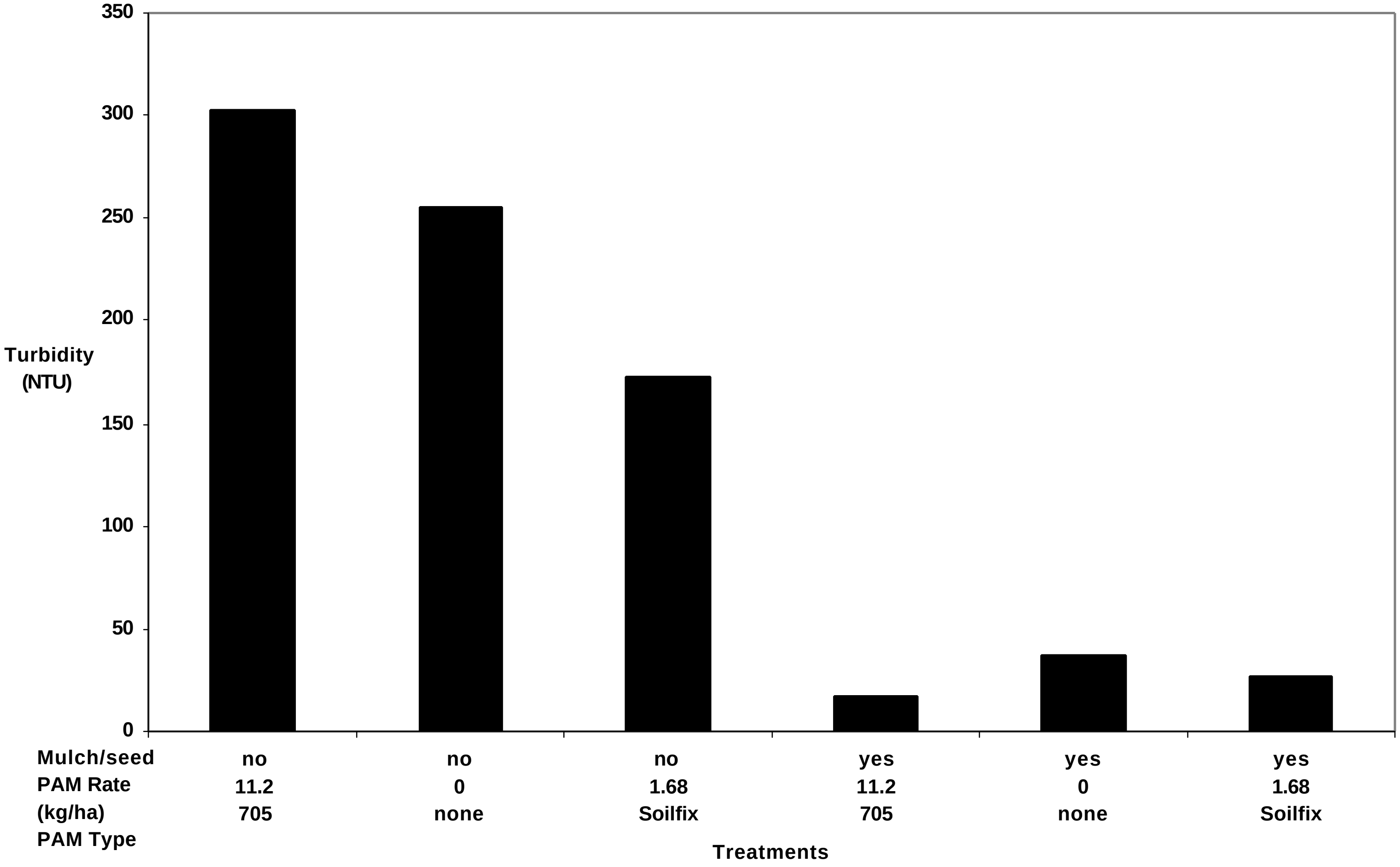


Figure 65: January 23 Turbidity
Fayetteville I-95

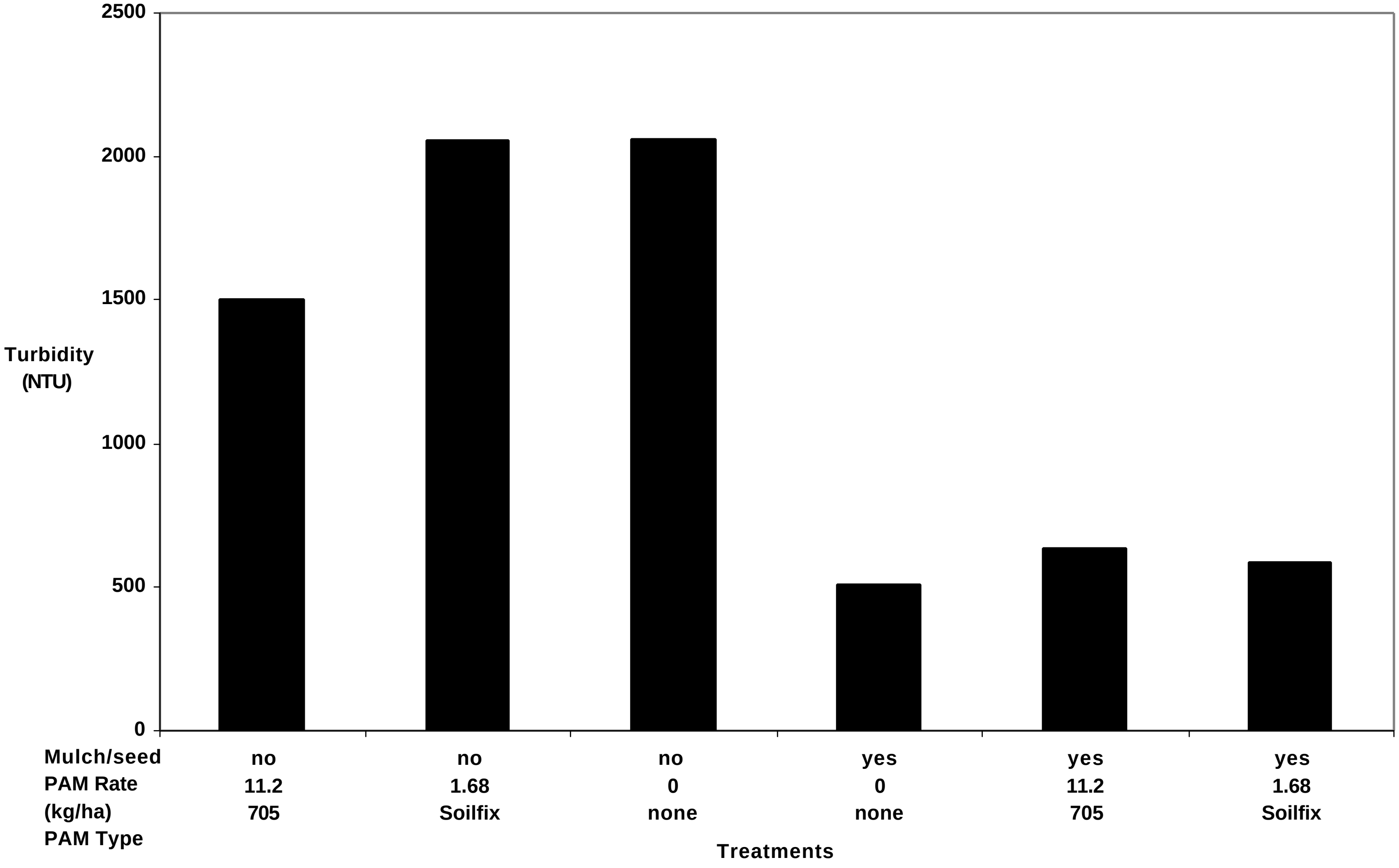


Figure 66: January 25 Turbidity
Fayetteville I-95

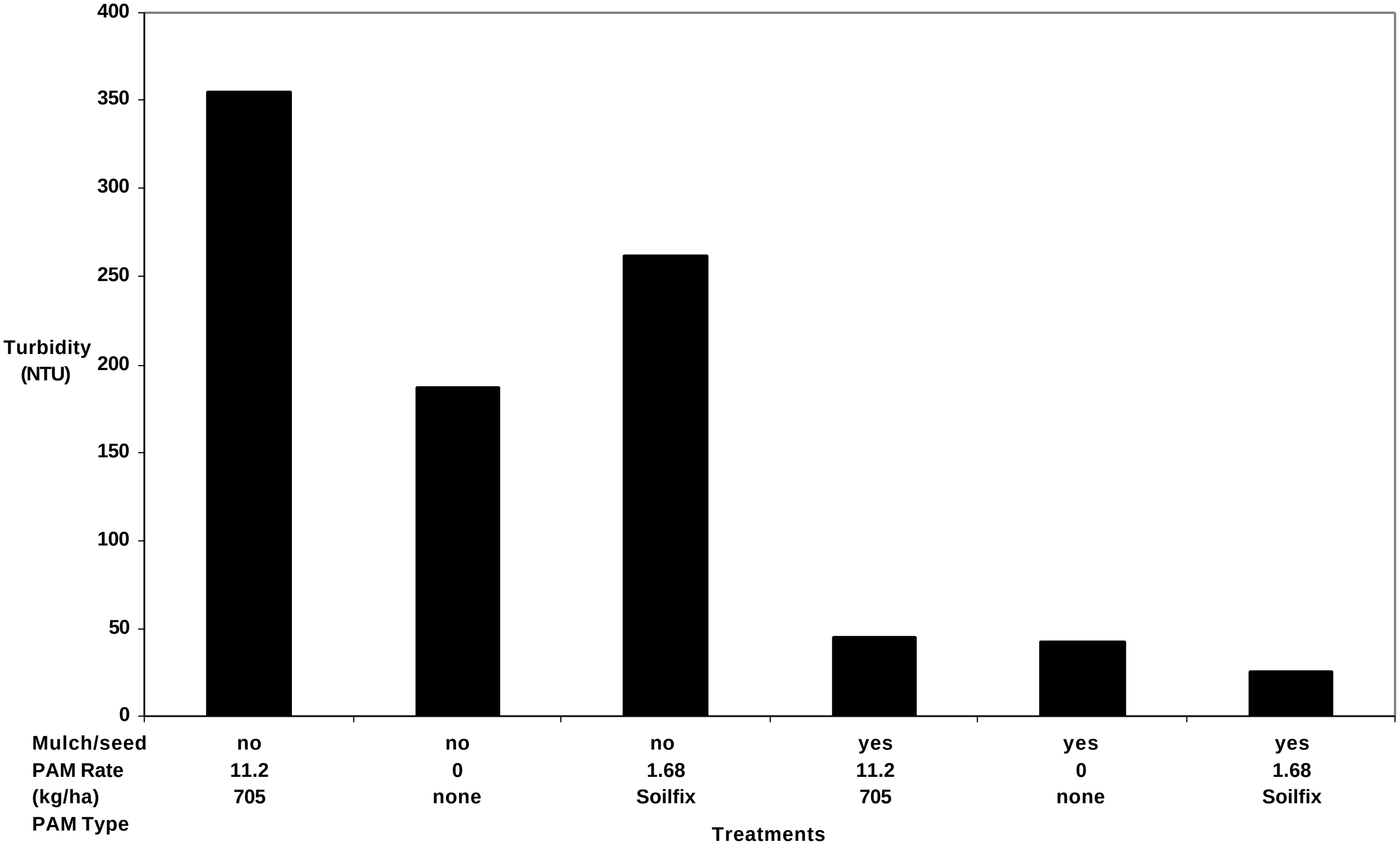


Figure 67: February 8 Turbidity
Fayetteville I-95

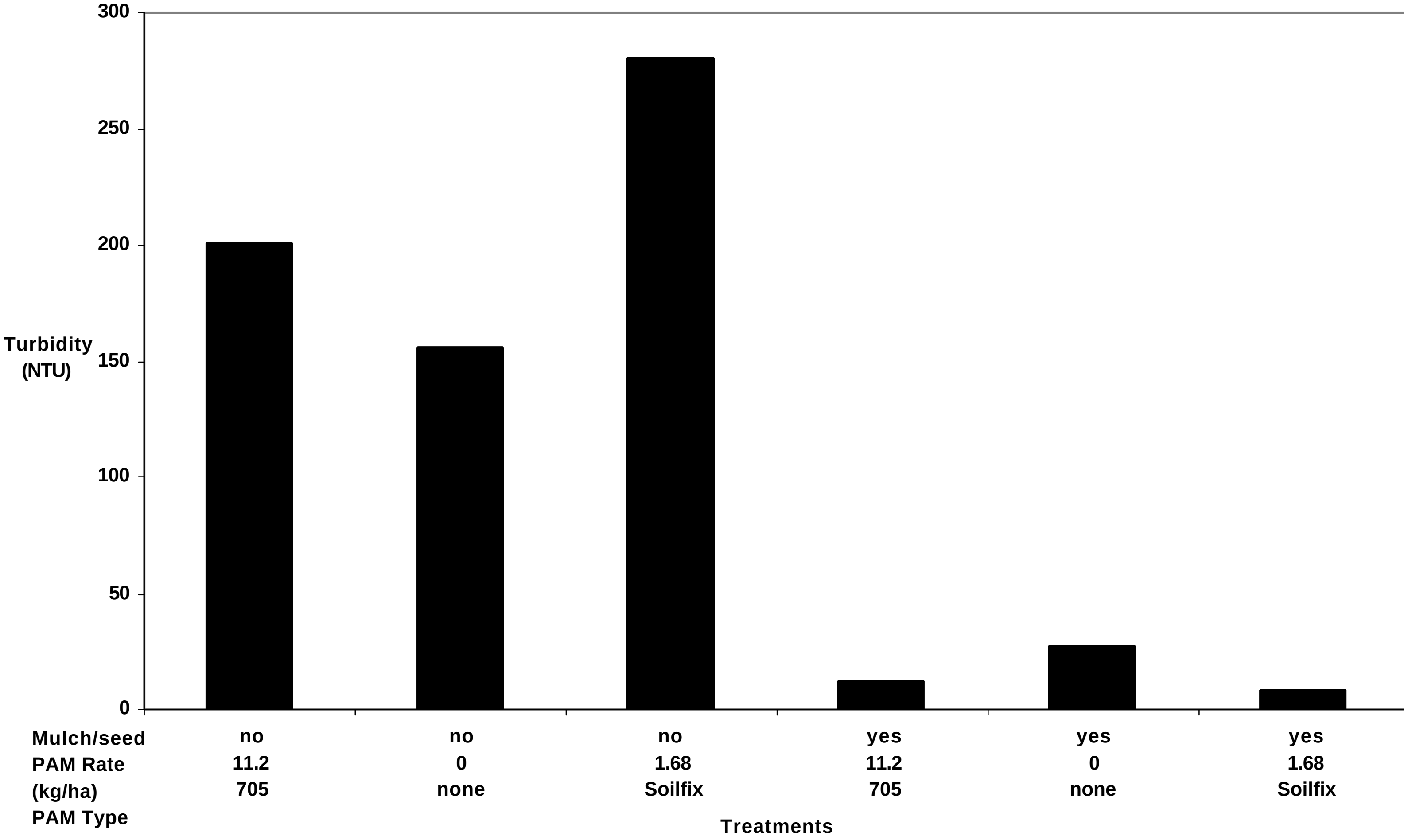


Figure 68: Average Turbidity
Fayetteville I-95

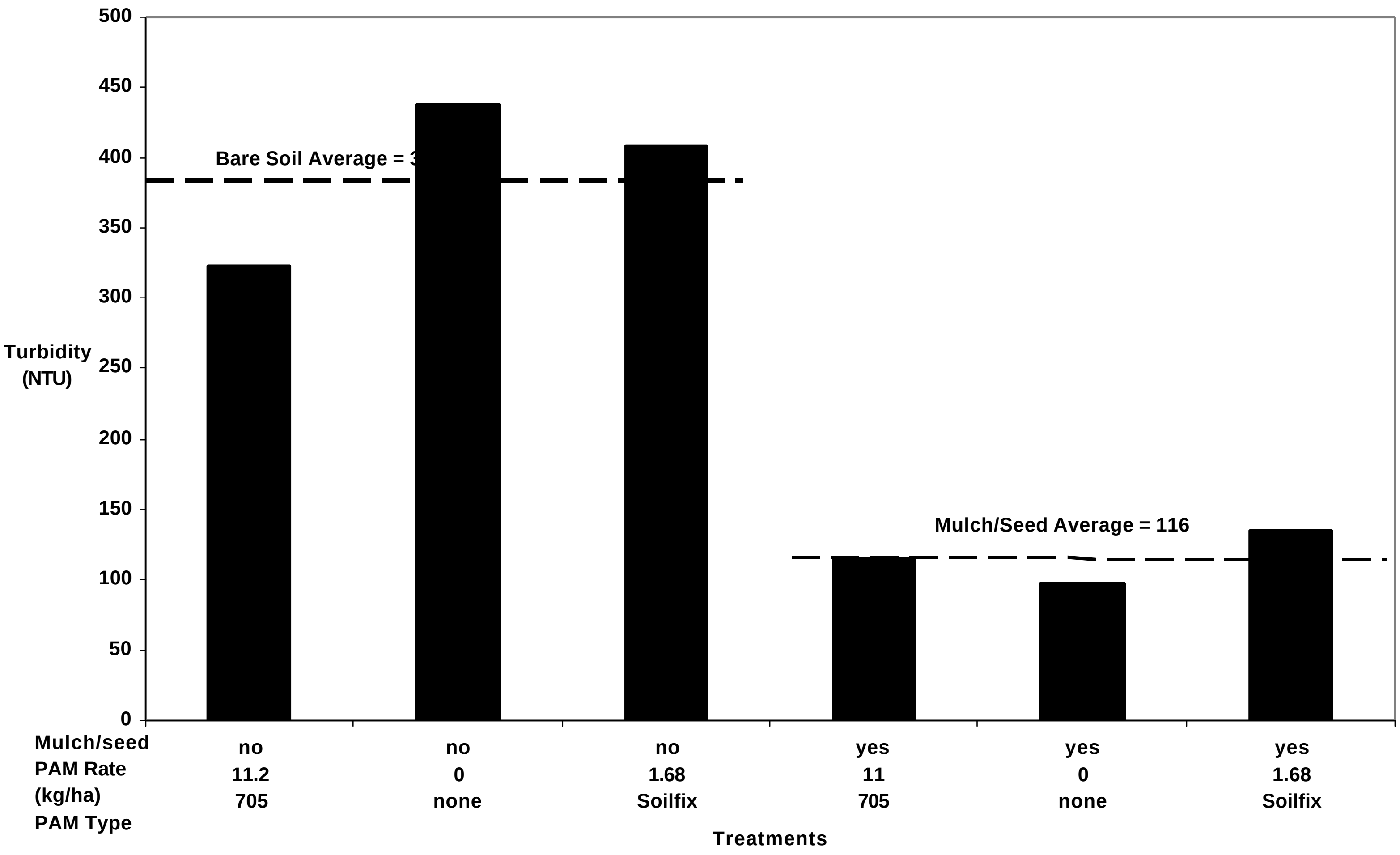


Figure 69: December 17 Sediment Loss
Fayetteville I-95

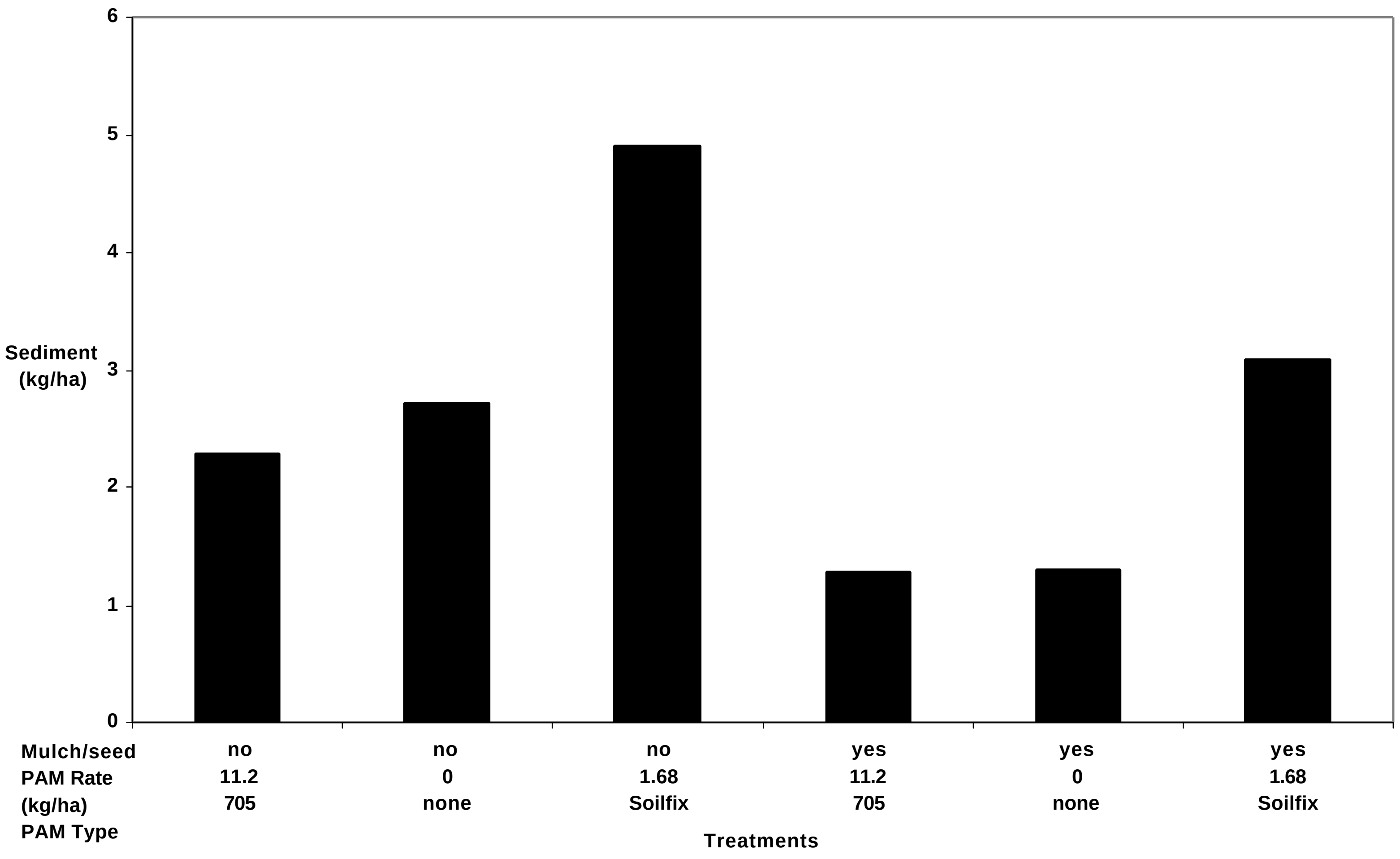


Figure 70: January 14 Sediment Loss
Fayetteville I-95

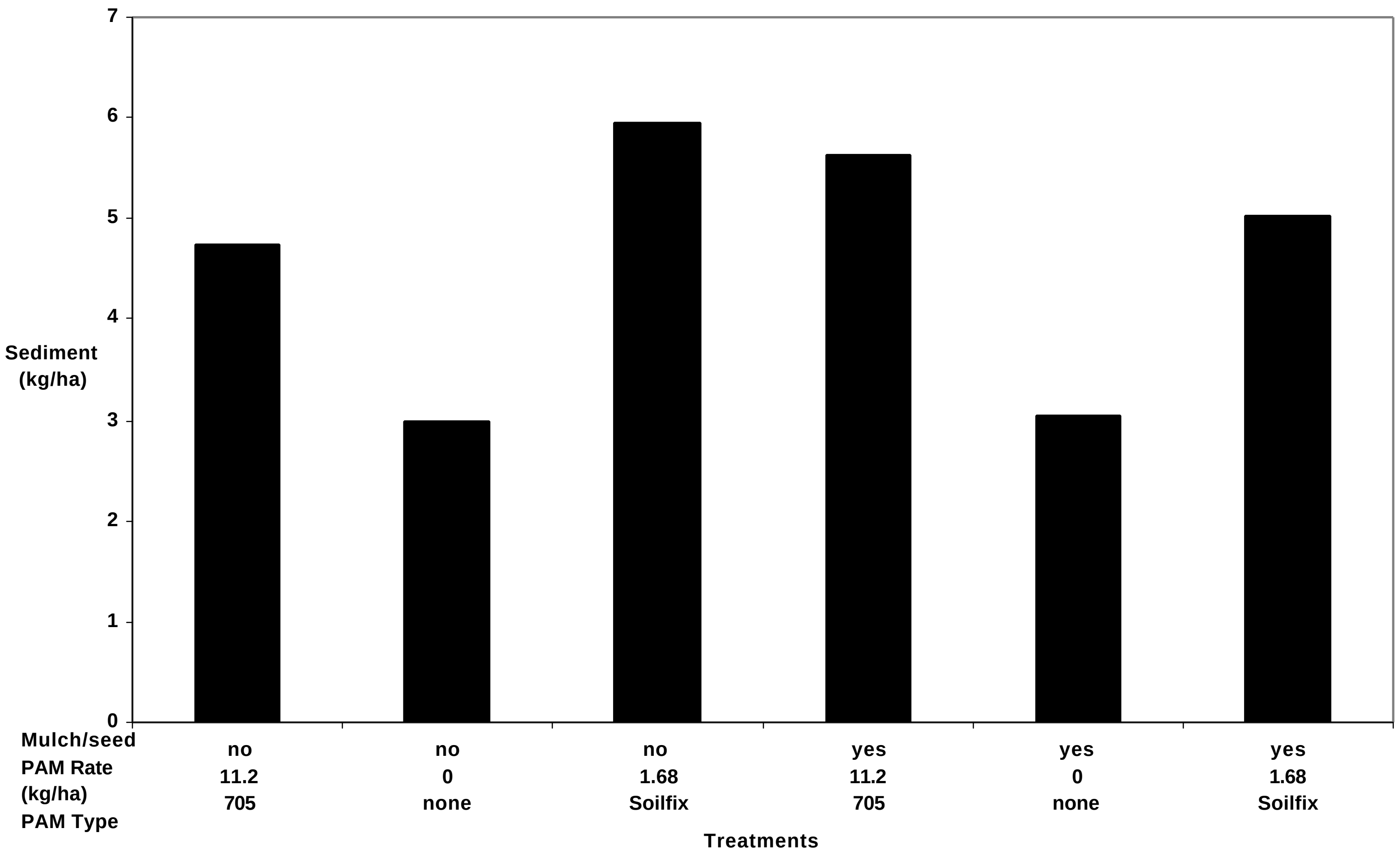


Figure 71: January 21 Sediment Loss
Fayetteville I-95

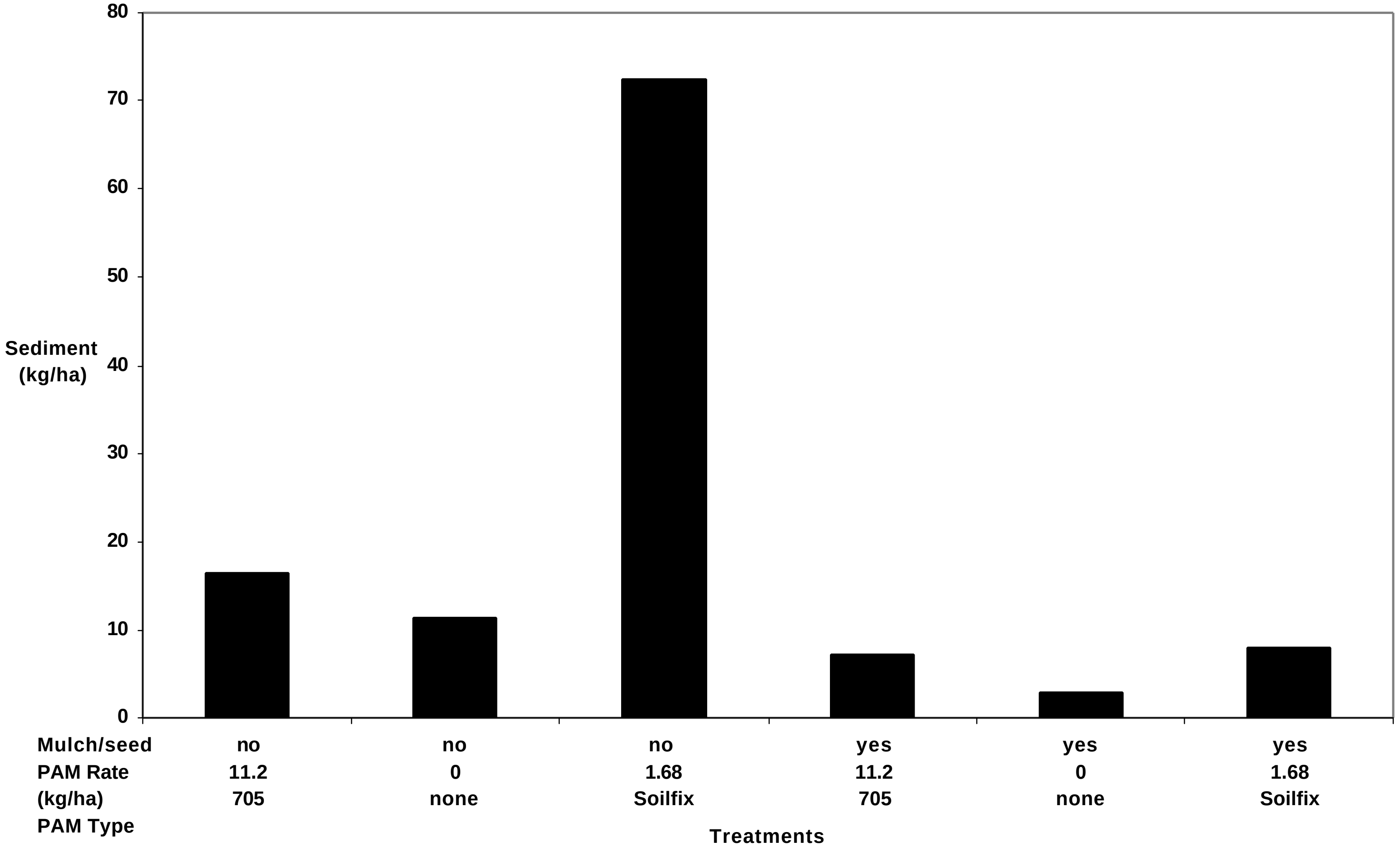


Figure 72: January 23 Sediment Loss
Fayetteville I-95

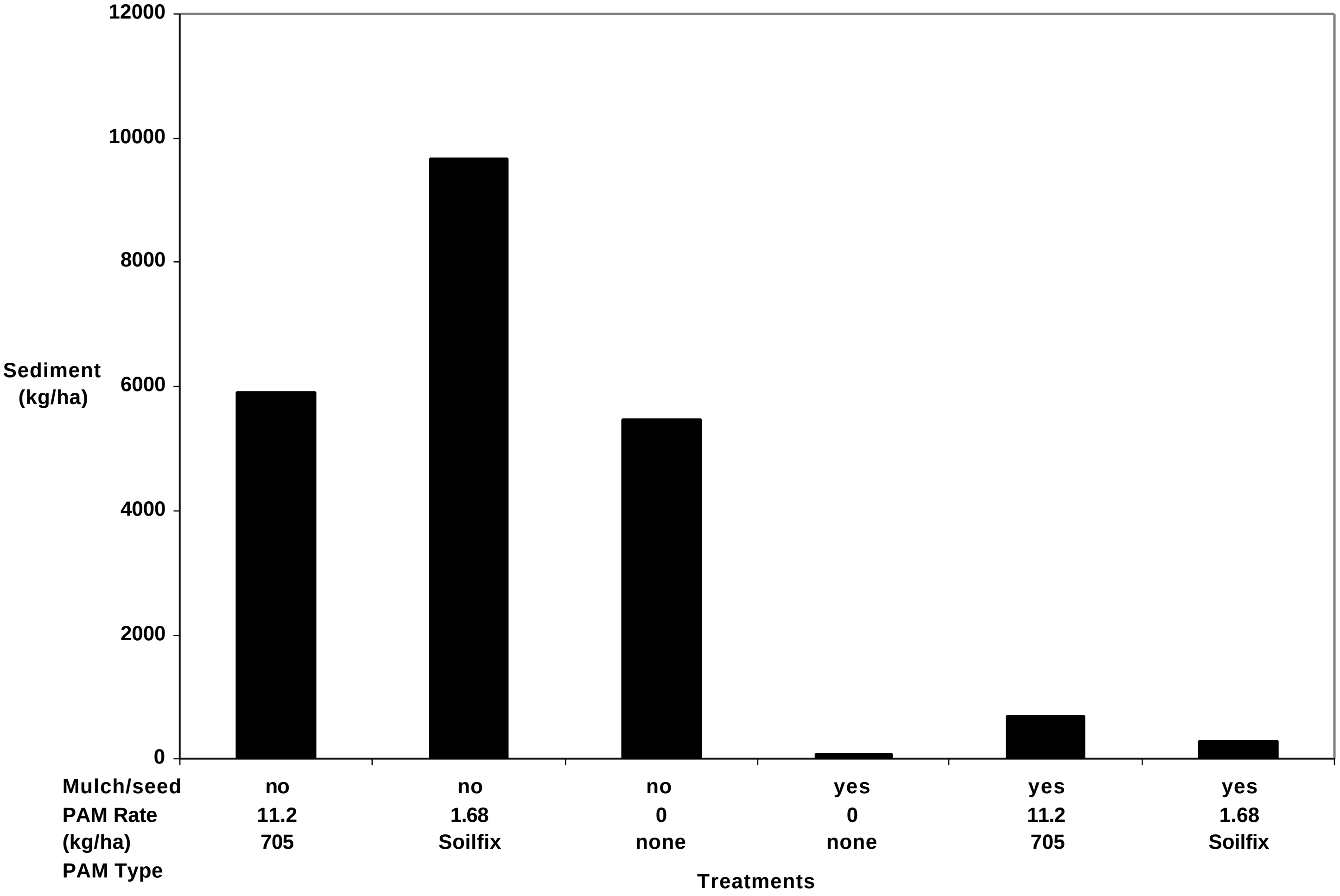


Figure 73: January 25 Sediment Loss
Fayetteville I-95

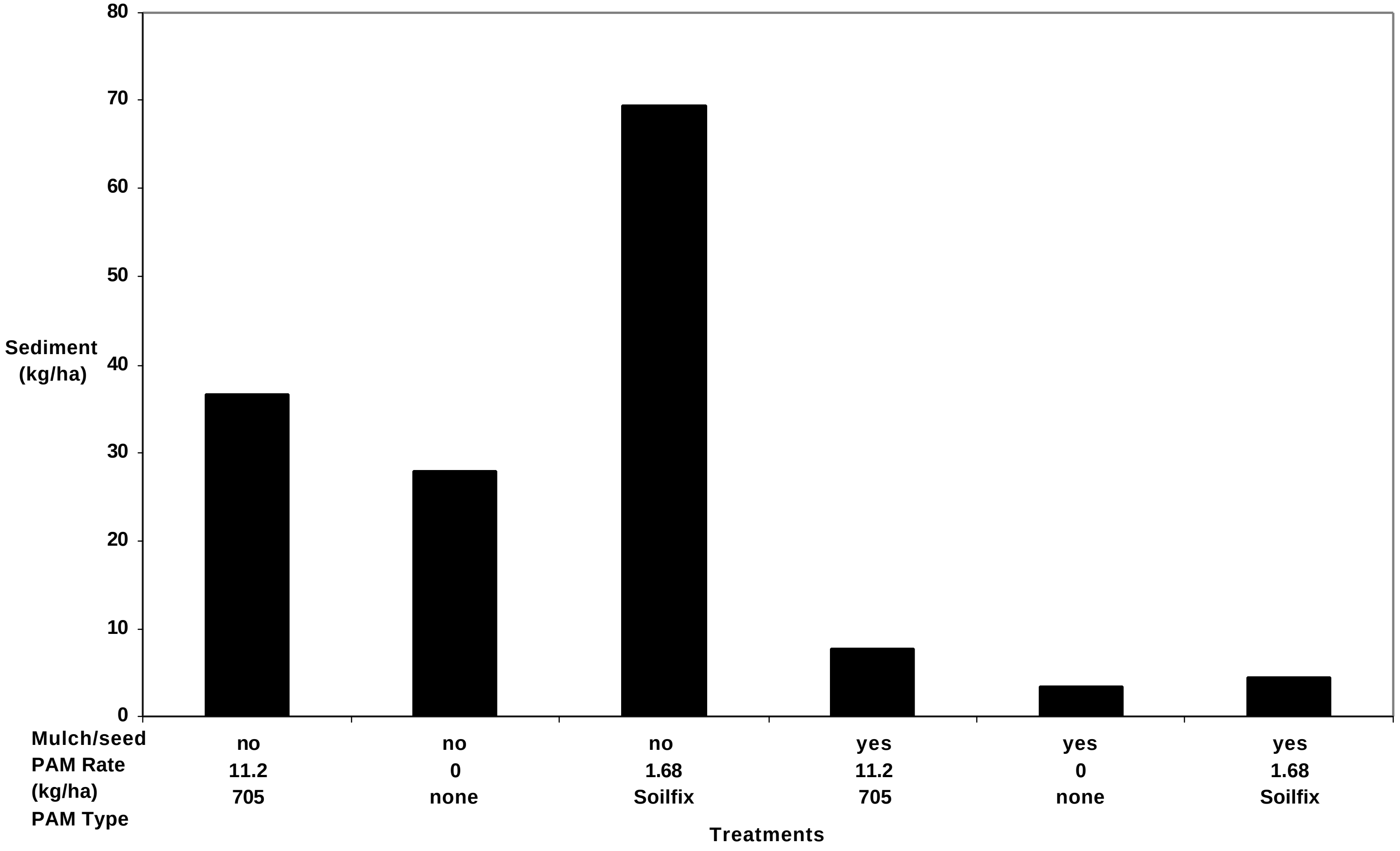


Figure 74: February 8 Sediment Losses
Fayetteville I-95

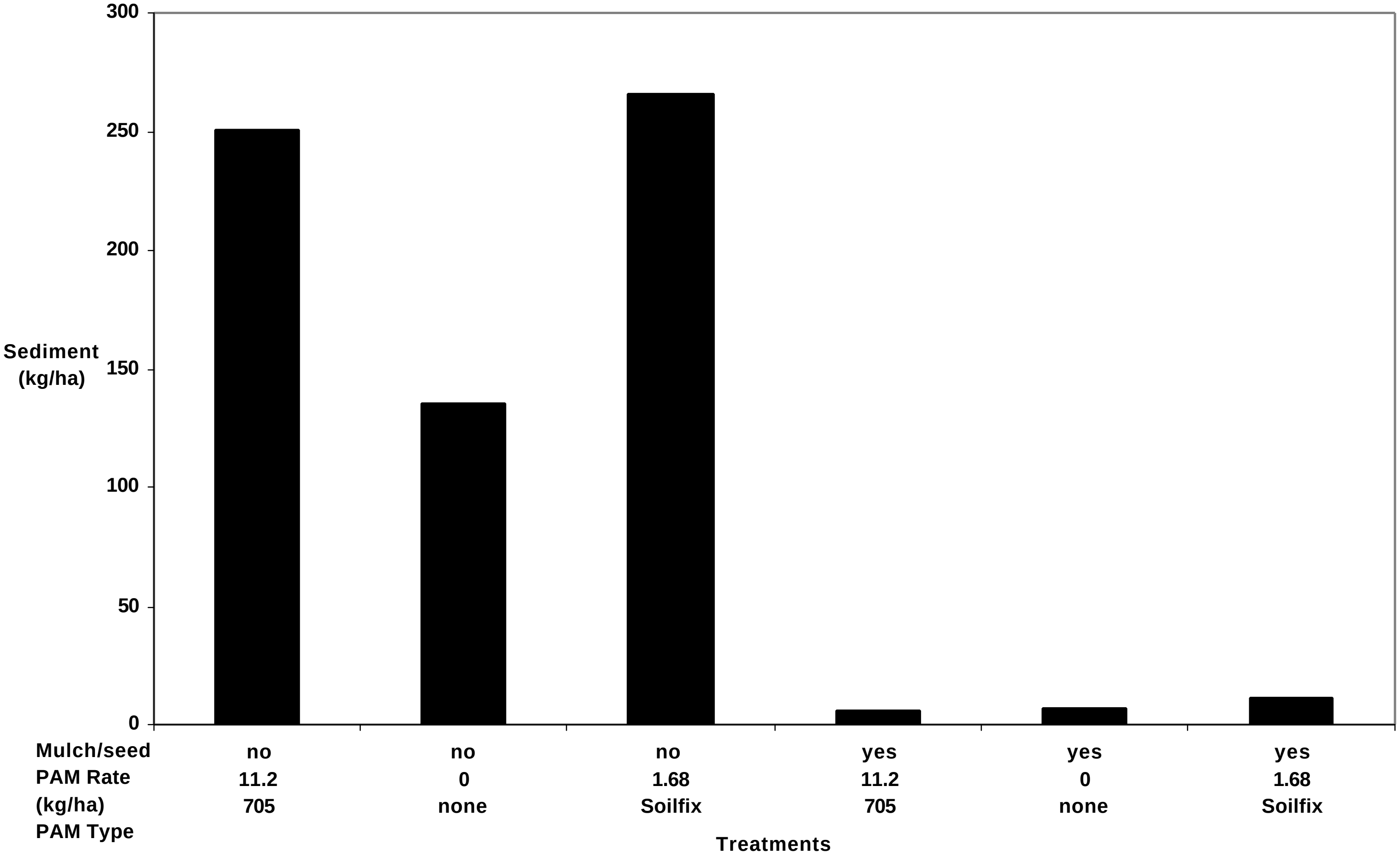


Figure 75: Total Sediment Losses
Fayetteville I-95

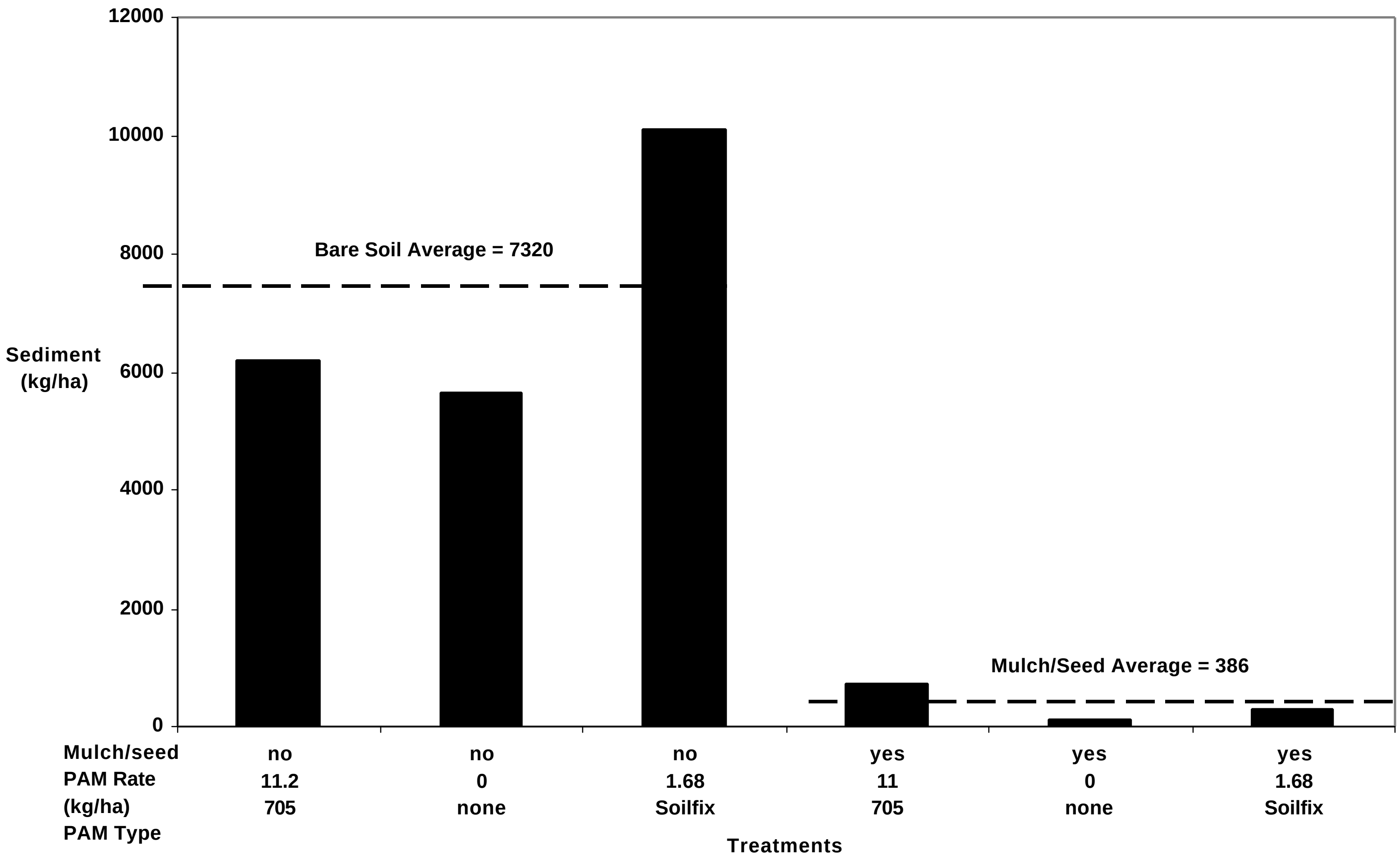


Figure 76: Second PAM Application Test, First Storm, 3/03/02
Fayetteville I-95

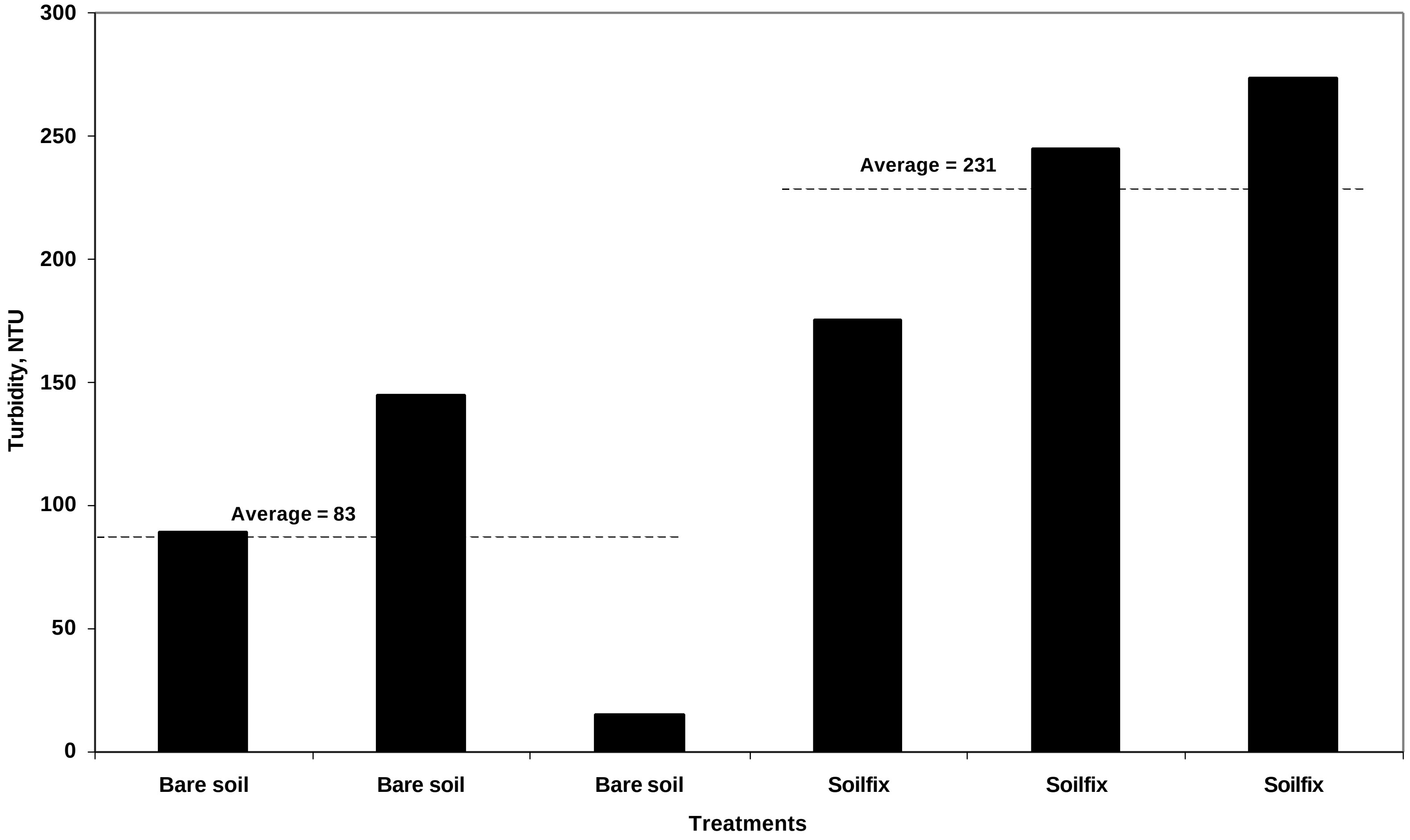


Figure 77: Second PAM Application Test, 2nd Storm, 3-21-02
Fayetteville I-95

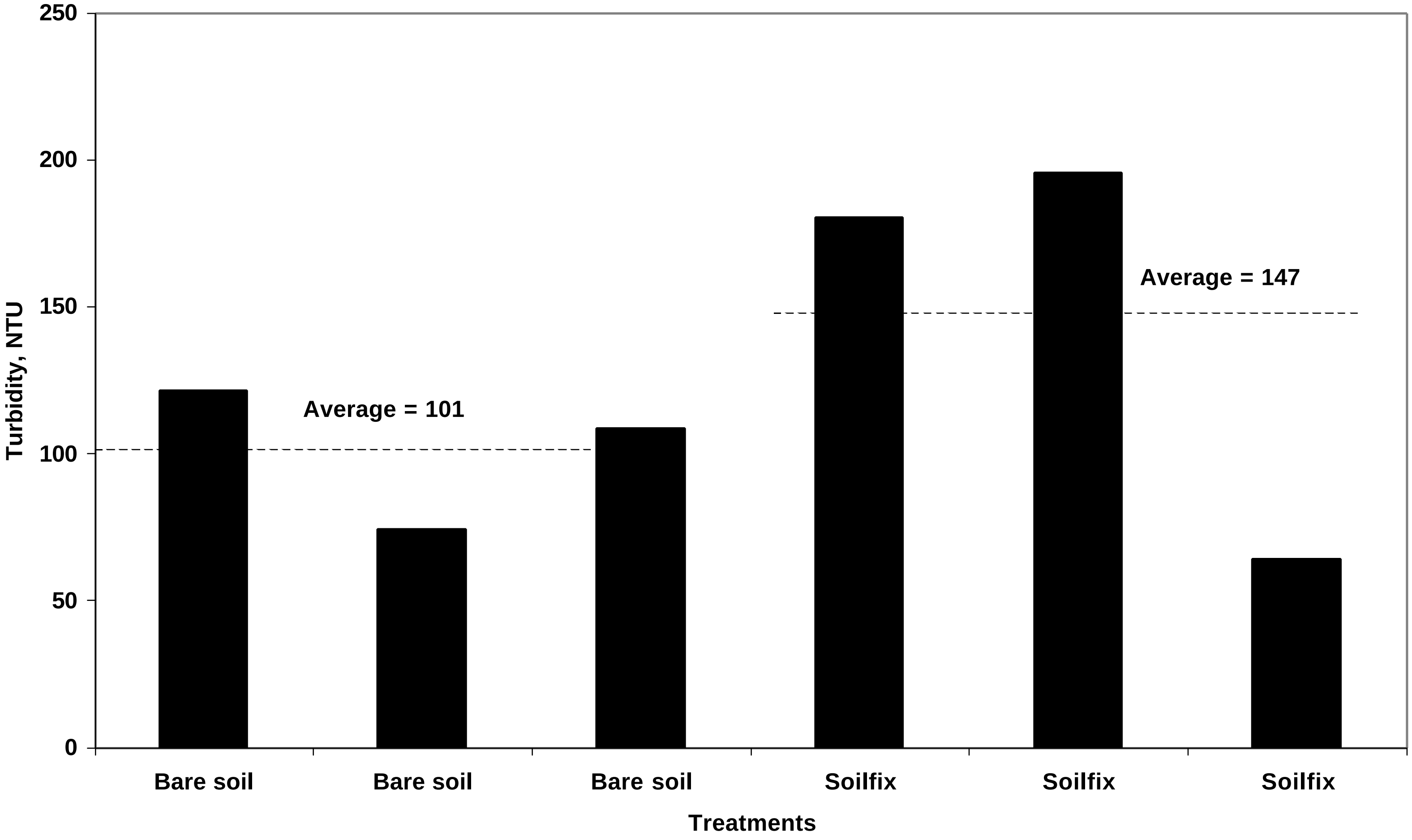


Figure 78: Second PAM Application Test, Third Storm, 3/31/02
Fayetteville I-95

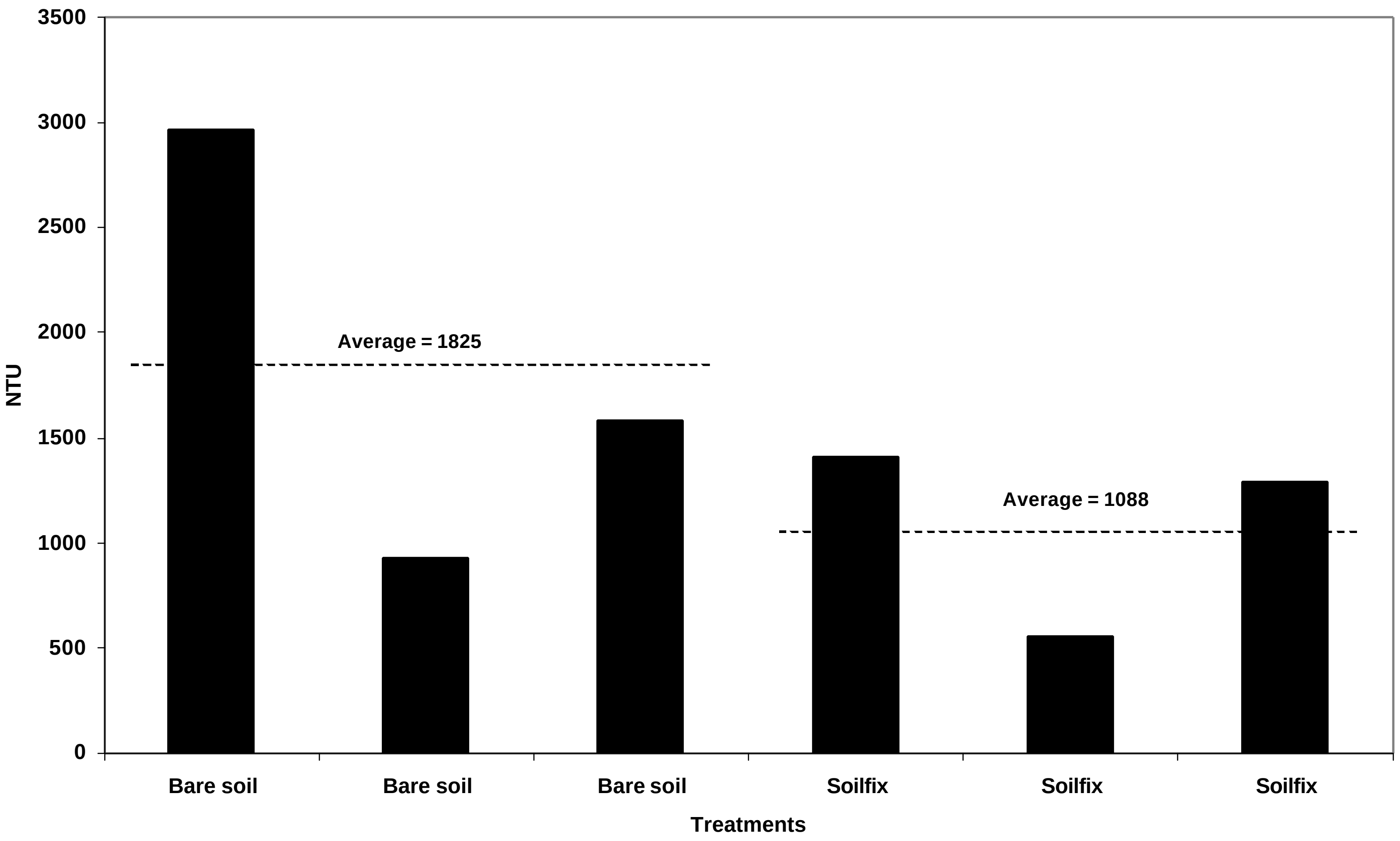


Figure 79: Runoff Initiation Time, Rainfall Simulation Tests
3.7 cm/hour for 15-16 Minutes

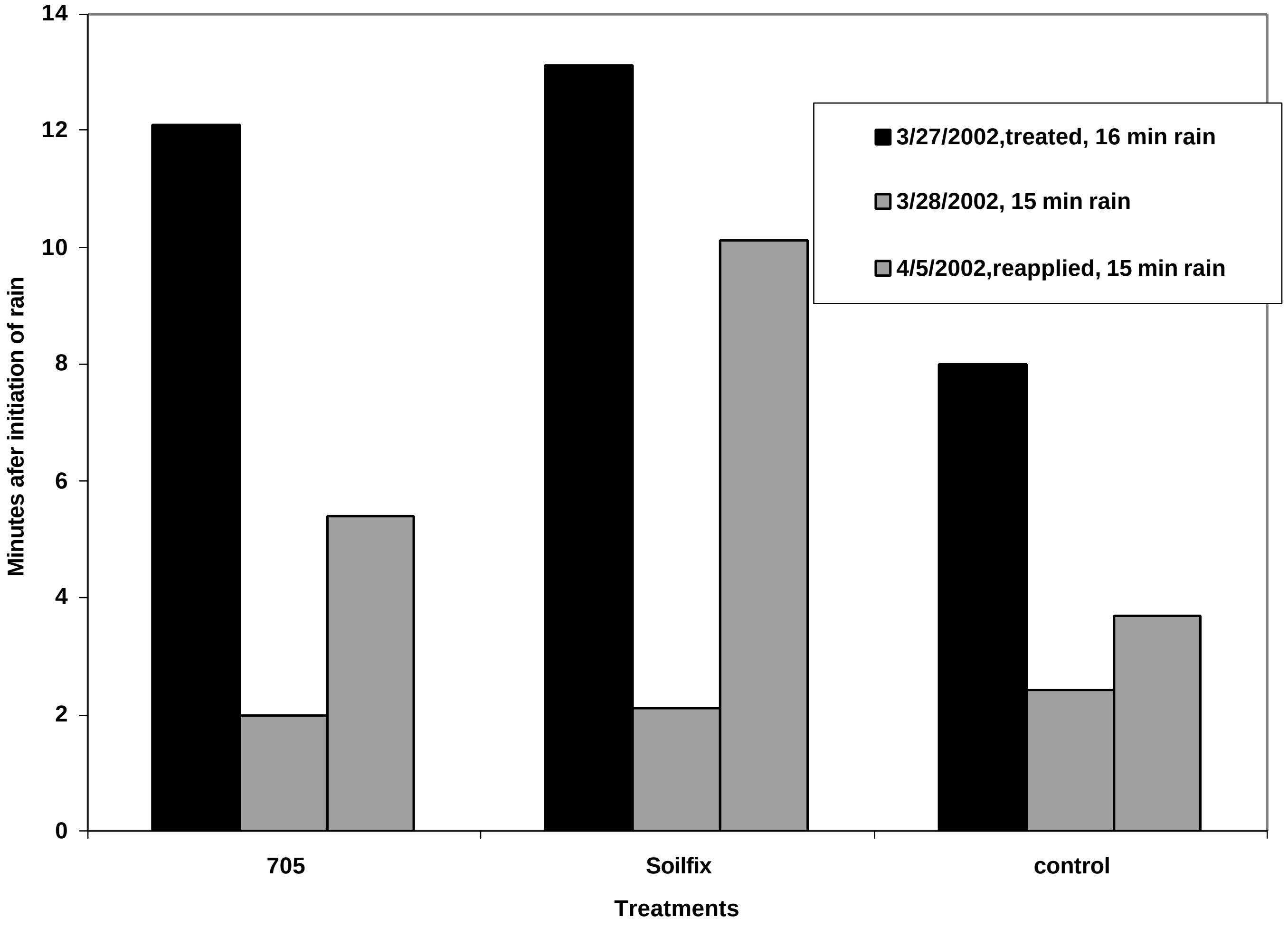


Figure 80: Total Runoff Volume, Rainfall Simulation Tests

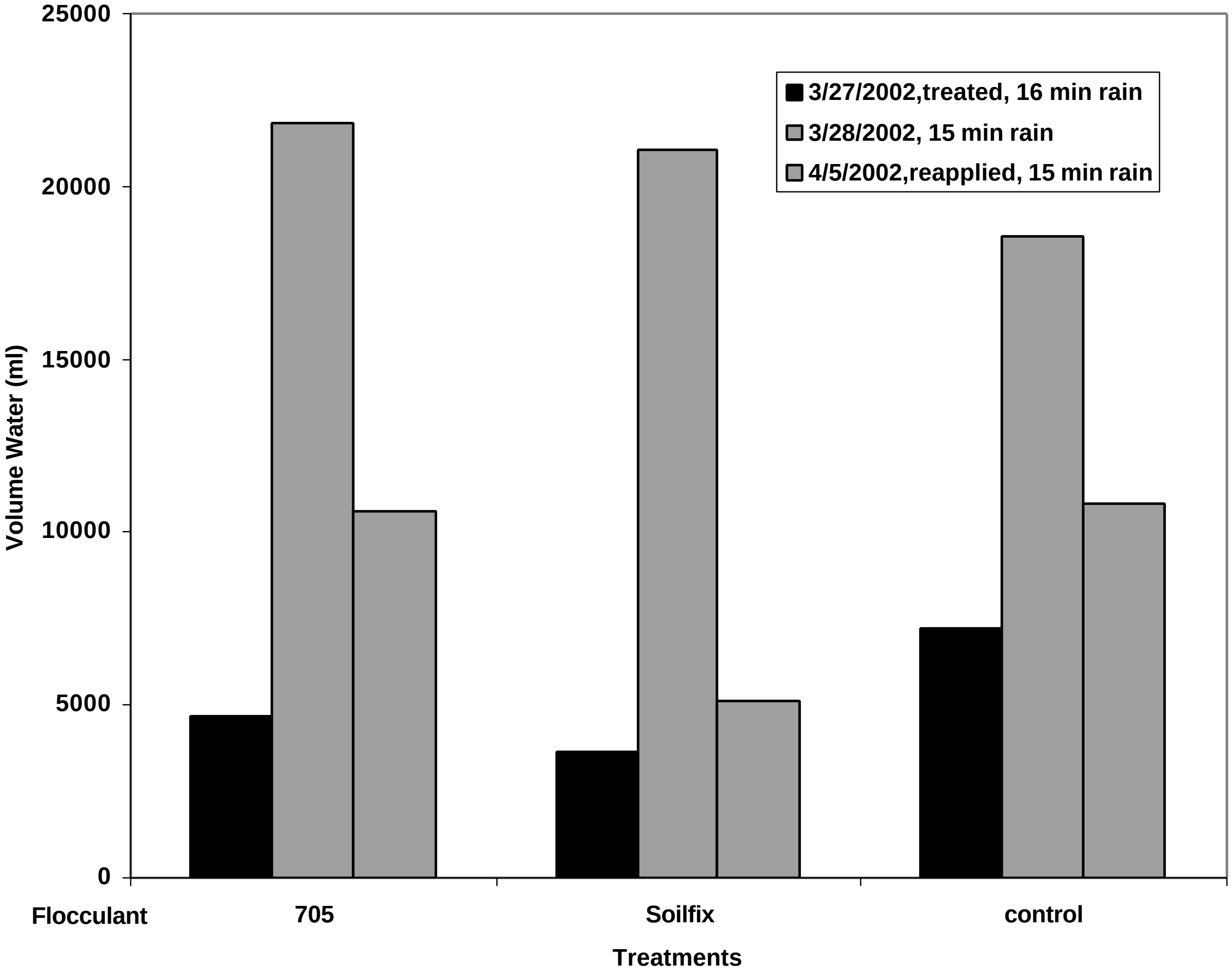


Figure 81: TSS of Runoff, Rainfall Simulation Tests

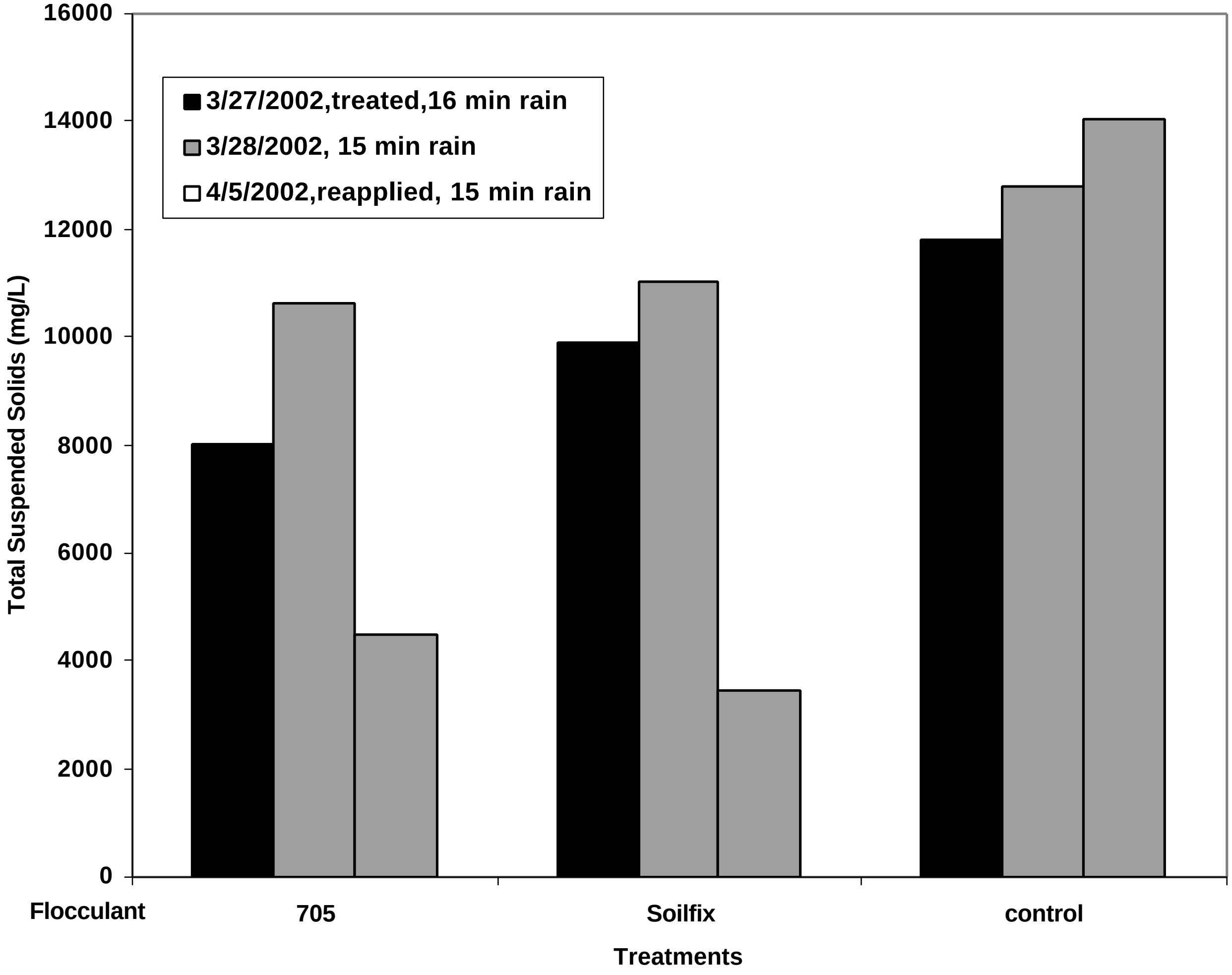


Figure 82: Time to Runoff Initiation, Rainfall

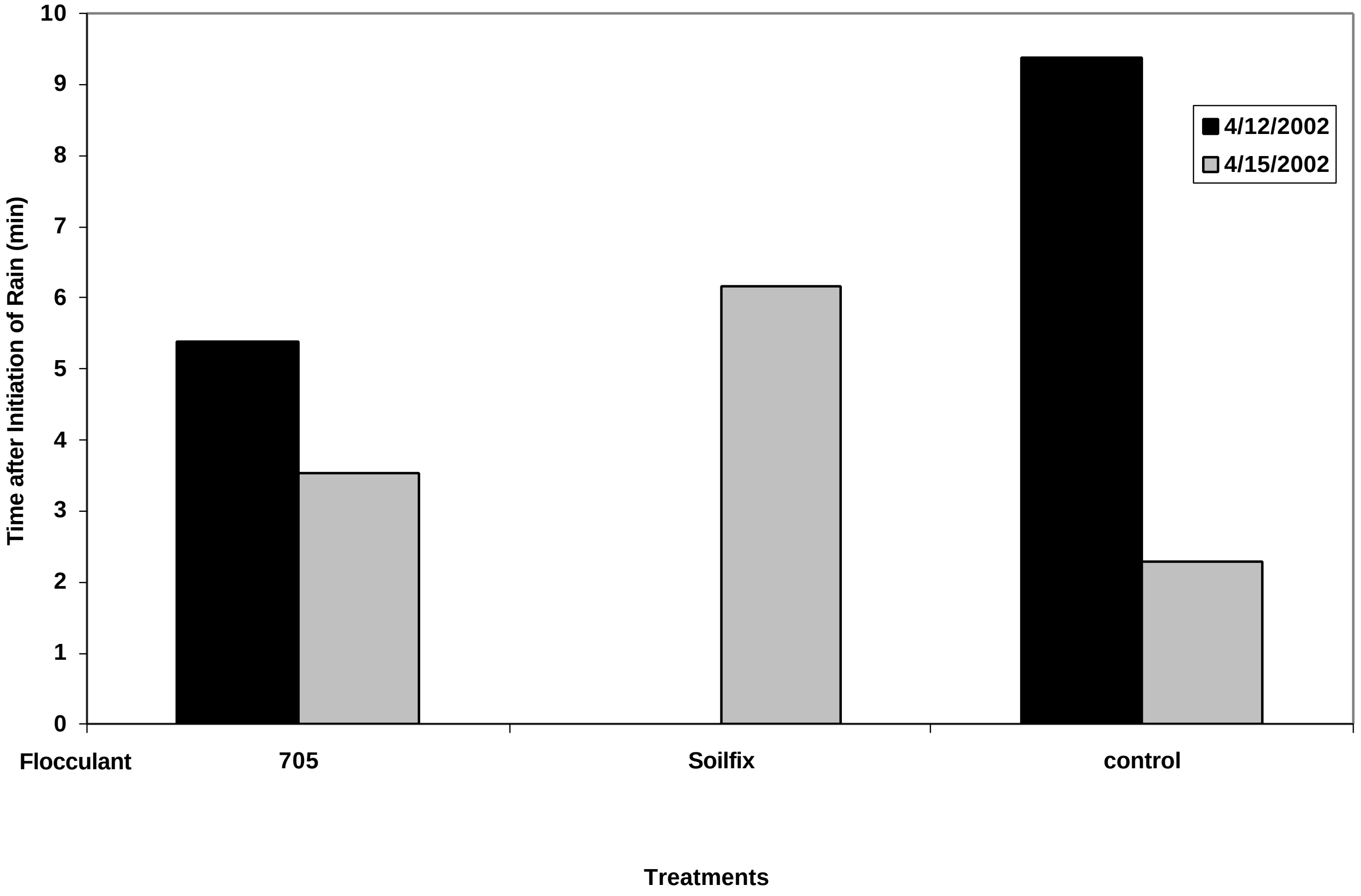


Figure 83: Total Runoff Volume, Rainfall Simulation Tests

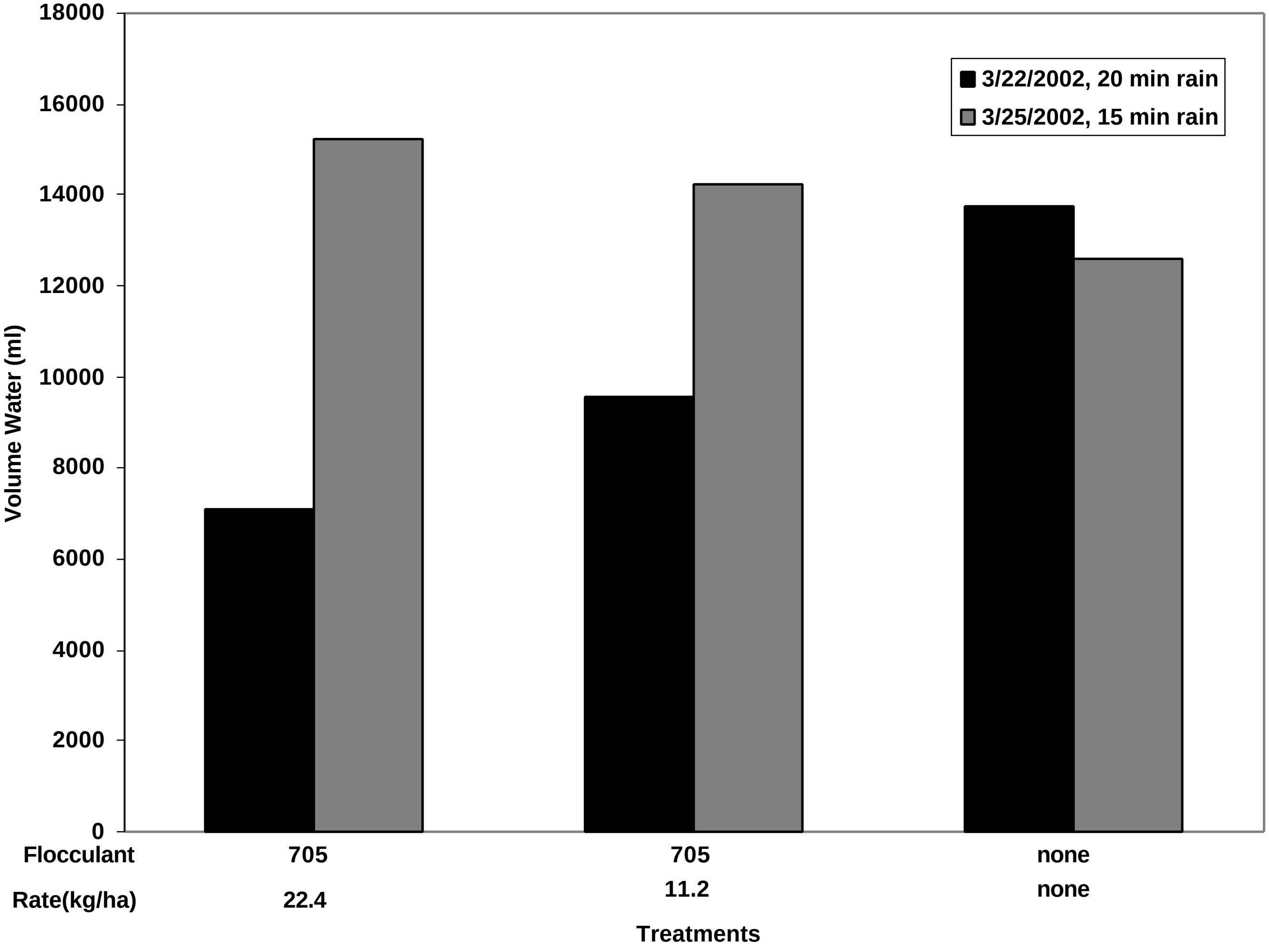


Figure 84: TSS of Runoff, Rainfall Simulation Tests

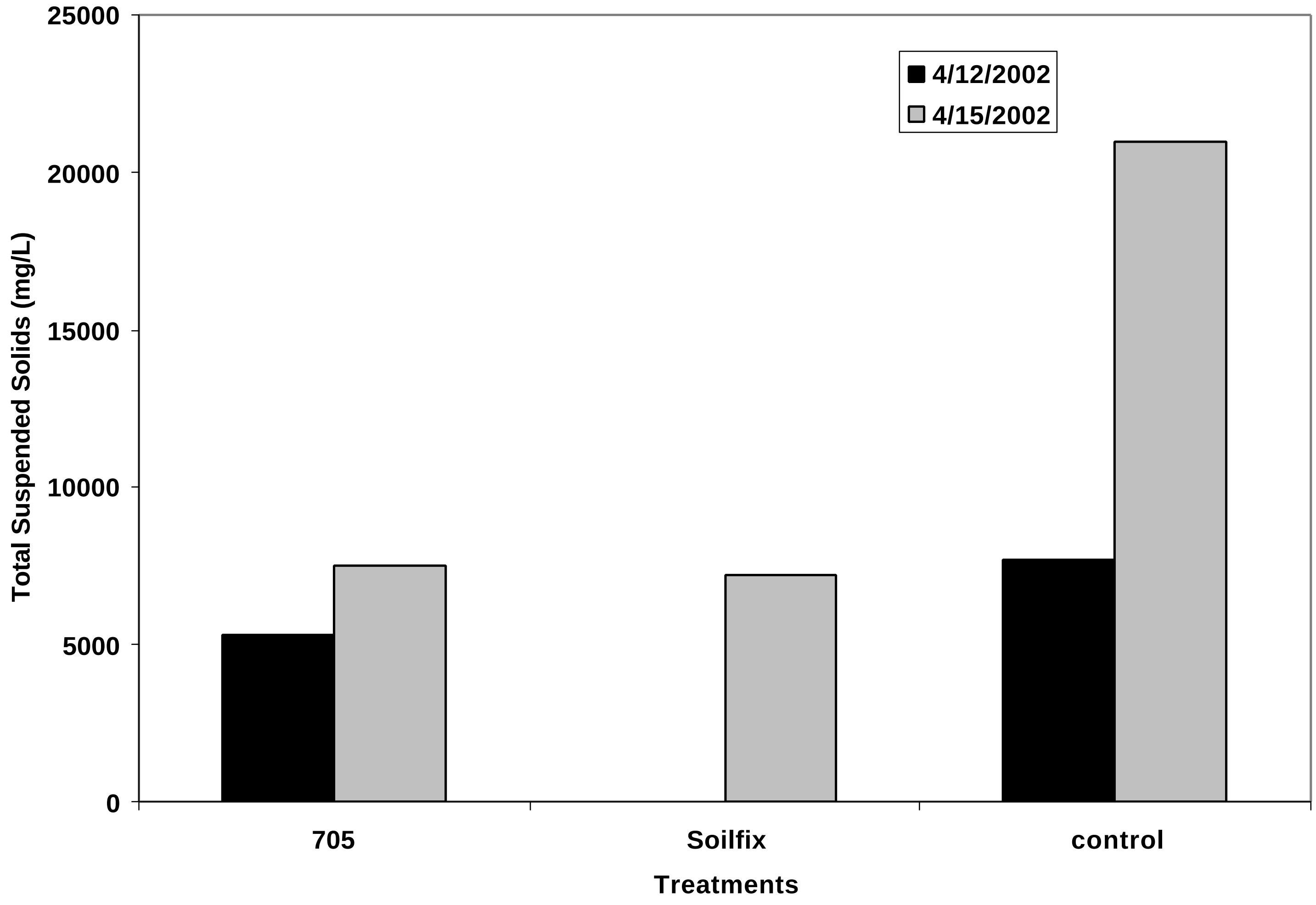


Figure 85: Turbidity in Stilling Basin After PAM Treatment: Samples Shaken

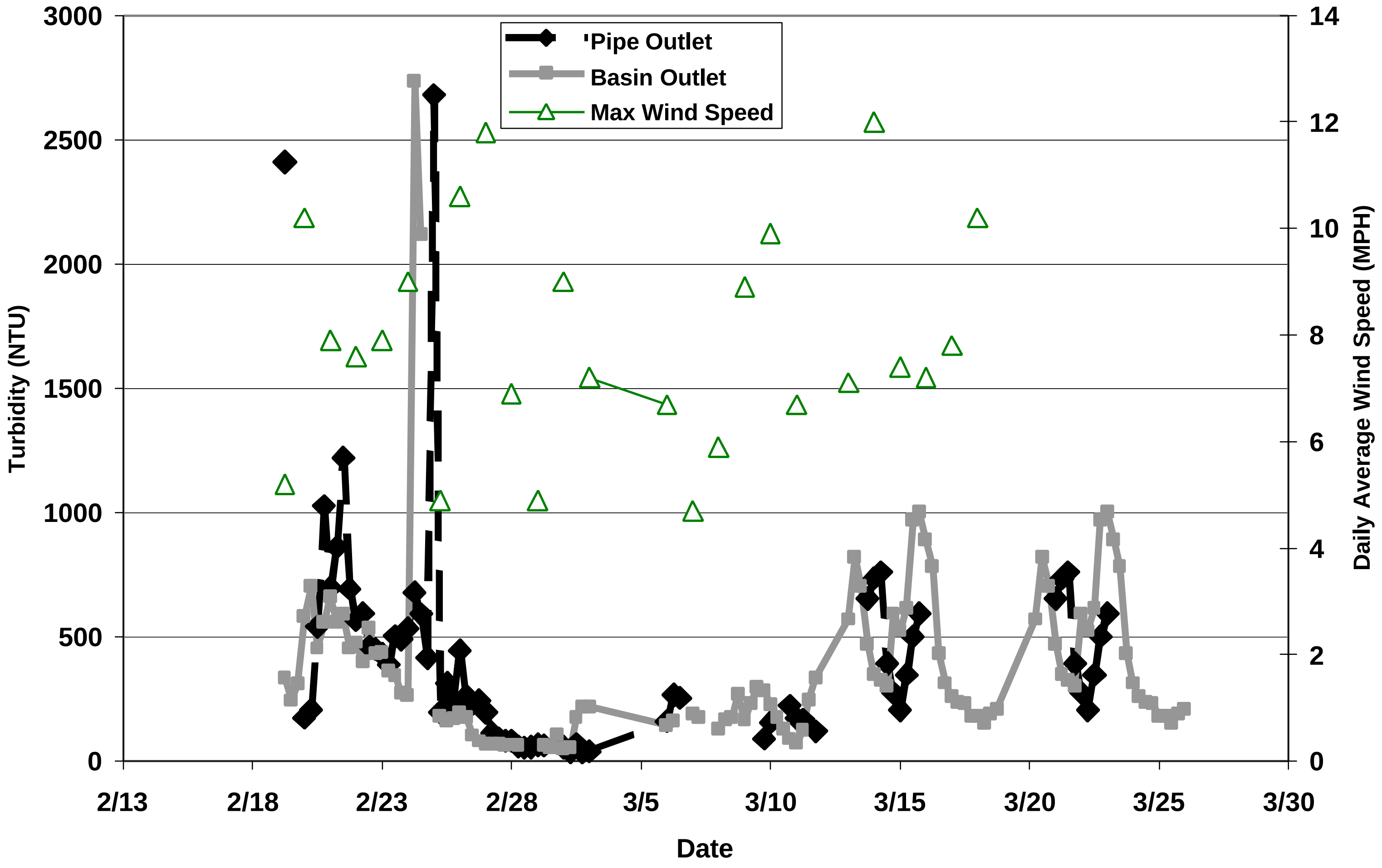


Figure 86: Turbidity in Stilling Basin After PAM Treatment: Samples Not Shaken

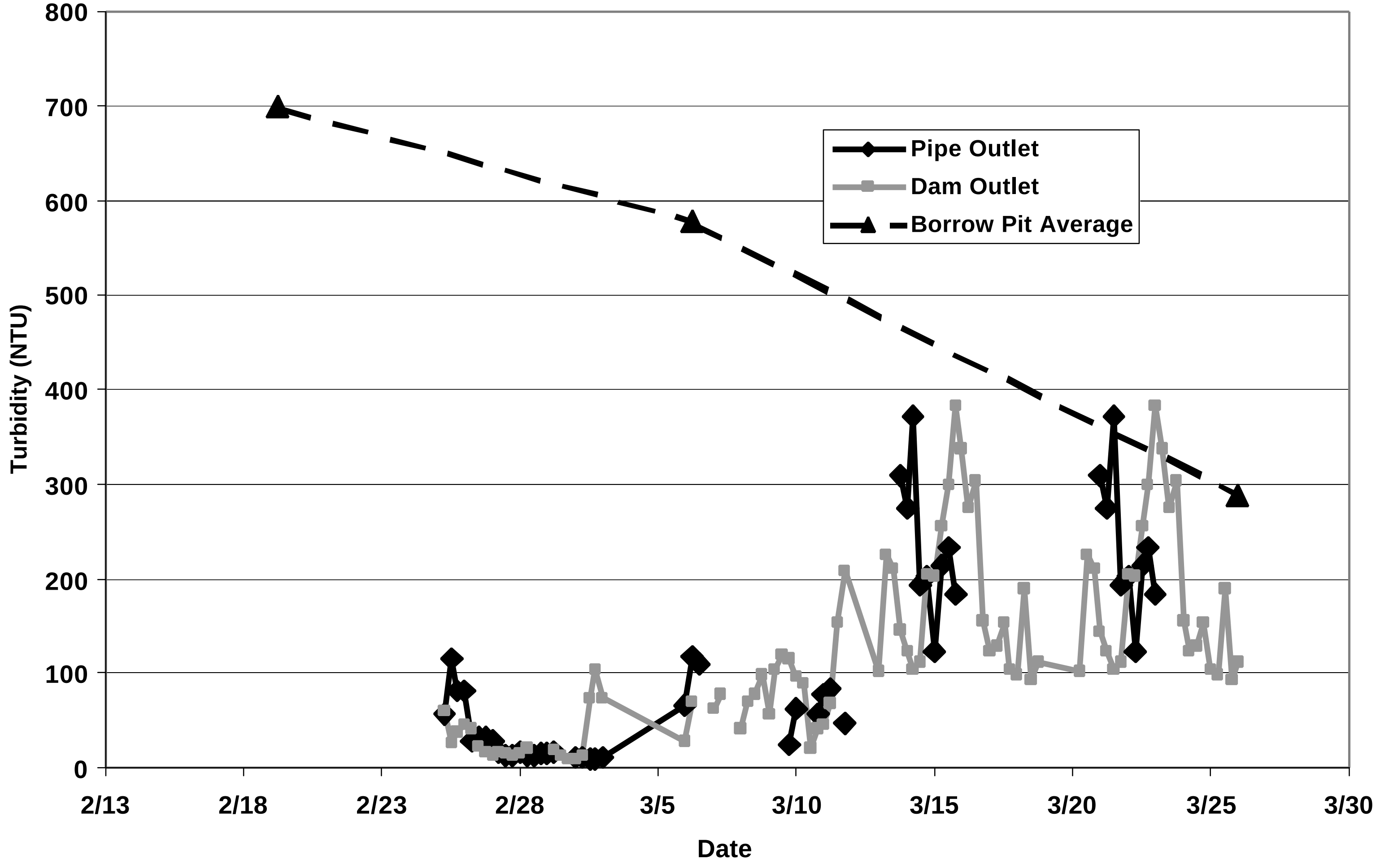


Figure 87: Effect of Time on Differences Between PAM Concentrations
Soil 0749, PAM A-100

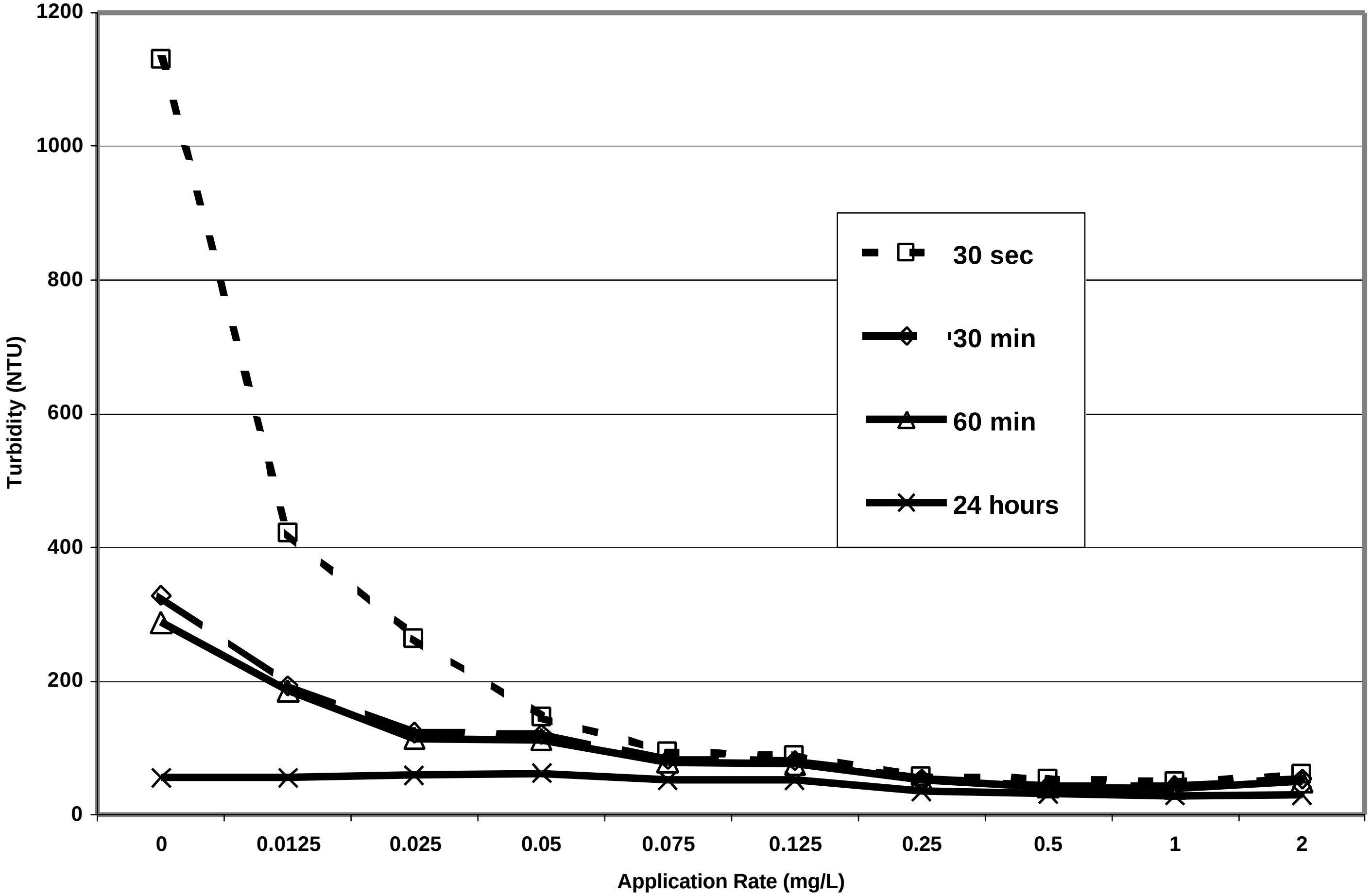


Figure 88: PAM Concentration Effects on Sediment Source 1337B

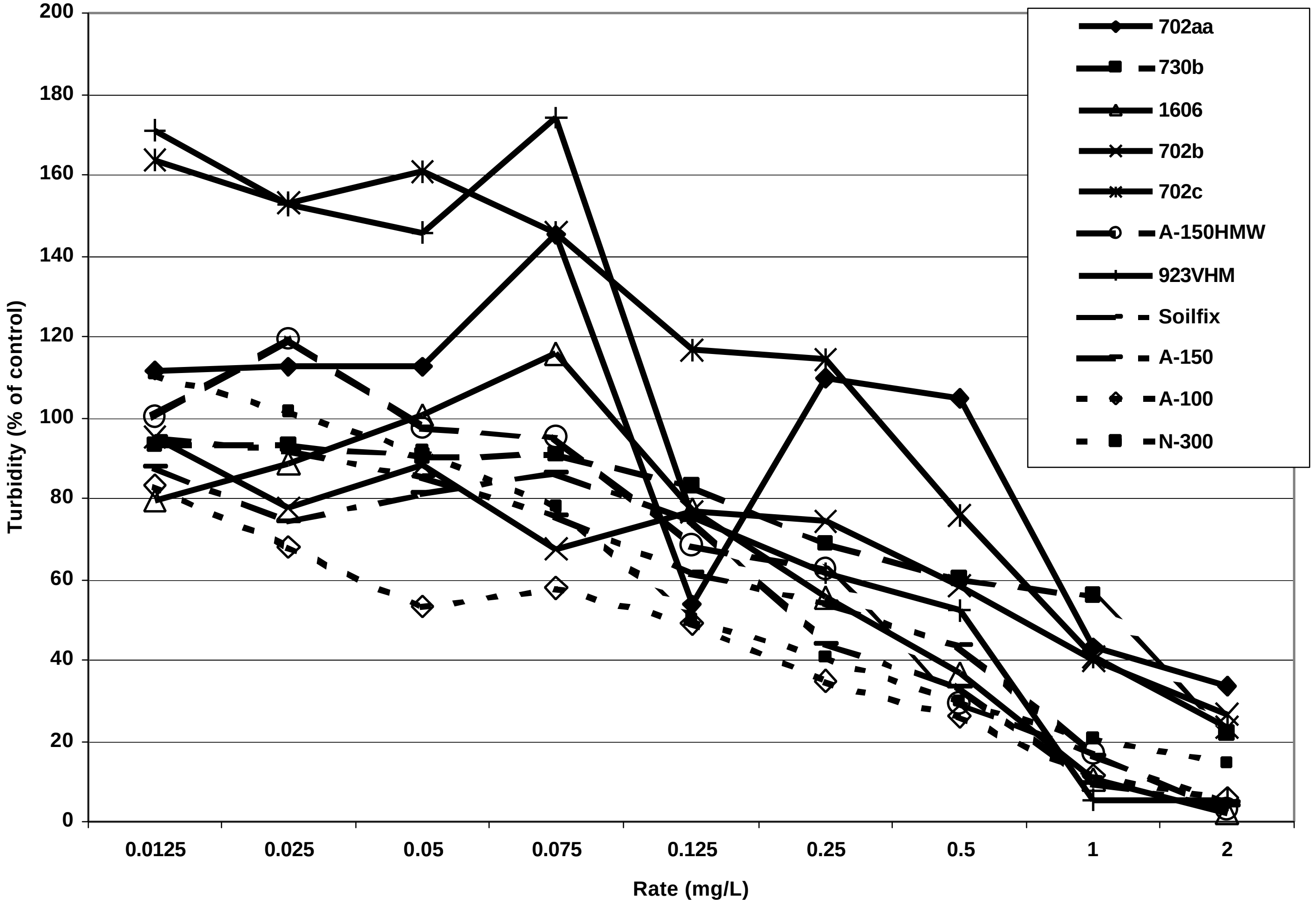


Figure 89: PAM Concentration Effects on Sediment Source 0326b

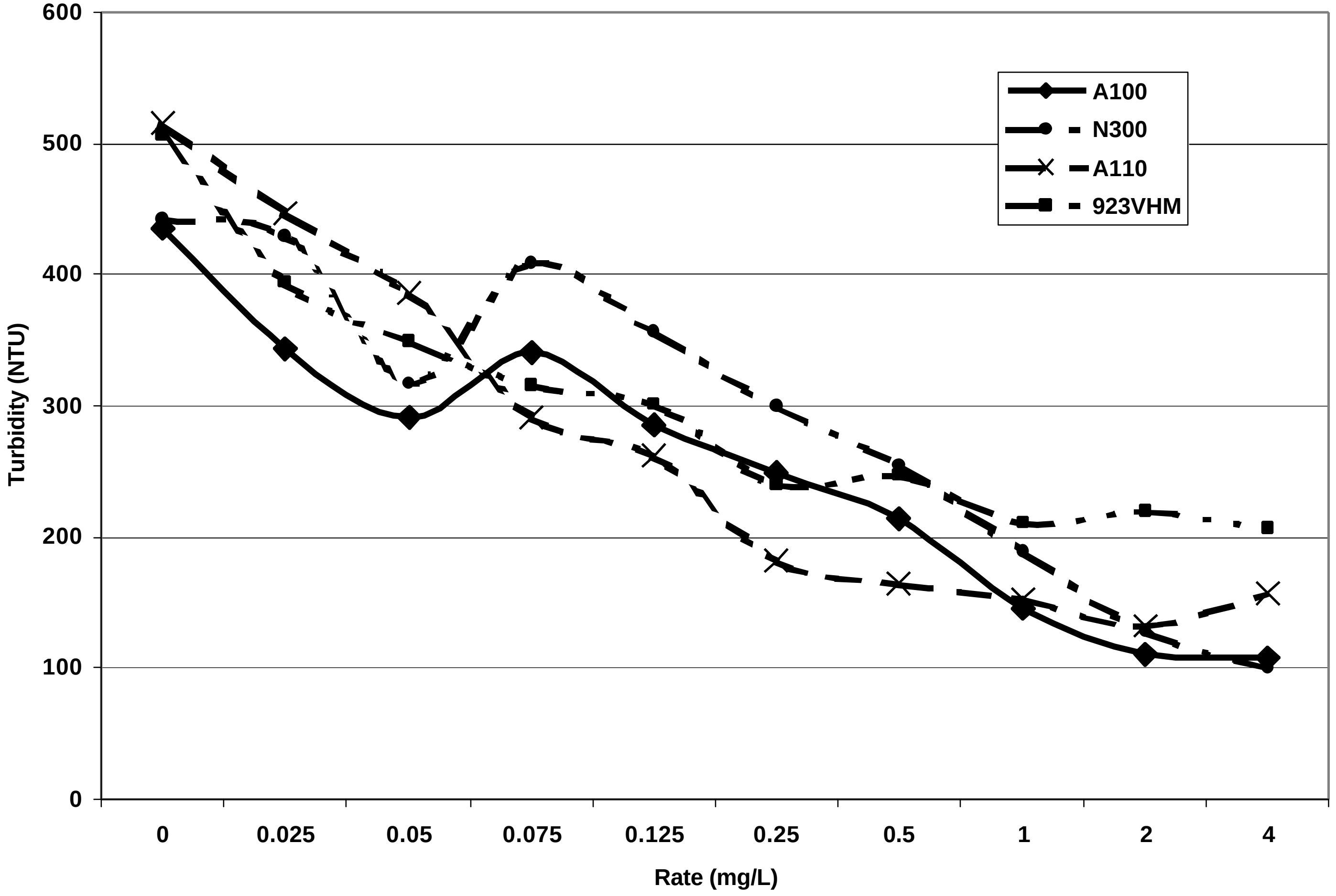


Figure 90: PAM Concentration Effects on Sediment Source 0540P

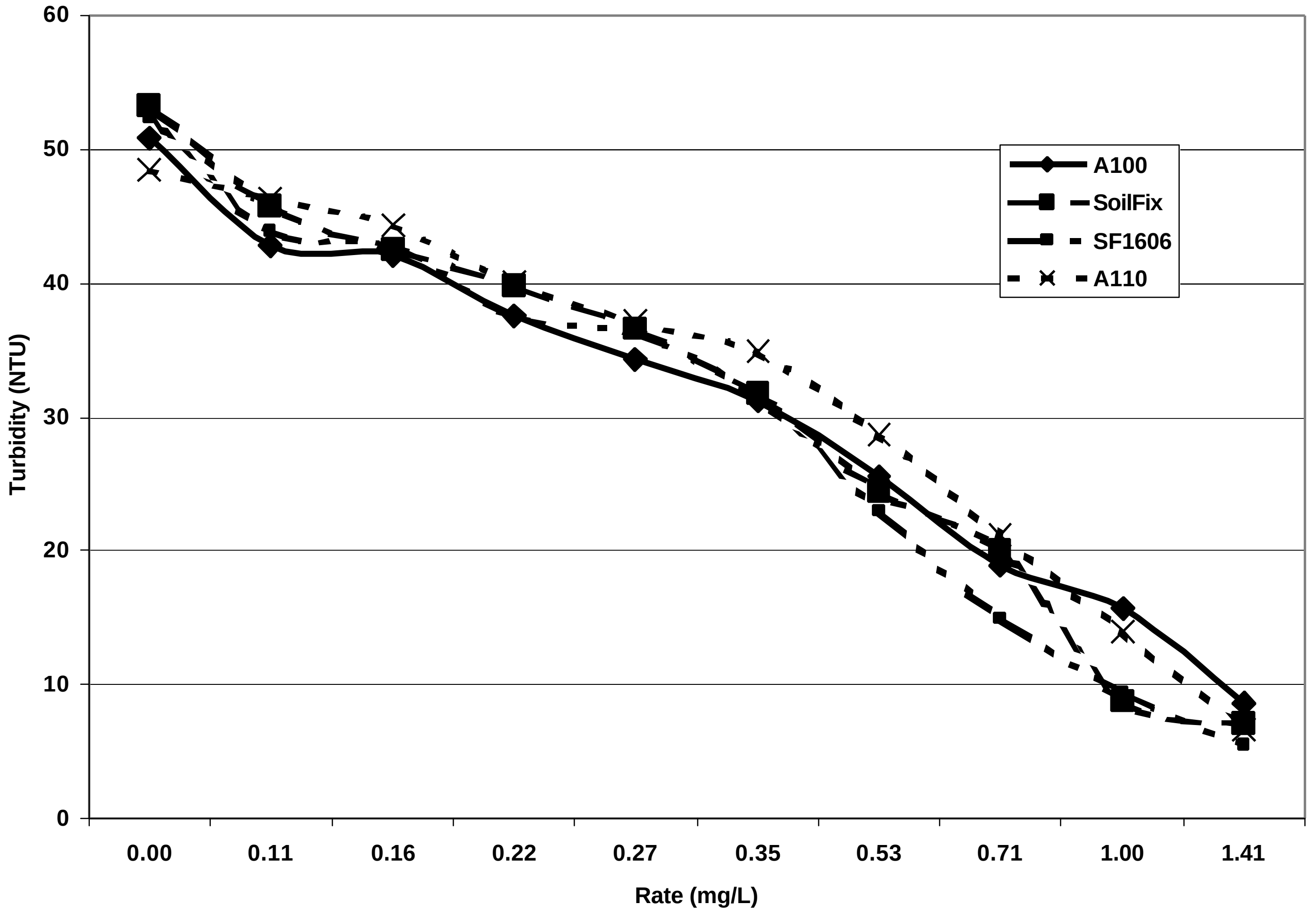


Figure 91: PAM Concentration Effects on Sediment Source 0644s

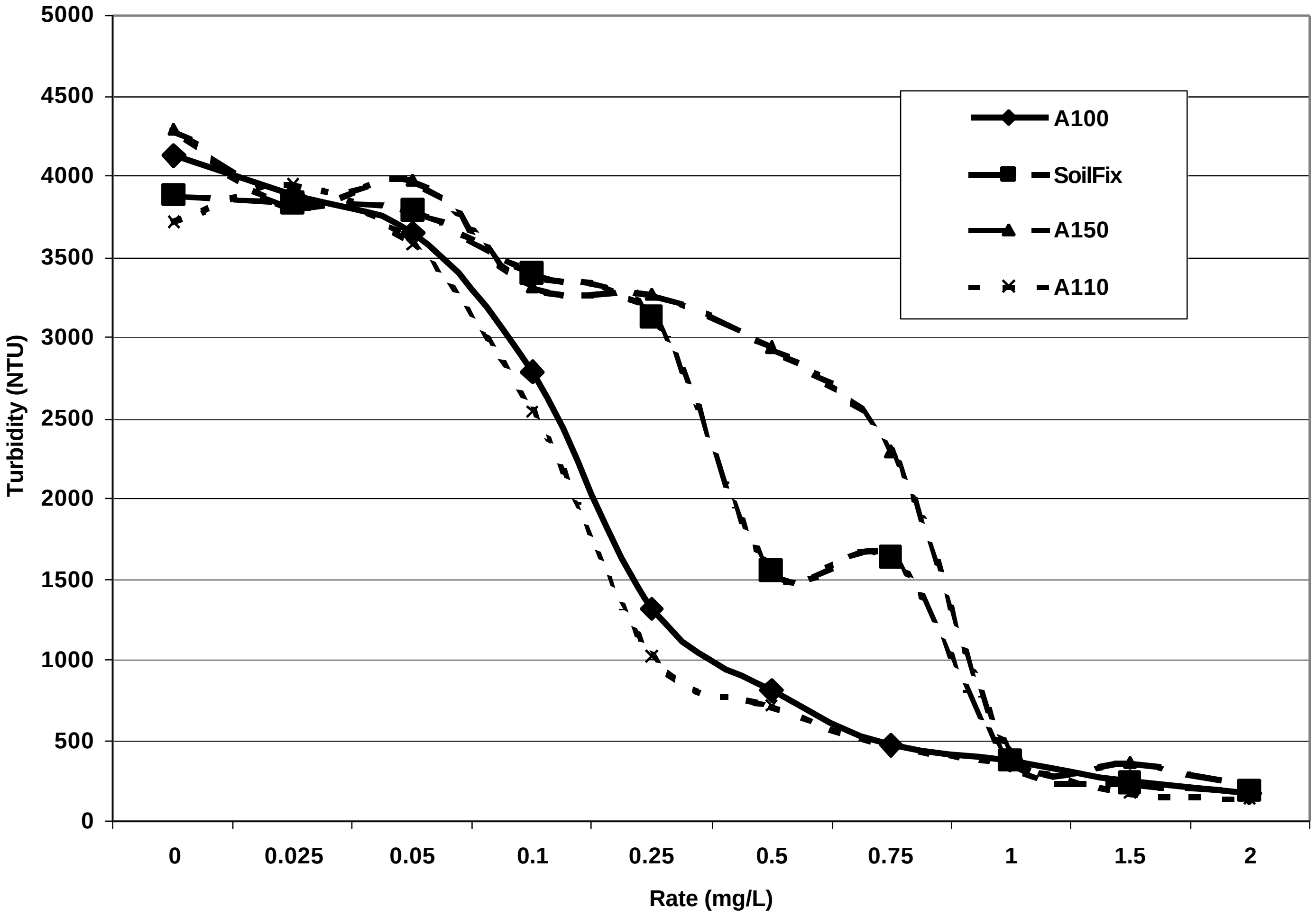


Figure 92: PAM Concentration Effects on Sediment Source 0977p

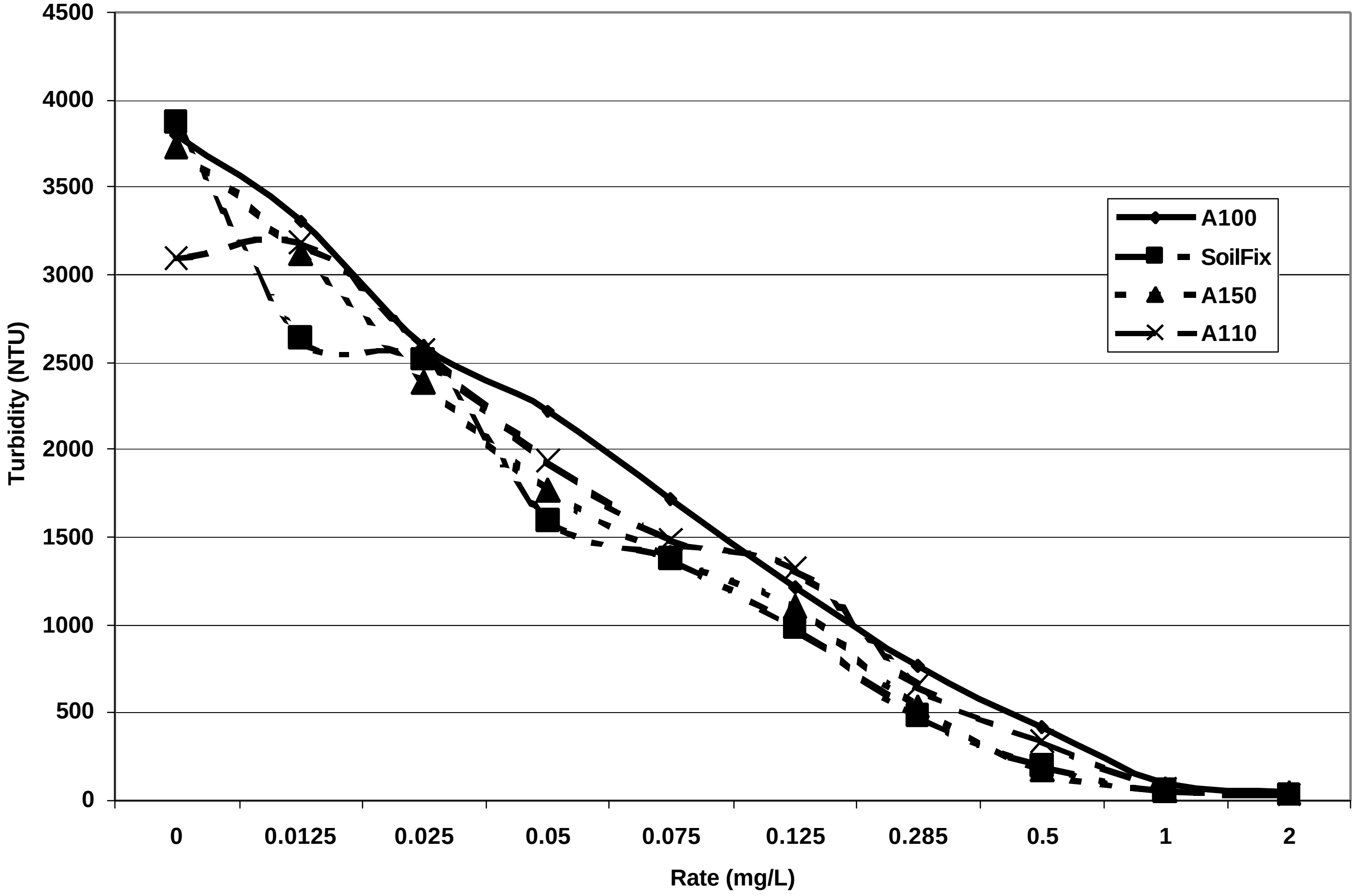


Figure 93: PAM Concentration Effects on Sediment Source 1279s

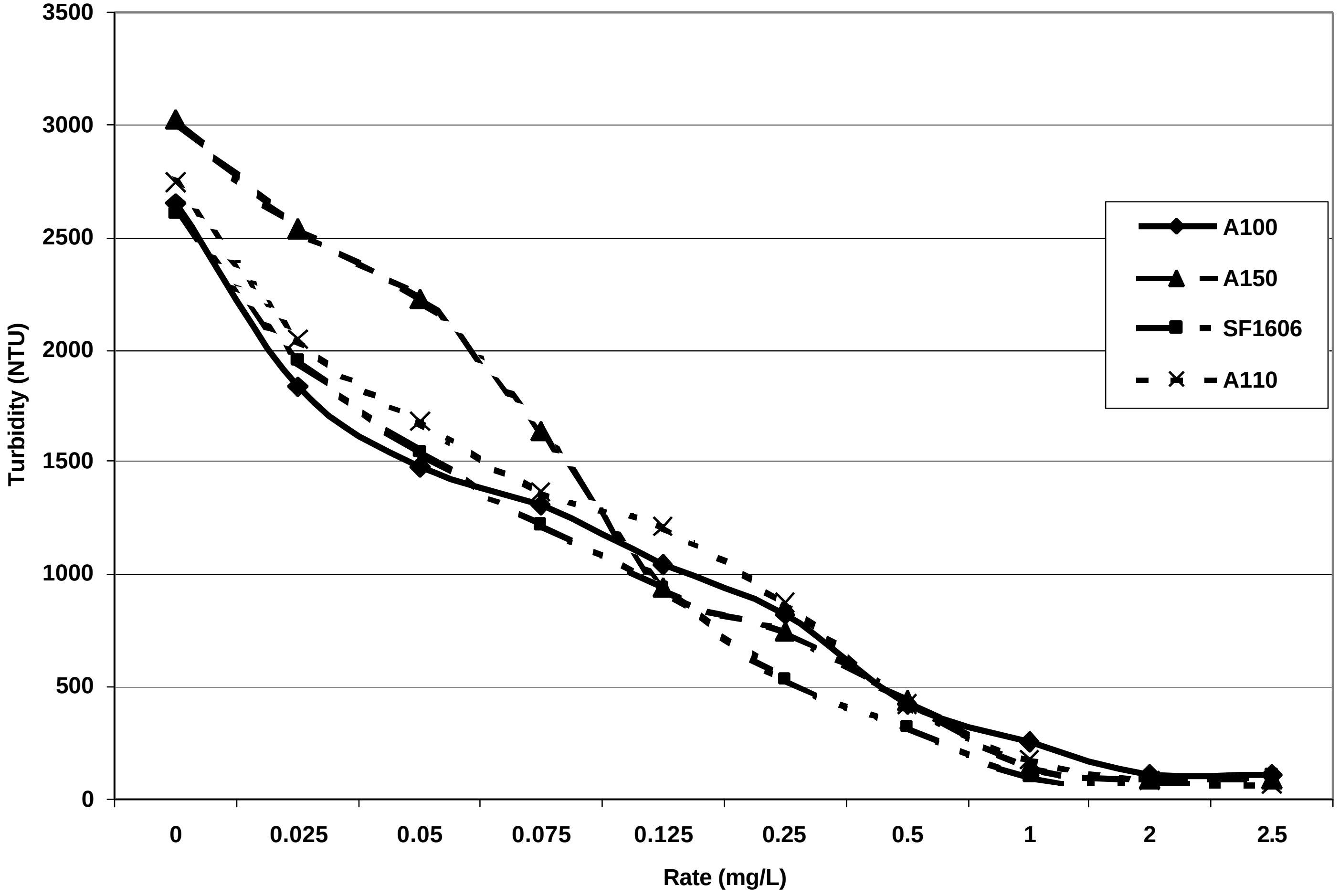


Figure 94: PAM Concentration Effects on Sediment Source 1337b

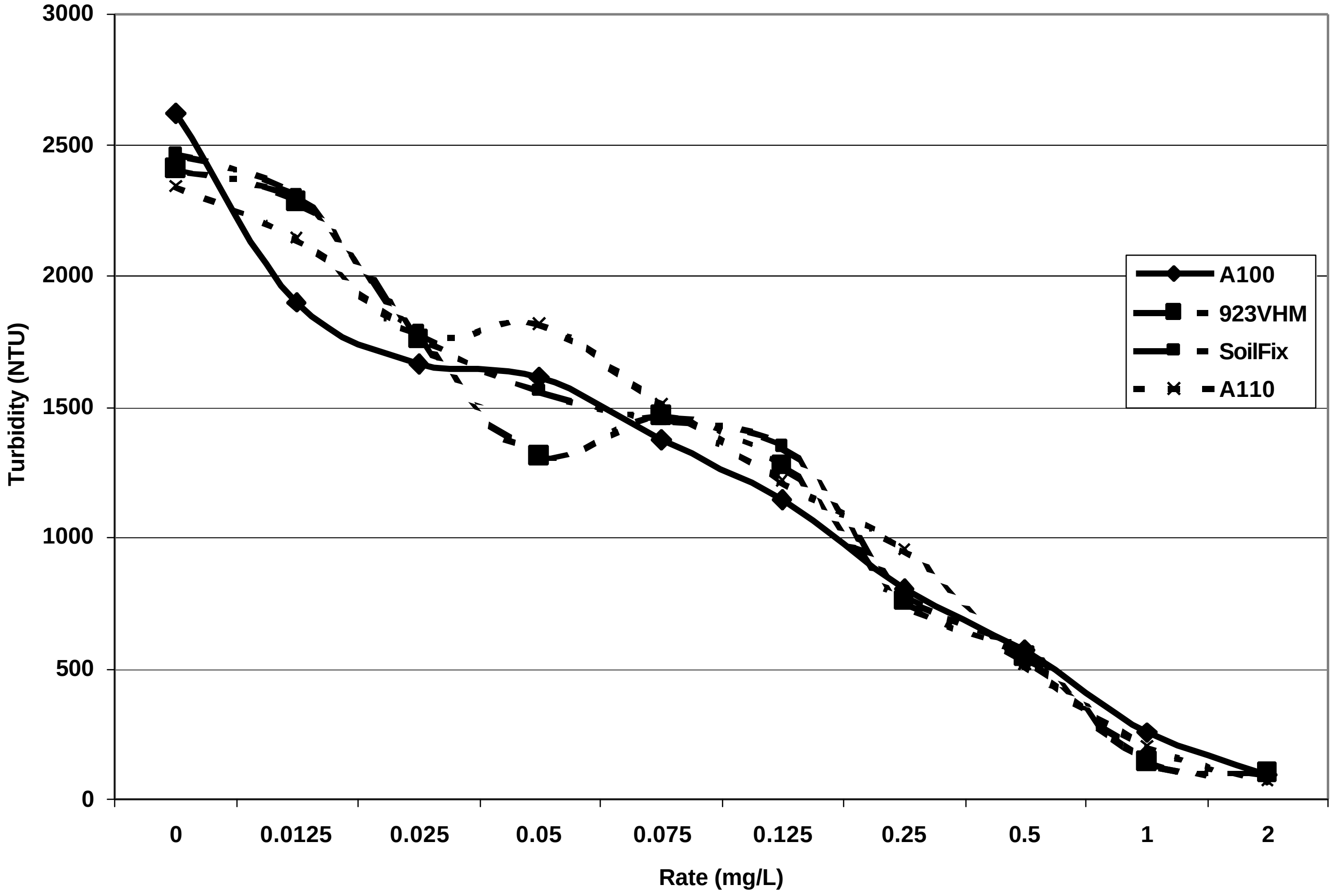


Figure 95: PAM Concentration Effects on Sediment Source 1495s

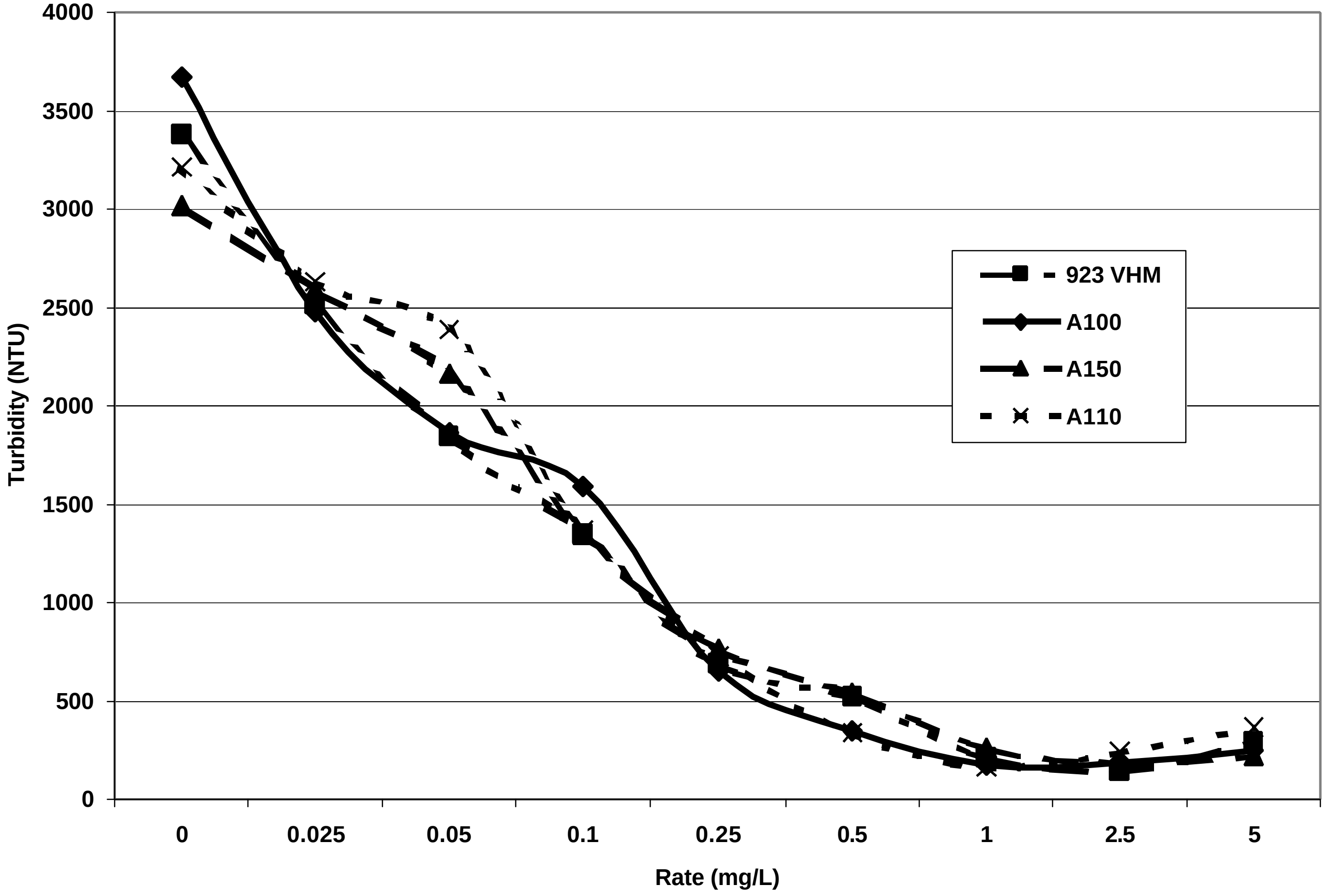


Figure 96: PAM Concentration Effects on Sediment Source 0111t

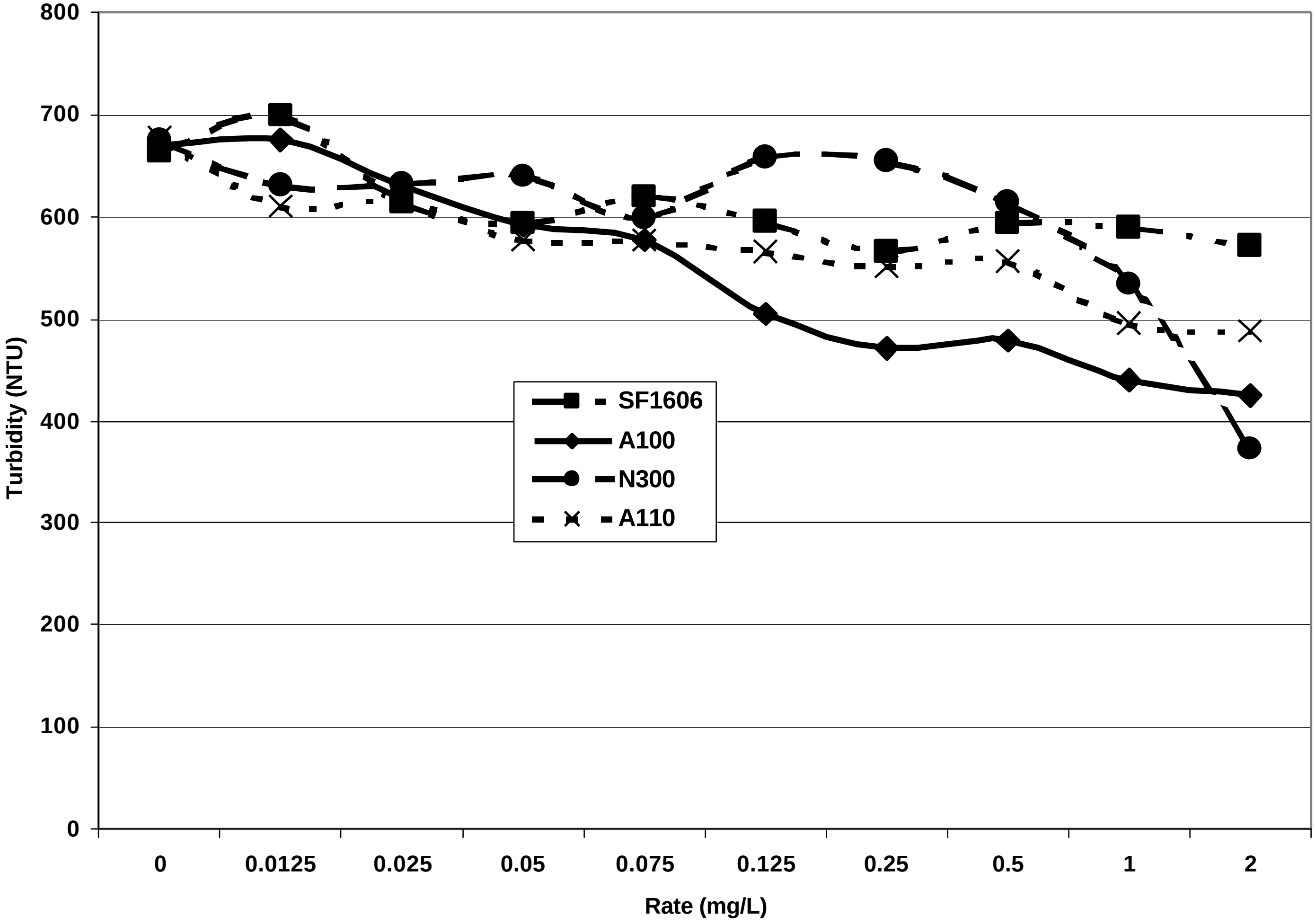


Figure 97: PAM Concentration Efects onf Sediment Source 0434b

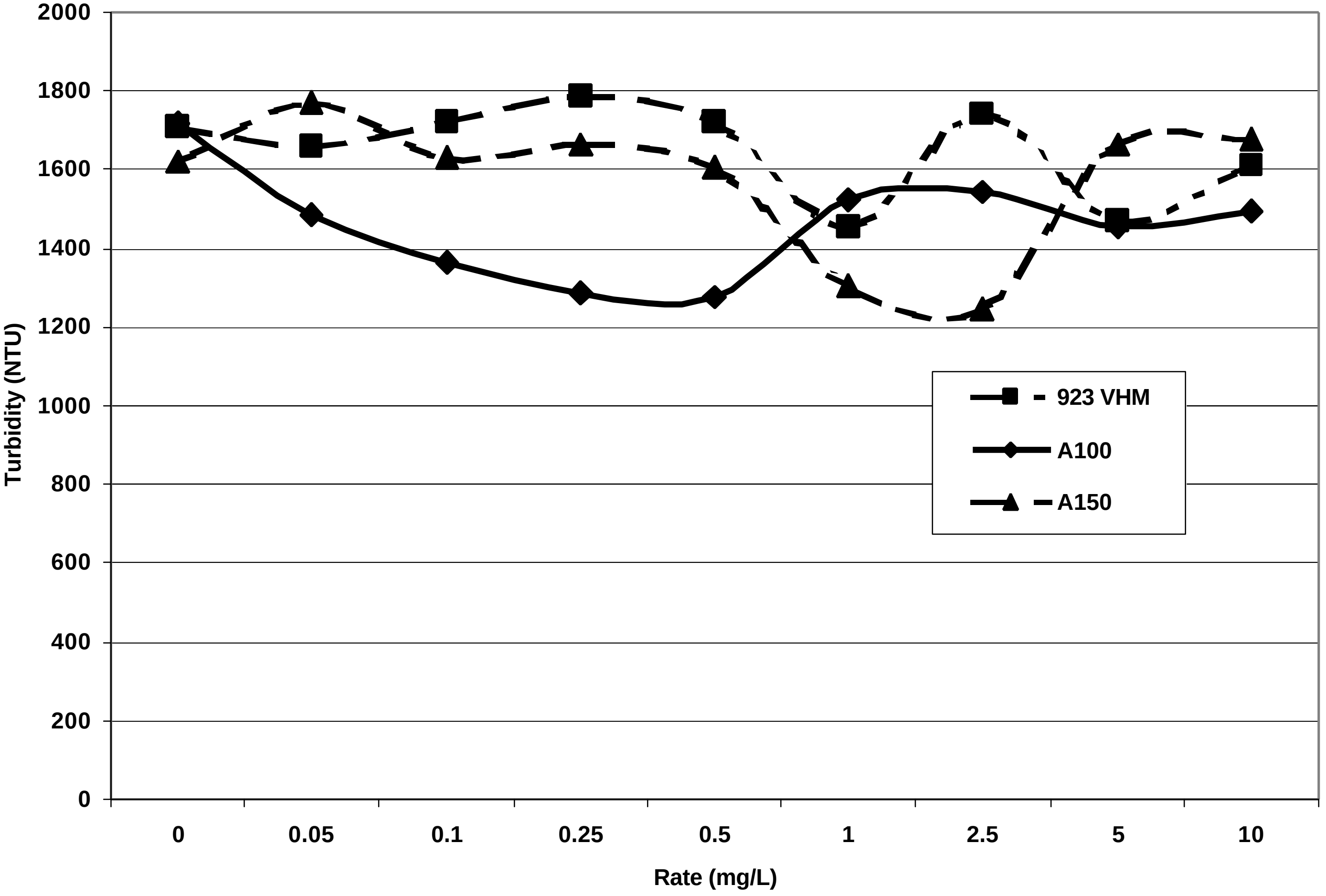


Figure 98: PAM Concentration Effects on Sediment Source 0215b

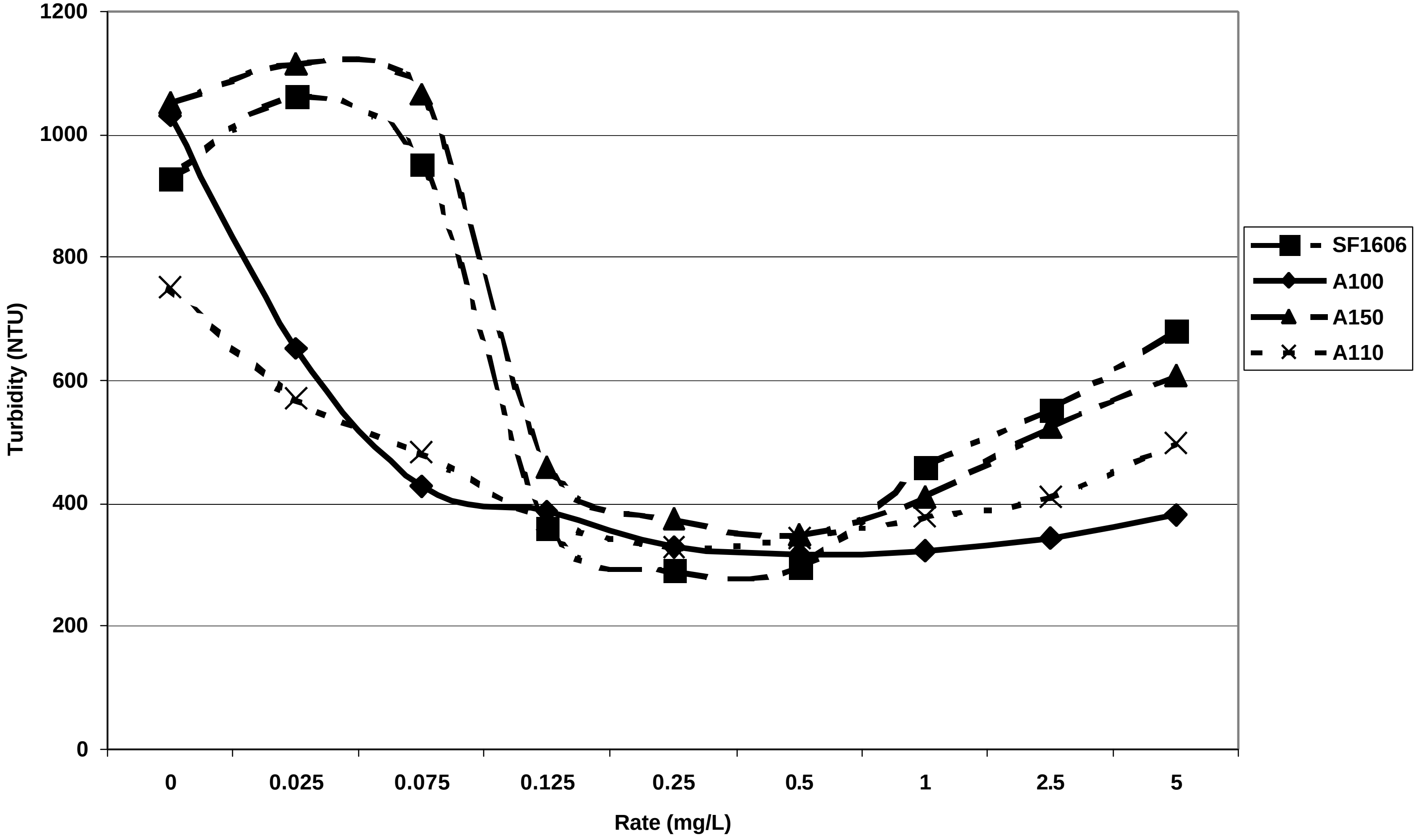


Figure 99: PAM Concentration Effects on Sediment Source 0749b

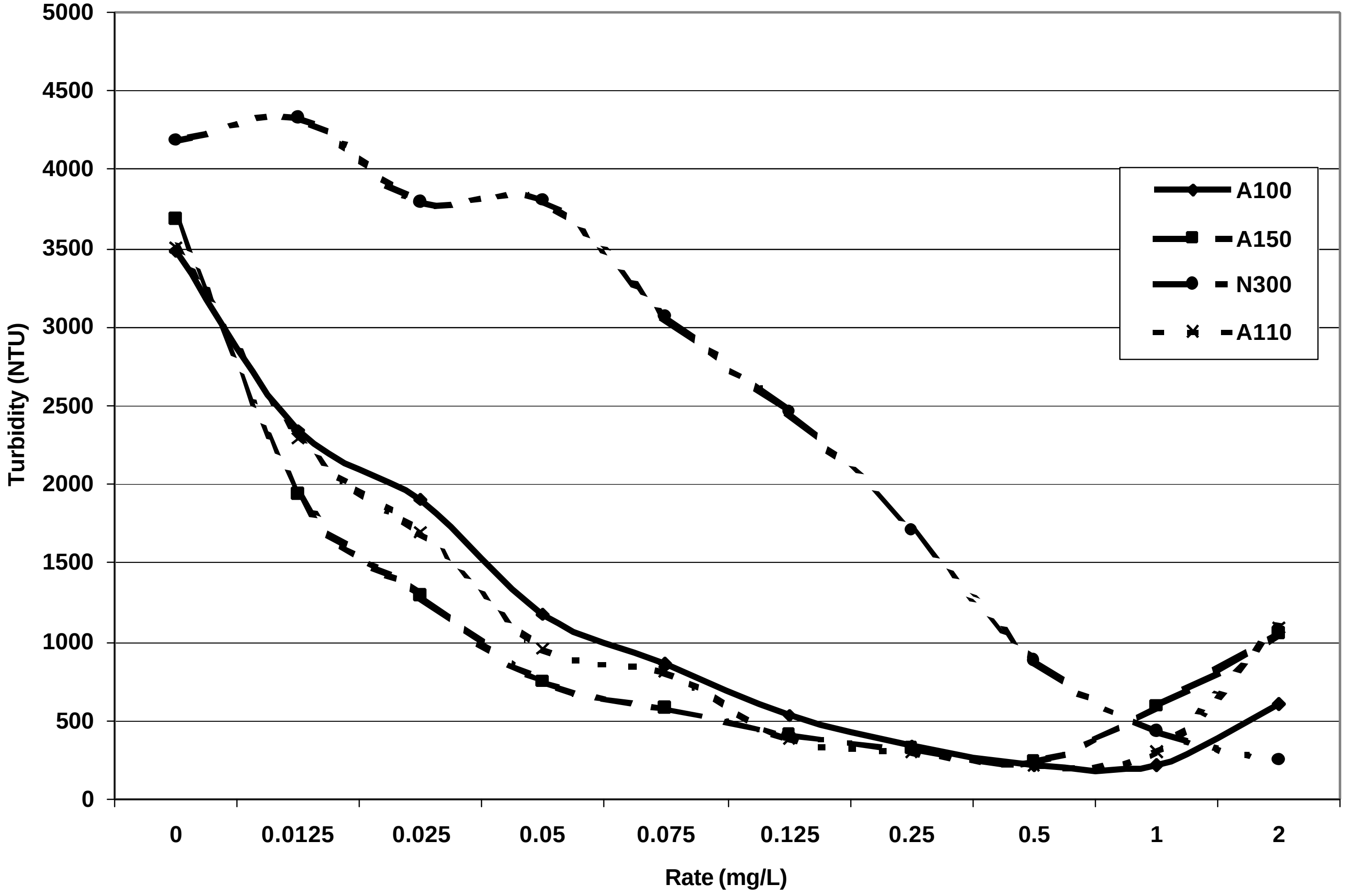


Figure 100: PAM Concentration Effects on Sediment Source 1177p

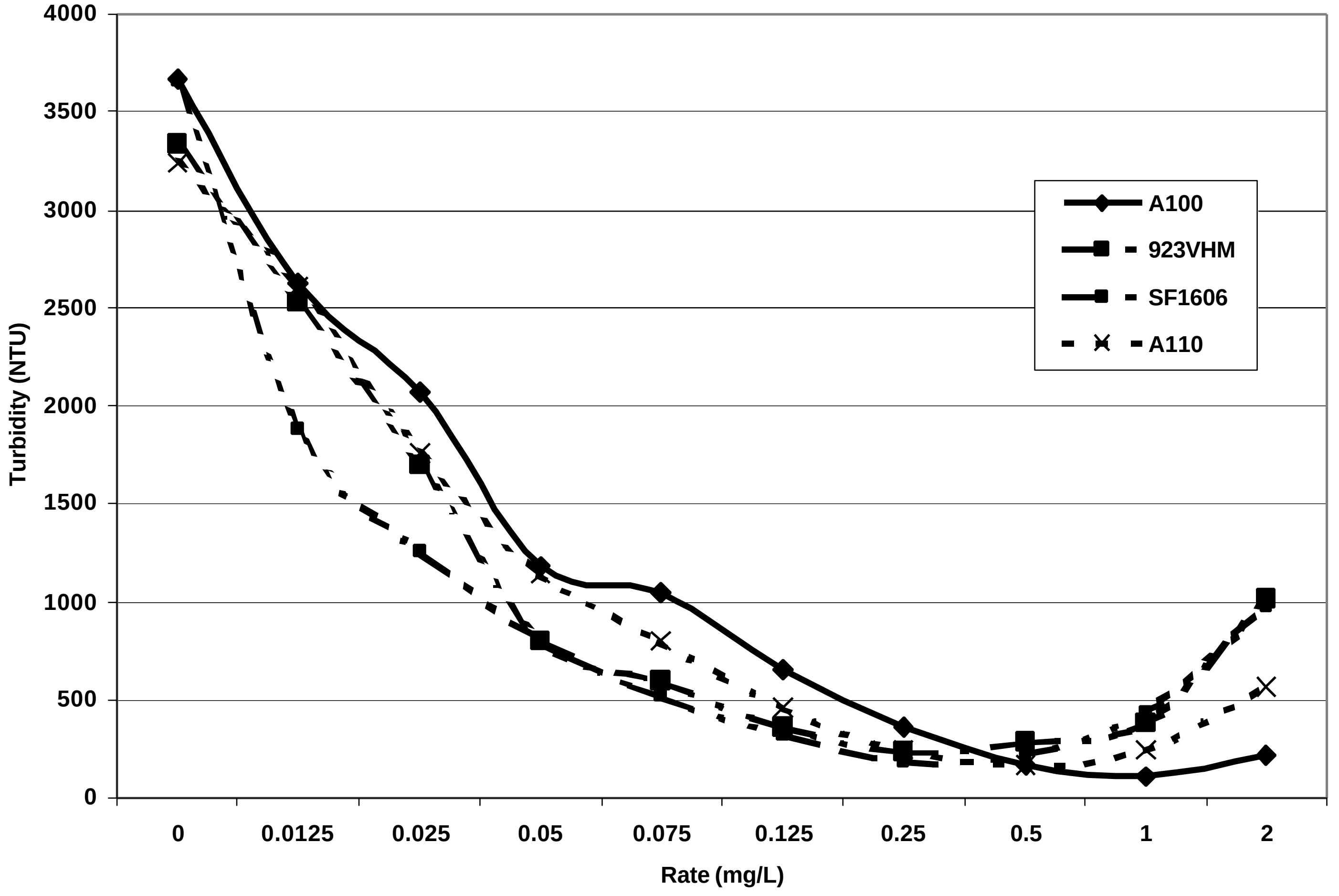


Figure 101: PAM Concentration Effects on Sediment Source 0858b