

Using polyacrylamide to mitigate post-fire soil erosion



Assaf Inbar^{a,b}, Meni Ben-Hur^b, Marcelo Sternberg^c, Marcos Lado^{d,*}

^a Porter School of Environmental Studies, Tel-Aviv University, Ramat Aviv 69978, Israel

^b Institute of Soil, Water and Environmental Sciences, The Volcani Center, ARO, P.O. Box 6, Bet-Dagan 50250, Israel

^c Department of Molecular Biology and Ecology of Plants, The George S. Wise Faculty of Life Sciences Tel-Aviv University, Ramat Aviv, 69978 Tel Aviv, Israel

^d Area of Soil Science, Faculty of Sciences, University of A Coruna, A Zapateira s/n, 15071 A Coruna, Spain

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ABSTRACT

One of the consequences of wildfires is the modification of the hydrology of the affected area, usually resulting in increased overland flow and soil erosion. In this work, we tested granular anionic polyacrylamide (PAM) to reduce post-fire soil erosion, and the mechanisms by which this polymer modifies infiltration rate (IR), runoff and soil loss. Two contrasting soils affected by fire were exposed to three consecutive simulated rainstorms separated by drying periods. During the 1st rainstorm, PAM decreased IR and increased runoff in both soils while soil loss was reduced compared to the untreated controls. In the following storms, the reduction in soil loss persisted, but the effect of PAM on IR and runoff was reversed. The reduction of soil loss was attributed to two mechanisms: (i) an increase of the viscosities of runoff and soil solution as PAM dissolved during the 1st storm, which resulted in more runoff but with reduced erosivity; and (ii) the stabilization of soil aggregates throughout the 1st rainstorm and drying period, when PAM was irreversibly adsorbed to soil particles. Field erosion plots constructed on a burnt area in Biryia forest, Israel, confirmed the laboratory results. The application of 25 and 50 kg ha⁻¹ of granular PAM reduced soil erosion by 23 and 57%, respectively, compared to the untreated control. We suggest that granular PAM could be an alternative to current post-fire erosion mitigation measures.

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1. Introduction

Wildfires are one of the main causes of forest destruction, soil erosion and land degradation (Benavides-Solorio and MacDonald, 2005; Neary et al., 2012; Prosser and Williams, 1998; Wittenberg and Inbar, 2009). In addition to the loss of a non-renewable resource like soil, sediments and nutrients transported by the runoff can produce offsite ecological damage, especially when they reach surface water bodies. Therefore, the first measures after a wildfire are usually designed to mitigate soil erosion, either by protecting the soil surface against the disrupting action of raindrops and overland flow (e.g., seeding, mulching and hydro-mulching) or by constructing barriers to slow down runoff and allow the transported sediments to settle (e.g., log barriers). The effectiveness of these strategies depends on rainfall amounts and intensities, especially during the first three years after the fire (Robichaud, 2005), with mulching with wood-chips, straw, or chopped bark being the most effective method (Diaz-Ravina et al., 2012; Fernandez et al., 2011; Robichaud et al., 2010).

An alternative method to protect the soil against erosion is the application of substances that improve soil structure and modify the processes that lead to runoff and soil loss. Some of the most effective agents are

synthetic polymers, whose application to the soil has been found to improve soil physical properties (Ben-Hur, 2006; Sojka et al., 2007). Several types of polymers have been successfully used to reduce soil erosion, such as polysaccharides and linear polyacrylamides (PAM) (Ben-Hur, 2006; Levy and Ben-Hur, 1998), and nowadays the addition of high molecular weight anionic PAM to the soil surface is widely used for soil conservation in irrigated agriculture (Aase et al., 1998; Levy et al., 1991, 1992; Sojka et al., 2007), and to stabilize unconsolidated steep slopes in infrastructure projects (Flanagan et al., 2002a, 2002b). Despite the proven effectiveness of PAM in solution, dissolving PAM in water is difficult and the application of the resulting high-viscosity solutions requires significant amounts of water. Therefore, research efforts have been made in the last decade to successfully apply PAM in granular form (Tang et al., 2006; Yu et al., 2003), which improves handling and reduces the cost of its use. The application of granular PAM to agricultural soils reduces erosion but increases runoff compared to untreated controls (Yu et al., 2003). Moreover, its effectiveness is enhanced when combined with a source of electrolytes like gypsum (Yu et al., 2003). The mechanisms behind this behavior are not fully understood yet.

Anionic PAM stabilizes soil structure due to the ability of the polymer chains to adsorb onto clay particles and bridge them together forming stable domains. This adsorption can be a result of interactions between the negatively-charged functional groups of the PAM molecules and the positively-charged edges of clay minerals, or

* Corresponding author.

E-mail address: marcos.lado@udc.es (M. Lado).

exchangeable polycations (mainly Ca^{2+}) acting as 'bridges' between the negative charges of the PAM's functional groups and the negatively-charged planar surfaces of the clay (Ben-Hur, 2006; Theng, 1982; Wallace and Terry, 1998). High molecular weight anionic PAM is the most effective flocculant, especially in the presence of polyvalent cations (Roberts, 1974), due to its long grappling distance that facilitates interparticle bridging (Theng, 1982). Besides polymer and soil characteristics, the efficiency of PAM to stabilize soil structure depends on environmental factors, such as electrolyte concentration of the soil solution (Ajwa and Trout, 2006; Shainberg et al., 1990; Yu et al., 2003) that mediates in the adsorption process between the anionic PAM and the planar surface of the clay; or drying periods after the polymer application, which reduce the distance between the polymer chains and solid surfaces and enhances their interaction making sorption irreversible (Ajwa and Trout, 2006; Nadler et al., 1992; Shainberg et al., 2011).

Despite the potential beneficial effect of PAM in reducing soil loss, only few studies have tested its effectiveness as a post-fire erosion control method, and their results were not conclusive. Davidson et al. (2009) conducted a three year experiment in which they compared the effects of PAM and straw-mulch application on soil erosion and vegetation recovery. In this study, recycled paper pellets containing PAM with an average molecular weight of 18×10^6 Da were spread on the soil surface at a rate of 8 kg ha^{-1} . Soil erosion was reduced, although not significantly, with the addition of PAM. However, PAM contributed to a significant increase in vegetation recovery in the first and second years after the fire compared with the untreated plots. In another study, Rough (2007) tested the effect on erosion of micronized PAM (30–50 μm in diameter) applied at a rate of 5.6 kg ha^{-1} to the surface of a coarse sandy loam. The PAM application did not modify the sediment yield compared to the untreated soil. These results were attributed to the low PAM application rate and the partial loss of PAM blown by the wind before the first rain event. However, Rough (2007) also found that applying wet PAM at a rate of 11.2 kg ha^{-1} significantly reduced sediment yield by 39–85% compared to the untreated control during a three-year period after its application. The effectiveness of the wet PAM was attributed to its immediate binding to soil particles, unlike dry PAM that needs a certain amount of rain before binding can occur and off-site mobilization by wind is prevented (Rough, 2007).

In the present study, we hypothesized that the addition of granular PAM to the soil in higher doses than the previously used ones can be an effective method to reduce post-fire soil erosion in different soil types. Moreover, its capacity to stabilize soil structure and reduce soil erosion would improve after drying cycles between storms that facilitate the adsorption of PAM molecules on soil particles. Therefore, the objectives of this study are: (i) to test the effectiveness of granular PAM as a post-fire amendment to maintain infiltration rate (IR) and to reduce runoff and soil loss in soils with contrasting properties; and (ii) to identify the mechanisms by which granular PAM modifies soil IR and erosion.

2. Materials and methods

2.1. Soil sampling and analysis

Two soils with contrasting properties were used in this study: (i) a calcareous montmorillonitic sandy clay loam (*Lithic Xerorthent*) from the Biry forest, N Israel; and (ii) a non-calcareous kaolinitic sandy loam (*Typic Xerorthent*), from Barbanza, NW Spain. Both soils have very different chemical and structural properties: the presence and amount of montmorillonite clay particles are the main factors responsible for aggregation in the soils from Biry (Singer, 2010), while the amount and composition of organic matter determine aggregation in the soils from Barbanza, since these soils contain a small amount of clay (mainly kaolinite) that does not contribute significantly to stabilize soil structure (Benito and Diaz-Fierros, 1992).

The Biry forest is located in Northern Israel ($32^\circ 59' 52''\text{N}$, $35^\circ 30' 27''\text{E}$), and it is one of the largest planted forests in Galilee spreading over 2000 ha. The average height of the forest is 840 m above sea level; with a typical Mediterranean climate: the average annual temperature and precipitation are 22°C and 600 mm, respectively. The study area was located in a planted *Pinus halepensis* stand where the soils are *Lithic Xerorthents* on top of marl and chalk sedimentary rocks. Due to arson, some of the aforementioned forest area was burnt on the 21st of July, 2009. The fire was classified as of low–moderate severity according to the definitions of Pausas et al. (2003) and reached the soil surface, where the litter layer, consisting mainly of pine needles, was scorched and black ash deposits accumulated on the soil surface. Most of the trees in the burnt area died and pine needles were found on the forest floor soon after the fire.

The hills of Barbanza are located in NW Spain ($42^\circ 43' 39''\text{N}$, $8^\circ 54' 22''\text{W}$). Soils in the sampled area are *Typic Xerorthents*, developed on top of granitic rocks, under oceanic climate: the average annual temperature and precipitation are 15°C and 1800 mm, respectively. Soil samples were collected from a *Pinus pinaster* stand located 550 m above the sea level.

In both sites, samples were collected in November 2009, from the top 3 cm of the mineral soil after carefully removing the overlying litter or ash layer. In Biry, samples were collected inside a burnt area after the fire that occurred in July 2009, and posterior storms that accounted for 56 mm of rain. In Barbanza, although forest fires are frequent in this area, it was not possible to find any recently burnt area at the time of sampling, and therefore unburnt-soil samples were collected. All samples were transported to the laboratory, air-dried and crushed. A small portion was sieved through a 2-mm mesh sieve for chemical analysis, and the remaining material was sieved through a 4-mm mesh sieve. The Barbanza soil was heated in a muffle at a temperature of 300°C during 8 h. Although the duration of this heating treatment is larger than most of the natural wildfires, it was necessary to produce changes in soil OM similar to those occurring under the most common natural fires in the area, when temperatures reach $220\text{--}300^\circ\text{C}$ and soil OM decreases approximately by 50% (Fernandez et al., 1997). With this heating treatment, the OM of this soil decreased from 12.1 to 5.2% (Table 1). Soil analyses were performed using standard methods and included texture determined using the hydrometer method (Klute and Page, 1986) after oxidation of organic matter (OM) with hydrogen peroxide; OM content was measured using the Walkley–Black method (Page, 1983), CaCO_3 content was measured by a volumetric method (Page, 1983), and cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) were determined by saturation with ammonium acetate at pH 7 (Page, 1983). Some parameters of the soil solution composition were measured after batch extraction. In this procedure, 0.05 kg of <2-mm soil samples were mixed with 75 mL of deionized water (DW) in 200-mL Teflon centrifuge tubes. The tubes were sealed with Teflon lined cups and shaken mechanically for 1 h at 160 rpm. Following this process, the tubes were centrifuged for 10 min at 7000 rpm and the supernatant was collected. The pH values were determined using a pH meter; electrical conductivity (EC) was measured with a standard EC meter; sodium adsorption ratio was calculated after measuring the concentrations of Na^+ using a flame photometer and Ca^{2+} and Mg^{2+} by standard titration, and dissolved organic carbon (DOC) concentration was measured using a combustion TOC analyzer (Skalar Analytical, the Netherlands). Some of the properties are presented in Table 1.

2.2. Rainfall simulation experiment

Disturbed samples of both soils (aggregate size $<4 \text{ mm}$) were packed in perforated trays measuring $0.30 \times 0.50 \text{ m}$ and 0.02 m deep. The trays were placed on top of a 0.08 m-thick layer of crushed and washed shells in a box positioned under a rotary disc rainfall simulator (Morin et al., 1967) at a slope of 30%. Two polymer treatments were

Table 1

Mechanical composition, organic matter (OM), CaCO₃ content, exchangeable sodium percentage (ESP), cation exchange capacity (CEC), soil solution pH, electrical conductivity (EC), sodium adsorption ratio (SAR) and dissolved organic carbon (DOC) in the studied soils.

	Mechanical composition						Soil solution composition (1:1.5)				
	Clay	Silt	Sand	OM	CaCO ₃	ESP	CEC	pH	EC	SAR	DOC
	%						mmol _c kg ⁻¹		dS m ⁻¹	(cmol _c L ⁻¹) ^{0.5}	mg L ⁻¹
Birya	25	25	50	10.7	57.6	1.1	235	7.2	0.3	0.1	294.4
Barbanza	13	18	69	5.2	0.3	0.5	263	5.3	0.8	nd*	nd

* Not determined.

tested, with 4 replicates for each soil and treatment: (i) 0 (control), and (ii) 50 kg ha⁻¹ PAM. The polymer used was an anionic PAM (Superfloc A-110 Flocculent, manufactured by Kemira Water Solutions BV, Netherlands) with a molecular weight of 1 × 10⁷ Da and 15% hydrolysis. Polymer was applied spreading the granules manually on the soil surface before the first rainstorm. Following the application of PAM, the trays were exposed to three consecutive rainstorms of 80 mm-depth each, using deionized water applied at a rainfall intensity of 47 mm h⁻¹. The typical mechanical parameters of the simulated rain were: 1.9 mm raindrop mean diameter; 6.2 m s⁻¹ median drop velocity; and 18.1 J mm⁻¹ m⁻² kinetic energy. The rainstorms were separated by drying periods of 72 h in an oven at 37 °C. Water percolating through the soil (leachate) was collected and measured every 80 s to determine the infiltration rate. Since the soil was initially dry, this process was delayed until the soil was saturated, after approximately 20 mm into the rainstorm. In addition, the leachate and runoff were collected in 4 fractions during periods of 20 mm of cumulative rainfall each, and the runoff volume was measured. The runoff and leachate fractions were left to rest to allow fine particles to settle down, and 20-ml samples from each fraction were used to measure EC and relative viscosity. Soil loss was measured by drying the runoff samples at 105 °C and weighing the dry material. The measured soil loss was considered as interrill erosion, because the trays in the rainfall simulator were short (Meyer and Harmon, 1984).

Relative viscosity of the leachate and runoff was measured using an Ostwald glass tube viscometer, and calculated using Eq. (1):

$$RV = \eta_s / \eta_w \quad (1)$$

where η_s is the viscosity of the solution; and η_w is the viscosity of deionized water.

2.3. Aggregate stability experiments

In order to determine the effect of PAM on soil structural stability, aggregate stability tests were performed in dry-soil samples of Birya soil. The soil was sieved to obtain two aggregate fractions with sizes of <2 mm and 2 to 4 mm. Both aggregate fractions were slowly wetted until saturation with deionized water (untreated) or with 1000-mg L⁻¹ PAM-solution (PAM-treated) mimicking an application of 50 kg ha⁻¹ PAM at the soil surface. After wetting, the aggregates were dried in an oven during 24 h at 37 °C, prior to their use in aggregate stability tests according to Ben-Hur et al. (2009), which include slaking and dispersion tests.

2.3.1. Slaking test

Five grams of PAM-treated and untreated aggregates 2 to 4 mm in size were subjected to two different wetting rates: (i) fast wetting rate-aggregates were immersed for 10 min in 50 mL of deionized water; (ii) slow wetting rate-aggregates were placed inside a desiccator on a cotton cloth whose edges were immersed in deionized water and wetted slowly under vacuum for 24 h. After the fast and slow wetting rates, the aggregates were transferred to a 50- μ m sieve immersed in ethanol and gently moved up and down 5 times. The >50 μ m fraction was oven-dried at 105 °C during 3 h and sieved through a column of

sieves of mesh sizes 2.0, 1.0, 0.5, 0.25, and 0.1 mm. The weight of each fraction was measured and that of the <50- μ m fraction was calculated as the difference between the initial weight and the sum of the weights of the other fractions. The mean weight diameter (MWD) was calculated using Eq. (2):

$$MWD = \sum_{i=1}^7 \bar{x}_i w_i \quad (2)$$

in which w_i is the weight fraction of aggregates in the size class i with a mean diameter of \bar{x}_i .

The slaking value (SLV) was calculated using Eq. (3):

$$SLV = MWD_s / MWD_f \quad (3)$$

in which MWD_s and MWD_f are the mean weight diameters under slow and fast wetting conditions, respectively.

2.3.2. Dispersion test

A 2-g sample of <2-mm aggregates was suspended in 0.05 L of deionized water in a 0.5-L centrifuge tube, shaken on a reciprocal shaker for 30 min at 20 rpm, and centrifuged at a relative centrifugal force of 960 rcf for 5 min (J2-21M, Induction Drive Centrifuge, Beckman, USA). The concentration of dispersed clay in the turbid supernatant was determined by measuring its absorbance at 420 nm with a spectrophotometer (Thermo Scientific. Genesys 10 uv), and comparing the result with a calibration curve of absorbance vs. suspended clay concentration that had previously been prepared for each soil type. The dispersion value (DV) for each soil sample was determined by using Eq. (4):

$$DV = (M_d / M_t) * 100 \quad (4)$$

where M_d is the mass of the dispersed clay in the turbid supernatant per 1 g of tested soil sample, and M_t is the total clay mass in 1 g of tested soil sample.

2.4. Water repellency tests

Water repellency was measured using the water drop penetration time (WDPT) test (Letey, 1969) on aggregates <2 mm of both soils. This test consists of the measurement of the time required for a drop of deionized water placed on the surface of a soil sample to fully penetrate into the soil. The longer the WDPT, the more water-repellent the soil is. The definition of the water repellency for each soil was done using the categories proposed by Bisdom et al. (1993).

2.5. Field experiments

A field experiment was conducted in the burnt area of the Birya forest where soil samples were collected for laboratory experiments. An area of ~0.2 ha inside the burnt zone, in a hill slope with westerly aspect and a uniform 40% slope, was logged after the fire and cut trees and branches were carefully removed from the site to avoid surface disturbance. Twelve 4.5-m² erosion plots were then built at the end of November 2009, using metal plates inserted into the soil to define its

perimeter and isolate its interior from external runoff and soil loss. At the bottom of each plot, a funnel with a sediment trap was placed and connected to a 200-L container located at the end of the slope. Ash deposits on the soil surface were minor and not evenly distributed in the entire area, so they were carefully removed to maintain uniform surface conditions.

Since experimental conditions in the field were different from those in the laboratory, and unpredictable, the PAM application rate that would be effective to reduce soil loss could differ between experimental setups. Therefore, an additional PAM treatment was included in the field experiments, with an application rate of 25 kg ha⁻¹ PAM. Thus, granular PAM (A-110) was applied on the soil surface at three different rates: (i) 0 (control treatment); (ii) 25; and (iii) 50 kg ha⁻¹ PAM. Each treatment was applied to 4 runoff plots randomly selected, inside the plots and in a buffer area of 0.5 m around each plot. Herbicide was sprayed on the surface of all plots (control and PAM-treated) after the application of PAM to avoid the growth of vegetation that could affect runoff and soil loss measurements.

Five rainfall gauges were randomly placed in the study area in order to determine the rainfall amount on each rainstorm and its spatial variation in the experimental area. No significant differences were seen among the rainfall amounts measured by the gauges, so the rainfall amount for each storm was calculated as the average of the five measured values. After each storm, a 100-mL runoff sample was collected from each container to measure runoff viscosity, and the content of each barrel was thoroughly mixed, total runoff volume was measured, and 1 L of the runoff-sediment mixture was sampled, dried in the laboratory (105 °C for 48 h), and weighed to calculate the sediment concentration. Eroded soil was also collected from the sediment trap of each plot, oven dried in the laboratory and weighed. Total soil loss was calculated as the sum of weights of sediments collected in the trap and sediments from each barrel.

2.6. Data analysis

All experiments were conducted with four replicates per treatment in a complete randomized design. Numerical data was statistically analyzed using the software JMP 5.0.1 (SAS Institute, Inc). The differences between the means were subjected to analysis of variance (ANOVA) and the means were separated using Tukey's Significant Difference test (Steel and Torrie, 1981). All tests were performed at 0.05 significance level.

3. Results and discussion

3.1. Rainfall simulator experiment

Infiltration rate in Birya and Barbanza soils treated with 0 (control treatment) and 50 kg PAM ha⁻¹ (PAM treatment), measured during three consecutive rainstorms separated by drying periods are presented in Fig. 1 as a function of cumulative rainfall in each storm. Total runoff and soil loss for each storm and treatment are presented in Table 2. Since the soil was initially dry, the onset of recordable IR began after approximately 20 mm of rain. During the first rainstorm, and in the control treatment, both soils show a decrease in IR as the storm progressed, until final IR values were obtained (Fig. 1A and D). Both soils are hydrophilic, since WDPT was in all cases <5 s (Bisdorn et al., 1993), and therefore the decline in IR was a result of aggregate breakdown with the subsequent seal formation at the soil surface (Agassi et al., 1981; Ben-Hur, 2008; Morin et al., 1981). The decrease of IR in the control treatment was more pronounced in the Birya soil than in the Barbanza soil (Fig. 1A and D), their respective final IR values being 18.4 and 34.2 mm h⁻¹. These differences in IR indicate that a more developed surface seal with lower hydraulic conductivity was formed in the Birya soil compared to the Barbanza soil. Probably, the higher montmorillonite content of the former caused it to be more sensitive to seal formation and IR reduction than the latter (Lado and Ben-Hur, 2004; Stern et al., 1991).

In the two studied soils, the IR values were higher in the control than in the PAM-treated soil during the entire 1st rainstorm (Fig. 1A and D). In Birya, the final IR of the PAM-treated soil was 3.6 mm h⁻¹. In the PAM-treated Barbanza, IR increased as the storm progressed to reach a final IR of 28.2 mm h⁻¹. Nevertheless, in both soils the final IR was significantly lower after the application of PAM than their respective control treatments, and as a consequence, runoff amounts were higher in the PAM than in the control treatments during this 1st storm (Table 2). Despite the higher runoff amounts, the application of PAM reduced soil loss in this 1st rainstorm from 396.9 to 222.8 g m⁻² in the Birya soil and from 364.2 to 226.3 g m⁻² in the Barbanza soil (Table 2). Similar results were found by other authors (Yu et al., 2003), who reported that the addition of granular PAM on the soil surface reduced soil erosion despite a reduction of infiltration rates and an increase in runoff yields.

The apparent contradiction between higher runoff and lower soil loss after the application of PAM could be a result of the different mechanisms that operate concomitantly as rain reaches the surface of the soil

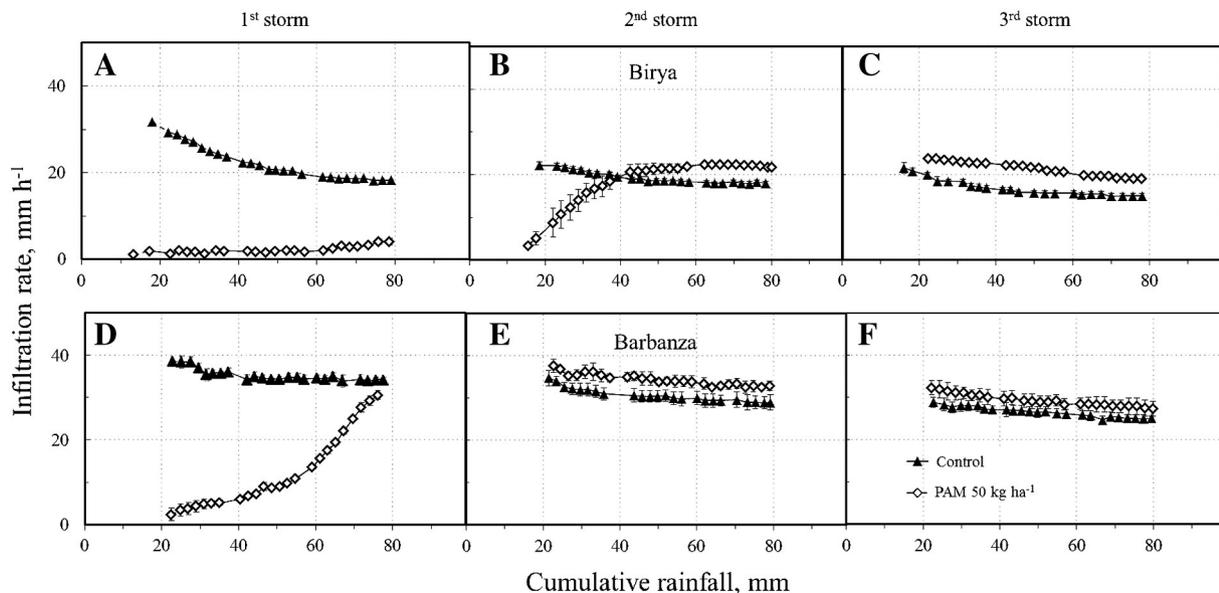


Fig. 1. Infiltration rate as a function of cumulative rainfall for the Birya and Barbanza soils during three consecutive storms. Bars indicate standard error.

Table 2

Runoff and soil loss collected during each consecutive rainstorm. Different upper case letters within a soil and treatment indicate significant differences between storms. Different lower case letters within a storm and soil indicate significant differences between treatments.

	Treatment	Birya			Barbanza		
		Number of accumulated rainstorms					
		1	2	3	1	2	3
<i>mm</i>							
Runoff	Control	18.8 bC	23.6 aB	27.9 aA	5.3 bC	10.5 aB	15.7 aA
	PAM	50.6 aA	25.4 aB	23.1 bB	36.0 aA	6.5 aB	12.0 bB
<i>g m⁻²</i>							
Soil loss	Control	396.9 aC	505.9 aB	589.0 aA	364.2 aB	629.4 aAB	905.3 aA
	PAM	222.8 bB	379.9 bA	377.5 bA	226.3 bB	413.5 aAB	738.6 aA

and PAM granules dissolve: i) dissolved PAM molecules enhance flocculation and soil aggregation, reducing soil loss (Levy and Ben-Hur, 1998; Sojka et al., 2007). ii) At the same time, the presence of long linear chains of PAM in aqueous solution produces an increase of the solution viscosity (Ben-Hur and Keren, 1997; Malik and Letey, 1992). Hydraulic conductivity of porous media, and thus flow rate through it, is inversely proportional to fluid viscosity (Malik and Letey, 1992). Therefore, an increase in viscosity of the percolating solution can cause a decrease in the IR due to the reduction of the hydraulic conductivity of the soil (Ajwa and Trout, 2006; Ben-Hur and Keren, 1997; Malik and Letey, 1992; Young et al., 2009).

The relative viscosity of the runoff was higher at the beginning of the 1st storm in the PAM-treated than in the control soils, as a result of the dissolution of the polymer granules with the first millimeters of rain (Fig. 2A). The viscosity of the dissolved-PAM solution decreased the hydraulic conductivity and most likely it was responsible for the significantly lower IR and higher runoff yields during the first rainstorm when PAM granules were applied to the soil surface (Fig. 1A and D, Table 2). In both soils, as the rainstorm progressed, relative viscosity of the runoff decreased in the PAM-treated soils, and at the end of the rainstorm it reached similar values to those of the control treatments (Fig. 2A and B). At this stage, PAM molecules already infiltrated into the soil, adsorbed onto soil particles, or were washed by runoff, so no free PAM remained at the surface. In the Barbanza soil, the decrease in the relative

viscosity of the runoff in the PAM-treated soil was simultaneous with an increase of the IR (Figs. 2B and 1D), which reached a final value close to that of the control treatment. Conversely, in the Birya soil, IR remained lower during the entire rainstorm in the PAM than in the control treatment (Fig. 1A) and the differences in final IR were pronounced despite final viscosity values of the runoff being similar in both treatments (Fig. 2A). Contrary to Barbanza, in this soil leachate viscosity was maintained higher in the PAM-treatment than in the control during the entire rainstorm (Fig. 2C), and this probably resulted in differences in IR even at the end of the rainstorm, when the viscosity of the runoff was similar for both treatments (Fig. 2A).

Several factors are responsible for the viscosity of PAM solutions (Ajwa and Trout, 2006; Ben-Hur and Keren, 1997; Malik and Letey, 1992; Mamedov et al., 2009; Yu et al., 2003): molecular weight, type of charge, charge density, conformational structure of the PAM molecule, concentration of PAM in the solution, and electrolyte concentration of the solution. High electrolyte concentrations and the presence of divalent cations cause the linear PAM molecules to coil up, making the solution less viscous. Furthermore, coiled PAM molecules are less capable of clogging pores or causing steric interferences in the soil profile (Ajwa and Trout, 2006; Yu et al., 2003). During the 1st rainstorm, the EC values (which indicate the electrolyte concentration) of the runoff (Fig. 3A) are significantly lower in the Barbanza than in the Birya soil, which could explain the higher viscosity of the runoff of the PAM-

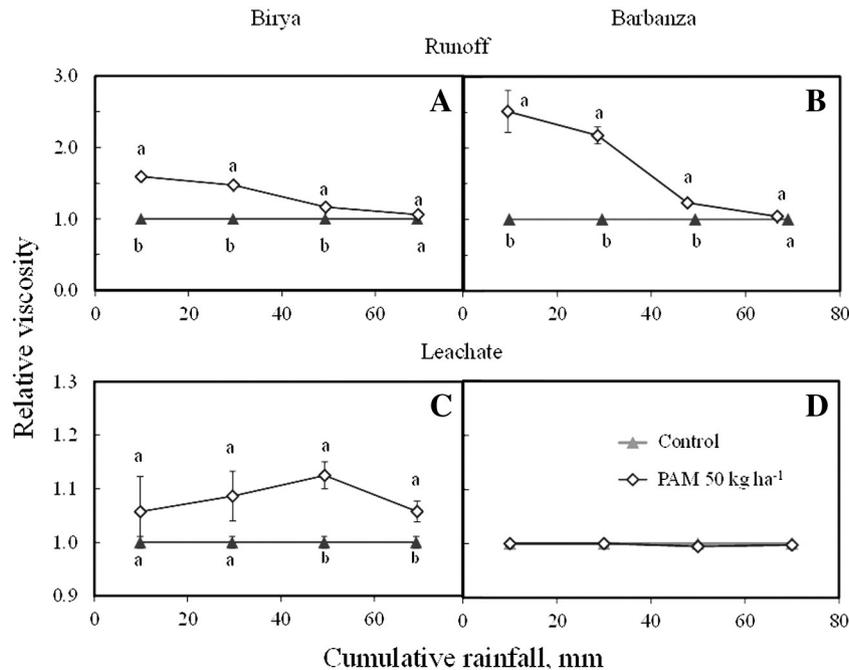


Fig. 2. Relative viscosity of the runoff (A, B) and leachate (C, D) collected at different stages during the 1st simulated rainstorm. Bars indicate standard error. Different lower case letters within each soil and fraction indicate significant differences between control and PAM treatments.

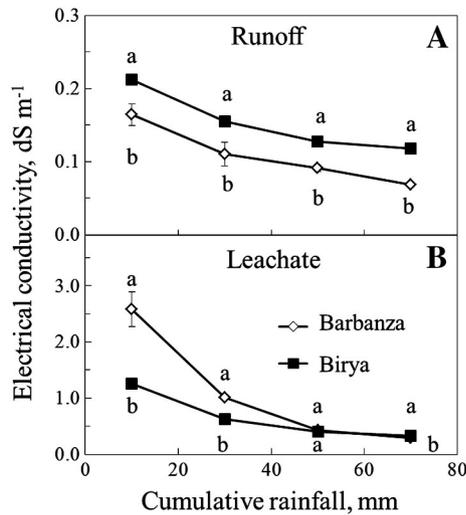


Fig. 3. Electrical conductivity of the runoff (A) and leachate (B) of the Birya and Barbanza soils collected during the 1st simulated rainstorm after the application of PAM. Bars indicate standard error. Different lower case letters within each fraction indicate significant differences between soils.

treated Barbanza soil (Fig. 2A and B). On the contrary, the leachate of Barbanza showed higher EC than the one from Birya at the beginning of the storm (Fig. 3B). It is likely that the high proportion of bigger pores in the coarse-textured Barbanza soil allowed the penetration of the viscous PAM solution formed at the soil surface, and the following movement of the PAM solution through the soil was facilitated by the high EC of the leachate (Fig. 3B), which caused the coiling of the PAM molecules and reduced the viscosity of the leachate to similar values than those observed without PAM (Fig. 2D). Towards the end of the storm, PAM molecules already infiltrated into the soil, adsorbed onto soil particles, or were washed by runoff, so no free PAM remained at the surface, and therefore the viscosity of solutions was low despite the low EC of runoff and leachate. In Birya, the pore size distribution (dominated by pores of smaller size than those of Barbanza) and the low EC of the leachate at the beginning of the rainstorm (Fig. 3B), which maintained its relative viscosity in the PAM-treatment above that of the control (Fig. 2C), resulted in a slow movement of the PAM solution into the soil that maintained IR low until the end of the rainstorm (Fig. 1A).

Despite the increase of runoff in the first rainstorm in both soils with the application of granular PAM, soil loss was reduced by the polymer treatment (Table 2). Soil erosion comprises two main processes: (i) detachment of particles from the soil surface by raindrop impact and/or shear forces of the runoff; and (ii) transport of detached particles by the runoff and splash (Ben-Hur and Agassi, 1997; Watson and Lafen, 1986). During the 1st storm, the effectiveness of granular PAM to decrease soil erosion may depend on the balance between its positive effect on flocculation and aggregation, and its adverse impact on soil permeability and runoff generation. Several mechanisms may have contributed to the reduction of soil loss in PAM-treated soils compared to the control soils in the 1st rainstorm (Table 2), regardless of the higher runoff yield.

- i) The increase in runoff viscosity (Fig. 2A and B) decreased flow velocity and reduced shear or drag forces that can detach soil particles (Trout and Neibling, 1993).
- ii) The PAM-containing runoff acted as a protective layer on the soil surface, absorbing some of the kinetic energy of the raindrops and reducing detachment of soil particles.
- iii) PAM had aggregating (Ben-Hur et al., 1990; Levy and Ben-Hur, 1998; Sojka et al., 2007) and flocculating effects that produced bigger particles resistant to be transported by the runoff (Graber et al., 2006; Lentz and Sojka, 2009; Trout et al., 1995).

In general, in both soils, IR values in the control treatment decreased slightly (Fig. 1) and runoff and soil loss increased with consecutive rainstorms (Table 2). The accumulation of kinetic energy increased soil detachment and seal formation, and drying cycles between the rainstorms did not reverse this process. However, the positive effect of granular PAM on soil structure was maintained or even enhanced after the first drying cycle. In the 2nd and 3rd rainstorms, higher final IR, and lower runoff and soil loss were observed in the PAM-treated soils compared to their respective control soils (Fig. 1 and Table 2). At the beginning of the 2nd rainstorm, IR values of the PAM-treated Birya soil were low. However, this situation was rapidly reversed during the first 40 mm of rain, and by the end of the storm, higher final IR, lower runoff and soil loss were observed in the PAM-treated soil compared to its respective control soil. When PAM molecules adsorb onto soil particle surfaces, some segments of the polymer extend away from the surfaces as loops and tails and can cause steric interference with infiltrating PAM molecules, decreasing the solution flow rate through pores (Ben-Hur and Keren, 1997). It is possible that due to the dominance of pores of small size in this soil, parts of the PAM chains that were not adsorbed onto the solid surfaces limited the infiltration of water, and as the storm progressed, conformational changes in PAM allowed a better infiltration of water through the soil layer.

A drying cycle after the dissolution and penetration of PAM into the soil allowed a closer interaction between the infiltrated PAM molecules and soil particles, resulting in its irreversible adsorption (Nadler et al., 1992). As a consequence, the relative viscosity of the runoff and leachate in the 2nd and 3rd rainstorms was low and similar to that found in the control soils (data not shown), and the negative effect of the PAM-solution viscosity on hydraulic conductivity disappeared. The irreversible soil-PAM interactions resulted in a further increase of aggregate stability in the PAM-treated soil, and therefore seal formation was reduced, IR was higher (Fig. 1) and runoff and soil loss were lower than those of control treatments (Table 2).

To illustrate the impact of a drying cycle on the effect of PAM on soil structure, slaking and dispersion tests were made with the Birya soil. The results of the slaking experiment for untreated and treated (0 and 50 kg ha⁻¹ PAM, respectively) soils are presented in Fig. 4. Mean weight diameter (MWD) after slow wetting was significantly higher than after fast wetting in the control treatment, while MWDs of PAM-treated soil were similar in both treatments (Fig. 4). As a result, the slaking value was higher in the control treatment than in the PAM-treated soil, indicating a higher sensitivity of the former soil to aggregate breakdown due to the fast wetting that occurs when rain falls on dry soil (Fig. 4). The dispersion values, measured with the dispersion test, for the PAM and control treatments were 3% and 19.8%, respectively, indicating the amount of clay that could be dispersed when these soils are exposed

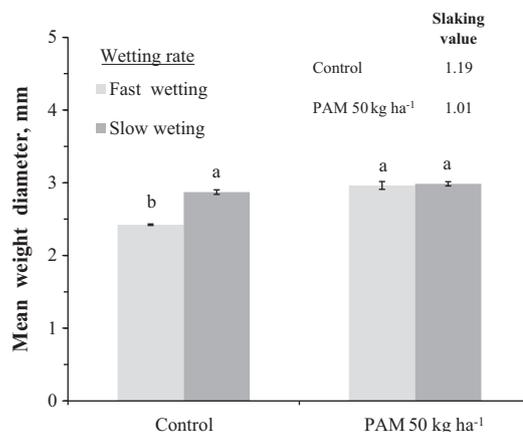


Fig. 4. Aggregate stability parameters measured in the Birya soil. Bars indicate standard error. Different lower case letters within each treatment indicate significant differences between wetting rates.

to rainwater. These results are in agreement with those of runoff and soil loss obtained in the 2nd and 3rd rainfall simulations (Fig. 1). The stabilization of soil structure by PAM was maintained at least until the end of the 3rd storm, after 240 mm of rain accumulated on the soil surface.

3.2. Field experiment

Total runoff collected during the length of the field experiment, conducted during winter of 2009–2010, was not significantly different between the control and the two PAM treatments, although the application of 50 kg ha⁻¹ PAM resulted in the lowest runoff yields (Fig. 5A). However, a significant reduction in soil loss with increasing PAM dose up to 50 kg ha⁻¹ was observed throughout the rainy season: an application of 25 kg ha⁻¹ PAM reduced soil loss by 35% with respect to the control plots, and this reduction reached 57% when PAM was applied at a rate of 50 kg ha⁻¹ (Fig. 5B). It is evident that the effective reduction of soil loss with the application of the polymer observed in the rainfall simulations was also detected in field conditions.

Relative viscosity measurements of the runoff were conducted throughout the winter and differences between the treatments were only found in the 1st rainstorm, where relative viscosity values were 50 kg ha⁻¹ and 25 kg ha⁻¹ and control treatments were 1.18, 1.09 and 0.97, respectively (Fig. 6), confirming the trend observed in the rainfall simulation experiments. However, the differences in runoff viscosity in the 1st rainstorm did not have a significant effect on the total runoff collected in the whole winter season (Fig. 5). The rainfall depth registered in this 1st storm was 16 mm precipitated over 24 h, which was not enough to produce large amounts of runoff. The following eleven-day drying period after this rainstorm allowed the PAM molecules to penetrate into the soil and adsorb to soil particles, eliminating the negative effect of PAM dissolution on runoff viscosity but reducing soil loss.

Our results differ from those of Prats et al. (2014), which applied a similar granular polymer at a rate of 50 kg ha⁻¹ to a sandy loam soil after a forest fire in Portugal. A layer of ash on the soil surface was reported in their experiments, which could lead to an increase of electrolyte concentration in the runoff and soil solution, or interact with PAM molecules directly, decreasing the effectiveness of the polymer. Further work is necessary to clarify how a source of electrolytes, like ash on the soil surface, could modify the effect of PAM on soil loss.

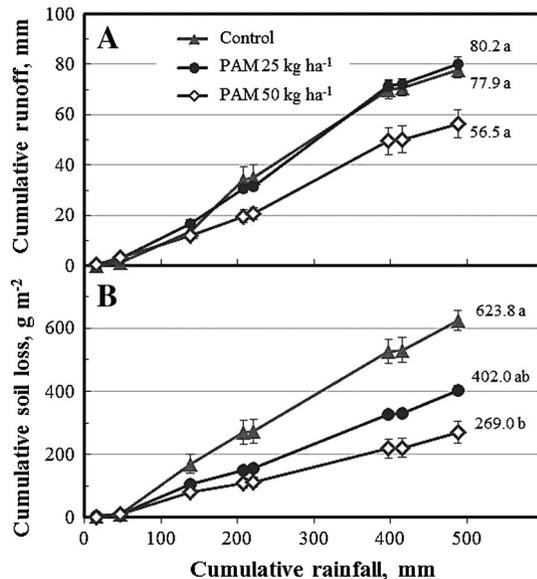


Fig. 5. Cumulative runoff (A) and soil loss (B) collected in the field experiments with different PAM treatments. Bars indicate standard error. Different lower case letters within each parameter indicate significant differences between treatments.

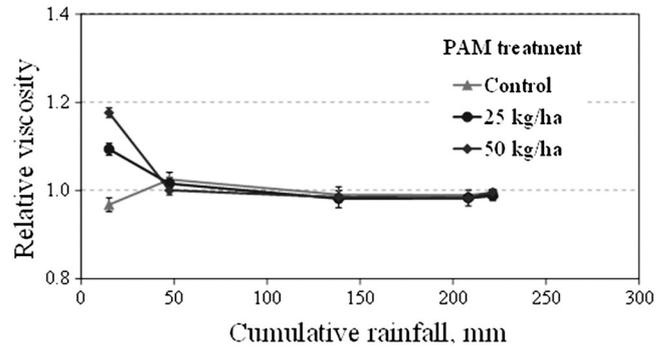


Fig. 6. Relative viscosity of the runoff collected in the field experiments after the different PAM treatments.

In light of these results, two are the main aspects that need further investigation.

1. The effectiveness of PAM to reduce soil erosion when ash is present on the soil surface. Being a source of electrolytes, ash could modify the conformation of dissolved PAM molecules and consequently the viscosities of runoff and soil solution. Moreover, PAM could bind to ash particles (Prats et al., 2014), reducing its penetration on the soil surface and therefore altering its capability to bridge soil particles and to reduce soil erosion.
2. The increase of runoff during the first storm after the application of PAM could have implications on the hydrological response at catchment scale. Large scale experiments are needed to validate the results from the present work, obtained in the laboratory and small erosion field plots, at catchment scale.

4. Conclusions

In the present study, we tested the effect of adding granular PAM to the soil surface to reduce post-fire soil erosion. Laboratory rainfall simulations and field erosion studies in which granular PAM was added to the surface of fire-affected soils and exposed to several consecutive storms suggest the following.

1. The application of granular PAM to the soil surface is a promising and cheap method to reduce post-fire soil erosion in soils with different properties.
2. Wetting the soil with a relatively low rainfall amount and intensity after the application of PAM helps to maximize the effect of the PAM on soil loss throughout the rainy season.
3. The polymer efficiency increases after a drying cycle, when PAM adsorption onto soil particles becomes stronger.

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