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# Using polyacrylamide to mitigate post-fire soil erosion

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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 Birya 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.



## 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

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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 $18 \times 10^6$ 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 Birya 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 Birya (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 Birya forest is located in Northern Israel (32° 59′ 52″N, 35° 30′ 27E), 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° 43′ 39″N, 8° 54′ 22″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 overlaying litter or ash layer. In Birya, 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 220–300 °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 mm) were packed in perforated trays measuring 0.30 × 0.50 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