Geoenvironmental Impacts of Post-Wildfire Hillslope Stabilization with Xanthan Gum and Polyacrylamide

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ABSTRACT

Wildfire-burnt hillslopes are vulnerable to erosion, precipitation-induced landslides, and debris flows. Xanthan gum (XG) and polyacrylamide (PAM) were recently shown as attractive alternatives for controlling surface erosion. However, their mobility on the hillslopes or effects on downstream waters are unknown. This study showed that after three wet-dry cycles, vertical movement of XG and PAM into the soil with rainfall is possible. Controlled water quality experiments showed that XG could have negative impacts on acidity and turbidity if its concentration in water is 0.25% or higher. Both additives showed potential concerns related to total nitrogen at concentrations of 0.25% (XG), 0.1% (PAM), and higher. Further, even at the lowest concentration (0.01%), both increased the total organic carbon concentration, which can be problematic for water treatment and control of toxic disinfection byproduct formation. However, further research is needed as the benefits of controlling post-fire erosion may overcome the water quality degradation from XG and PAM seen in controlled experiments.

INTRODUCTION

In recent decades, the magnitude and frequency of wildfires have been continuously increasing in the western regions of the United States (Westerling 2016, Dennison et al. 2014). These wildfire events are more frequent in summer in Washington State and Idaho and are typically followed by rainfall and snow (Westerling et al. 2006). After a wildfire, hillslopes are prone to precipitation-induced shallow landslides, runoff-dominated surface erosion, and debris flows (Cannon et al. 2003, Staley et al. 2017, Robichaud et al. 2013, Wagenbrenner et al. 2006, Robichaud 2005). Therefore, in addition to immediate catastrophic consequences such as loss of life, property, and habitat, wildfires can have cascading effects on the environment, economy, and ecosystems.

Eroded sediment may clog culverts and cause flooding of roads, resulting in road closures and partial or complete collapse of the transportation system. Furthermore, increased sediment load in streams can have a detrimental effect on aquatic life. For instance, research has shown that the clogging of interstitial spaces of stream soil in the Pacific Northwest region increases salmon mortality rate and reduces salmon growth rate and immunity against diseases (Smith and Caldwell 2001, Newcombe and MacDonald 1991). Therefore, it is imperative to stabilize the wildfire-burnt slopes in critical locations to control post-wildfire erosion and prevent slope stability issues.

The most widely used methods to control soil erosion are mulching and seeding for vegetation regrowth (Robichaud et al. 2013, Peppin et al. 2011). Mulching includes application of wheat and rice straws, wood shreds, wood strands, tackifiers, suspension agents, and seeds (hydromulch) to critical slopes (Riechers et al. 2008, Robichaud et al. 2013, Wohlgemuth et al. 2011). Although widely used, mulching can cause environmental concerns primarily related to invasive plant species. Therefore, there is a need to investigate alternative techniques for surficial soil stabilization that does not significantly impact the ecosystem.

Recent studies have found that additives such as xanthan gum (XG) and polyacrylamide (PAM) can be effective for various geotechnical applications, including soil stabilization, anti-desertification, and erosion control (Chang et al. 2016, Cabalar and Canakci 2011, Lentz and Sojka 1994, Lee at el. 2017, Akin et al. 2021). However, the effects of PAM and XG on water quality has not been studied thoroughly. Both PAM and XG may infiltrate into soil and come in contact with the groundwater or may be transported with runoff and enter downstream water bodies, potentially altering water quality.

This study investigates the rainfall-induced transport of XG and PAM used for erosion control of wildfire-burnt soil collected after the 2018 Mesa Wildfire and evaluates the potential impact of these additives on water quality. Indoor rainfall experiments were conducted on wildfire-burnt soil treated with XG or PAM. Three wet-dry cycles were simulated. Total soil loss and runoff were reported after three wetting events. Direct shear tests were used to evaluate the possible infiltration of XG or PAM into soil. Both PAM and XG were shown to increase soil strength measured with direct shear tests (e.g., Amiri et al. 2019, Wang et al. 2019, Cabalar and Canakci 2011). An increase in normal stress-shear stress relationship measured with the direct shear test would be an indication of PAM or XG infiltration into soil. Therefore, soil samples were cored after the third drying event to run direct shear tests. Controlled water quality experiments were conducted to assess the influence of XG and PAM on water quality at various concentrations.

MATERIALS AND METHODS

Study site and sample collection

The Mesa Wildfire started in the Payette National Forest on 26 July 2018 and was contained on 25 August 2018. The fire burned 14,000 ha of forest and rangelands of which, 450 ha was classified as high soil burn severity area (USDA Forest Service 2018). Bulk soil samples were obtained from the surface (0-~10 cm depth) of a 200 m^2 of high burn severity area. The collected soil was passed through a 1.27-cm diameter custom-made sieve in the field before being transported to the laboratory, passed through a 0.63-cm diameter sieve, and used in the rainfall simulation experiments and determination of soil properties (Table 1).

Soil additives

A biopolymer (xanthan gum from Sigma-Aldrich, CAS 11138-66-2, St. Louis, MO) and a polymer (polyacrylamide, FLOBOND™ A 30, SNF Inc, Riceboro, GA) were used as soil additives.

Table 1: Properties of 2018 Mesa fire-burnt soil

Gravel	3%	Liquid Limit	53%
Sand	34%	Plasticity Index	11%
Silt	48%	Specific Gravity	2.6
Clay	15%	USCS Classification	MH

Rainfall simulation experiments

The rainfall simulation experiments were conducted on the wildfire-burnt soil as described in Akin et al. (2021). Soil was compacted in custom-made plots (Pannkuk and Robichaud 2003) having a length and width of 68.5 cm, front and rear depth of 7 cm and 15 cm, respectively. The soil was compacted to a target void ratio of 2.1 and water content of 10% to simulate the field conditions. To each plot, 2.8 g (~60 kg/ha) of powdered XG or PAM were uniformly sprinkled on the compacted soil surface. The plots were inclined at 30° angle during wetting (Fig. 1a) and were placed horizontally during drying (Fig. 1b). Wetting and drying events were alternately applied using a modified Purdue-type rainfall simulator (Meyer 1995) and two 5700-watt ultraviolet (UV) light sources, respectively. At the end of each wetting and drying event, disc shaped samples were cored from three different locations in the rainfall plots: upslope, midslope, and downslope to determine changes in the void ratio.

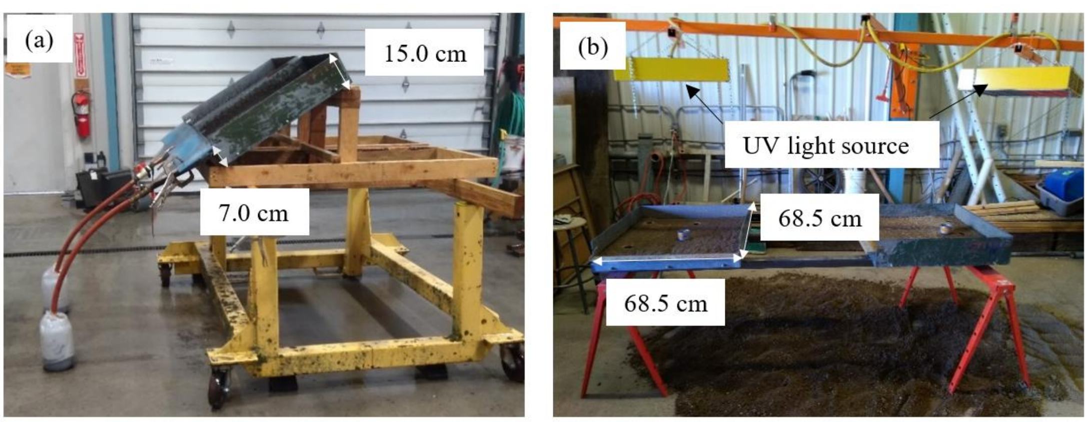

Fig. 1: Rainfall simulation experimental setup during (a) wetting and (b) drying

Direct shear testing

6.35 cm-diameter, 2.55 cm-height soil samples were cored from the plots from three locations (upslope, midslope, downslope) at the end of the third drying event. The normal stress was maintained as 25 kPa, 50 kPa, and 100 kPa for the upslope, midslope, and downslope samples, respectively. A displacement rate of 0.5 mm/min was maintained during the direct shear tests. The applied normal stresses are greater than what surface soil would experience in the field and selected only to demonstrate the effect of XG gum or PAM on normal stress-shear stress relationship. A deviation in normal stress-shear stress relationship of soil reflects the presence of PAM or XG (e.g., Amiri et al. 2019, Wang et al. 2019).

Loss on ignition

Loss on ignition (LOI) tests were run to determine the additive concentration in soil after the third wetting event. After the direct shear test, three subsamples were collected from each core sample. The subsamples were first dried at 105°C for 12 h to 16 h to remove water, weighed, placed in a high temperature furnace (550°C) for 4 h, and weighed again as described by Scalia et al. (2014). The mass difference gave the organic content, which includes the soil organic matter and XG or PAM.

Water quality experiments

Controlled water quality experiments were performed to evaluate the influence of various concentrations (i.e., 0.01%, 0.03%, 0.1%, 0.25%, and 0.5%) of XG and PAM on pH, turbidity, total nitrogen (TN), and total organic carbon (TOC). The additive concentrations of 0.01% and 0.03% were selected to represent the scenario where the entire mass of additive that was added to the soil (i.e., 2.8 g) was washed off with runoff at the end of three wetting events and at the end of the first wetting event, respectively. The highest concentration of 0.5% was selected as an extreme to test a worst-case scenario and 0.10% and 0.25% were selected as intermediate concentrations. Powdered XG and PAM were added to ultrapure water and mixed for 16 h to 24 h using a magnetic stirrer. Following mixing, samples were analyzed in triplicate for the abovementioned water quality parameters. A controlled sample of ultrapure water was also included for comparison. Standard method 4500-H was used to measure the pH. Turbidity was measured using HACH 2100N Turbidimeter, and TOC and TN were measured using a Shimadzu TOC L CSH analyzer with total nitrogen module.

RESULTS AND DISCUSSION

Runoff and soil loss

The initial 5 min of the first wetting event did not result in any runoff until the rainfall saturated the soil (Fig. 2a). For the untreated soil, runoff started at ~20 min and increased thereof, whereas, both XG and PAM treatment resulted in the runoff starting earlier (after 5 min of rainfall for XG and after 10 min of rainfall for PAM treatments). At the end of the three wetting events, XG and PAM increased the total runoff by ~12% and ~4%, respectively, indicating that both treatments cause a slight decrease in infiltration but neither seals the soil surface entirely (Fig. 2a).

The first wetting event on the untreated soil did not cause any soil loss for ~20 min, after which, the soil loss increased exponentially. The second wetting event commenced soil loss immediately. The rate of soil loss doubled after 5 min and remained the same throughout the second wetting event. The third wetting event did not cause significant soil loss for the first 10 min, but the soil loss increased linearly after 15 min (Fig. 2b).

For both XG- and PAM-treated soil, minimal soil loss (< 10 g) was observed during the first 5 min for all wetting events. The first wetting event caused ~20 g of soil loss after 10 min for both XG and PAM, after which it remained constant. An increase in soil loss with time was observed during second and third wetting events (Fig. 2b). The third wetting event resulted in greater soil loss compared to the second wetting event (2.3 times more for PAM and 1.9 times more for XG). This increase in soil loss was attributed to the loss of particle binding upon wetting (Lee et al. 2017) or soil additives getting washed with the runoff. The total soil loss due to the first, second, and third wetting events combined was 2365 g for untreated soil, 850 g for XG-treated soil, and 345 g for PAM-treated soil.

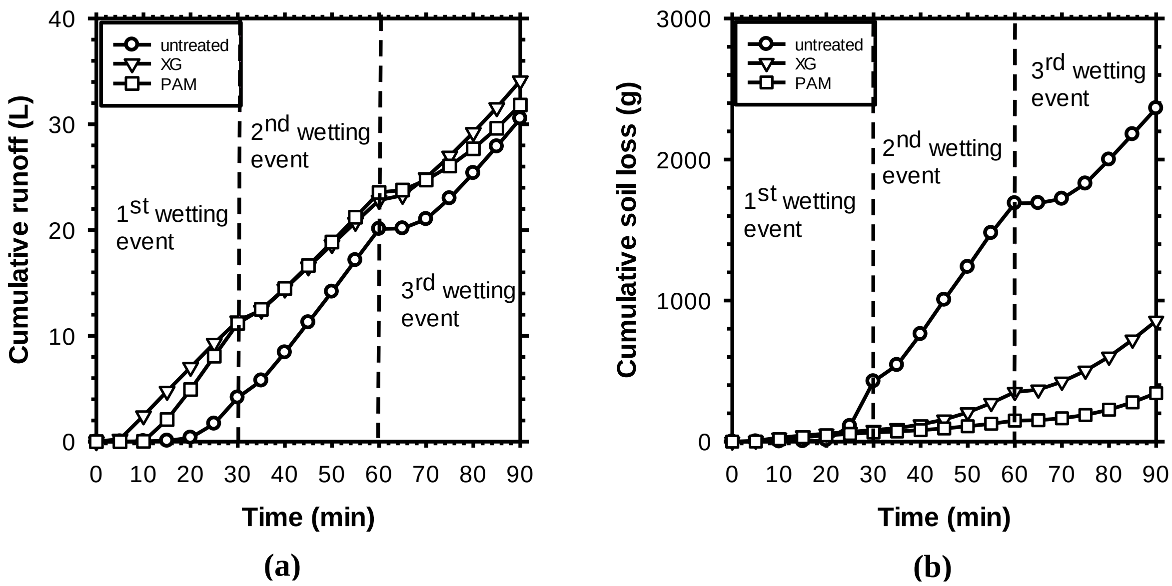

Fig. 2: (a) Cumulative runoff and (b) cumulative soil loss for untreated, XG-, and PAM-treated soil

Influence of XG and PAM on shear stress-normal stress relationship and evidence for vertical mobility

After the three rainfall events, the void ratio of all the untreated samples was within 0.1 of the initial void ratio (2.1), indicating negligible soil volume change upon wetting and drying. However, for the XG and PAM treated soil, an increase in the void ratio was observed with a maximum of 2.5 for the downslope PAM samples. The increase in void ratio was attributed to swelling of polymers upon hydration (Zhou et al. 2020).

A linear Mohr-Coulomb failure envelope was obtained for the untreated samples with cohesion of 13.8 kPa and friction angle of 32.1°, whereas the treated samples showed non-linear failure envelopes (Fig. 3a). The non-linearity was attributed to reflect the effect of XG or PAM on normal stress-shear stress relationship. XG and PAM are mobile and can migrate vertically into the soil by rainfall or can move downslope by runoff. Addition of XG or PAM in soil alters soil strength (Khatami et al. 2013, Jang 2020).

The vertical mobility of XG and PAM was also reflected in LOI results (Fig. 3b). LOI for untreated soil ranged from 11.2% to 12.3%, while for treated soils the range was between 13.0% and 15.0%. The LOI for the treated soils was greater than that for the untreated soil, indicating the presence of an additional organic material in the treated soils. No trend was observed between the LOI and sample locations that might indicate the downslope movement of the additives with runoff. However, in all three locations, XG showed the highest LOI, followed by PAM, and untreated soil, reflecting vertical movement of additives, with XG showing the maximum infiltration.

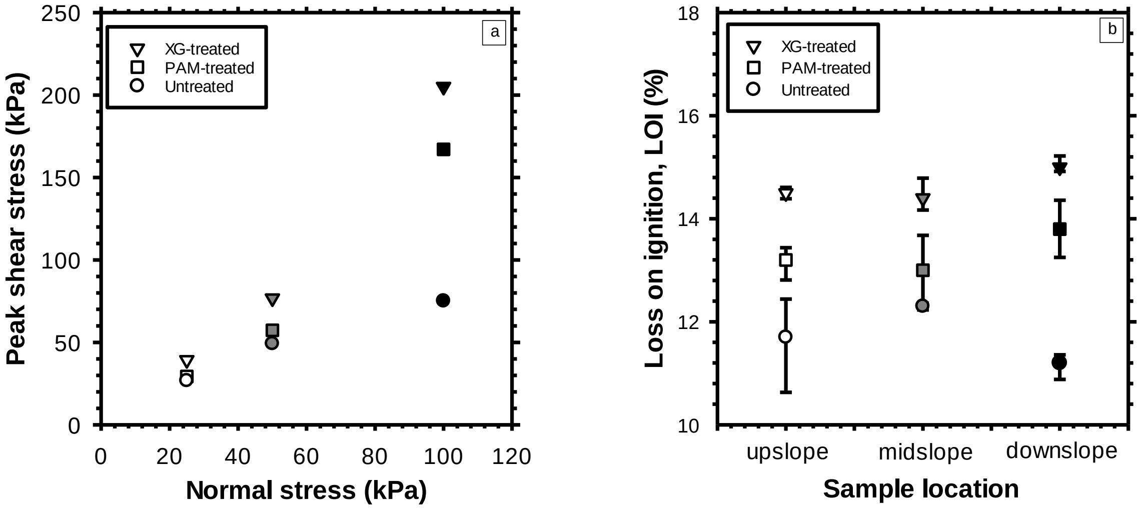

Fig. 3: (a) Normal stress-shear stress relationship and (b) LOI with sample locations white: upslope, gray: midslope, black: downslope

Influence of XG and PAM on water quality

The addition of XG to water resulted in a decrease in pH (Fig. 4a). While PAM only had a marginal effect on the pH at all concentrations, XG reduced the pH of the control water from 7.4 to 6.1 (at 0.25% and 0.5% concentration), which is outside the pH 6.5-9 safe limit for aquatic life (US EPA 2000). The pH was within the safe limit for XG concentrations of 0.10%, and lower and for all tested concentrations of PAM.

Both XG and PAM increased the turbidity of water (Fig. 4b). Turbidity was 5.6 NTU (for 0.5% PAM), 14.5 NTU (for 0.10% XG), 28.7 NTU (for 0.25% XG) and 43.9 NTU (for 0.5% XG). At 0.01% and 0.03% concentration, XG and PAM showed a smaller increase in turbidity (1.5 NTU for 0.01% XG, 4 NTU for 0.03% XG, 0.2 NTU for 0.01% PAM, and 0.9 NTU for 0.03% PAM). Similar results were observed for the 0.1% PAM mixture (1.3 NTU) and 0.25% PAM mixture (1.4 NTU). Depending on the ecoregion, EPA criteria for turbidity in river and stream water for aquatic life ranges between 1.3-17.5 NTU (US EPA 2000). Results show that at high concentrations (0.25% and 0.5%), XG increased the turbidity in water above 17.5 NTU. For PAM, turbidity was within the EPA recommended limits even at the highest concentration, however stream waters will contain background turbidity from natural sources of particles.

TOC (Fig. 4c) was 36 mg/L (in 0.01% PAM mixture), 120 mg/L (in 0.03% PAM mixture), 720 mg/L (in 0.10% PAM mixture), 1440 mg/L (in 0.25% PAM mixture), and 2175 mg/L (in 0.5% PAM mixture). Similarly, for 0.01%, 0.03%, 0.10%, 0.25% and 0.5% XG solution, TOC was 28 mg/L, 83 mg/L, 276 mg/L, 664 mg/L, and 1319 mg/L, respectively. While the EPA does not have recommended limits of TOC for aquatic life, TOC is a key variable for drinking water treatment process design and control of toxic disinfection byproduct (DBP) formation (USEPA 2010).

A high concentration of TN was measured in PAM mixture (203 mg/L in 0.10%, 405 mg/L in 0.25% and 611 mg/L in 0.5% mixture, Fig. 4d). The high nitrogen concentration was attributed to the presence of nitrogen in PAM (structure of PAM is $(C_3H_5NO)_n$), which dissolved in solution. For XG, TN concentration was 0.13 mg/L for 0.01%, 0.39 mg/L for 0.03%, 1.30 mg/L for 0.10%, 3.5 mg/L for 0.25%, and 8 mg/L for 0.50% mixture. According to EPA criteria for rivers and streams for aquatic life, the recommended concentration of TN ranges from 0.12 mg/L to 2.18 mg/L depending on the ecoregion (US EPA 2000). At XG and PAM concentrations greater than, or equal to 0.25% and 0.1%, respectively, TN was above 2.18 mg/L. In addition, nitrogen can cause challenges during drinking water treatment and lead to the formation of nitrogen based DBPs (Liew 2016).

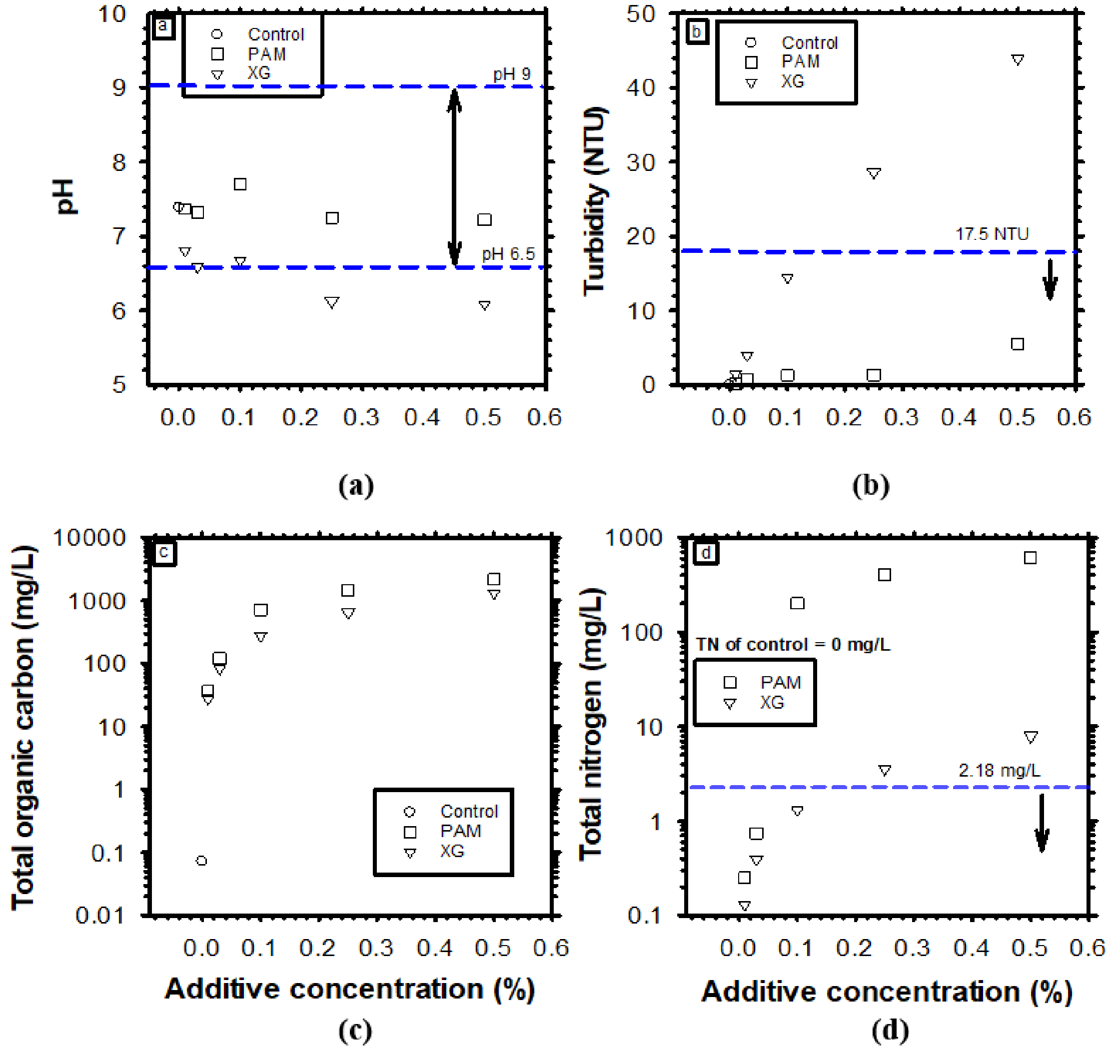

Fig. 4: Effect of additives on water quality and EPA recommended ranges (US EPA 2000) for aquatic life (shown with dashed lines and arrows); a) pH, b) turbidity, c) TOC, and d) TN. Turbidity and TN safe limits vary based on the region; dashed lines show the recommended concentrations for ecoregion 6 (TN) and 10 (turbidity), which have the maximum upper limits

The results showed that at 0.25% or higher concentrations in water, XG increased the acidity and turbidity of water above the recommended limits for aquatic life. For all concentrations of PAM, pH and turbidity of water were within the recommended limits. Further, even at the lowest concentration (i.e., 0.01%), both XG and PAM increased TOC in water considerably. Moreover, TN was above the EPA recommendation when the concentrations of XG and PAM were equal to, or higher than 0.25% and 0.1%, respectively. High concentrations of TOC and TN in the downstream waters due to the transportation of XG or PAM with the runoff could potentially lead to water quality challenges for aquatic life and drinking water supplies (Liew 2016, Kritzberg et al. 2020). However, further research is needed to investigate the actual mass of additives mobilized to aquatic systems to better assess the applicability of the lab-based findings to field-application of additives. Moreover, the water quality benefits of stabilizing burnt slopes and mitigating post-fire erosion may prove more significant than the potential degradation in water quality from polymer treatments.

SUMMARY AND CONCLUSIONS

Surficial soil collected after the 2018 Mesa Wildfire was subjected to three wetting and drying events. Direct shear and LOI tests were performed to evaluate the migration of XG and PAM into the soil and the effects of XG and PAM on water quality were assessed. The results showed that both XG and PAM significantly (i.e., 64% for XG and 85% for PAM) reduced the soil loss without sealing the soil surface completely. Direct shear experiments showed higher shear strengths and nonlinear failure envelopes for the XG- and PAM-treated soils as compared to the untreated soil. This was attributed to the vertical movement of XG and PAM into the soil with rainfall, which was also supported by LOI. Acidity and turbidity in water increased above the EPA recommended limits for aquatic life when the concentration of XG was 0.25%, or higher. TN concentration increased significantly on addition of ~0.25% XG and ~0.1% PAM, or higher. Further, even at small concentrations in water (~0.01%), both XG and PAM increased the total organic carbon concentrations to levels that could cause challenges for drinking water treatment facilities.

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REFERENCES

Akin, I. D., Garnica, S. S., Robichaud, P. R., and Brown, R. E. (2021). Surficial stabilization of wildfire-burnt hillslopes using xanthan gum and polyacrylamide. *Geotechnical and Geological Engineering*.

Amiri, E., and Emami, H. (2019). Shear strength of an unsaturated loam soil as affected by vetiver and polyacrylamide. *Soil and Tillage Research*, 194 (July), 104331.

Cabalar, A. F., and Canakci, H. (2011). Direct shear tests on sand treated with xanthan gum. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, 164(2), 57–64.

Cannon, S. H., Gartner, J. E., Parrett, C., and Parise, M. (2003). Wildfire-related debris flow generation through episodic progressive sediment bulking processes, Western USA,

Proceedings of 3rd international conference, "Debris-flow hazards mitigation—mechanics, prediction, and assessment," Davos, Switzerland, pp. 71–82.
Chang, I., Im, J., and Cho, G. C. (2016). Introduction of Microbial Biopolymers in Soil Treatment for Future Environmentally-Friendly and Sustainable Geotechnical Engineering. *Sustainability*.
Dennison, P. E., Brewer, S. C., Arnold, J. D., and Moritz, M. A. (2014). Large wildfire trends in the western United States, 1984-2011, *Geophysical Research Letters*, 41: 2928-2933.
Jang, J. (2020). A review of the application of biopolymers on geotechnical engineering and the strengthening mechanisms between typical biopolymers and soils. *Journal*?.
Khatami, H. R., and O'Kelly, B. C. (2013). Improving mechanical properties of sand using biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(8), 1402–1406.
Kritzberg, E. S., Hasselquist, E. M., Škerlep, M., Löfgren, S., Olsson, O., Stadmark, J., Valinia, S., Hansson, L. A., and Laudon, H. (2020). Browning of freshwaters: Consequences to ecosystem services, underlying drivers, and potential mitigation measures. In *Ambio* (Vol. 49, Issue 2, pp. 375–390).
Lee, S., Chang, I., Chung, M. K., Kim, Y., and Kee, J. (2017). Geotechnical shear behavior of xanthan gum biopolymer treated sand from direct shear testing. *Geomechanics and Engineering*, 12(5), 831–847.
Lentz, R. D., and Sojka, R. E. (1994). Field results using polyacrylamide to manage furrow erosion and infiltration, *Soil Science*, 158(4): 274-282.
Liew, D., Linge, K. L., and Joll, C. A. (2016). Formation of nitrogenous disinfection by-products in 10 chlorinated and chloraminated drinking water supply systems. In *Environmental Monitoring and Assessment* (Vol. 188, Issue 9).
Meyer, L. D. (1995). Rainfall simulators for soil erosion research, in *Soil Erosion Research Methods*, edited by R. Lal, pp. 83–105, Soil and Water Conserv. Soc., Ankeny, Iowa.
Newcombe, C. P., and MacDonald, D. D. (1991). Effects of Suspended Sediments on Aquatic Ecosystems, *North American Journal of Fisheries Management*, 11: 72-82.
Pannkuk, C. D., and Robichaud, P. R. (2003). Effectiveness of needle cast at reducing erosion after forest fires, *Water Resources Research*, 39(12): 1333.
Peppin, D. L., Fule, P. Z., Sieg, C. H., Beyers, J. L., Hunter, M. E., and Robichaud, P. R. (2011). Recent trends in post-wildfire seeding in western US forests: costs and seed mixes, *International Journal of Wildland Fire*, 20: 702-708.
Riechers, G. H., Beyers, J. L., Robichaud, P. R., Jennings, K., Kreutz, E., and Moll, J. (2008). Effects of three mulch treatments on initial postfire erosion in North-Central Arizona, Gen. Tech. Rep. PSW-GTR-189. Albany, CA: US Department of Agriculture Forest Service, Pacific Southwest Research Station. pp.107-113.
Robichaud, P. R. (2005). Measurement of post-fire hillslope erosion to evaluate and model rehabilitation treatment effectiveness and recovery, *International Journal of Wildland Fire*, 14(4): 475-485.
Robichaud, P. R., and Ashmun, L. E. (2013). "Tools to aid post-wildfire assessment and erosion-mitigation treatment decisions," *International Journal of Wildland Fire*, 22: 95-105.
Robichaud, P. R., Lewis, S. A., Wagenbrenner, J. W., Ashmun, L. E., and Brown, R. E. (2013). Post-fire mulching for runoff and erosion mitigation part I: Effectiveness at reducing hillslope erosion rates, *Catena*, 105: 75-92.

Scalia, J., IV, Benson, C. H., Bohnhoff, G. L., Edil, T. B., and Shackelford, C. D. (2014). "Long-term hydraulic conductivity of a bentonite-polymer composite permeated with aggressive inorganic solutions." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0001040, 140(3), 04013025.
Smith, C. J., and Caldwell, J. (2001). Salmon and steelhead habitat limiting factors in the Washington coastal streams of WRIA 21," Water Resources Inventory Area 21 Final report, Washington State Conservation Commission, 300 Desmond Drive, Lacey, WA 98503.
Staley, D. M., Negri, J. A., Kean, J. W., Laber, J. M., Tillery, A. C., and Youberg, A. M. (2017). Prediction of spatially explicit rainfall intensity-duration thresholds for post-fire debris flow generation in the western United States. *Geomorphology* 278: 149-162.
USEPA. (2000). Ambient Water Quality Criteria Recommendations of State and Tribal Nutrient Criteria Rivers and Streams in Nutrient Ecoregion I. US Environmental Protection Agency EPA 822-B-00-016, December, 70.
USEPA. (2010). Comprehensive Disinfectants and Disinfection Byproducts Rules (Stage 1 and Stage 2): Quick Reference Guide. U. S. Environmental Protection Agency, 816-F, 4. http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100C8XW.txt.
USDA Forest Service. (2018). *Burned Area Report of the 2018 Mesa Fire*, US Department of Agriculture, Forest Service, Payette National Forest, McCall, ID. 15 p.
Wagenbrenner, J. W., MacDonald, L. H., and Rough, D. (2006). Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range, *Hydrological Processes*, 20: 2989-3006.
Wang, H., She, D., Fei, Y., and Tang, S. (2019). Synergic effects of biochar and polyacrylamide amendments on the mechanical properties of silt loam soil under coastal reclamation in China. *Catena*.
Westerling, A. L., Hidalgo, H. G., Cayan, D. R., and Swetnam, T. W. (2006). Warming and earlier spring increase Western U.S. forest wildfire activity. *Science Journal*????vb400, 1054.
Westerling, A. L. (2016). Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring, *Philosophical Transactions of the Royal Society B*, 371: 20150178.
Wohlgemuth, P. M., Beyers, J. L., and Robichaud, P. R. (2011). The effectiveness of aerial hydromulch as an erosion control treatment in burned chaparral watersheds, Southern California, *The Fourth Interagency Conference on Research in the Watersheds*. 26-30 September 2011, Fairbanks, AK. 6 p.
Zhou, C., So, P. S., and Chen, X. W. (2020). A water retention model considering biopolymer-soil interactions. *Journal of Hydrology*, 586, 124874.