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RESEARCH ARTICLES

Evaluating the Recovery of Hydraulic Conductivity in Fire-Affected Soils

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In the natural environment, wildfires affect how water interacts with soil leading to potentially catastrophic phenomena such as flooding, debris flows, and decreased water quality. Wildfires can cause soil sealing from increased soil water repellency, which in turn reduces infiltration and increases flood risk during rainfall. A 2017 meta-analysis found two properties that were affected by soil burning processes: Sorptivity (the capacity of a soil to absorb or desorb liquid by capillarity, S) and hydraulic conductivity (the ability for soil to transmit water when saturated, Kfs). Changes in these properties act synergistically to reduce infiltration, which increases erosion by accelerating and amplifying surface runoff. Thus, this research seeks to understand how soils subjected to severe burning compare to unburned soils. Using a mini-disk infiltrometer, field tests measured hydraulic conductivity of soils burned under slash and burn piles during the winters of 2016-17, 2020-21, and 2023-23 to better understand changes that occur in soil-hydraulic properties over time. These slash and burn piles served as approximate impacts for wildfires. Slash and burn piles also allow for paired measurements of unburned soils immediately adjacent to the burned area. Hydraulic conductivity was not significantly different when comparing burned and unburned soils 1 year after being burned. However, there was a significant difference between the hydraulic conductivity of soils burned 3 years ago compared to both unburned soil and soils burned 1 year ago. This suggests an interim process between 1- and 3-years post-burn that reduces hydraulic conductivity of burned soils.

Wildfires are widely regarded as a principal agent of soil erosion and land degradation, causing dangerous debris flows, damage to water quality infrastructure, and risk to human life (Vieira et al., 2015). Between 1998 and 2017, debris flows took the lives of more than 18,000 people worldwide—25 to 50 of those people were killed in the United States annually (Oreskes, 2023). Wildfires alter the hydrology of forests by removing its canopy and litter/duff layers, reducing organic content in soil, creating ash that is deposited on top of the soil, and changing the physical and hydraulic properties of the soil (Ebel et al., 2012). These effects cause wildfire-induced soil water repellency which reduces the affinity of soils to infiltrate water such that they resist wetting periods ranging from days to years (Doerr et al., 2000; Ebel & Moody, 2017).

a Faculty mentor

Of primary concern in recent research is the reduced infiltration capacity of wildfire-affected regions (Doerr et al., 2000). Infiltration is the downward entry of water from precipitation into soil, which is dependent on soil texture and minerology, existing soil-water content, and organic matter makeup. The gravity component of infiltration is controlled by hydraulic conductivity (K_{fs}) — a fundamental property when applying Richards equation, derived by Lorenzo A. Richards in 1931 (Moody et al., 2013; Richards, 1931). It combines the effects of several physical characteristic into a single property, making it a "lumped parameter."

Researchers generally characterize reduced infiltration into soils as a primary reason for debris flows and increased runoff in fire-affected areas. For instance, Zheng et al. (2017) found wildfire induced soil water repellency alters hydrological responses and vadose zone processes of hillslopes, causing a range of processes like unstable wetting fronts, preferential flow, restricted soil-water movement, decreased rate of infiltration, and increased surface runoff. Additional studies illustrate that these effects on the soil matrix increase the likelihood of post-wildfire debris flows and consequent flash floods through overland flow and erodibility (Doerr et al., 2000; Huffman et al., 2001).

Wildfires substantially reduced K_{fs} in burned soil compared to unburned soil by two orders of magnitude (Ebel et al., 2012). Burned soils in this study exhibited an essentially impermeable layer of soil. However, a critical gap in knowledge concerning post-wildfire hydrology research exists regarding the recovery of wildfire-affected soils. Ebel & Martin (2017) generated preliminary results showing soil hydraulic properties do recover over time; however it remains uncertain whether those properties recover at a linear, logarithmic, or exponential rate. Their meta-analysis used data from various studies that collected K_{fs} in a specific region across various years. However, these datasets did not include measurements from immediately post-wildfire to three-years-post-wildfire, possibly excluding an important time-period where K_{fs} recovery occurs.

Therefore, this study aims to better understand the hydraulic changes that soils undergo immediately post-fire by up to 6 years. Using multiple slash and burn piles burned 1-year, 3-years, and 6-years ago, K_{fs} was compared between soil subject to burn and unburned soil immediately outside the burn piles. Slash and burn piles are a form of fire mitigation which keeps forests healthy by cutting low hanging and dead limbs to effectivity "thin" the forest, then burning them in large piles along with leaves, needles, and other deposits (see Figure 1). The slash and burn piles analyzed in this study served as an approximate condition for wildfire affected soils.

Figure 1. Slash piles being burned during the 2022-2023 winter.

Courtesy of Dr. Glen Liston.

Methods

Study Area

This study took place on private property near Horsetooth Mountain in Northern Colorado. The study site is primarily composed of the Fort Collins-Harlan complex based on data provided by the National Resource Conservation Service's Web Soil Survey. The typical profile for this soil is: *A* – 0 to 10 inches, loam; *Btk* – 10 to 27 inches, clay loam; and *Bk* – 27 to 60 inches, loam.

Based on a tree ring analysis performed on a dead ponderosa pine killed by pine beetle in 2009, the last major fire to sweep through the area surrounding Horsetooth Mountain was in 1891 (David Cawrse, personal communication, 2013), meaning the soil and vegetation has not been exposed to fire for 131 years. The tree analyzed was due East, approximately 1,000 feet of the study site in Red Canyon. Only a single tree ring analysis was used because it was the closest in proximity and most recent data available for the study site.

To preserve trees if a major fire were to occur, the property owner, Dr. Glen Liston, thinned most of the trees on his property, burning the slash over the past decade. Each pile was dried for one year prior to burning and burned over the winter according to local regulations dictating they be no greater than 8 feet in diameter and 6 feet high and burned only when there is 3 inches of snow on the ground and a lack of wind (Larimer County Public Health, n.d.). We sampled 10 of these slash and burn piles: 1 burned 6 years ago over

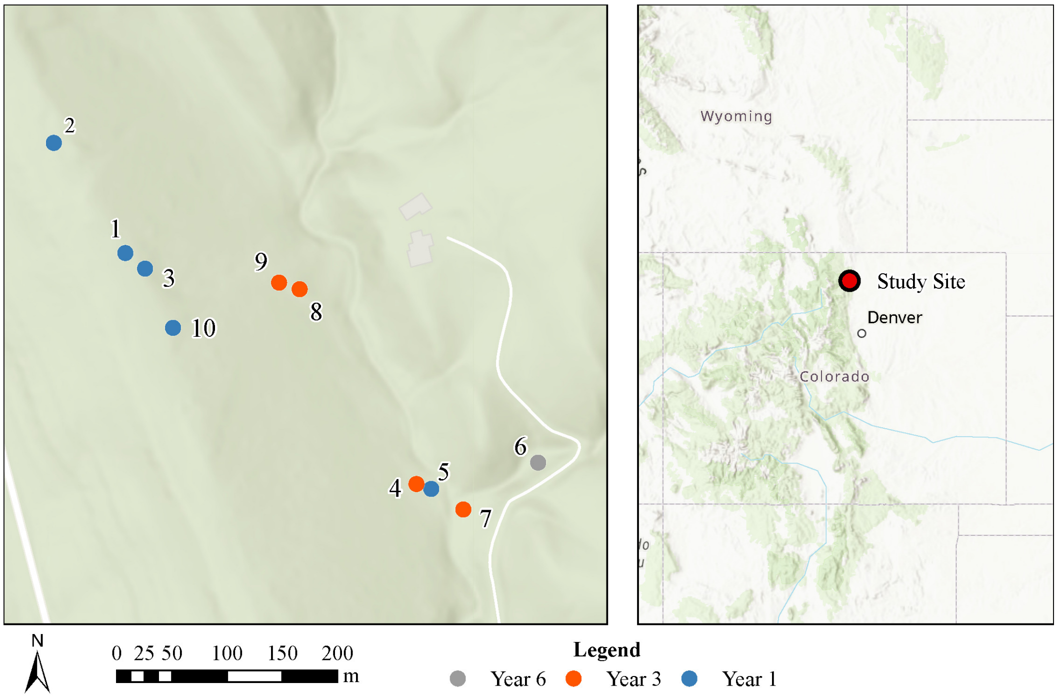

Figure 2. Study site map.

Dot color corresponds to which year each pile was burned.

the 2016-17 winter, 4 burned 3 years ago over the 2020-21 winter, and 5 burned within 1 year over the 2022-23 winter. Figure 2 shows the location of each pile and the exact date they were burned.

We dug a shallow pit in the 10th burn pile to classify the piles as low-, moderate-, or high-burn severity; the burn depth was ~1.4 cm where we measured but varied across the pile. Based on the lack of organic matter, lack of the litter and duff layers, and the burn depth, we assumed these burns were severe.

Field Measurements

For piles 1-9 we took hydraulic conductivity (K_{fs}) measurements at three locations within the burn scar area and three locations outside the burned area. These three measurements within and outside the burn pile were 0.5 m apart in a triangular pattern (Figure 3). For pile 10, we sampled 12 points within the burn scar 0.5 m apart, 12 points outside the burn scar 1 m from its edge and dug a shallow pit to investigate burn depth (Figure 4).

To collect K_{fs} data we used mini-disk infiltrometers (Meter Group, Pullman, WA) which are highly compact, tension infiltrometers ideal for field use. A main tube is separated by a water-tight seal that divides the device into a lower water reservoir and upper bubble chamber used to control the suction. The device contains a porous, stainless-steel disk at its base, which serves as the contact point with the soil. Once in contact with the soil, the mini-disk infiltrometer creates a pressure gradient, drawing water from the water reservoir into the soil.

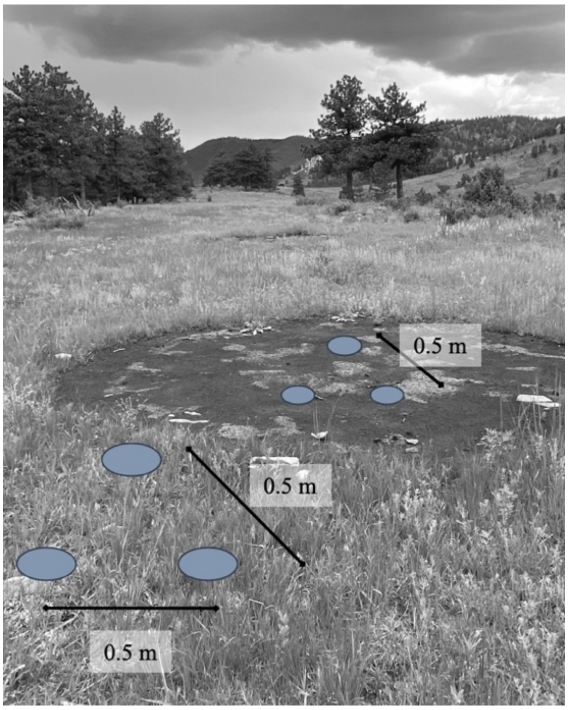

Figure 3. Sample layout for burn piles 1-9.

3 measurements were taken within the burn area 0.5 m apart, then 3 were taken outside the burn area 0.5 m apart.

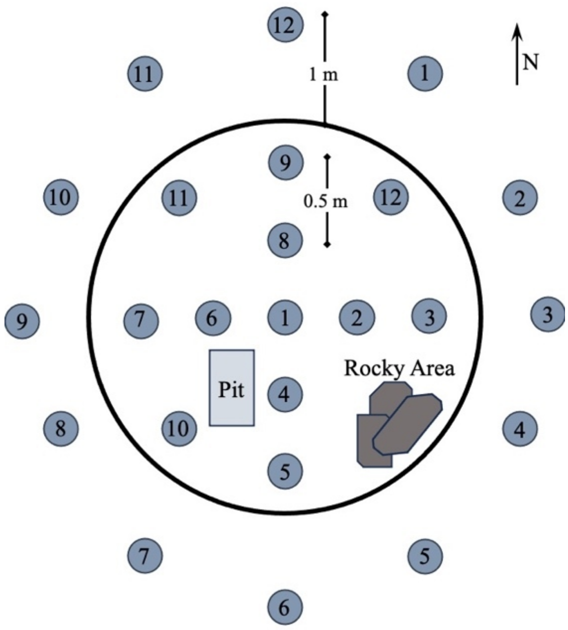

Figure 4. Sample layout for burn pile 10.

12 measurements were taken within the burn area (0.5 m apart) along with 12 outside (1 m from the edge). We dug a shallow pit in the third quadrant of the pile.

Based on initial measurements, we set the suction between -0.5 cm and -2.0 cm depending on the rate at which we expected water to infiltrate. For soils within the burn scar, we used -0.5 cm of suction, whereas we used up to

-2.0 cm of suction in unburned areas. After setting a suction, we placed the device on top of level soil and took readings of the water level in the reservoir at regular intervals for up to an hour, or until 30-40 mL of water infiltrated.

We used a flow diagram from Thien (1979) to characterize the soil by texture in the field. This analysis was performed at each burn scar, and we found the study site to be primarily loamy, which substantiates data gathered from the National Resources Conservation Service web soil survey.

Calculating Hydraulic Conductivity

A spreadsheet provided by Meter Group made calculating K_{fs} straightforward and relatively easy. We input the corresponding infiltration at regular time intervals, selected the mini-disk infiltrometer type used in the field, the soil type, soil suction, and input the radius (cm) of the porous disk.

This spreadsheet follows the model assumed by Philip (2006) to calculate K_{fs}:

$$I = C_1 t^{\frac{1}{2}} + C_2 t \tag{1}$$

where I is the cumulative infiltration rate $[L]$, t is time [T], and C_1 $[L/T^{\frac{1}{2}}]$ and C_2 $[L/T]$ are constants whose values are obtained via curve fitting. To estimate K_{fs}, Zhang (1997) developed the following relationship by using numerical methods:

$$K_{fs} = \frac{C_2}{a_2} \tag{2}$$

where

$$a_2 = \frac{11.65\left(N^{0.1} - 1\right)\exp\left[7.5\left(N - 1.9\alpha\psi_0\right)\right]}{\left(\alpha r_0\right)^{0.91}} \tag{3}$$

a_2 is a dimensionless coefficient, r_0 $[L]$ is the radius of the porous, stainless-steel disk, and ψ_0 is the pressure head of applied from the disk $[L]$ (Ronayne et al., 2012). N and α are van Genuchten moisture retention parameters based on the soil classification (Ronayne et al., 2012); for loamy soil we used 1.89 and 0.036, respectively.

For statistical analysis, we used the Wilcoxon rank-sum test to evaluate if there was a significant difference between K_{fs} in the burned soil and unburned soils. It is often considered the non-parametric version of a two-sample t-test. This test assumes the data between two samples (burned and unburned soil in this case) 1) are independent of one another, 2) have equal variance, and 3) are normally distributed. The Wilcoxon rank-sum test uses only the first two assumptions and is ideal for data sets with less than 30 observations.

Results

The average K_{fs} across all burned soils was slightly lower than unburned soils, though this difference is not significant. For soils burned ~1-year-ago, the average was $K_{fs-1Year} = 0.00103$ cm s^{-1}(n = 25). For soils burned ~3-years-ago, the average was $K_{fs-3Year} = 0.00031$ cm s^{-1} (n = 12). Soils burned ~6-years-ago had an average $K_{fs-6Year} = 0.00021$ cm s^{-1} (n = 3).

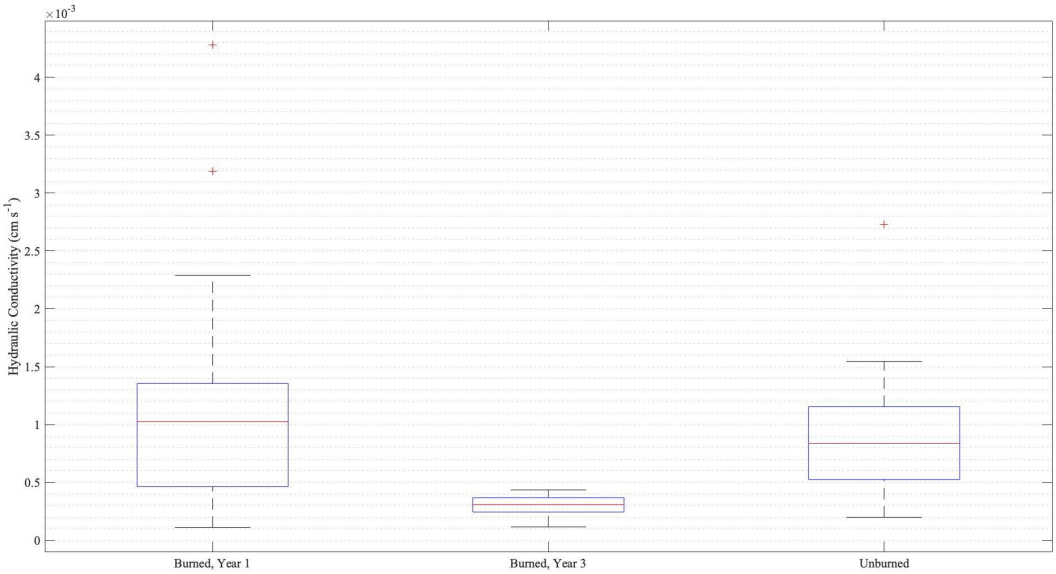

Figure 5. Box and whisker plot of data from piles burned 1-year- and 3-years-ago and all data from unburned soil. Sample sizes for each plot are: Burned Year 1, n = 25; Burned Year 3, n = 12; and Unburned, n = 33.

The average of all unburned samples collected was $K_{fs-unburned} = 0.00084$ cm s^{-1} (n = 33). Figure 5 shows a box and whisker plot of data collected from soil burned 1 year and 3 years ago as well as all data for unburned soils. Data from the pile burned 6 years ago was omitted because of a low sample size. Though there was no statistical difference between soils burned 1-year-ago and unburned soils (Wilcoxon rank sum test, $p = 0.3710$), there was a significant difference between the K_{fs} of soil burned 3-years-ago and unburned soil (Wilcoxon rank sum test, $p = 0.00005$). There was also a significant difference between the K_{fs} of piles burned 1-year-ago and 3-years-ago (Wilcoxon rank sum test, $p = 0.0008$).

There was no statistical significance between the data sampled from burned and unburned soils in Pile 10 (Wilcoxon rank sum test, $p = 0.1260$), similar to other piles. However, samples from burn pile 10 show soils subject to burn have lower variability than unburned soils. The coefficients of variation for burned and unburned soils at burn pile 10 were 0.3607 and 0.7947, respectively.

To determine how representative three sample points were, we randomly selected 3 samples of burned soils from Pile 10. We compared the standard deviation and coefficient of variability of these three randomly selected points to the standard deviation and coefficient of variably of Pile 10 as a whole and repeated this four times. The coefficient of variation for each 3-point selection was 0.57403, 0.245031, 0.286501, and 0.423770 and the standard deviations were 0.000650, 0.000269, 0.000290, and 0.000386, respectively. The coefficient of variability and standard deviation of soils subject to burn from Pile 10 fall between this set of points. Thus, the 3 samples taken for Piles 1-9 are likely not entirely representative of the whole pile.

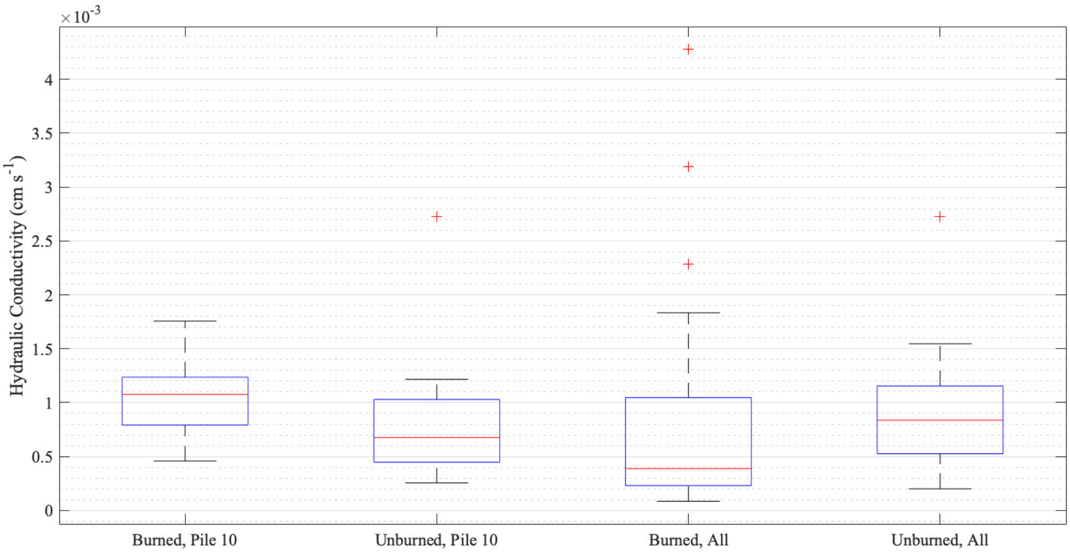

Figure 6. K_{fs} of all data for burned and unburned soil collected in the field.

The K_{fs} of burned soil was more variable and less than the K_{fs} of unburned soil across all sites, except site 10. Sample size for each plot is: Burned, Pile 10 (n = 12); Unburned, Pile 10 (n = 12); Burned, all (n = 40); and Unburned, all (n = 40).

Table 1. Summary of hydraulic conductivity including data for each burn pile and averages of all data sampled from burned and unburned soil.

	Burned, All (cm/s)	Unburned, All (cm/s)	Burned, Pile 10 (cm/s)	Unburned, Pile 10 (cm/s)	Burned, Year 1 (cm/s)	Burned, Year 3 (cm/s)	Burned, Year 6 (cm/s)
Standard Deviation	8.7E-04	4.8E-04	3.8E-04	6.7E-04	9.7E-04	9.3E-05	8.0E-05
Mean	8.2E-04	8.5E-04	1.0E-03	8.5E-04	1.1E-03	3.0E-04	1.8E-04
Median	4.5E-04	8.4E-04	1.1E-03	6.8E-04	1.0E-03	3.1E-04	2.1E-04
Mode	8.4E-05	2.0E-04	4.6E-04	2.6E-04	1.1E-04	1.2E-04	8.4E-05
Variance	7.6E-07	2.3E-07	0.0E+00	0.0E+00	9.4E-07	8.6E-09	6.4E-09
Coefficient of Variability	1.1E+00	5.6E-01	3.6E-01	7.9E-01	8.5E-01	3.1E-01	4.6E-01

Discussion

We found the K_{fs} of soil subject to burning was not significantly altered in the first year after being burned but was significantly reduced 3 years after burning. Since data from burned treatments sampled after 3 years and data sampled from unburned soil showed significant changes, whereas soil burned 1 year ago showed no significant change compared to unburned soil, our results suggest there is an underlying process that takes place between 1- and 3-years post-burn that reduces the hydraulic conductivity of the affected soil.

This differs with previous findings that K_{fs} was reduced by two orders of magnitude after being burned (Ebel et al., 2012). Ebel et al. measured K_{fs} also using a tension infiltrometer in field conditions within 1 year following wildfire. However, Ebel et al. (2012) compared burned soil data to unburned soil data over 400 meters away which makes it difficult to be certain that pre-burn conditions are being accurately measured. Our research, instead, used paired burned and unburned soil measurements 1-2 meters apart to investigate the recovery of fire affected soils. Though in a relatively similar geographic region, it may be difficult to make accurate comparisons between the K_{fs} burned and unburned soils 400 meters away because of soil variability that not only occurs on a small scale, but variability that also occurs at larger scales between plots of land (Usowicz & Lipiec, 2021; Woods et al., 2007).

Despite these findings in 2012, Ebel & Moody (2017) found K_{fs} was not substantially reduced in wildfire-affected regions, which aligns with this present study's findings; however, Ebel & Moody (2017) did not capture the 1-3 year post fire reduction in K_{fs}. One difference is the present study did not consider sorptivity (*S*), the capillary component of infiltration. Ebel & Moody (2017) found sorptivity, instead of K_{fs}, was significantly affected in burned soils. Future research may investigate both parameters to disentangle the complex interactions therein.

Our findings agree with a study conducted by Plaza-Álvarez et al. (2019) that monitored K_{fs} of a soil immediately after a prescribed fire up to 1 year following the prescribed fire. They found prescribed fires burned at a low-intensity did not alter soil hydraulic properties, including K_{fs}, in Mediterranean forest ecosystems in the first year following burning. Though we were unable to categorize the intensity of the slash and burn piles, based on burn depth and observations made during the burns we assumed these piles were burned at moderate- to high-intensity.

Past studies have attempted to investigate the relationship between time since wildfire and hydraulic conductivity and fit it with a curve. A meta-analysis conducted by (Ebel & Martin, 2017) fit data with a linear and logarithmic curve to investigate changes in K_{fs} that occur each year following a wildfire. They were not successful in determining if the relationship between time since burning and K_{fs} is linear or logarithmic, but they found each year following wildfire K_{fs} increased. This differs from our collected data showing a significant decrease in K_{fs} from 1-year post-fire to 3-years post-fire.

Our data suggest moderate- to high-intensity fires do not significantly alter K_{fs} within 1-year-post-fire. However, there may be processes in the interim that are affected by burning and lead to decreased K_{fs} after 1-year post-fire as suggested by our data (Figure 5). One possible reason for this is the removal of organic material in the top layer of the soil from burning that leaves void spaces which take one to three years to compact. This compaction would reduce K_{fs} of the top layer below the unburned soils beneath, controlling the K_{fs} values thereafter. However, further research is necessary due to the relatively limited number of data points burned 3-years ago in this study (n = 12). Studies for comparison are not readily available to compare our third year of data to because studies like Plaza-Álvarez et al. (2019) only measured soil properties for one year after burning. Recent studies that include more years of data, specifically data from burns that took place 3-years ago, either lack data from before 3 years (Ebel & Martin, 2017) or related data sampled from burned and unburned soils from different hillslopes (e.g., Ebel et al., 2012).

Conclusion

Our research sought to determine when a soil recovered back to its pre-burn conditions in a field setting. We investigated the differences in K_{fs} between piles burned 1-year-, 3-years-, and 6-years-ago and compared them to unburned conditions. We excluded data from 6-years-ago because of a lacking sample size (n = 3), though qualitative observations show vegetation regrowth occurring within this timeframe. In this study, there were no signs of vegetation regrowth in piles burned 1 year ago, some vegetation regrowth in piles burned 3 years ago, and abundant vegetation in piles burned 6 years ago, almost to the extent of them being unidentifiable. Between years 1 and 3, however, we found a statistically significant reduction in K_{fs}, representing a degradation of hydraulic properties rather than a recovery.

Future studies may benefit from including variables other than K_{fs}. For example, Ebel & Moody (2017) found sorptivity, instead of K_{fs}, was significantly affected in burned soils. The ratio of S^2/K_{fs} in unburned soils was constant across all unburned measurement points despite varying measurements of each but the ratio was highly variable in burned soil. It is suggested that the balance between K_{fs} and S is more influential in a landscape's response than each alone — the sum is greater than the parts. This ratio may be a future consideration for evaluating the recovery/degradation of fire affected soils through time—there may be a relationship between time since fire and how constant this ratio is.

Ultimately, determining the level of risk that a wildfire-affected plot of land is at for flooding and/or debris flows to occur is the goal. Understanding the severity of a wildfire and thus how the hydraulic properties of the affected soil behave would allow first responders and land managers to place resources where needed within an appropriate timeframe. Wildfires themselves are catastrophic to infrastructure, but their impact afterwards must also be considered. Our study found that there was no change in effective hydraulic conductivity during the first year after a soil is burned. However, there is a reduction in hydraulic conductivity between 1 and 3 years after burning during the time when vegetation was qualitatively observed to begin re-growth at our site. Future studies on burned soils may benefit from observing property changes over the long-term to determine if our observations are specific to the soil type found at our site or representative of processes that occur more broadly.

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