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Triggering rainfall intensities for post-wildfire debris flows in the Sonoran Desertscrub plant community

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Abstract. Wildfire makes landscapes more vulnerable to debris flows by reducing soil infiltration capacity and decreasing vegetation cover. The extent to which fire affects debris-flow processes depends on the severity of the fire, the climatology of intense rainfall, the pre-fire plant community, and sediment supply, among other factors. As fire expands into new plant communities and geographic regions, there is a corresponding need to expand efforts to document fire-induced changes and their impacts on debris-flow processes. In recent years, several large wildfires have impacted portions of the Sonoran Desertscrub plant community in Arizona, USA, a plant community where fire has been historically infrequent. Following two of these fires, we monitored debris-flow activity at the watershed scale and quantified wildfire-driven changes in soil hydraulic properties using in-situ measurements with mini disk tension infiltrometers. Results indicate that rainfall intensity-duration thresholds for the initiation of post-fire debris flows in recently burned watersheds within the Sonoran Desertscrub plant community are substantially greater than those in nearby areas dominated by other plant communities, such as chaparral. Results provide insight into the impact of fire on debris-flow processes in a plant community where it is likely to be more impactful in the future and help expand existing post-fire debris flow databases into a plant community where there is a paucity of observations.

1 Introduction

Landscapes that have been recently disturbed by wildfire are more susceptible to extreme hydrologic and geomorphic responses to rainfall, including debris flows. In the first several years following fire, debris flows often initiate in recently burned areas when runoff rapidly entrains sediment on steep slopes [1-3]. Rainfall intensity-duration (ID) thresholds have proven to be effective tools to help anticipate and mitigate the negative impacts of debris flows [4]. However, derivation of rainfall ID thresholds requires historical observations of rainfall and debris-flow occurrence. This presents a problem in geographic regions or plant communities that have not been historically impacted by wildfire, because we lack the requisite data. In the Sonoran Desertscrub plant community, fire has been historically rare due to sparse and discontinuous fuels, but it is increasing in part due to the presence of invasive grasses [5].

We monitored rainfall and debris-flow activity in low-order watersheds dominated by plants that are typical of the Sonoran Desertscrub community, including several species of cactus (e.g., *Carnegiea gigantea*, *Opuntia* spp.) as well as succulents and shrubs (e.g., *Larrea tridentata*, *Encelia farinosa*, *Simmondsia chinensis*, *Agave* spp.), to better understand how fire affects debris-flow processes in this plant community. The main objectives of this study are to quantify rainfall ID thresholds for post-fire debris flows in the Sonoran Desertscrub plant community and to provide insight into the time required for recovery from a debris-flow hazards perspective. We compare and contrast results with those from recent studies in nearby burned areas with different plant communities.

2 Methods

2.1 Debris flow monitoring

We monitored debris-flow activity during the first two summers following the 2019 Woodbury Fire and the 2020 Bighorn Fire, both of which are located in Arizona in the southwestern USA. Post-fire debris flows in Arizona are often initiated by short-duration, high intensity rainfall associated with the North American Monsoon [6]. Monitoring at the Woodbury Fire builds directly from [7], who documented debris flows several months following the fire in a series of monitored watersheds in the Superstition Mountains to the east of Phoenix, Arizona. The Woodbury Fire burned over a large area and across a range of elevations that included a number of different plant communities. We focused on a small section of the fire at a relatively low elevation, where the dominant plants were those common to the Sonoran Desertscrub community. Upper elevations of some study watersheds, particularly on north-facing

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aspects, were located in a transition from Sonoran Desertscrub to chaparral. Our study watersheds, described in detail in [7], burned primarily at low severity (Figure 1), though pockets of soil burned at moderate severity were not uncommon on higher elevation, north-facing slopes. Rainstorms that produced debris flows were identified using post-rainstorm surveys, pressure transducers, and time lapse cameras [7]. Rainfall characteristics were quantified using tipping bucket rain gages.

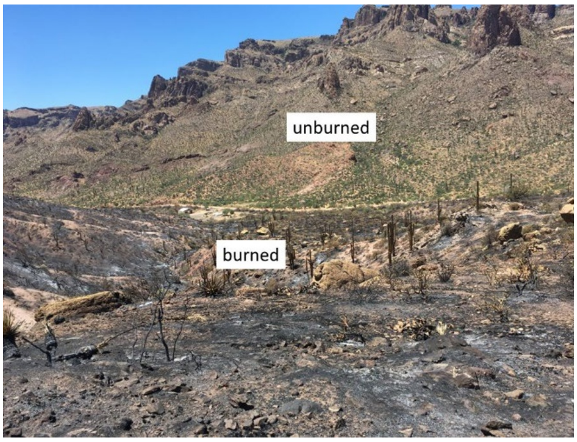

Fig. 1. Burned and unburned hillslopes at the 2019 Woodbury Fire in central Arizona, USA.

Debris flow monitoring efforts following the Bighorn Fire focused on a series of watersheds near Tucson, Arizona, that burned primarily at low severity. Upper elevations of some study watersheds were located in a transition from Sonoran Desertscrub to oak woodland. Rainfall was quantified using tipping bucket rain gages and the presence or absence of debris-flow activity during rainstorms was determined from post-event surveys. We used characteristic debris-flow depositional patterns identified within or near the channel as an indicator of debris-flow activity.

2.2 Rainfall intensity-duration thresholds

We derived a rainfall ID threshold following the procedure developed by [4]. For a given rainfall duration, D, we employed receiver operating characteristics analysis to determine the intensity, I, averaged over that duration, that maximized the threat score. For each duration, we defined the threshold intensity as the intensity that maximized the threat score. We determined thresholds for durations of 5, 10, 15, 30, and 60 minutes since previous studies have found that initiation of post-fire debris flows is best predicted by rainfall over short (< 60 minute) durations [4]. Runoff in small, steep, recently burned watersheds is correlated with rainfall intensity over a 15-minute duration, I15 [1,6].

2.3 Soil hydraulic properties

We quantified temporal changes in field saturated hydraulic conductivity (K_{fs}) over time at the Woodbury Fire site, focusing on areas burned at moderate severity where fire-induced changes are likely to be most accentuated. A more detailed description of methodology is given by [7]. Assuming similar or more rapid recovery in areas that burned primarily at low severity, these measurements provide an upper bound on the time needed for recovery of soil hydraulic properties in low severity areas. Measurements were also made in a nearby unburned area in May 2020 and April 2021 for comparison with the data collected in the burn scar.

3 Results and Discussion

We observed 18 runoff-generated debris flows in our monitored watersheds. Ten debris flows initiated approximately 2 months following containment of the Woodbury Fire while the 8 remaining debris flows initiated 12 months following containment of the Bighorn Fire. The threat scores associated with the rainfall ID thresholds for durations of 5, 10, 15, 30, and 60 minutes are 0.27, 0.31, 0.39, 0.55, 0.51. The relatively poor performance of thresholds based on extremely short durations, such as 5 minutes, likely reflects a threshold for runoff-generation. In other words, runoff generated in response to a particular intensity of rainfall over a 5-minute interval will be highly variable depending on prior rainfall. The rainfall intensity thresholds for durations of 30-minutes and 15-minutes are 54 mm/h and 83 mm/h. In contrast, [6] determined that the I15 and I30 thresholds for post-fire debris flows in the Pinal Mountains of central Arizona are 56 mm/h and 16 mm/h. Arizona chaparral was the dominant plant community in the area studied by [6]. Similarly, the 15-minute threshold derived for our sites are more than a factor of two greater than the peak 15-minute rainfall intensities of debris-flow producing storms following the 2017 Frye Fire in southern Arizona [8]. Vegetation in the steep, upper portions of the monitored watersheds burned by the Frye Fire consists of Ponderosa pine dominated pine-oak forests, dry and mesic mix conifer forests, and spruce-fir forests [9].

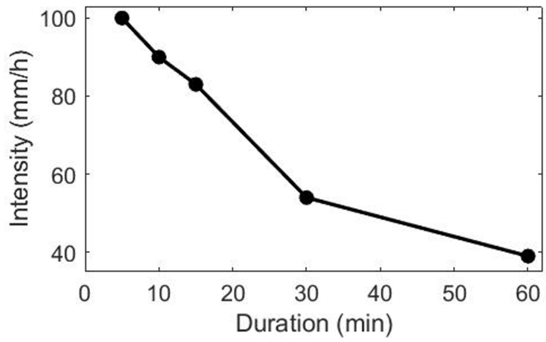

Fig. 2. A rainfall intensity-duration threshold derived using observations of watersheds dominated by the Sonoran Desertscrub plant community following the Woodbury and Bighorn Fires.

Greater rainfall ID thresholds at our Sonoran Desertscrub sites relative to those from other nearby burned areas could be attributed to differences in soil burn severity. The majority of the watersheds monitored in this study burned predominantly at low soil burn severity, as is common in the Sonoran Desert [10], while those in the Pinal Mountains burned almost entirely at moderate or high soil burn severity [6]. The potential for runoff, erosion, and runoff-generated debris flows generally increases with soil burn severity [11]. These differences in soil burn severity are not only unique to the specific fires monitored in this study, but also reflect more general differences in the fire regimes associated with different plant communities [9]. Part of the difference between these two thresholds could also be attributed to methodology. In [6], pressure transducers constrained debris-flow timing within rainstorms at all monitored watersheds. In many cases, we were unable to determine the timing of debris flows within rainstorms and assumed that the rainfall intensity responsible for debris-flow initiation was the same as the peak rainfall intensity during the storm that produced the debris flow.

Field-saturated hydraulic conductivity (K_{fs}) in soils burned at moderate severity during the Woodbury Fire was lowest shortly following the fire and then increased with time. A series of measurements made within the first three months following the fire had a median of 11 mm/h (n=20). Measurements taken approximately 10 months and 22 months following the fire had medians of 15 mm/h (n=9) and 25 mm/h (n=19), respectively. In the unburned area, the median K_{fs} was 22 mm/h (n=23). Therefore, any fire-induced reductions in K_{fs} were likely minimal or non-existent after two full years of recovery. Due to the strong link between runoff-generation and initiation of post-fire debris flows, these constraints of the rate of K_{fs} recovery also provide insight into the temporal window during which there is an increased likelihood of debris flows following fire in the Sonoran Desertscrub plant community.

4 Conclusions

It is critical to expand datasets that document postfire debris-flow responses across the range of plant communities and geographic locations where fire is emerging as an agent for geomorphic change. In this study, we monitored recently burned watersheds within the Sonoran Desertscrub plant community and observed 18 debris flows within the first two summer monsoon seasons following the fires. Data indicate that rainfall intensity-duration thresholds for debris-flow initiation are greater relative to those observed in recently burned areas where vegetation is dominated by chaparral. The observed differences in ID thresholds are likely due, at least in part, to differences in soil burn severity. Based on field measurements, fire-induced reductions in field-saturated hydraulic conductivity likely do not persist for more than two years following fire at our Sonoran Desertscrub sites. These increases in infiltration capacity likely help contribute to increases in rainfall ID thresholds required for debris-flow initiation as the landscape recovers.

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