EFFECTS OF REPEAT HIGH-SEVERITY FIRE ON HEADWATER STREAMS ALONG THE MOGOLLON RIM

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ABSTRACT

EFFECTS OF REPEAT HIGH-SEVERITY FIRE ON HEADWATER STREAMS ALONG THE MOGOLLON RIM

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This study analyzes the recovery process of stream biology and geomorphology along the Mogollon Rim after multiple disturbances including the Dude Fire (1990), Highline Fire (2017), and subsequent flooding events. Geomorphic and macroinvertebrate data collected after the Highline Fire was compared to data collected in 2011, 21 years after the Dude Fire. This study builds upon previous research which looked at the long-term recovery of first order streams following fire related disturbances along the Mogollon Rim in central Arizona. We hypothesized that the twice-impacted streams would show a reset in their recovery timeline for macroinvertebrate communities and geomorphology two years after the Highline Fire relative to the other study creeks. Results show that repeated flooding disturbances on Ellison Creek had substantial changes to stream geomorphology and macroinvertebrate communities. Bonita Creek which was also affected by the Highline fire but not a concurrent debris flow only showed changes to the macroinvertebrate communities. Results indicate that repeated physical alteration by flooding events following can reset the long-term recovery of headwater stream systems.

Keywords: Headwater streams, macroinvertebrates, geomorphology, post-fire impacts, reburn, Mogollon Rim, Arizona

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Preface

This thesis uses manuscript-style formatting with the intention of submitting Chapter 2 to a scientific journal. The manuscript chapter has not yet been submitted, but it has been formatted to align with the requirements of the journal *Fire Ecology*. The exact journal has not been selected, although *Fire Ecology* is the currently the journal my committee and I decided would be the best fit, both because of the topic area and because it builds on a key study previously published there. References were cited using the Chicago reference style to match requirements in that journal. Figures in the manuscript chapter are at the end of the chapter to match guidelines for submission. For all other chapters, figures are included where they are referenced in the text. Due to the manuscript-style format there is repetition in the text and figures between the manuscript chapter and other thesis chapters. The theme of this thesis is geomorphologic and biotic responses to multiple high-severity wildfires. The study area is located in Central Arizona on the Tonto National Forest including part of the forest that was affected by the Dude Fire (1990) and the Highline Fire (2017). Chapter 1 includes a comprehensive introduction, literature review, and discussion of methods & materials. Chapter 2 contains the manuscript section which condenses all other sections into a publishable product. Chapter 3 included the overall conclusions with recommendations of future work. Chapter 4 includes the appendices with supplemental materials uploaded to ProQuest including information on data storage.

1 Introduction

1.1 Project Outline

The fundamental theme of this thesis is to examine the physical and biological responses of repeat high-severity fire on headwater streams in central Arizona. This project is a continuation of previous work done in the study area. The first projects were completed before the Dude Fire in 1990. Other post-fire research was completed up to 21 years after the Dude Fire. The Highline Fire in 2017 presented the opportunity to begin a new project to see how streams have reacted to the second fire disturbance. This project acknowledges the previous studies but focuses mainly on data collected after the Highline fire. Multiple parameters of geomorphic and biologic data were collected on refence and burned streams to understand their response to multiple fires. The thesis was compiled and condensed into a manuscript format in Chapter 2 of this document.

1.2 Comprehensive Literature Review

1.2.1 Fire in the Southwest

Wildfires have been a natural part of southwestern United States forests since pre-settlement. In ponderosa pine (*Pinus ponderosa*) dominated forests, fires historically had a return interval of every 2-47 years (Fitzgerald 2005). Fires were typically low severity surface fires, and forests were open with substantial space between trees (Covington et al. 1997). Post-settlement practices such as grazing, logging, and fire suppression has altered the natural fire regime of ponderosa pine forests (Covington and Moore 1994). As a result, forests are significantly denser and have an accumulation of surface fuel that causes them to be prone to large-scale high-severity fire (Covington and Moore 1994). Changes to historical fire regimes are also driven by climate change. Temperature increases during spring and summer months as well as earlier snowmelt has led to a longer fire season with an increased number of fires (Westerling et al. 2006). Fires have also seen an increase in size and amount burned at high-severity (Dennison et al. 2014, O'Conner et al. 2014).

Some southwestern ponderosa pine forests are not only seeing a change in fire regimes but are also experiencing vegetation type conversion. Studies have concluded that in some cases, wildfires in a ponderosa pine environment can change the regeneration succession pattern and the vegetation community composition (Minor et al. 2017, Roccaforte et al. 2012). Regeneration of shrubs and grasslands can be common following high-severity fire in a ponderosa pine forest and last for extended periods of time (Minor et al. 2017). With the increased amount of large high-severity fires, it is likely that some of the burned areas will reburn. In the event of a reburn, a conversion from ponderosa pine to shrubs or grasses in the first fire may be reinforced by the second fire (Coop et al. 2016).

1.2.2 Post-fire Watershed Disturbance

The changes in fire regimes on forests that have been seen in recent decades also have implications on the watersheds within the forests. Specifically, the frequency increase of large, high-severity fires can have major impacts on aquatic environments both physical and biological. A dominant driver for physical changes in aquatic environments is post-fire flooding. Post-fire flooding is common in the Southwest due to the timing of peak fire season and the monsoon season coinciding (Youberg et al. 2011). The monsoon season in the Southwest can produce storms with intense and localized bursts of rainfall (Adams and Comrie 1997). In normal conditions, these bursts are capable of causing flash floods. However, if these bursts of precipitation occur over a recently burned landscape, it may cause significant flooding or debris flows.

A number of factors are responsible for the occurrence of floods following wildfires. One of the most significant factors is soil water repellency. Soil water repellency or hydrophobic soils can occur when waxes from the organic matter in trees are burned, then deposited below the surface of the soil (Debano 2000). Soil water repellency is more common in areas burned at moderate to high-severity but is possible in low severity fires as well (Cawson et al. 2016, MacDonald and Huffman. 2004). Water repellent soils reduce the amount of precipitation infiltration and can lead to a large amount of soil erosion, overland flow, and debris flows. Reduced infiltration can also occur due to the loss of upland vegetation cover that slows down overland flow and rainwater interception (Levabre and Torres 1993).

Streams within a burned watershed can see a large increase in water discharge following normal precipitation events (Moody and Martin 2001). Wildfires followed by rainfall can cause fluctuations in sediment erosion, transport, and deposition (Moody and Martin 2009), which can change particle size distribution of channel substrate. Significant rainstorms can cause debris flows that would exacerbate channel erosion (Wondzell and King 2003). In most cases, loss or change in streamside vegetation can decrease soil stability and therefore increase erosion (Wainwright et al. 2000). Riparian vegetation loss can also cause streamwater temperature to increase due to the loss of canopy cover that increases incoming solar radiation (Dunham et al. 2007). Elevated streamwater temperature levels can persist for more than a decade (Dunham et al. 2007). Smoke and ash inputted during and after the fire can result in changes in stream chemistry, such as increased nitrate levels, that may last for at least five years (Rhoades et al. 2011). These changes within stream systems affect the makeup of all biota dependent on the morphology of the stream.

1.2.3 Post-Fire Response of Macroinvertebrates

Direct impacts of wildfire may have minimal impacts to macroinvertebrate communities. However, indirect impacts such as flooding can cause significant changes to macroinvertebrate communities and their habitats. In some cases, post-fire flooding can lead to extensive macroinvertebrate mortality (Rinne 1996). The post-fire recovery time for macroinvertebrate communities can vary, although studies have concluded that about 10-15 years are needed to return to reference conditions (Minshall 2003). It is unclear how macroinvertebrate recovery would be affected in streams that had their watershed reburn; however, one report suggests that a full recovery could be impossible if fire return intervals become shorter than the time needed to recover (Arkle 2010).

Increased runoff and channel alteration of streams affected by wildfires have can result in the greatest changes in macroinvertebrate communities (Minshall 2003). Macroinvertebrates communities favor cobbles, stones, and pebbles; therefore, a change in the dominant streambed substrate can have negative impacts (Duan et al. 2008). Increased inputs of ash from moderate severity wildfire to water quality may also influence macroinvertebrate communities, but they are typically short-lived with a return to pre-fire conditions within about four months (Earl and Blinn 2003).

However, high-severity fire may lengthen the recovery time. Increases of stream temperature can also have significant impacts on macroinvertebrates (Lessard and Hayes 2003). In one study, macroinvertebrate abundance declined 21% for each 1°C rise in stream temperature (Durance and Ormerod 2007). Macroinvertebrate sampling is important to understand stream health as well as the overall ecosystem (Wallace and Webster 1996). Changes to the macroinvertebrate communities can directly influence other aquatic and terrestrial species.

1.2.4 Macroinvertebrates as an Indicator of Stream Health

Analysis of benthic macroinvertebrate communities has long been used as an assessment of stream health (Rossenberg and Resh 1993). Macroinvertebrate analysis is typically done using metrics such as Shannon's Divesity, Richness, and Pielou's Evenness to determine stream health. A decrease in any of these metrics could indicate that a stream's macroinvertebrate communities are responding to a disturbance (Barbour et al. 1999). When looking at specific macroinvertebrate taxa to identify stream health, the three most common are Ephemerotera (mayflies), Plechoptera (stoneflies), and Trichoptera (caddisflies). The three taxa together are also referred to as EPT. EPT taxa are sensitive to disturbances, therefore a decrease in the abundance of EPT taxa (Figure S4.3) would also indicate a disturbance in a stream (Dewalt et al. 1999). Other taxa such as Diptera (true flies), can be found in both disturbed and undisturbed streams (Paine and Gaufin 1956), so their use as an indicator of stream health may not be as valuable.

1.3 Comprehensive Discussion of Methods and Materials

1.3.1 Study Area

The study area is within the Tonto National Forest just below the Mogollon Rim in Central Arizona (Figure 1.1). The elevation ranges from about 1450 m - 2350 m. Lower elevations are typically composed of pine-juniper-oak (*Pinus spp.-Juniperus spp.-Quercus spp.*), while higher elevations are dominated by ponderosa pine (*Pinus ponderosa*) (Leonard et al. 2017). A majority of the area burned by the Dude Fire in 1990 has regenerated as oak-manzanita (*Arctostaphylos* spp.) and much of what pine regeneration has occurred has been affected by elk browsing (Leonard et al. 2015). The geology of the area is predominately composed of Paleozoic sedimentary rock (Parker and Flynn, 2000). Soil types were identified using a GIS shapefile from the US Forest Service Terrestrial Ecological Unit Inventory. The soil composition within the watersheds include Lithic and Typic Eutroboralfs, Eutro Glossoboralfs, and Lithic Dystrochrepts (United States Forest Service 2019).

Climate data was received from the PRISM Climate group using a 4 km resolution point in the center of the study area. The 30-year normal for this point covered years from 1981 to 2010 and resulted in an annual precipitation amount of 840mm. Precipitation typically occurs in a bimodal pattern with rain in summer monsoons months and snow or rain in winter. The 30-year normal maximum temperature in the hottest month, July, is 29.3°C while the minimum temperature in the coldest month, December, is -5°C (PRISM). Data for the past three years (2017, 2018, 2019) was also recorded to display the current conditions while the study was conducted. The average annual precipitation was 741 mm. The average maximum temperature in July was 29.5°C and the minimum in December was -2°C (Figure S4.3).

The study includes five first-order spring-fed streams originating at the base of the Mogollon Rim, all draining toward the southwest. The streams include the most western location of Pine Creek in the city of Pine, Arizona, and progressively eastward to Dude, Bonita, Ellison, and Horton Creeks. The distance between Pine and Horton Creek is approximately 35 km (Figure 1.1). The study creek catchments have been variably impacted by two major fires, Dude (1990) and Highline (2017) (Table 1.1, Figure 1.2, Figure S4.1)

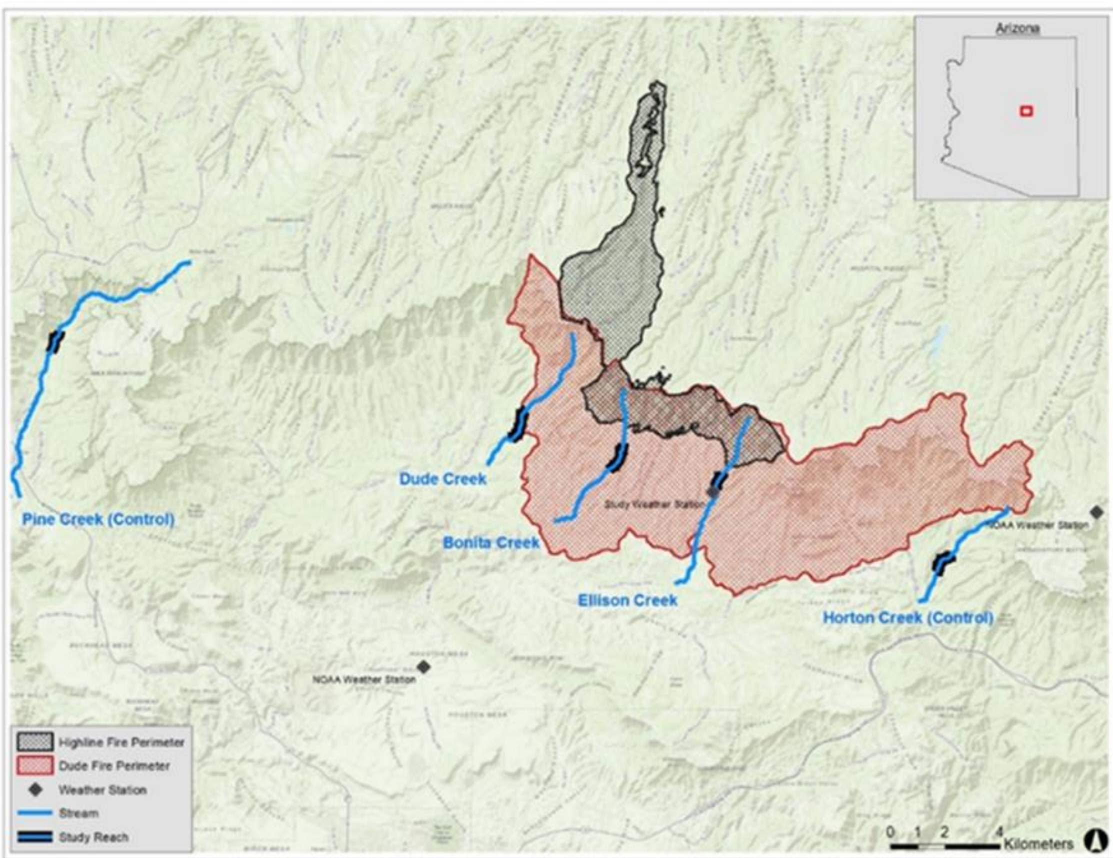

Figure 1.1: Map of the study area in central Arizona along the Mogollon Rim. Included are the five first order streams with approximate locations of the transect sites as well as the fire perimeters of the Dude Fire (1990) and the Highline (Fire 2017).

1.3.2 Disturbance History

On June 25, 1990, a lightning strike started the Dude Fire that burned along the Mogollon rim approximately 16 km northeast of Payson, Arizona. At the time, this fire was the largest and most destructive fire in Arizona's history with an area of over 10,150 ha, over 50 structures lost, and 6 fatalities. The fire burned the uplands of several watersheds including Dude, Bonita, and Ellison Creek, most of which burned at high-severity. Multiple monsoon rain events occurred the weeks and months following the fire that produced floods rich in ash and debris. These floods initiated channel destabilization and degradation (Medina and Royalty 2002). The floods also resulted in the mortality of almost all macroinvertebrates and fish in the impacted streams (Rinne 1996). Bonita and Ellison Creeks were stocked with trout a year after the fire and their population declined 75% within a year of being introduced (Rinne 1996). Large floods continued to occur in the area the years following the fire, including one in January 1993 that was predicted to be the largest flood in over 300 years (Fuller et al. 1996). A 2005 study concluded that the burned uplands had converted pine-dominated forest to an oak-manzanita (*Arctostyphylos* spp.) dominated forest (Leonard et al. 2015). The combination of the Dude Fire and ensuing floods resulted in changes to Dude, Bonita, and Ellison Creeks both geomorphologically and biologically.

On 10 June 2017, the Highline Fire started inside the almost 27-year-old Dude Fire scar. The fire was smaller at 2910 ha, but again high-severity fire was observed in a large part in the Bonita and Ellison Creek watersheds (Figure 1.2). On 15 July 2017, a monsoon storm produced an estimated 25 to 40 mm of precipitation in a 40-minute period over the Highline Fire scar (National Weather Service 2017). Soils in the watershed were likely saturated from previous, less intense, and less isolated rain events. This rainfall, which was predicted as a 5- to 10-year event, resulted in a large debris flow on Ellison Creek with a head that was estimated at 1.5 m high on a downstream swimming hole leading to 10 fatalities (National Weather Service 2017). While other streams in the area may have had flooding, debris flows were only observed on Ellison Creek.

The reburn event likely supported the vegetation conversion to an oak-manzita (*Arctostaphylos* spp.) dominated system in the uplands of the twice burned watersheds. Observations of sparse pine regeneration have already been suppressed due to elk browsing (Leonard et al. 2015). Much of the pine regeneration within the Highline Fire was probably killed in the fire setting back the recovery and possibly Permanently converting the vegetation to resprouting shrubs.

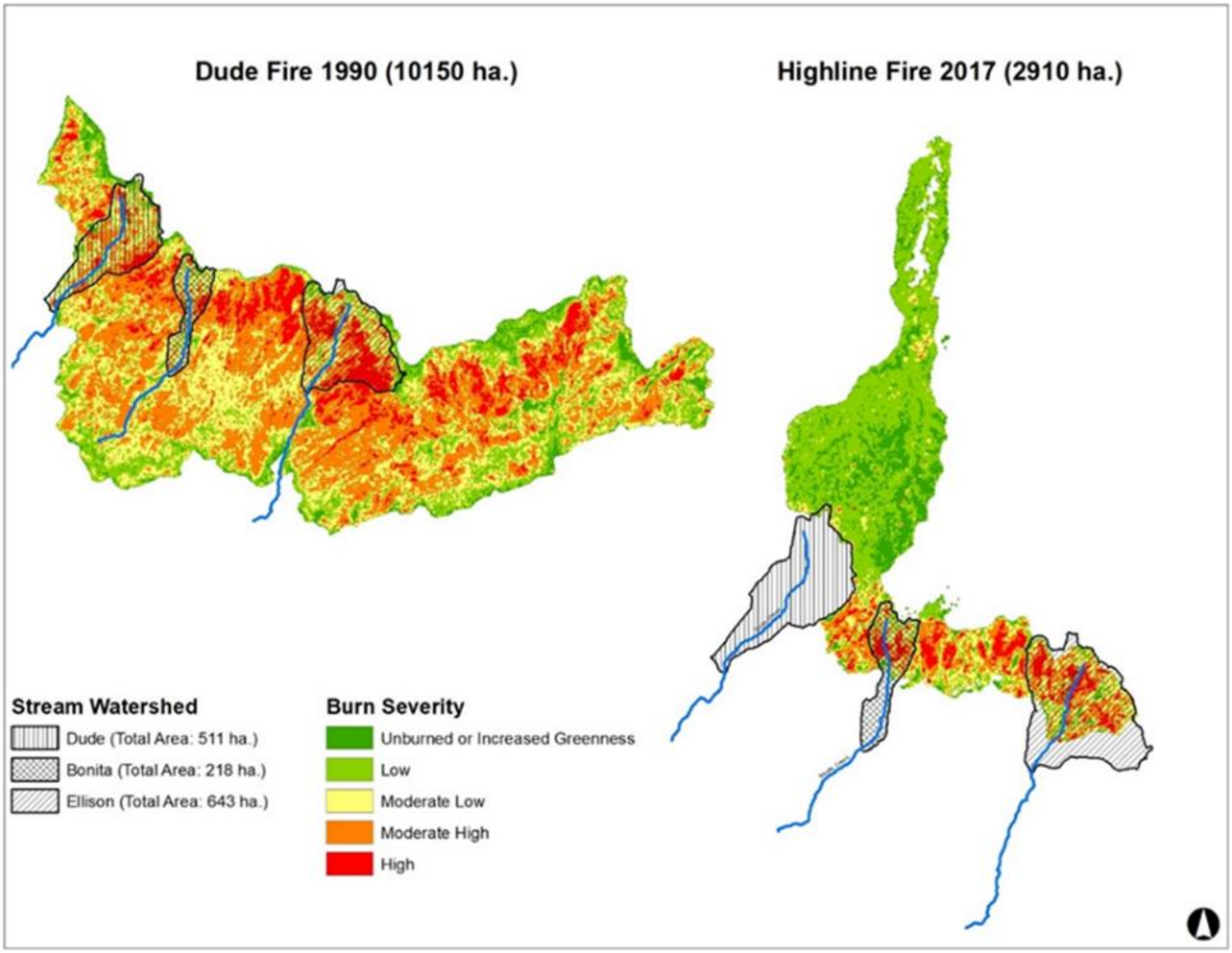

Figure 1.2: Dude Fire and Highline Fire burn severity maps with affected watersheds. Data from MTBS and USFS BAER teams.

Table 1.1: Percentage of burn severity type with affected watersheds for the Dude Fire and Highline Fire.

	Watershed size (ha)	Outside Fire Perimeter	Unburned	Low	Mod-Low	Mod-High	High
Dude Creek, Dude Fire	511	2%	3%	13%	36%	38%	8%
Bonita Creek, Dude Fire	218	0%	1%	17%	49%	29%	6%
Bonita Creek, Highline Fire	218	39%	1%	11%	19%	20%	11%
Ellison Creek, Dude Fire	643	2%	2%	11%	23%	35%	27%
Ellison Creek, Highline Fire	643	37%	2%	8%	19%	24%	11%

1.3.3 Site Selection

Site selection decisions were made to match previous studies in the study area (Rinne 1996, Medina and Royalty 2002, Leonard et al. 2017). Bonita and Ellison Creek were selected as streams impacted by multiple disturbances including the Dude Fire in 1990, the Highline Fire in 2017, and post-fire floods. Dude Creek was selected as only being impacted by the Dude Fire and the floods that followed. Pine Creek and Horton Creek were selected as unburned reference streams. Each stream had study reaches of about 450 m with five transects within the reach. A total of 25 transects were therefore sampled, spanning once burned, twice burned, and reference streams. Data was collected within a reach 20 m upstream and 20 m downstream from the center of the transect (Figure S4.4). Transect reaches were selected to include at least one riffle, run, pool habitat (Medina and Royalty 2002, Leonard et al. 2017)

1.3.4 Geomorphology

Stream morphology assessment was conducted on all five transects of each stream included in the study. Data was for this study was collected in 2018 and 2019. Data from a previous study (Leonard et al. 2017) was also included as a baseline for streams pre-Highline Fire. Geomorphology transects sites were inherited from previous studies set up by the Rocky Mountain Research Station and the Tonto National Forest (Leonard et al. 2017). Start and end points of the transects were marked by rebar on the banks. An initial field visit with researchers from the previous study was done to locate and mark the transects. Geomorphology surveys were conducted using an RL-HA Topcon rotary laser level (Topcon Corp., Tokyo, Japan) with an accuracy of ±25 cm at 50 m (Figure 1.3). A cross-sectional profile of the channel was created using measurements of vertical displacement along a horizontal line. Measurements were taken starting at a similar reference point at 0 m and then about every 1-3 m based on the topography along the transect.

Figure 1.3: Photo of Topcon laser level

Cross sectional survey data was analyzed using WinXSPRO software (Hardy et al. 2005). Estimated change in area was recorded for each transect comparing one year to another. Some of the transects were not useable due to errors noticed when inputted into the WinXSPRO program. The start points and end points should be static since they were denoted with rebar on the banks above the floodplain. Errors were likely due to the comparison of historic transects that had extra transects or rebar (Figure 1.4). Transects with errors were not used in the comparison.

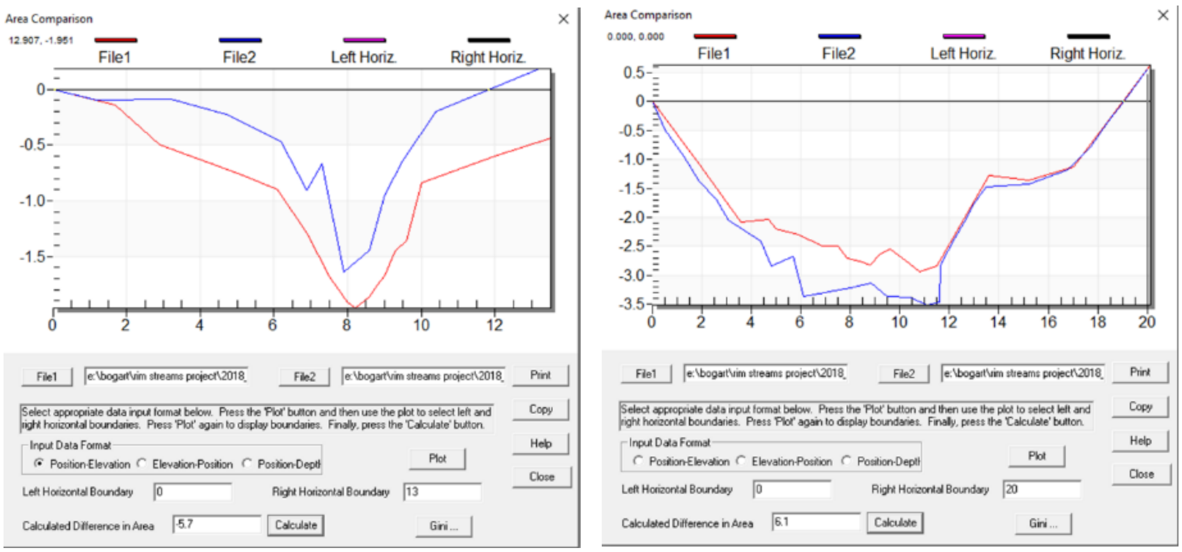

Figure 1.4: Example of WinEXSPRO outputs. The image on left is an example of a transect that was disregarded due to the difference on the right edge of the chart. Start points and end points should be in the same place as seen in the image on the right.

To determine the bedload sediment size or substrate, a pebble count of 300 samples was performed by randomly selecting 300 samples (Bevenger and King 1995). 100 samples were collected at the first, third, and fifth transects. Samples were randomly selected by walking in a zigzag pattern through the banks and channel. Every third step a pebble was selected by blindly reaching down and pointing the sample touching the end of one’s shoe. Samples were measured using a foldable measuring tape and recorded on a field sheet. Dominant particle size was recorded by averaging the 300-sample size and then placed in its corresponding size class.

1.3.5 Macroinvertebrates

Macroinvertebrate samples were collected at each transect on all five streams in 2011, 2018, and 2019. Samples were also collected in 2017 on Ellison and Bonita Creek after the fire but before the flood (Figure S4.2). The sample procedure included using a using a hard-bristled brush to scrape channel substrate within a 0.09 m^2 Surber sample frame. Samples were taken within the transect at similar riffle habitats and preserved in 90% ethanol diluted with stream water. Samples were preserved on ice for transportation from the study area to the lab. The sample methodology was equivalent to the process done in the previous studies (Rinne and Medina 1998, Leonard et al. 2017). In these previous studies including the 2011 data, one sample for each transect was collected and processed separately. In our study, samples were collected at each transect, but they were combined as one sample for processing. The Bug Lab at Utah State University, Logan Utah, performed the processing of samples.

Figure 1.5: Macroinvertebrate on the Surber sample net.

Post processing techniques were required to make the raw macroinvertebrate data comparable between each sample. Techniques were developed based on guidance from the professionals at the Bug Lab. If a split count was used during the macroinvertebrate identification process, then those samples needed to be expanded to a 100 percent count. For example, if the split count was .5 then each individual count was divided by .5 to create a sample with 100% count. Once this was done, the samples were rarefied to a 300-fixed count subsample for each stream per year collected. This process was done by randomly selecting 300 individual macroinvertebrates from each 100% sample. Since 2011 data was processed separately for each transect, they were combined together to conduct the 300-count sample. The 300 macroinvertebrates were standardized to Operational Taxonomic Units (OTU) based on a generic model from the Utah State Bug Lab. Most of the individuals were standardized at the genus level while the rest used the next coarsest level available.

Metrics including Shannon's Diversity, richness, and evenness were calculated for each subsample. The percent abundance was calculated for each order and individuals that were not identifiable to order were recorded as null. The order Diptera was left out of the of the percent order abundance due to its insignificance as an indicator of stream health. In 2018, Ellison had a total number of 86 macroinvertebrate individuals. This did not allow for rarefaction, and the fixed count was set to 86 for metric calculation.

1.3.6 Water Quality and Temperature

General water quality measurements were collected using OAKTON portable meters (OAKTON Instruments, Vernon Hills, Illinois, USA). A pH/CON 450 meter was used to record pH and conductivity. Dissolved oxygen readings were collected using a DO 450 meter. Water chemistry samples were collected on each stream using a grab-sample method in 100 ml bottles. Three samples at every transect were taken giving a total of 15 samples per stream. Samples were stored on ice for transportation to the lab for processing. Samples were processed following US EPA Method 300.0 (Pfaff 1993). Anion analysis was done using Dionex™ Aquion™ Ion Chromatography (IC) System with a Dionex™ IonPac™ AS4A-SC column. Analysis of water chemistry was done using R statistical software (Rstudio Team 2015) comparing unburned reference streams to twice burned streams in an ANOVA calculation. The once burned creek, Dude, was left out of the calculation to maintain statistical balance.

Figure 1.6: Macroinvertebrate and water quality samples stored on ice for transport.

Streamwater temperature readings were recorded using HOBO ™ Pro V2 data loggers (Onset Computer Corp., Bourne, Massachusetts, USA). One logger was placed on each stream in similar habitats and set to record every 15 minutes. Multiple loggers were lost or destroyed on Ellison Creek resulting in an incomplete dataset.

1.3.7 Stream Photography

One reference stream, Pine, and one twice burned stream, Ellison, had cameras set up for time lapse photography on the channels. Reconyx MicroFire™ cameras were used to capture photos every 15 minutes (RECONYX, LLP, Holmen, Wisconsin, USA). The cameras were faced upstream in the middle of transects one and two on Ellison and Pine Creek. The cameras were secured to a nearby tree, with an extended battery pack. A t-post with reflective tape was placed within the channel for scale. Reflective tape started at the 30 cm mark and then 10 cm intervals to the top at about 180 cm.

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2 EFFECTS OF REPEAT HIGH-SEVERITY FIRE ON HEADWATER STREAMS ALONG THE MOGOLLON RIM

2.1 Abstract

This study analyzes the recovery process of stream biology and geomorphology along the Mogollon Rim after multiple disturbances including the Dude Fire (1990), Highline Fire (2017), and subsequent flooding events. Geomorphic and macroinvertebrate data collected after the Highline Fire was compared to data collected in 2011, 21 years after the Dude Fire. This study builds upon previous research which looked at the long-term recovery of five first order streams (Pine Creek, Dude Creek, Bonita Creek, Ellison Creek, and Horton Creek) following fire-related disturbances along the Mogollon Rim in central Arizona. We hypothesized that the twice-impacted streams would show a reset in their recovery timeline for macroinvertebrate communities and geomorphology after the Highline Fire relative to the other study creeks. Results show that repeated flooding disturbances on Ellison Creek had substantial changes to stream geomorphology and macroinvertebrate communities. Bonita Creek which was also affected by the Highline fire but not a concurrent debris flow only showed changes to the macroinvertebrate communities. Results indicate that repeated physical alteration by flooding events following a fire can reset the long-term recovery of headwater stream systems. Finally, we found that both streams affected by repeat burns were found to be more vulnerable to short-term drought conditions which followed suggesting a decrease in resilience to climate change.

2.2 Introduction

In recent decades within the western United States, elongated wildfire seasons (Westerling et al. 2006) have resulted in larger fires burning at higher severities

(Dennison et al. 2014, O'Conner et al. 2014). This is attributed mostly to increased temperatures during the spring, as well as increased fuel loading due to decades of fire suppression (Westerling et al. 2006). Wildfires of varying severities in a ponderosa pine forest can change the regeneration succession pattern and the vegetation community composition (Minor et al. 2017, Roccaforte et al. 2012). Regeneration of shrubs and grasslands can be common following high-severity fire in a ponderosa pine forest and last for extended periods of time (Minor et al. 2017, Guiterman et al. 2018). With the increased amount of large high-severity fires, it is likely that some of the burned areas will reburn. In the event of a reburn, a conversion from ponderosa pine to shrubs or grasses in the first fire may be reinforced by the second fire (Coop et al. 2016). Changes to the historic fire regimes and vegetation type conversion can have significant impacts on watersheds, which may result in changes in stream channel geomorphology, stream temperature, and streamwater chemistry (Hitt 2003, Shakesby and Doerr 2006, Rhoades et al. 2011). These physical changes in streams may then disturb chemical and biological functions of the riparian and aquatic environments.

A dominant driver of physical changes in aquatic systems is post-fire flooding. In the Southwest, peak fire season is typically directly followed by intense monsoon storms which can readily initiate flooding and sometimes debris flows. Burned watersheds can see a large increase in water discharge following normal precipitation events (Moody and Martin 2001). Wildfires activate this response by increasing hydrophobic soils especially in areas burned at moderate to high-severity (DeBano 2000, MacDonald and Huffman 2004) and reducing rainwater infiltration due to loss of vegetation cover (Levabre and Torres 1993). Wildfires followed by rainfall can cause fluctuations in sediment erosion, transport, and deposition (Moody and Martin 2009), which can change particle size distributions of channel substrate. Significant rainstorms can cause debris flows that would exacerbate channel erosion (Wondzell and King 2003).

Loss or change in streamside vegetation can decrease soil stability and therefore increase erosion (Wainwright et al. 2000). Riparian vegetation loss can also cause streamwater temperature to increase due to the loss of canopy cover that increases incoming solar radiation (Dunham et al. 2007). Elevated streamwater temperature levels can persist for more than a decade (Dunham et al. 2007). Smoke and ash inputted during and after the fire can result in changes in water quality, such as increased nitrate levels, that may last for at least five years (Rhoades et al. 2011). These changes within stream systems affect the makeup of all biota dependent on the morphology of the stream.

Analysis of benthic macroinvertebrate communities has long been used as an assessment of stream health (Rossenberg and Resh 1993). Direct impacts of wildfire may have minimal impacts to macroinvertebrate communities. However, indirect impacts such as flooding can cause significant changes to macroinvertebrate communities and their habitats. In some cases, post-fire flooding can lead to extensive macroinvertebrate mortality (Rinne 1996). The post-fire recovery time for macroinvertebrate communities can vary, although studies have concluded that about 10-15 years are needed to return to reference conditions (Minshall 2003). It is unclear how macroinvertebrate recovery would be affected in streams that had their watershed reburn; however, one report suggests that a full recovery could be impossible if fire return intervals become shorter than the time needed to recover from a single burn (Arkle 2010). Increased runoff and channel alteration of streams affected by wildfires can result in the greatest changes in macroinvertebrate communities (Minshall 2003). Macroinvertebrates communities favor cobbles, stones, and pebbles; therefore, a change in the dominant streambed substrate can have negative impacts (Duan et al. 2008). Increased inputs of ash from moderate severity wildfire may also influence water quality and macroinvertebrate communities, but they are typically short-lived with a return to pre-fire conditions within about four months (Earl and Blinn 2003). However, high-severity fire may lengthen the recovery time. Increases of stream temperature can also have significant impacts on macroinvertebrates (Lessard and Hayes 2003). In one study, macroinvertebrate abundance declined 21% for each 1°C rise in stream temperature (Durance and Ormerod 2007). Macroinvertebrate sampling is important to understand stream health as well as the overall ecosystem (Wallace and Webster 1996). Changes to the macroinvertebrate communities can directly influence other aquatic and terrestrial species.

The goal of this study was to examine the physical and biological effects of a high-severity reburn and subsequent flooding events on the recovery process in previously impacted streams. Previous research studied the long-term impacts of the high-severity Dude Fire (1990) on watersheds in central Arizona (Leonard et al. 2015 & 2017). In 2017, the Highline Fire reburned two of the watersheds impacted earlier by the Dude Fire, allowing for the opportunity to study the effects these repeated wildfire events have on the recovery of headwater streams systems. This study hypothesized that the Highline Fire has reset a 27-year recovery process due to repeated changes to geomorphologic and biologic factors compared to once burned and unburned stream systems.

2.3 Methods

2.3.1 Study Area

The study area is within the Tonto National Forest just below the Mogollon Rim in Central Arizona (Figure 2.1). Elevations range from 1450 to 2350 m with lower elevations typically composed of pine-juniper-oak (*Pinus spp.-Juniperus spp.-Quercus spp.*), and higher elevations are dominated by ponderosa pine (*Pinus ponderosa*) (Leonard et al. 2017). The geology of the area is predominately composed of Paleozoic sandstone and limestone parent material (Parker and Flynn, 2000). The soils within the watersheds include Lithic and Typic Eutroboralfs, Eutro Glossoboralfs, and Lithic Dystrochrepts (United States Forest Service 2019). Spatially interpolated climate data (1981-2010) show average precipitation in the study to be about 840 mm annually (1981 – 2010 Normals, Parameter-elevation Regression on Independent Slopes Model [PRISM] Climate Group, Oregon State University, http://prismclimate.org, accessed February 2020). Precipitation typically occurs in a bimodal pattern with monsoonal rain in summer months and snow or rain in winter. The average maximum temperature in the hottest month, July, slightly exceeds 29°C while the average minimum temperature in the coldest month, December, is about -5°C (PRISM). The study includes five first-order spring-fed streams originating at the base of the Mogollon Rim, draining north to south. The streams include the most western location of Pine Creek in the city of Pine, Arizona, and progressively eastward to Dude, Bonita, Ellison, and Horton Creeks. The distance between Pine and Horton Creek is approximately 35 km (Figure 2.1). The study creek catchments have been variably impacted by two major fires, Dude (1990) and Highline (2017) (Table 2.1, Figure 2.2).

On 25 June 1990, a lightning strike started the Dude Fire that burned along the Mogollon rim approximately 16 km northeast of Payson, Arizona. At the time, this fire was the largest and most destructive fire in Arizona's history with an area of over 10,150 ha, over 50 structures lost, and 6 fatalities. The fire burned the uplands of several watersheds including Dude, Bonita, and Ellison Creek, most of which burned at high-severity. Multiple monsoon rain events occurred the weeks and months following the fire that produced floods rich in ash and debris. These floods initiated channel destabilization and degradation (Medina and Royalty 2002). The floods also resulted in the mortality of almost all macroinvertebrates and fish in the impacted streams (Rinne 1996). Bonita and Ellison Creeks were stocked with trout a year after the fire and their population declined 75% within a year of being introduced (Rinne 1996). Large floods continued to occur in the area in the years following the fire, including one in January 1993 that was predicted to be the largest flood in over 300 years (Fuller et al. 1996). A 2005 study concluded that the burned uplands had converted pine-dominated forest to an oak-manzanita (*Arctostyphylos* spp.) dominated forest (Leonard et al. 2015). The combination of the Dude Fire and ensuing floods resulted in changes to Dude, Bonita, and Ellison Creeks both geomorphologically and biologically.

On 10 June 2017, the Highline Fire started inside the almost 27-year-old Dude Fire scar. The fire was smaller at 2910 ha, but again high-severity fire was observed in large parts of the Bonita and Ellison Creek watersheds (Figure 2.2). On 15 July 2017, a monsoon storm produced an estimated 25 to 40 mm of precipitation in a 40-minute period over the Highline Fire scar (National Weather Service 2017). Soils in the watershed were likely saturated from previous, less intense, and less isolated rain events.

This rainfall, which was estimated to be a 5- to 10-year event, resulted in a large debris flow on Ellison Creek with a head that was estimated at 1.5 m high on a downstream swimming hole leading to 10 fatalities (National Weather Service 2017). While other streams in the area may have had flooding, debris flows were only observed on Ellison Creek.

The reburn event may support the vegetation conversion to an oak-manzita (*Arctostaphylos* spp.) dominated system in the uplands of the twice burned watersheds. Observations of sparse pine regeneration have already been suppressed due to elk browsing (Leonard et al. 2015). Much of the pine regeneration within the Highline Fire was probably killed in the fire setting back the recovery and possibly permanently converting the vegetation to resprouting shrubs.

2.3.2 Site Selection

Site selection decisions were made to match previous studies in the study area (Rinne 1996, Medina and Royalty 2002, Leonard et al. 2017). Bonita and Ellison Creek were selected as streams impacted by multiple disturbances including the Dude Fire in 1990, the Highline Fire in 2017, and post-fire floods. Dude Creek was selected as only being impacted by the Dude Fire and the floods that followed. Pine Creek and Horton Creek were selected as unburned reference streams. Each stream had study reaches of about 450 m with five transects within the reach. A total of 25 transects were therefore sampled, spanning once burned, twice burned, and reference streams. Data was collected within a reach 20 m upstream and 20 m downstream from the center of the transect. Transect reaches were selected to include at least one riffle, run, and pool habitat (Medina and Royalty 2002, Leonard et al. 2017)

2.3.3 Data Collection and Analyses

2.3.3.1 Geomorphology

Stream morphology assessments were conducted on all five transects of each stream included in the study. Data was collected in 2011, 2018, and 2019. Geomorphology surveys were conducted using an RL-HA Topcon rotary laser level (Topcon Corp., Tokyo, Japan) with an accuracy of ±25 cm at 50 m. A cross-sectional profile of the channel was created using measurements of vertical displacement along a horizontal line. Measurements were taken starting at a similar reference point at 0 m and then about every 1-3 m based on the topography along the transect. Cross sectional survey data was analyzed using WinXSPRO software (Hardy et al. 2005). Estimated change in cross sectional area was recorded for each transect comparing one year to another. To determine the bedload sediment size or substrate, a pebble count of 300 samples was performed by randomly selecting 100 samples at the first, third, and fifth transects (Bevenger and King 1995).

2.3.3.2 Macroinvertebrates

Macroinvertebrate samples were collected at each transect on all five streams in 2011, 2018, and 2019. Samples were also collected in 2017 on Ellison and Bonita Creek after the fire but before the flood. The sample procedure included using a using a hard-bristled brush to scrape channel substrate within a 0.09 m^2 Surber sample frame. Samples were taken within the transect at similar riffle habitats and preserved in 90% ethanol diluted with stream water. Samples were placed on ice for transportation from the study area to the lab. The sample methodology was equivalent to the process done in the previous studies (Rinne and Medina 1998, Leonard et al. 2017). In 2017, 2018, and 2019 all five samples from each transect were combined into one sample per stream and sent to the Bug Lab at Utah State University for processing. The 2011 samples were processed separately for each transect resulting in five separate datasets for each stream.

The raw data from macroinvertebrate samples were rarefied to a 300-fixed count subsample for each stream per year collected (Cuffney et al. 1993, Moulton et al 2000). The 300 macroinvertebrates were standardized to Operational Taxonomic Units (OTU) based on a generic model from the Utah State Bug Lab. Most of the individuals were standardized at the genus level while the rest used the next coarsest level available. Metrics including Shannon's Diversity, richness, and evenness were calculated for each subsample (Shannon 1948, Pielou 1966). The percent abundance was calculated for each order and individuals that were not identifiable to order were recorded as null. In 2018, Ellison had a total number of 86 macroinvertebrate individuals. This did not allow for rarefaction, and the fixed count was set to 86 for metric calculation.

2.3.3.3 Water Quality and Temperature

General water quality measurements were collected using OAKTON portable meters (OAKTON Instruments, Vernon Hills, Illinois, USA). A pH/CON 450 meter was used to record pH and conductivity. Dissolved oxygen readings were collected using a DO 450 meter. Water chemistry samples were collected on each stream using a grab-sample method in 100 ml bottles. Three samples at every transect were taken giving a total of 15 samples per stream. Samples were stored on ice for transportation to the lab for processing. Samples were processed following US EPA Method 300.0 (Pfaff 1993). Analysis was done using Dionex™ Aquion™ Ion Chromatography (IC) System with a Dionex™ IonPac™ AS4A-SC column (Dionex Corp. Sunnyvale, California, USA). Statistical analysis of water chemistry was done using R statistical software (Rstudio

Team 2015) comparing unburned reference streams to twice burned streams in an ANOVA calculation. The once burned creek, Dude, was left out of the calculation to maintain statistical balance.

Streamwater temperature readings were recorded using HOBO ™ Pro V2 data loggers (Onset Computer Corp., Bourne, Massachusetts, USA). One logger was placed on each stream in similar habitats and set to record every 15 minutes. Multiple loggers were lost or destroyed on Ellison Creek resulting in an incomplete dataset.

2.3.3.4 Stream Photography

One reference stream, Pine, and one twice burned stream, Ellison, had cameras set up for time lapse photography on the channels. Reconyx MicroFire™ cameras were used to capture photos every 15 minutes (RECONYX, LLP, Holmen, Wisconsin, USA). A t-post with reflective tape was placed within the channel for scale and measuring stream height. Reflective tape started at the 30 cm mark and then 10 cm intervals to the top at about 180 cm.

2.4 Results

2.4.1 Geomorphology

Results from cross sectional surveys are represented by change in area on a single transect from one year to another. Some transects were discarded due to inconsistencies in reference points. All the streams had survey data from 2011 and 2018 with at least three transects compared. Pine and Ellison were re-surveyed in 2019 allowing a comparison to 2018 although only two transects from Pine were usable and three from Ellison (Table 2.2).

Ellison Creek, a twice burned stream, had the most change in area and variability of aggradation and degradation from 2011 to 2018. Two of the transects had an average loss of 3.3 m^2 and one transect had aggraded 2.9 m^2 in the 7-year period. The other twice burned stream, Bonita, had three transects with an average loss of 0.6 m^2 and no accumulation of area. Dude Creek, which was only burned in the Dude Fire, had five transects with an equal amount of 0.6 m^2 aggraded and degraded. The unburned reference stream, Horton, had five transects compared with an average aggradation of 0.3 m^2 and 0.3 m^2 degraded. The other reference stream, Pine, had four transects included with 0.6 m^2 aggraded and 0.1 m^2 degraded between 2011 and 2018. The two transects re-surveyed on Pine in 2019 had an average of 0.7 m^2 of aggradation and no degradation when compared to 2018. The three transects on Ellison resulted in no aggradation and 2.4 m^2 of degradation from 2018 to 2019.

All of the streams besides Bonita and Horton Creeks had a change in channel substrate (Table 2.3). The biggest transition occurred in Dude Creek, changing from being dominated by large boulder/bedrock in 2014 to medium cobble in 2019. Ellison had the second largest change, increasing to medium cobble in 2019 from coarse sand in 2014. Pine Creek moved down one size class from large cobble in 2014 to medium cobble in 2019. Bonita Creek had no change in dominant particle size remaining at large cobble for 2014 and 2019. Horton Creek had large cobble as the dominant size class in 2019 and no data was collected in 2014.

2.4.2 Macroinvertebrates

From 2011 to 2018, all streams except Pine Creek showed a decrease of diversity, richness, and evenness values (Table 2.4). When comparing 2018 to 2019 all streams besides Dude Creek presented decreased values for diversity, richness, and evenness. In

2011, Ellison Creek had the highest values compared to any stream and year with a diversity at 3.09, richness of 33, and evenness of 0.88. By 2019, two years after the Highline Fire, Ellison's diversity dipped to 0.98, richness to 10, and evenness to 0.43. Bonita Creek and Horton Creek had low values similar to Ellison's in 2019. Results from Dude Creek showed little change from year to year. Pine Creek had all values increase from 2011 to 2018 and then decrease in 2019.

Diptera (True Flies) were the dominant macroinvertebrate order for most streams in most of the sample years (Table 2.5). Diptera is found in both disturbed and undisturbed streams (Paine and Gaufin 1956), so their use as an indicator of stream health may not be as valuable. Therefore, it was left out of our percent abundance calculations to highlight the number of unique orders of other taxa.

2.4.3 Water Quality and Temperature

The maximum summer streamwater temperature was recorded in 2018 for each stream except Ellison Creek, due to damaged dataloggers. Bonita Creek had a maximum temperature of 22.4 C, Dude 22.1 C, Horton 20.2 C, and Pine 22.9C (Table 2.6). Water quality results for pH indicate that all streams are neutral to slightly basic with a range of 7.96 to 8.60. Pine, Horton, and Dude had super saturated dissolved oxygen values. Ellison and Bonita were slightly below saturation dissolved oxygen levels at 90.4% and 95.4%, respectively. Conductivity values ranged from 230 µs to 315 µs. Water chemistry results comparing unburned reference streams to twice burned streams displayed significant differences ($P < 0.001$) in Nitrate, Chloride, Sulfate, Potassium, and Sodium. (Table 2.7).

2.4.4 Stream Photography

Cameras set up on Pine and Ellison Creek caught multiple events of increased flow on both creeks. The events primarily occurred in monsoon months or winter runoff months. Three sequences of 3 photos were selected to represent increased flow, two of which were on Ellison Creek and one was on Pine Creek (Figure 3). The first sequence on Ellison Creek displays a summer monsoon event with a rapid increase of flow with 15 minutes in between the first and second photo. The flow also quickly dissipates within an hour shown in the final photo of the sequence. The other sequence on Ellison was captured during a winter rain on snow event. This winter flow differs from the monsoon flow as it is sustained for a longer period. This flow also caught bank erosion in progress with the large boulder falling into the channel in the third photo. The sequence on Pine Creek shows a monsoonal flow with a more sustained flow with the first photo captured at 2:15 PM and the final photo with still an increased flow the next day at 7:00 AM.

2.5 Discussion

Ellison Creek cross sectional surveys showed a high degree of variability, with accumulation as well as loss of sediment across transects between 2011 and 2018. It is likely that much of this movement was initiated by the debris flow that occurred following the Highline fire in 2017. Ellison continued to have movement in the channel with an average of 2.4 square meters of degradation from 2018 to 2019, which is a larger change in area than other burned and reference streams saw in the 7-year period from 2011 to 2018. This suggests that the channel continues to show signs of significant instability even with normal seasonal flows. The change in dominant particle size from coarse sand to medium cobble may also reflect continued channel instability. While medium cobble may be better for the long term health of aquatic communities (Duan et al. 2008), it is likely still in flux, and particle size may continue to change with the aggressive seasonal floods observed on Ellison Creek (Figure 2.3). Repeat photography on Ellison shows that much of its riparian vegetation, including small trees and sedges, was removed from 2017 to 2019 (Figure 2.4). The loss of this bank stabilizing vegetation exacerbates continued instability of the stream channel.

Bonita, the other creek that had its watershed burned to a similar extent and severity in the Highline Fire (Table 2.1), did not respond with similar amounts of channel change as observed for Ellison. Bonita Creek's transect survey found an average loss of 0.6 square meters from 2011 to 2018, which was less change in area than Dude Creek and the unburned reference streams. It also had no change in the streambed dominant particle size. Field observations indicated that bankfull floods had occurred (Figure 2.5) but results from the geomorphology data collection suggest that sediment transport was minimal, and the stream remained physically stable due to the intact riparian woody vegetation that survived the both fires.

Dude Creek, which was not affected by the Highline Fire, but was the most affected by the Dude Fire (Leonard et al. 2017), had some movement from 2011 to 2018 but is showing more signs of physical stability. Dude Creek's pebble count shows that the bedrock-dominated channel in 2014 had started to fill with cobble by 2019. This could account for the small amount of cross-sectional change. Grasses and sedges on the banks were also observed on the stream banks, which could also reflect increasing sediment stability.

The reference streams, Pine and Horton, exhibited low amounts of aggradation and degradation from 2011 to 2018 justifying them as good depictions of physically stable stream conditions in the study area. Photos captured on Pine Creek show that in cases of high flows, water levels slowly increase, but when returned to low flow the riparian vegetation and channel substrate remained undisturbed (Figure 2.3). Pine Creek only lowered one size class to medium cobble and Horton's 2019 collection resulted in large cobble as the dominant class, although there was no previous pebble count data to compare on Horton. The minimal change on Pine Creek and identification that Horton Creek's channel substrate is cobble, suggest overall stability of stream health on the reference streams (Duan et al. 2008).

Our observations of riparian vegetation cover loss suggest that temperatures would have increased on Ellison (McGurk 1978). However, due to the repeated flash floods, we were unable to have a data logger capture stream temperature throughout the summer. It is unknown if temperatures increased to unfavorable levels for fish or macroinvertebrates. Bonita Creek had a maximum temperature value similar to the reference stream, Pine Creek and the once burned Dude Creek. The differences of stream chemistry between twice burned and unburned streams indicated some significant changes in nutrient dynamics. Significant increases in nitrate on twice burned streams is consistent with other post-fire studies (Rhoades et al. 2011). The variability of the nutrient levels we found in twice burned streams, are likely due to the initial impacts from the fire as well as the continued geomorphic response of the channel and coupled slopes we observed. It is our assumption that stream chemistry levels will remain disturbed in the twice burned streams for decades after the Highline Fire (Leonard et al. 2017).

The physical stability of a channel has direct impacts on stream habitat function. If a stream is unstable, then macroinvertebrate communities would be expected to show signs of disturbance as well. Our macroinvertebrate results suggest this to be true, but we also saw some signs of variability on streams that had minimal fire and flood impacts to the physical environment. While all streams observed negative macroinvertebrate responses over the studies timeline, the twice burned streams showed the most significant decline.

Macroinvertebrate metrics from 2011 showed that streams had recovered back to reference conditions 21 years after the Dude Fire (Leonard et al. 2017). This allowed for us to use 2011 as a baseline for how the impacted streams were affected by the Highline Fire and subsequent flooding. All the streams had some of their metrics decrease in 2019 which we attribute to the drought conditions which existed that year (Figure 2.6).

The study area had an estimated monsoon season total of 108 mm of precipitation in 2019 compared to 319 mm in 2018, 253 mm in 2017, and an average of 297 mm from 1981 to 2010 (PRISM). While all streams had relatively average metric numbers for 2018, twice burned streams stood out by their response to the drought in 2019. Historic precipitation data from PRISM showed 2019 as the driest monsoon in over 100 years. The National Weather Service reported that for the entire Southwest 2019 was the ninth driest and the third hottest monsoon season in their record (National Weather Service 2019). The results from our study may suggest that twice burned streams are more vulnerable when an additional disturbance such as drought is introduced to the system.

Ellison Creek went from having the highest metrics of all streams in terms of diversity, evenness, and richness in 2011 to having some of the lowest numbers in 2019

(Table 2.4), two years after the Highline Fire. From 2017 to 2019 there were five orders that were removed from the system. There were only four total orders found in 2019, including Diptera. It is also important to note that in 2018 only 86 individual macroinvertebrates were collected in the five samples on Ellison, well below the suggested 300 fixed count threshold, which could result in the metrics being skewed high on Ellison that year. All other streams in 2018 had at least 500 individual macroinvertebrates identified in their samples. The flooding that occurred in 2017 on Ellison Creek may have led to a high rate of macroinvertebrate mortality. The fixed count limit was satisfied for Ellison in 2019, and the diversity, evenness, richness, and order breakdown suggest the stream was severely impacted.

The reference stream Horton also responded negatively in diversity, richness, and evenness although not as significantly as Ellison and Bonita. When looking at the order breakdown, Horton's response to the drought in 2019 stood out as a reference stream when compared to Ellison and Bonita. Horton had a higher richness and the percent abundance of each order was more dispersed than Ellison and Bonita. In 2018, sensitive orders, such as Plecoptera, were present on Ellison and Bonita, but by 2019 they had disappeared. Plecoptera were present in Horton in 2018 and 2019, although their abundance decreased in 2019. This suggests that the reburn and flooding events have removed available habitat for more sensitive species and supports the persistence of short-lived species like Ephemeroptera and Diptera. Other studies have had similar results with short lived species increasing after fire and flood disturbance, while Plecoptera and other species being depressed for up to 10 years (Vieira et al. 2004).

It is probable that the macroinvertebrate communities on Ellison Creek will not return to reference conditions until the stream stabilizes and the aggressive flash floods do not occur. With the repeat burn and floods, it is also possible that Ellison Creek's macroinvertebrate communities will be unable to recover to pre-fire conditions (Arkle et al. 2010). Since Bonita Creek's physical environment was relatively undisturbed by the Highline Fire, it's macroinvertebrate communities may return to reference conditions within a few years if climatic conditions returned to normal. Drought frequency and surface temperatures are predicted to increase (IPCC 2014), so all the streams are vulnerable to macroinvertebrate community changes (Burgmer et al. 2007). Given the results of this study, twice burned streams would especially vulnerable to climate change.

2.6 Conclusion

The Dude Fire in 1990 had severe impacts on these watersheds, but they were on the path to recovery when the Highline Fire occurred in 2017. The combination of the Highline Fire and post-fire floods severely disrupted the recovery process on Ellison Creek. Major geomorphic changes included sediment movement and change in streambed substrate. Macroinvertebrate measurements including richness, diversity, and evenness declined two years following the fire. Bonita Creek, which did not observe coincident debris flow activity, saw a decline in macroinvertebrate metrics, but not a similar geomorphic response. This suggests that a reburn alone may not degrade the streams. However, when reburns and significant flooding events are combined, they could have a lasting effect on physical and biological composition of the stream. We also found that macroinvertebrate communities on twice burned streams are more greatly susceptible to drought. All streams had a negative response to recent drought conditions, but twice burned streams were clearly more distressed two years after the Highline Fire. It is unclear how long increased vulnerability will last and if macroinvertebrate communities can recover in the new climate and fire regime. It is recommended that macroinvertebrate samples be collected in 2020 and continued in the future to evaluate longer term responses.

Results from our study demonstrate the role that established woody and herbaceous riparian vegetation serve in providing physical channel stability. We suggest utilizing available technology such as high-resolution multi-spectral remote sensing to assess riparian vegetation cover following wildfire-related disturbance events and assist land managers in restoration strategies to encourage riparian vegetation recovery. We believe with the increased availability and affordability of drones it may be an option for future projects. Having access to remote sensing technologies such as drones in the study site could allow data to be collected quickly, accurately, and affordably. It would also allow us to replace geomorphology data collection, quantify riparian vegetation loss, and upland vegetation response to reburns.

Results from this study could have implications for other semi-arid watersheds in the region. The Southwest has observed an increasing number of wildfires per season as well as an increase in the size of fires (Dennison et al. 2014). Fires burning more than 100,000 ha are now common, so it is very possible that forest reburns will become more frequent as well. With the timing of monsoon storm activity directly after peak fire season, similar reburn and post-fire flood scenarios as that documented in this study are increasingly probable (Youberg et al. 2011). This study provides insight into how streams react to a reburn event, but there is a lack of other published work exploring this topic. Future research on different headwater streams that have burned twice is needed to support our findings. There are many studies that investigate the effects of wildfire on aquatic systems, therefore we recommend that future research should prioritize twice burned systems.

2.7 Figures

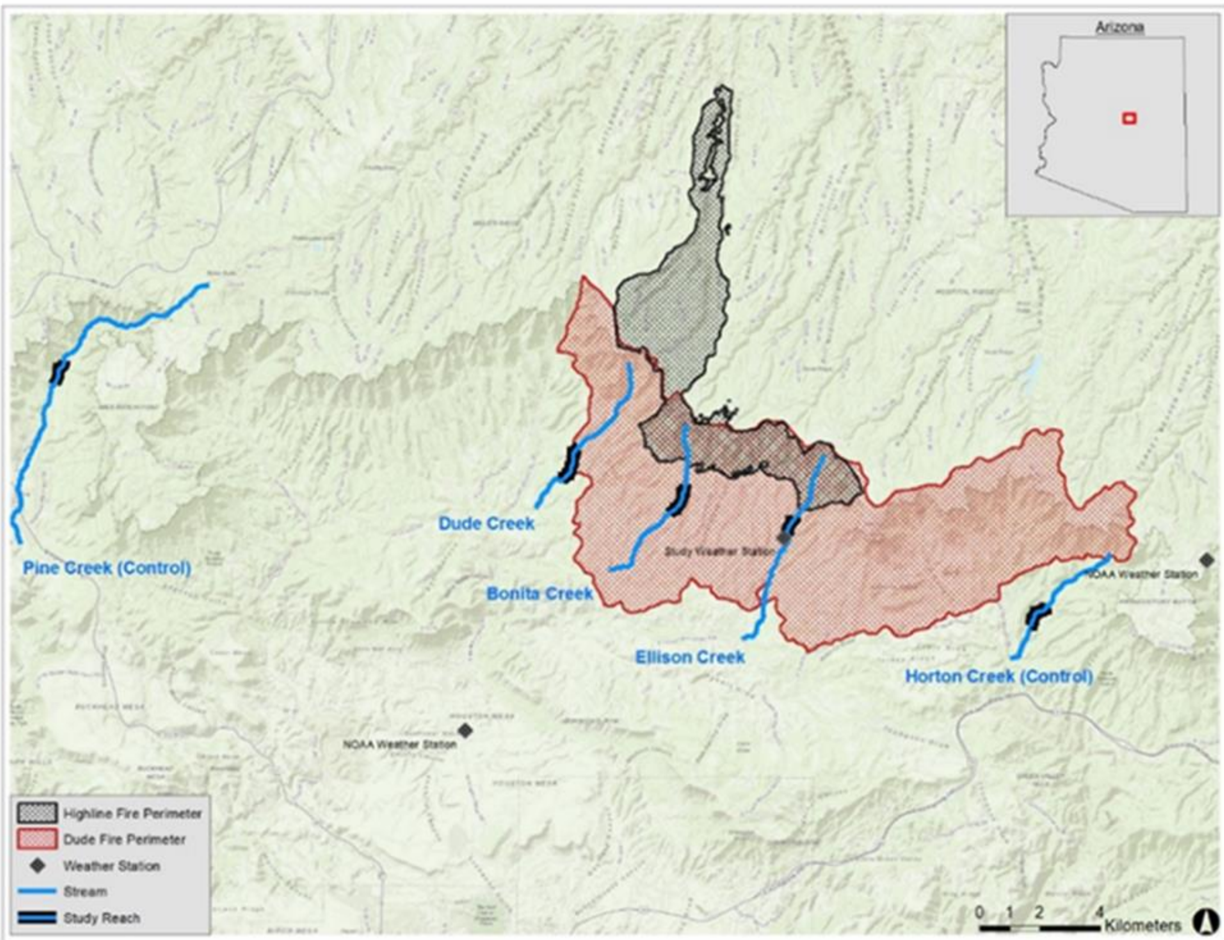


Figure 2.1. Map of the study area in central Arizona along the Mogollon Rim. Included are the five first order streams with approximate locations of the transect sites as well as the fire perimeters of the Dude Fire (1990) and the Highline (Fire 2017).

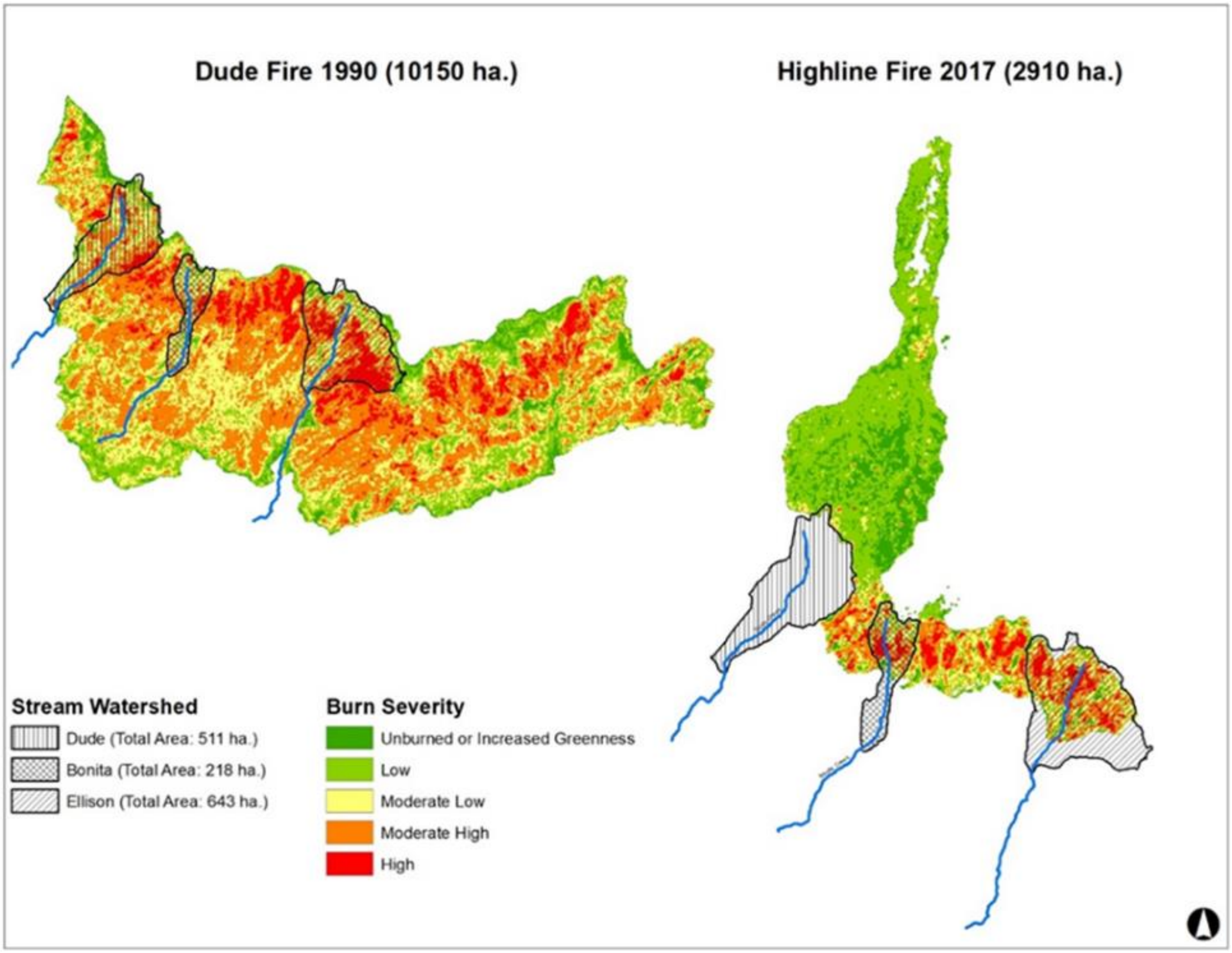


Figure 2.2. Dude Fire and Highline Fire burn severity maps with affected watersheds. Data from MTBS and USFS BAER teams.

Table 2.1. Percentage of burn severity type with affected watersheds for the Dude Fire and Highline Fire.

	Watershed size (ha)	Outside Fire Perimeter	Unburned	Low	Mod-Low	Mod-High	High
Dude Creek, Dude Fire	511	2%	3%	13%	36%	38%	8%
Bonita Creek, Dude Fire	218	0%	1%	17%	49%	29%	6%
Bonita Creek, Highline Fire	218	39%	1%	11%	19%	20%	11%
Ellison Creek, Dude Fire	643	2%	2%	11%	23%	35%	27%
Ellison Creek, Highline Fire	643	37%	2%	8%	19%	24%	11%

Table 2.2. Geomorphology transect surveys showing change in area (m^2) over the number of transects included.

Stream	Years compared	Average Aggradation	Average degradation	Number of transects	Condition
Ellison	2011 - 2018	2.9	-3.3	3	Twice burned
Ellison	2018 - 2019	0.0	-2.4	3	Twice burned
Bonita	2011 - 2018	0.0	-0.6	3	Twice burned
Dude	2011 - 2018	0.6	-0.6	5	Once burned
Horton	2011 - 2018	0.3	-0.3	5	Reference
Pine	2011 - 2018	0.6	-0.1	4	Reference
Pine	2018 - 2019	0.7	0.0	2	Reference

Table 2.3. Results from pebble count data collected in 2014 and 2019. Dominant particle size was recorded from a 300-sample size pebble count.

Stream	2014 dominant particle size (mm)	2019 dominant particle size (mm)	Condition
Ellison	0.5 - 0.9 Coarse Sand	90 - 128 Medium Cobble	Twice Burned
Bonita	128 - 191 Large Cobble	128 - 191 Large Cobble	Twice Burned
Dude	> 10,000 boulder or bedrock	90 - 128 Medium Cobble	Once Burned
Horton	No Data	128 - 191 Large Cobble	Reference
Pine	128 - 191 Large Cobble	90 - 128 Medium Cobble	Reference

Table 2.4. Macroinvertebrate metrics results from 2011, 2018, and 2019. Metrics were standardized using operational taxonomic unit (OTU) with a 300 fixed count. Values in parenthesis are the difference between that year and 2011.

	Shannon's diversity			Richness			Evenness		
	2011	2018	2019	2011	2018	2019	2011	2018	2019
Pine (Reference)	1.86	2.54 (+.68)	2.02 (+.15)	30	32 (+2)	23 (-7)	0.55	0.73 (+.18)	0.64 (+.10)
Horton (Reference)	2.74	2.26 (-.47)	1.16 (-1.58)	33	23 (-10)	13 (-20)	0.78	0.72 (-.06)	0.45 (-.33)
Dude (Once Burned)	2.07	1.90 (-.17)	2.09 (+.02)	28	24 (-4)	25 (-3)	0.62	0.60 (-.02)	0.65 (+.03)
Bonita (Twice Burned)	2.40	1.91 (-.49)	0.95 (-1.44)	27	22 (-5)	9 (-18)	0.73	0.62 (-.11)	0.43 (-.29)
Ellison (Twice Burned)	3.09	2.26 (-.83)	0.98 (-2.11)	33	17 (-16)	10 (-23)	0.88	0.80 (-.09)	0.43 (-.46)

Table 2.5. Percent abundance of order with Diptera excluded. Bolded 0.0% values highlight where an order was no longer present after detection in a prior survey.

	Pine 2011	Pine 2018	Pine 2019	Horton 2011	Horton 2018	Horton 2019	Dude 2011	Dude 2018	Dude 2019	Bonita 2011	Bonita 2018	Bonita 2019	Ellison 2011	Ellison 2018	Ellison 2019
Order Richness	7	9	7	7	8	6	5	6	5	8	6	4	8	7	3
Ephemeroptera	34.8%	36.6%	72.8%	39.8%	17.7%	67.7%	80.0%	61.1%	73.4%	21.4%	75.5%	93.0%	35.7%	38.2%	97.4%
Plecoptera	9.0%	2.8%	4.7%	7.1%	2.8%	1.5%	0.0%	0.0%	0.0%	3.7%	0.6%	**0.0%**	2.7%	1.8%	**0.0%**
Trichoptera	22.5%	5.5%	3.4%	19.9%	53.2%	24.6%	13.7%	25.3%	16.1%	10.3%	8.4%	2.6%	28.6%	47.3%	1.7%
Trombidiformes	3.4%	2.8%	0.9%	5.3%	2.1%	1.5%	2.3%	6.3%	8.0%	2.1%	0.6%	2.6%	4.9%	1.8%	0.9%
Coleoptera	24.7%	42.8%	17.0%	18.1%	20.6%	3.1%	3.4%	4.2%	2.0%	20.2%	12.9%	1.7%	10.8%	7.3%	**0.0%**
Odonata	0.0%	2.8%	0.4%	0.0%	0.7%	**0.0%**	0.6%	1.1%	0.5%	0.4%	1.9%	**0.0%**	0.5%	1.8%	**0.0%**
Veneroida	0.0%	5.5%	**0.0%**	6.2%	2.1%	1.5%	0.0%	2.1%	**0.0%**	41.2%	**0.0%**	0.0%	10.3%	1.8%	**0.0%**
Lepidoptera	1.1%	0.7%	**0.0%**	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Hemiptera	0.0%	0.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Null	4.5%	0.7%	**0.0%**	3.5%	0.7%	**0.0%**	0.0%	0.0%	0.0%	0.8%	**0.0%**	0.0%	6.5%	**0.0%**	0.0%

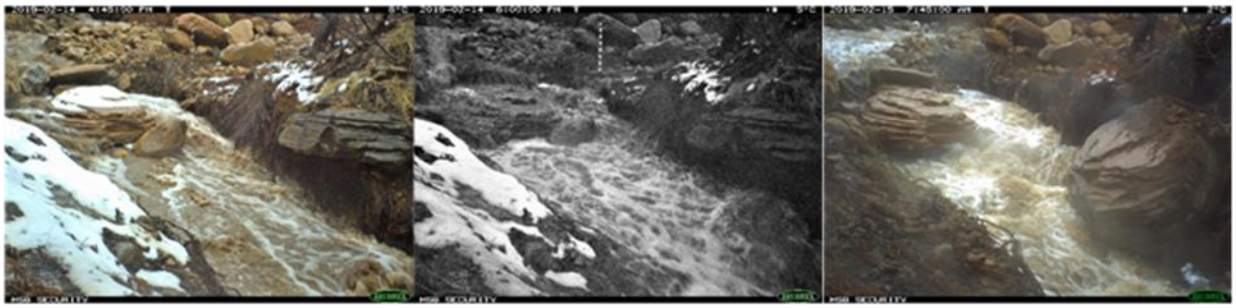
Table 2.6. Basic water quality and temperature for each stream in 2018.

	Twice Burned		**Once Burned**	**Reference**	
	Ellison	**Bonita**	**Dude**	**Horton**	**Pine**
Maximum summer temperature (C)	No Data	22.4	22.1	20.2	22.9
Average conductivity	246.5	236.2	257.5	230	314.5
Average dissolved oxygen (%)	90.4	95.4	105.5	103.9	100.4
Average pH	7.96	8.39	8.37	8.6	8.45

Table 2.7. ANOVA results comparing twice burned streams to unburned streams. Dude Creek, a once burned stream, was left out of the comparison. Arrows indicate if the significant values increased or decreased.

	Unburned mean	**Twice burned mean**	**F value**	**P value**
Flouride	0.9315	0.9255	0.012	0.914
Chloride	11.753	9.781 ↓	15.97	**< 0.001**
Nitrate	0.2805	1.206 ↑	91.85	**< 0.001**
Phosphate	0.4522	0.4174	1.02	0.317
Sulfate	6.0221	1.135 ↓	23.06	**< 0.001**
Ca	23.313	24.104	0.354	0.555
Mg	8.659	7.528	2.8	0.100
K	0.5092	1.3298 ↑	96.03	**< 0.001**
Na	2.124	1.45 ↓	112.1	**< 0.001**

Sequence of flood photos at Ellison Creek above Transect 1. Photo on left taken July 28, 2018 at 3:00 PM. Middle photo taken on July 28, 2018 at 3:15 PM. Photo on right taken on July 28, 2018 at 4:15 PM



Sequence of flood photos at Ellison Creek above Transect 1. Photo on left taken Feb. 14, 2019 at 5:45 PM. Middle photo taken on Feb. 15, 2019 at 7:00 AM. Photo on right taken on Feb. 15, 2019 at 8:15 AM. See large boulder fall from right bank.

Sequence of flood photos at Pine Creek below Transect 2. Photo on left taken Sept. 3, 2018 at 2:15 PM. Middle photo taken on Sept. 3, 2018 at 4:45 PM. Photo on right taken on Sept. 4, 2018 at 7:00 AM

Figure 2.3. Stream photography results from Ellison Creek (top two sequences) and Pine Creek (bottom).

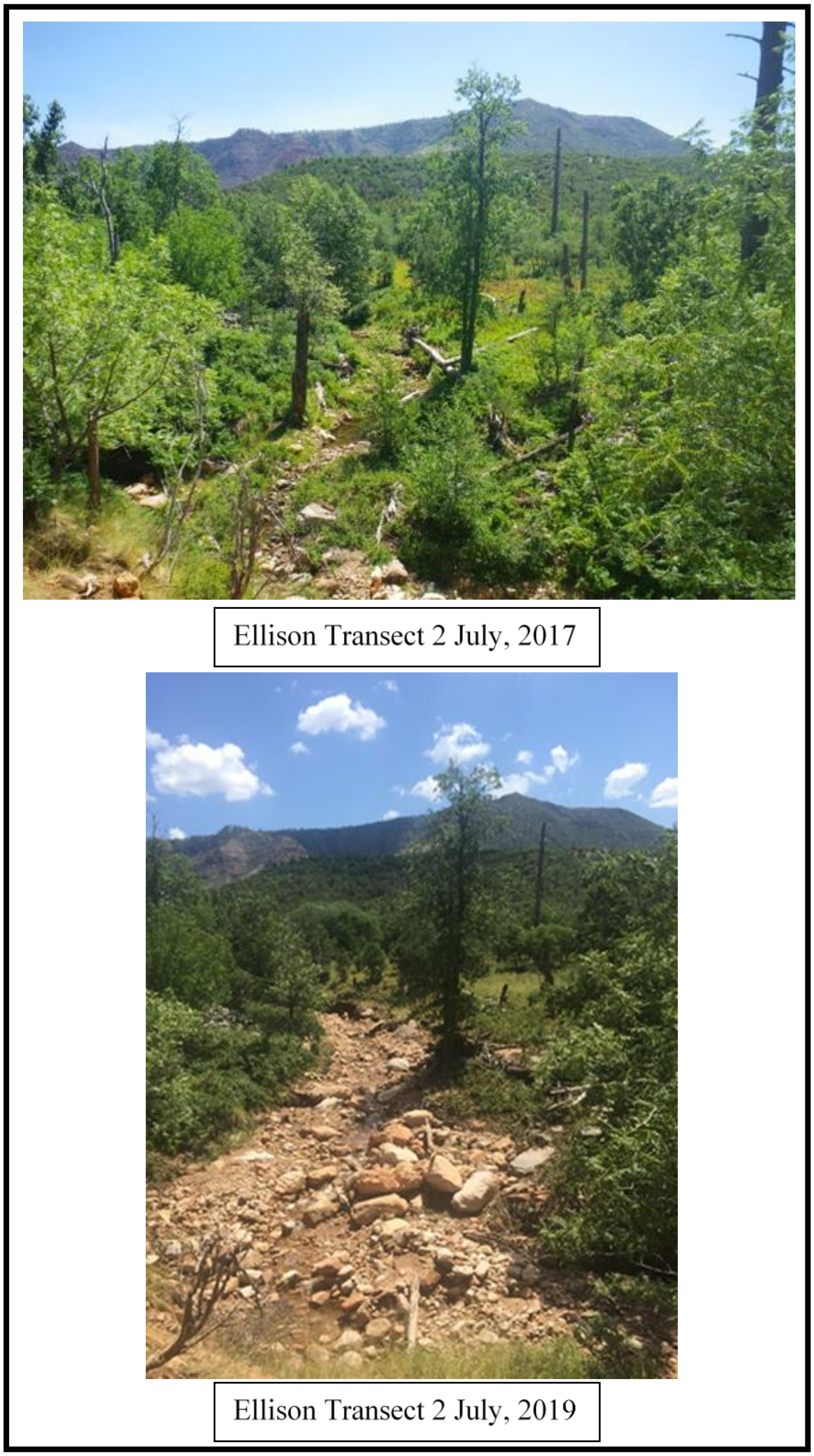


Figure 2.4. Repeat photography of Ellison Creek's transect 2. Top photo displays the stream post-fire, pre-flood. The bottom photo displays loss in riparian vegetation and channel movement.

Figure 2.5. Signs of recent high flows on Bonita Creek. Riparian vegetation disturbed on banks.

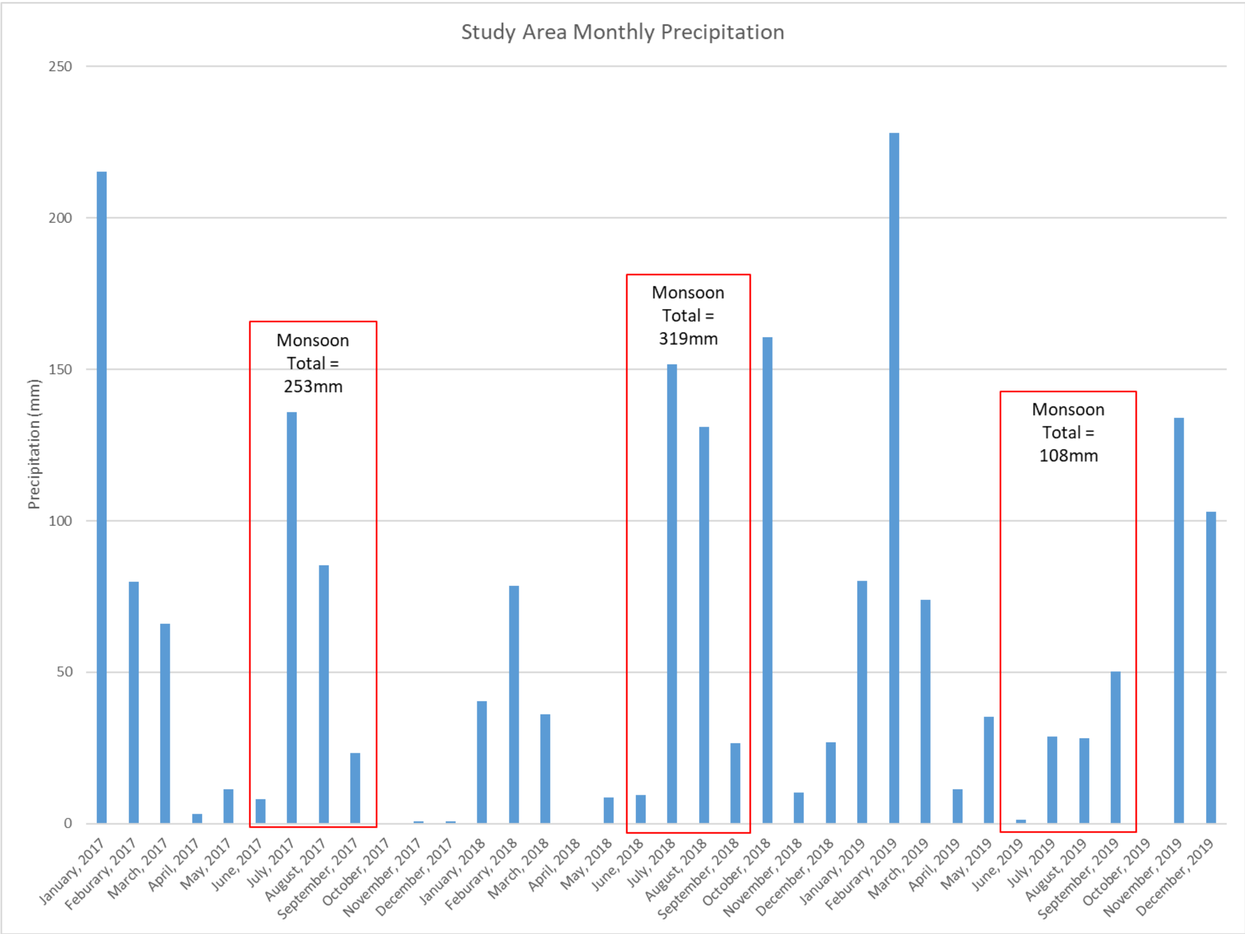


Figure 2.6. Monthly precipitation within the study area. Data from PRISM.

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3 CONCLUSION

3.1 Research Outcomes and Implications

Macroinvertebrate and geomorphic responses to twice burned headwater streams in Central Arizona have been investigated and compared to reference and once burned streams. Results from multiple physical and biological parameters suggest that twice burned streams respond negatively to the second burn and it has the potential to reset recovery up to 27-years following the first fire. Streams that saw a debris flow following the reburn, saw negative responses to macroinvertebrate communities as well as its physical environment. Streams that only experienced the repeat burn saw a negative response to their macroinvertebrate communities while their physical environments remained stable.

In both twice burned streams macroinvertebrate community decline lasted for the two-year period of the study and are expected to continue to show signs of disturbance. In 2019, the second year of our study, the study area had a lower than average total precipitation during the monsoon season. All of the streams saw a decline in macroinvertebrate diversity, richness, and evenness, however the twice burned streams had their values drop down significantly lower for these metrics compared to unburned and once burned streams. These findings suggest that twice burned streams are more vulnerable to drought than reference or once burned streams.

Physical disturbance was limited to the stream that experienced debris flow and flooding following the second fire. There was a large change in cross sectional area and loss in streamside vegetation attributed to the debris flow in 2017. We continued to see large changes in area in years without a debris flow event suggesting that the stream is now unstable. Normal seasonal flows now have the potential to move large amounts of sediment. We expect this stream to continue to be unstable until streamside vegetation returns, and the stream has reached equilibrium.

Results from this study could have implications for other semi-arid watersheds in the region. The Southwest has observed an increasing number of wildfires per season as well as an increase in the size of fires. Fires burning more than 100,000 ha are now common, so it is very possible that forest reburns will become more frequent as well. With the timing of monsoon storm activity directly after peak fire season, similar reburn and post-fire flood scenarios as that documented in this study are increasingly probable. This study provides insight into how streams react to a reburn event, but there is a lack of other published work exploring this topic. Future research on different headwater streams that have burned twice is needed to support our findings. There are many studies that investigate the effects of wildfire on aquatic systems, therefore we recommend that future research should prioritize twice burned systems.

3.2 Recommendations for Future Research

Considering the outcomes of this study and the history of research in the area, the following recommendations were made for future studies.

- Continue to collect macroinvertebrate samples on all streams. Since streams have responded negatively to draught in the last year sampled for this study, repeat samples would provide information on how long increased vulnerability would last. It is also recommended to increase the frequency of samples per year and include samples in different seasons throughout the year.

- Future studies on the effects of the repeat burn on the vegetation should examine vegetation response in areas that were burned in both fires. It would be important to investigate how combinations of burn severities from both fires affect vegetation composition.
- Since riparian vegetation loss was observed on Ellison Creek, it is recommended to examine options to quantify vegetation loss. We looked into using available NAIP and Sentinel imagery, however the resolution was not fine enough to catch the vegetation loss. Other options we have explored would be to use drones to capture changes in vegetation. We believe it is possible to fly a drone over the study reaches to produce high resolution images to quantify vegetation change. High resolution drone imagery would also provide opportunities for additional information for other factors in the physical environment of the streams.
- As lidar technology becomes increasingly available and affordable, we could use drones to also capture geomorphic change on the streams. This could allow a quicker and potentially more accurate geomorphology data collection method. Terrestrial or drone-based lidar data could be used to replace or supplement cross sectional survey data and pebble count data.
- Utilizing citizen science programs to involve more local interest in these sensitive stream ecosystems. Using citizen science programs could increase the knowledge and support from the local communities who live or recreate in the study area. It

could also potentially provide addition data to continue monitoring the study sites as well as expand the study reach. A new program could be created, or existing programs could be adapted for use in the study area. Examples of an existing program that may work include the Arizona Water Watch program developed by the Arizona Department for Environmental Quality.

4 APPENDIX Supplementary Material

4.1 Burn Severity Mapping Methods:

Burn severity mapping was done using ESRI ArcGIS software and data from the Monitoring Trends in Burn Severity (MTBS) and US Forest Service Burned Area Emergency Response (BAER) teams. Burn severity classes were standardized using the USGS document: The Normalized Burn Ratio (NBR) - Brief Outline of Processing Steps (Figure 4.1).

SEVERITY LEVEL	ΔNBR RANGE
Enhanced Regrowth, High	-500 to -251
Enhanced Regrowth, Low	-250 to -101
Unburned	**-100 to +99**
Low Severity	+100 to +269
Moderate-low Severity	+270 to +439
Moderate-high Severity	+440 to +659
High Severity	+660 to +1300

Figure S4.1. USGS burn severity classes

4.2 Additional Macroinvertebrate Figures:

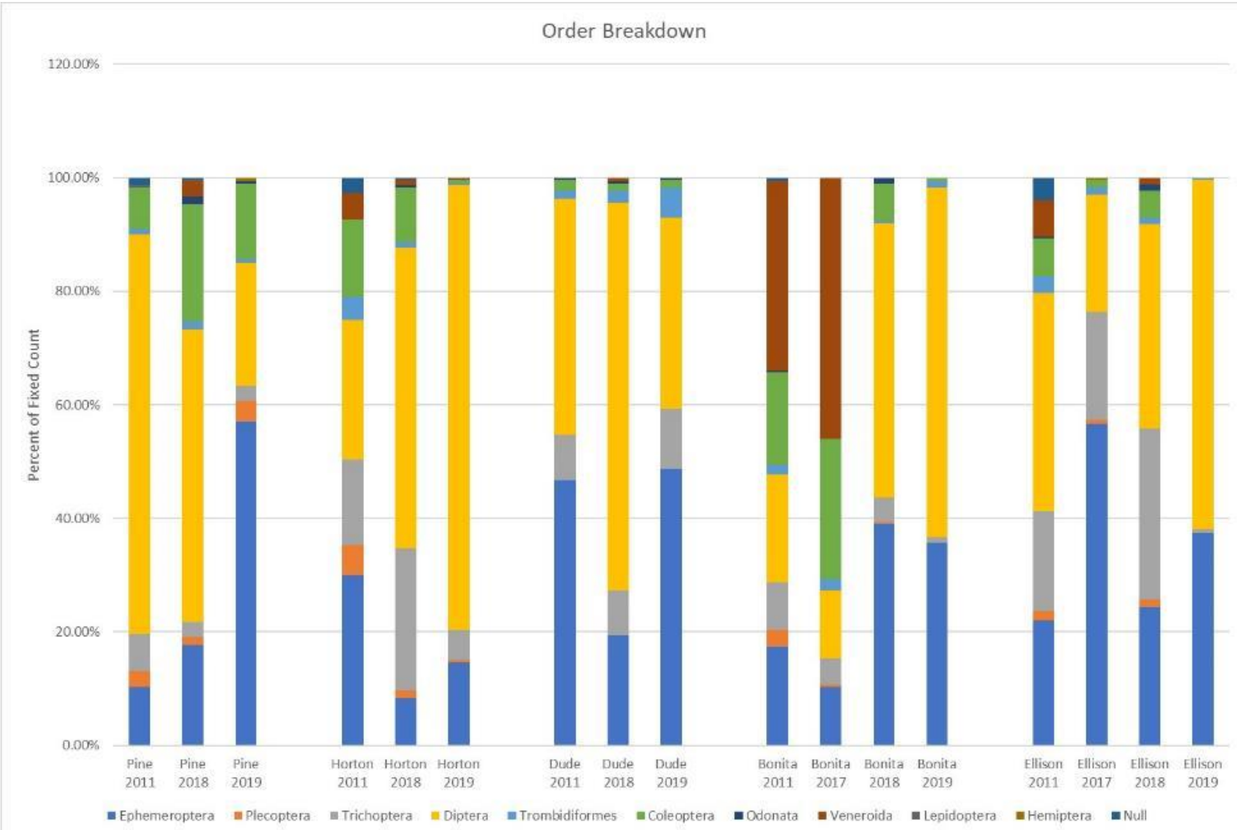

Figure S4.2. Order breakdown for all streams including grab samples from 2017.

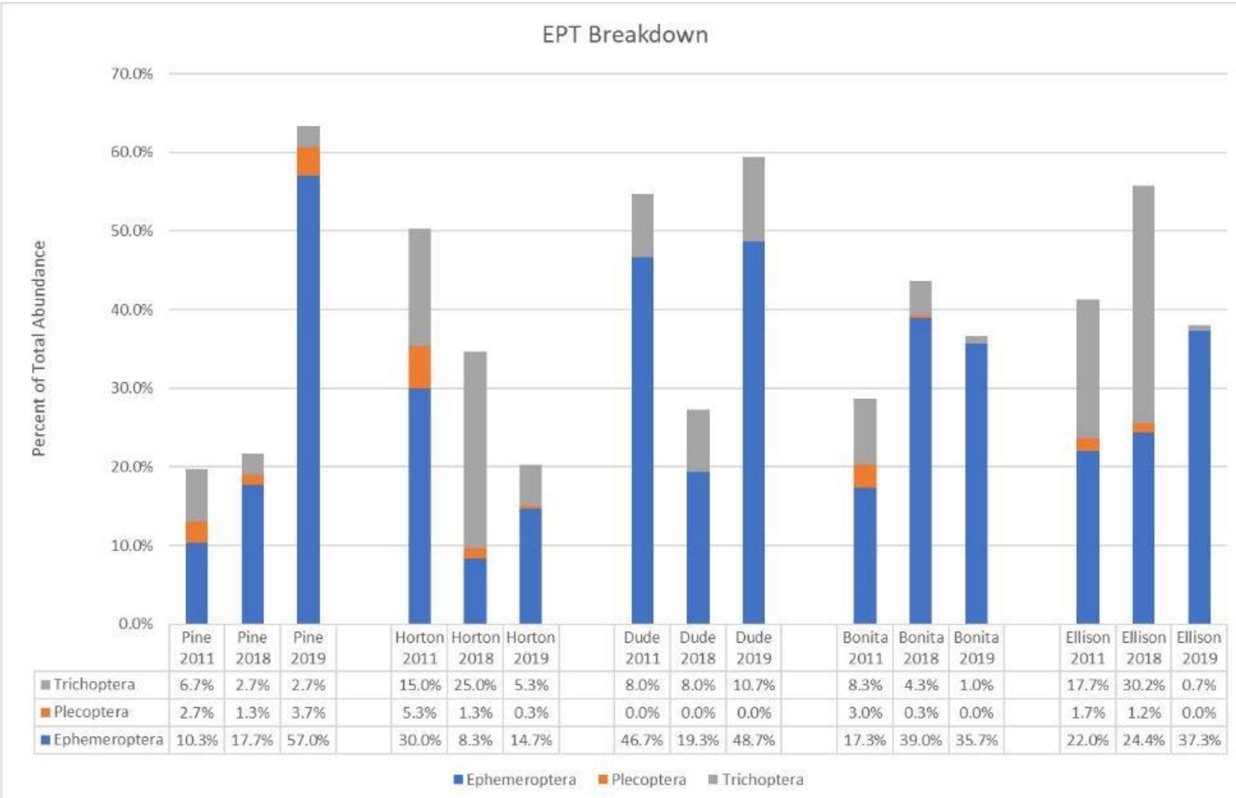

Figure S4.3. Percent of total abundance for EPT.

4.3 PRISM Climate Data Input Point:

A point in the center of the study was chosen for the input point for PRISM climate data download. The resolution of input point size was four kilometers

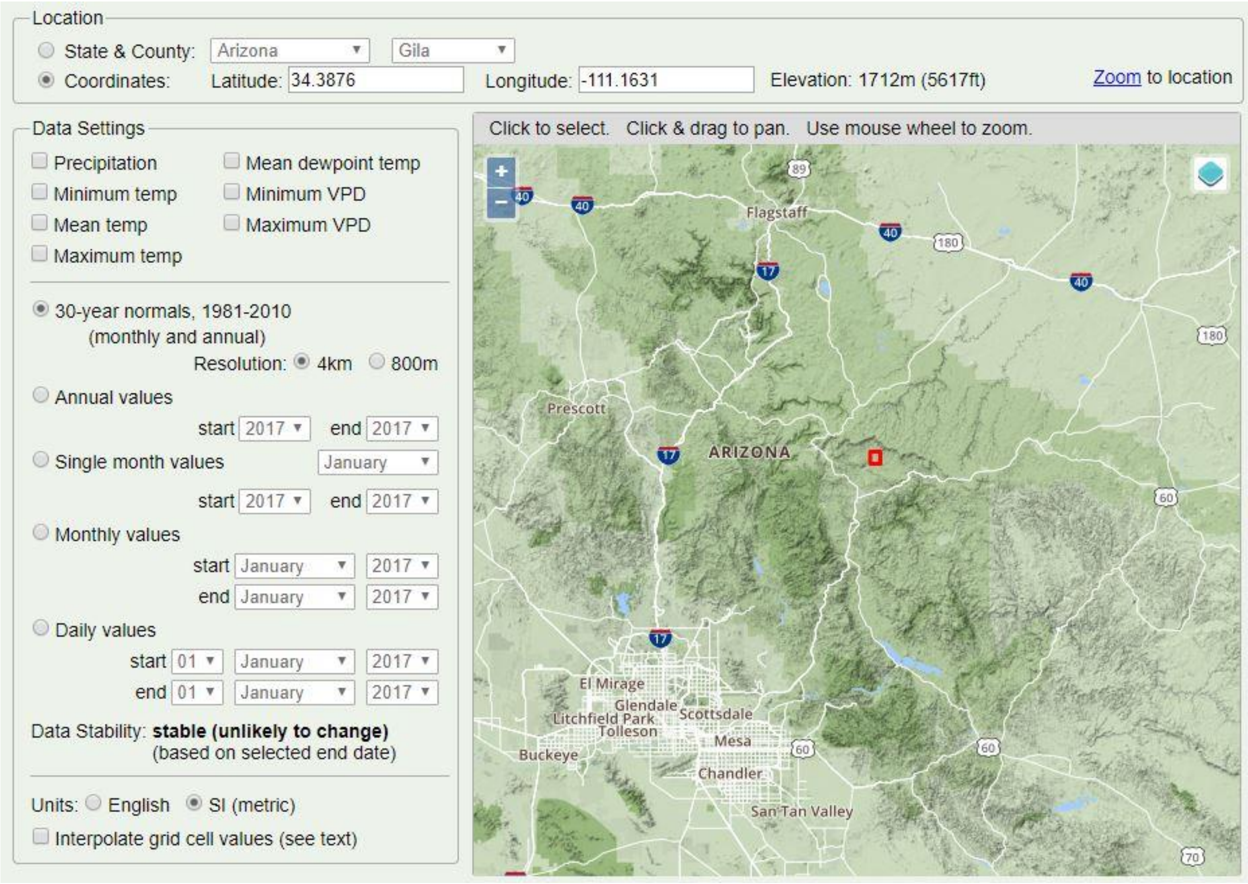

Figure S4.4. Input point for PRISM climate data denoted by the red square. Coordinates of the point are displayed in the top of the image.

4.4 GPS Coordinates of Transect Sites:

Table S4.1. GPS coordinates of the transects included in this study.

MAP DATUM: NAD 83 **POSITION FORMAT: UTM UPS**

Site Name	Elevation	Date		
PINE 1 11	5763 ft	23-MAY-11 10:47:16AM	12 N 459569	3809076
PINE 2 11	5787 ft	23-MAY-11 10:53:57AM	12 N 459613	3809203
PINE 3 11	5808 ft	23-MAY-11 11:05:38AM	12 N 459613	3809266
PINE 4 11	5800 ft	23-MAY-11 11:17:04AM	12 N 459642	3809347
PINE 5 11	5831 ft	23-MAY-11 11:29:22AM	12 N 459640	3809439
Dude 1 11	5722 ft	30-JUN-11 1:42:26PM	12 N 476686	3806394
Dude 2 11	5734 ft	30-JUN-11 12:48:05PM	12 N 476687	3806520
Dude 3 11	5774 ft	30-JUN-11 11:39:02AM	12 N 476706	3806691
Dude 4 11	5789 ft	30-JUN-11 11:29:44AM	12 N 476775	3806787
Dude 5 11	5785 ft	30-JUN-11 9:25:22AM	12 N 476904	3806900
Bonita 1 11	6005 ft	26-MAY-11 1:14:29PM	12 N 479841	3804646
Bonita 2 11	6025 ft	26-MAY-11 1:40:11PM	12 N 479903	3804701
Bonita 3 11	6036 ft	26-MAY-11 2:03:54PM	12 N 480044	3804791
Bonita 4 11	6104 ft	26-MAY-11 2:31:19PM	12 N 480226	3805009
Bonita 5 11	6134 ft	26-MAY-11 3:13:18PM	12 N 480256	3805079
Ellison 1 11	6110 ft	26-MAY-11 9:52:49AM	12 N 483785	3804058
Ellison 2 11	6132 ft	26-MAY-11 10:14:31AM	12 N 483828	3804111
Ellison 3 11	6151 ft	26-MAY-11 10:40:09AM	12 N 483853	3804157
Ellison 4 11	6150 ft	26-MAY-11 11:20:27AM	12 N 483871	3804208
Ellison 5 11	6175 ft	26-MAY-11 11:12:36AM	12 N 483857	3804305
Horton 1 11	5753 ft	24-MAY-11 9:47:17AM	12 N 491820	3800817
Horton 2 11	5734 ft	24-MAY-11 10:13:23AM	12 N 491861	3800908
Horton 3 11	5759 ft	24-MAY-11 10:49:59AM	12 N 491893	3801066
Horton 4 11	5753 ft	24-MAY-11 11:48:35AM	12 N 491969	3801207
Horton 5 11	5782 ft	24-MAY-11 12:34:48PM	12 N 491985	3801286

4.5 Supplemental Files Directory:

Zipped folder named SupplementalFiles.zip. Stream photography would not upload in one folder due to the large files.

Folder: CrossSectionFiles

A. 2011 (folder)
    a. .txt files of 2011 cross section survey data. Data formatted for use in WinXSPRO software.
B. 2018 (folder)
    a. .txt files of 2018 cross section survey data. Data formatted for use in WinXSPRO software.
C. 2019 (folder)
    a. .txt files of 2019 cross section survey data. Data formatted for use in WinXSPRO software.
D. TransectCompare.xlsx
    a. Excel spreadsheet with summarization of transect data.

Folder: GPS_TransectLocations

A. SITE LOCATIONS.xlsx
    a. Excel spreadsheet with GPS locations of transect sites.

Folder: HistoricOverviewFigureData

A. CSV (folder)
    a. .csv files for overview figure creation. Files meant for input in ArcGIS software for figure creation.

Folder: HoboStreamTempLogger

A. StreamTemperatureData (folder)
    a. Excel files for each stream temperature data.

Folder: Macroinvertebrates

A. BugLabFiles (folder)
    a. Excel files received from the Bug Lab. Email screenshots in .JPG format with metric calculation assistance.
B. MetricCalculation (folder)
    a. Excel files with metric calculations.

Folder: PebbleCount

A. PebbleCount2019.xlsx
    a. Excel spreadsheet with pebble count data

Folder: PRISM_WeatherData

A. RawPRISM_Files (folder)
    a. Historic 1 month PRISM .csv files.
B. PRISM_FilesAndFigures (folder)
    a. Excel .xlsx files with organized weather data and figures.

Folder: TransectPhotos

A. 2018 (folder)
    a. Photos from each transect in 2018.
B. 2019 (folder)
    a. Photos from each transect in 2019.

Folder: WaterQuality

A. .xlsx and .docx files with water quality data.

Separate folders for stream photography uploaded to ProQuest. All are collections of photos in .JPG format. Here is a list of the stream photography folders: Ellison2018_1.zip, Ellison2018_2.zip, Ellison2018_3.zip, Ellison2018_4.zip, Ellison2019_1.zip, Ellison2019_2.zip, Ellison2019_3.zip, Ellison2019_4.zip, Ellison2019_5.zip, Ellison2019_6.zip, Pine2018_1.zip, Pine2018_2.zip, Pine2018_3.zip, Pine2018_4.zip, Pine2019_1.zip, Pine2019_2.zip, Pine2019_3.zip, Pine2019_4.zip, Pine2019_5.zip, Pine2019_6.zip