The Effect of Sediment Deposition on Sierra Riverine Ecosystems Following High-Intensity Fires

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The Tuolumne River Watershed recently experienced several large, anthropogenic forest fires including the Rim Fire. These hot, intense fires contributed to increased fine sediment in the Clavey and Mainstem Tuolumne rivers. The deposition and accumulation of fine sediment in various hydrologic zones affected aquatic biota such as benthic algae and macroinvertebrates by reducing substrate habitability through increased siltation. An adaptive management strategy that includes controlled burns, increased fire safety near development, and removal of heavy fuel loads would help reduce occurrences of these unnaturally-amplified large fire events and protect the integrity of the river's flow regime, habitats, and ecological communities.

Introduction

For thousands of years, the periodic presence of fire has played a crucial role in shaping the ecosystems of the Sierra Nevada mountain range in California. Fire affects ecosystems on a multitude of levels that, when viewed as a whole, prove to be quite complex, interdependent and dynamic. When fire occurs in a controlled manner it helps rejuvenate the natural habitat by recycling minerals, clearing out built up debris, and encouraging the development of new plant communities. The fire suppression policies enacted by local and federal agencies over the past century have not only disrupted the cycle of natural fires in the Sierra Nevada region, but have also resulted in a buildup of forest debris and alterations to species composition within upland habitats. By restoring the role of fire within the Sierra Nevada, fuel loads may be reduced and many of the natural ecosystem processes may be restored.

Historically, fire was a primary disturbance that sustained Sierra Nevada ecosystems. Prior to 20th century suppression efforts, fire return intervals were recorded at less than 50 years and more commonly less than 20 years (McKelvey, 1996). Within Yosemite National Park, American Indians once set fires to promote growth of plants they relied on for food, medicine, and producing materials for baskets and shelter construction. Lightning strikes were also a source of natural fires that prevented overgrowth and dense forests. By 1970, scientists realized the negative impacts fire suppression methods were having on the health of the forests. As a way to reintroduce fire to the forest ecosystems, land managers, such as the National Park Service, have utilized prescribed burns for the past 40 years to reduce fuel loads and for ecological restoration purposes (Than, 2013).

On August 17, 2013 a large wildfire, named the "Rim Fire," started within the central Sierra Nevada region in the Tuolumne River watershed to the west of Yosemite National Park. The Rim Fire was the third largest in California's history and burned roughly 257,000 acres of forest (Lopez, 2014). Started by a hunter's illegal fire, the Rim Fire was exacerbated by weather conditions at the time that included a heat wave and drought. Despite the efforts of over 5,000 firefighters, the fire was estimated to have caused $54 million in damages (Howard, 2014). While the human-incurred costs were extensive, the impacted ecosystem bore the most significant losses.

One of the largest ecosystem stressors from large fires is increased quantities of fine sediment eroded from bare and charred hill slopes that is then transported to, and through, river systems following the fire. This research paper aims to utilize previous knowledge regarding fire effects on sedimentation, post-fire stream hydrology, biotic impacts, and fire management strategies to assess whether increased sedimentation from the Rim Fire has affected aquatic resources in the Tuolumne river.

Sedimentation Effects from Fire

Fires can have devastating effects on soil structure and slope stability. Large, hot fires burn away soil organic matter, break up soil aggregates, and alter the hydrogeologic properties of effected areas. This in turn can cause soil mobilization and erosion from hillslopes that deposit sediment downstream. Because of this influx of sediment and the altered hydrologic properties of the watershed soils, large fires can significantly change the hydrograph of a stream in the short- and long-term as well as decrease the habitability of the stream.

Fires decrease soil organic matter (SOM), causing detrimental effects on nutrients and soil stability. Organic matter in soil is usually concentrated within the upper region of the soil as litter, duff, and humus. SOM stores nearly all of the nitrogen, sulfur, and phosphorus contained within the soil (DeBano, 1990). Other nutrients such as ammonium, potassium, and calcium rely on the high cation exchange capacity of SOM. Cations released during a fire replace hydrogen ions which then leach out in solution. Salt-rich ash also leaches out salt cations from the soil. The overall effect is a large increase in soil pH (Bruhjell and Tegart, 2013). SOM also helps aggregate soil particles, which increases the infiltration rate of the soil. Root systems act as a stabilizing structure that hold smaller soil particles in place and create pathways for water movements within the soil profile. Degradation of lignins and hemicellulose can occur at temperatures as low as 130^{o}F, and at 280^{o}F, organic matter starts to degrade exothermically causing chemical dehydration of cellulose and a loss of about 35% of the total soil weight (DeBano, 1990). As temperatures increase, the combustion of carbon becomes more rapid and the soil turns to char.

The removal of SOM causes large amounts of sediment to be mobilized and an increased hydrophobicity of the upper soil layer. At around 350^{o}F, distilled aliphatic hydrocarbons mobilize and condense on soil particles within the first 5cm of the soil profile forming a hydrophobic layer that impedes infiltration (Bruhjell and Tegart, 2013). The hydrophobic nature of the soil is exaggerated for coarse soils such as soils forming on decomposed granites and grus. These soils are also usually more susceptible to erosion. The decrease in infiltration usually only lasts for one rainy season but for exceptionally dry years, such as that currently in the Sierras, the layer can persist for several years. The overall effect of this decreased infiltration is an increase in Hortonian overland flow,increased erosion and rill formation (Wells, 1981).

Once soil structure is degraded, erosion rates are dictated by precipitation intensity and timing, wind, slope, aspect, and vegetation recovery time. Exposed soils are susceptible to raindrop splash, rill, and sheet erosion, dry ravel, mass wasting, and soil creep (Clark, 2001). On most moderate slope, post-fire granitic soils, erosion rates range from about 23 to 52 tons per acre (Wright and Bailey, 1982). This is up to 180 times greater than pre-fire conditions and even after 7 years, erosion rates can be 12-fold greater than previous conditions (Helvey et al., 1985). This massive influx of sediment has a huge effect on the channelized hydrology of a watershed.

Post-Fire Hydrology

The increased sediment loads into rivers post-fire increases stream viscosity, bank scouring, and channel aggradation, and deposits in large volumes into pools and other low-velocity hydrologic units. When erosive forces in the terrestrial environment lead to increased deposition in riverine systems, the river's own erosive capacity is enhanced. This occurs as the water column begins moving larger loads of sediment, increasing the viscosity of the water due to the large input of mass. Higher viscosity water in turn has greater potential energy and readily scours river banks at a higher rate than usual. Increased scour destabilizes banks, further adding more sediment into the river system (Sternburg 1961). Simultaneosly, natural deposition zones, usually characterized as low slope, low velocity reaches of the stream, will collect sediment at a higher rate. This sediment build up is known as aggradation and over time can lead to the damming of rivers if flow velocities are not high enough to move the sediment along. Together, localized scouring and aggradation can drastically change the channel shape and flow regime.

The natural flow regime is also altered by fire-induced sedimentation as routing times during storm events are increased. With healthy vegetation and soil structure, hill slopes are characterized as having a "rougher" surface. When a heavy precipitation event occurs, water hitting this rough surface is intercepted, diverted, and uptaken, resulting in a slower path from where rain makes contact with the ground to when water enters the river channel. Burned earth lacks many of these features and the ground is much smoother, allowing rainwater to run down the hill slope fast and unimpeded. This phenomena results in spiked rapidly changing hydrographs, with smooth ground surfaces producing high rates of discharge early in storm events as opposed to a gradual increase and decrease in discharge over a greater time span. The spikes, or flashiness, of storm events in burned areas can yield flash-like floods that can dramatically change stream quality. The abrupt input of large quantities of water, often carrying eroded fine sediment, will proceed to move through the channel at heightened discharge velocities (Murphy et.al., 2012). As a result, not only is stream hydrology and habitability altered by post-fire sediment loads but also many aquatic organisms are heavily impacted as well.

Effects on Biota

Sediment deposition along streams affects primary producers, macroinvertebrates, and fish in multiple ways, consequently leading to a decrease in biodiversity and an ecosystem shift favoring sediment-tolerant species. Some impacts are unique to each trophic level, while others span all aquatic organisms. Primary producers, such as periphyton at the base of the river food chain, become stressed during increased sediment loads due to impeded light penetration from suspended sediment in the water column, reduced cell organic content, and decreased ability to attach to the substrate. Aquatic macrophytes suffer abrasion of their stems and leaves due to sediment carried through the water, especially at higher velocities, and all primary producers can be smothered when severe sediment loading is present (Wood et.al., 1997). The damage and loss of primary producers in a stream decreases food sources for higher trophic levels and can alter stream hydraulics and habitat diversity.

Macroinvertebrates are impacted by declines in primary production as well as altered substrate composition, increased instability of the substrate, lower oxygen concentrations in the water column due to suspended sediment, and increased deposition on gill structures (Wood et.al., 1997). The Ephemeroptera, Plecoptera, and Trichoptera orders of macroinvertebrates, commonly called “EPT,” are especially impacted by these altered conditions. EPT taxa generally rely on high availability of oxygen, prey sources, and primary producers. One specific hardship is the loss of interstitial refuge space. Many macroinvertebrates use these interstitial spaces between course sediment to hide from predators. When excess fine sediment is introduced into the system, these spaces are filled, and macroinvertebrates are inclined to leave their original niche to find safety (Harrison et.al., 2007). Some taxa, such as Chironomidae, Oligochaeta, and Sphaeridae, are adapted to take advantage of fine sediment and flourish during sedimentation events in which EPT taxa decline. Oligochaeta and Sphaeridae are able to burrow into the sediment for shelter, while Chironomidae make use of the fine sediment to construct cases and tubes to live inside (Wood et.al., 1997). Unfortunately, EPT taxa are the most productive food sources for aquatic fishes, and their presence or absence plays a vital role in the suitability of a space for fish habitation (Harrison et.al., 2007).

Sedimented river reaches and murky waters can become taxing and inhospitable for fish due to the loss of productive prey, such as EPT taxa, reduced hunting ability of visual feeders, and clogged gill rakers and filaments. Sediment also disrupts fish during their most vulnerable egg and larval life stages. As sediment fills interstitial spaces between course sediment, there is a lack of intergravel flow necessary to oxygenate eggs. This reduces egg survival and can prompt premature hatching of larval fish, increasing the likelihood of mortality from predation. Extreme sedimentation events can entomb eggs, preventing them from developing. Additionally, sediment loading of ideal spawning gravels decreases the amount available spawning habitat, leaving few spaces for egg deposits (Wood et.al., 1997). Eventually, large quantities of fine sediment in a stream will alter the ecosystem to favor more tolerant primary producers and macroinvertebrate taxa, displace EPT orders, and alter fish communities. The case study below details the sediment and biotic composition at several locations within the Tuolumne River watershed following the extensive Rim Fire.

Case Study: Yosemite’s 2013 Rim Fire

Research Question

> Did the Yosemite Rim Fire increase fine sediment deposition within the Tuolumne watershed? And if so, did increased fine sediment along the streambed alter the composition and distribution of primary producers and macroinvertebrates?

Methods and Procedure

Three different methods at a series of study sites were used in order to determine the amount of sedimentation within the Tuolumne River and the characteristics of the silt-sized sediment deposited (Table 1; Figure 1). The first was a V* ("V star") measurement outlined by Hilton and Lisle (1993). V* was used to find the total volume of fine sediment being deposited within pools in relation to the total volume of the pool. A foil method developed by Dudley et al. (2001) was used to determine the thickness of fine sediment deposited on embedded cobbles within the main channel of the Tuolumne. Lastly, sediment samples were taken from the Tuolumne River within Tuolumne Meadows and around the confluence of the Clavey River and assessed for percent organic content. Samples from freshly deposited material were dried, weighed, burned in a muffle furnace at greater than 500°F to remove any organic material, and weighed again. Seven sampling locations were chosen in the upper and middle portion of the watershed: three within Tuolumne River, three on the Clavey River, and one on the mainstem Tuolumne River above Clavey Falls.

Table 1: Sample site locations and type of sample data collected.

	Upper Tuolumne Meadows	Middle Tuolumne Meadows	Lower Tuolumne Meadows	Upper Clavey	Middle Clavey	Lower Clavey	Mainstem Tuolumne	Lower Tuolumne
SEDIMENT								
V*		x	x	x	x	x	x	
Tin Foil			x			x	x	
Sediment Burning	x	x	x				x	
BIOTIC								
Algae	x	x	x			x	x	
Macro-inveretbrates	x	x	x	x		x	x	x

V* measurements were completed using a standard graduated V* probe constructed from rebar. The probe was driven by hand into fine sediment deposits accumulated within pool habitats. The Tuolumne Meadows and Clavey River V* measurements included three or more parallel transects per pool depending on the pool length, with the middle meadows reach including four transects and the middle Clavey reach including seven transects. The mainstem Tuolumne River measurement was taken immediately above the Clavey confluence on river left.

Figure 1: Location of Clavey River V* Sample Sites. Sites B-F were surveyed pre-fire, and sites 1-3 were surveyed post-fire.

Biotic data was collected throughout the Tuolumne Watershed at a series of sites, many of which overlapped with sediment sampling locations (Table 1). Algae were chosen as an example of a potentially impacted primary producer, and benthic macroinvertebrates were sampled to determine the relative abundance of sensitive versus tolerant taxa.

Algae was collected by randomly selecting cobbles embedded in the stream and washing exposed algae from the surface into a sealable plastic bag. In the laboratory, these samples were dried, weighed and burned to determine Ash-free Dry Mass (AFDM). Macroinvertebrate sampling was completed using the technique described by the EPA's Standard Operating Procedure for Macroinvertebrate Kick Net Sampling (Snook 2002). For the purposes of this study, the abundance of Ephemeroptera, Plecoptera, and Trichoptera (or "EPT") taxa were compared to sediment tolerant taxa: Chironomidae, Oligochaeta, and Sphaeridae. Fish were not directly sampled for abundance; however, results from sedimentation measurements and macroinvertebrate distributions provided insight as to whether suitable fish habitat was present or not throughout the sampled reaches of the river.

Future studies may involve hydrologic data, such as discharge and turbidity to enhance sediment and biotic findings; however, such sampling was outside the scope of the research for this study. Sediment and biotic data were prioritized because they provided the best representation of how the fire has changed habitability of the system.

Results & Discussion:

While data was collected from a variety of locations throughout the Tuolumne watershed, data collected from the Clavey River and the mainstem Tuolumne River in the

Figure 2: Thickness of deposited sediments on cobbles within the Clavey and mainstem Tuolumne

Rim Fire's burn zone provided the greatest information regarding the effect of fire. Cobble siltation samples using the foil method indicated that the mainstem Tuolumne experienced high siltation in the steam bed, with 162.06 g/m^2 as compared to 17.84 g/m^2 in the Clavey River sample sites (Figure 2). The percent of organic matter in the sediment collected through bulk soil sampling and burning shows that the mainstem Tuolumne River has a six-fold increase in organic matter compared to the Tuolumne Meadows sites (Figure 3). This is consistent with findings from Helvey et al. (1985) that erosion rates can persist for several years after the fire. The low carbon concentration within Tuolumne Meadows may be related to the decreased total amount of vegetation around the stream at high elevation. The significantly higher value of organic matter observed at the Clavey River may be the result of both large amounts of eroded sediment as well as an anthropogenic influx of nutrients from fertilizer application within the drainage area.

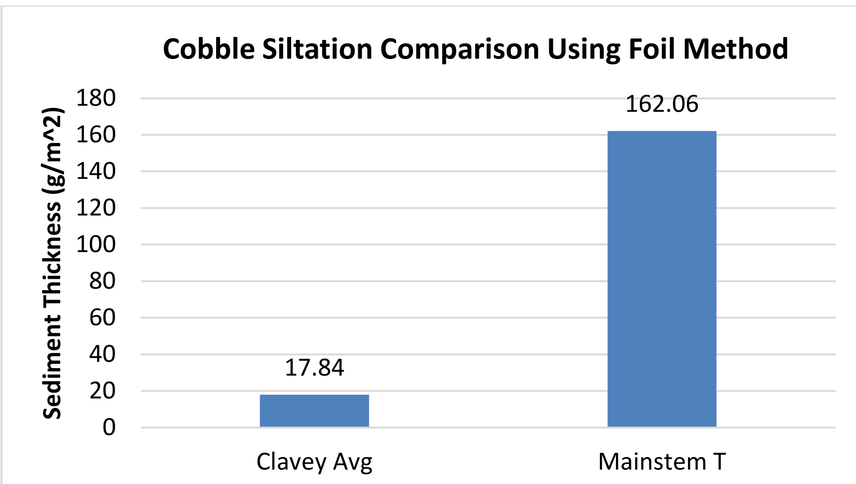

Figure 3: Average thickness of deposited sediment on cobbles within the Clavey and mainstem Tuolumne river sites.

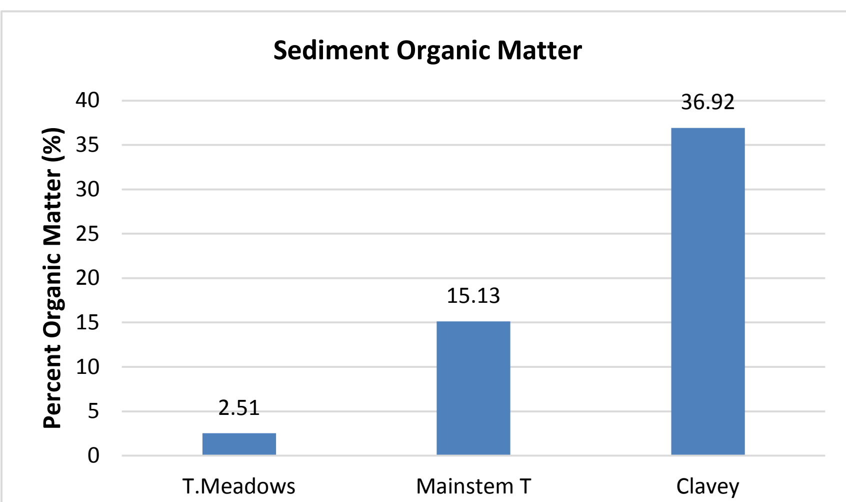

Figure 4: Percentage of organic matter contained in sediment samples.

Comparisons of V* measurements in the upper and lower watershed sites showed that relative sedimentation was highest in the Mainstem Tuolumne, moderate in Tuolumne Meadows and lowest in the Clavey River (Figure 4). This contrasts with typical expectations that a low-slope meadow environment would have higher sediment deposition than a sloped, higher velocity main river channel bordered by bedrock walls, typical of the mainstem. The high V* values observed on the Mainstem Tuolumne may be due to increased sediment from fire-induced erosion. Differences in sedimentation values on the Mainstem Tuolumne between high flow (0.42) and low flow (0.66) may reflect short-term differences in sediment deposition during and following daily rafting releases. The Clavey River had low V* values across all sample sites despite expected high inputs from fire-induced erosion and thus may indicate that sediment in the Clavey has been flushed more thoroughly from the river due to steep channel slopes and unregulated flows that surge during storm events.

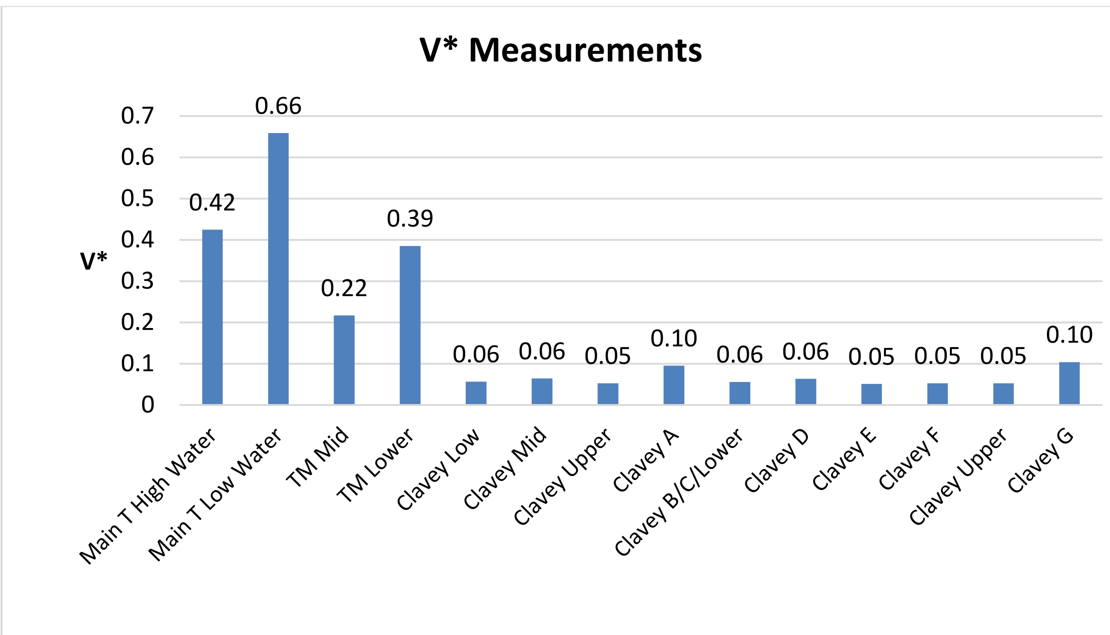

Figure 5: Relative fine sediment deposition, as measured by V*, by location. Mainstem Tuolumne sites are denoted as 'Main T' and Tuolumne Meadows sites are labeled 'TM'.

The Clavey River had less deposition of fine sediment than the mainstem Tuolumne, but deposition increased within the Clavey River sites when compared to measurements taken in September of 2013 by researchers at the Center for Watershed Sciences. The September measurements were immediately post-fire but prior to winter precipitation events that moved large amounts of sediment from the hill slopes to the river. Figure 5 shows the V* measurements for six Clavey River pools taken in September 2013 along with three pools measured in June 2014. In Clavey sites B/C/Lower and E, the two sites with data from both sampling periods, there is a small but notable increase in sediment deposition in the June values. This supports the assumption that sediment loads would increase in post-fire river systems after storm events have the opportunity to move eroded sediments from the hill slope to the river.

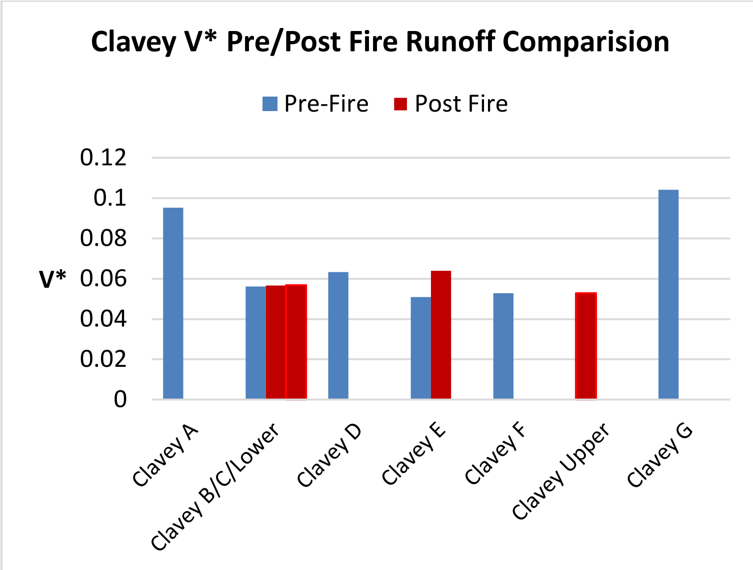

Figure 6: V* differences by location pre and post Rim Fire

Biotic results varied between the sampled trophic levels. Algae biomass (Figure 6) was inconsistent with our expectations that locations with greater sediment deposition would have less algal growth. The mainstem Tuolumne showed the highest algal biomass, up to 8.62 mg/cm^2, while the Tuolumne Meadows sites showed the lowest concentrations (< 1 mg/cm^2) and the Clavey River sites showed moderate concentrations. These results are inconsistent with the high siltation levels observed in the mainstem Tuolumne (Figure 2), in that high levels of fine sediment were expected to prohibit attachment by algae. One possible explanation is that a secondary factor, such as excess nutrient loading from higher organic matter inputs or from non-point sources along the river, is contributing to algae production.

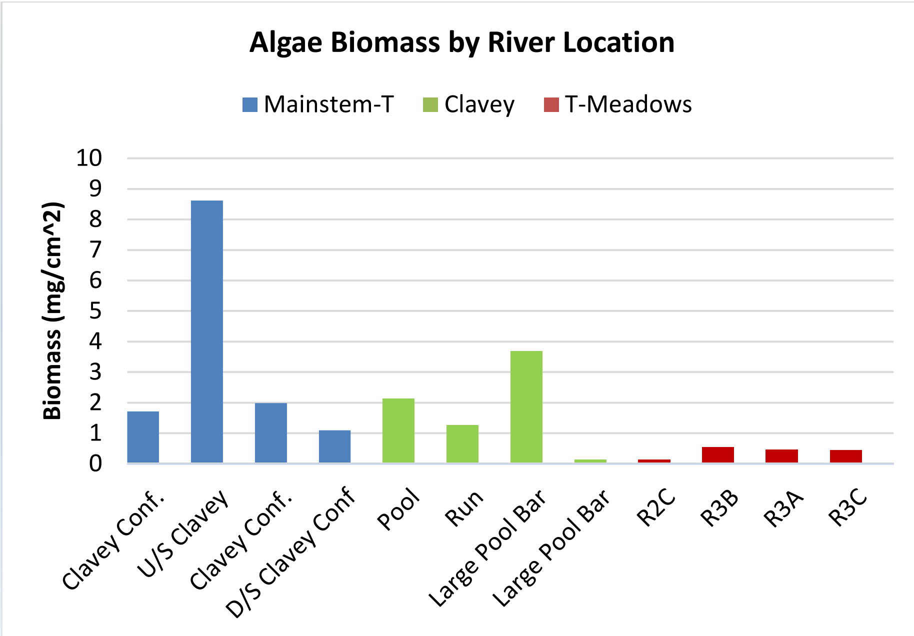

Figure 7: Algal biomass by specific location and overarching watershed zone

In Tuolumne Meadows, which was not affected by the Rim Fire, the benthic macroinvertebrate data supported a link between EPT index, tolerant orders and fine sediment deposition. Figure 7 compiles these results and illustrates that as sediment deposition increased (as measured by V*), the presence of sediment tolerant macroinvertebrate orders increased, and the percent of more sensitive EPT taxa decreased.

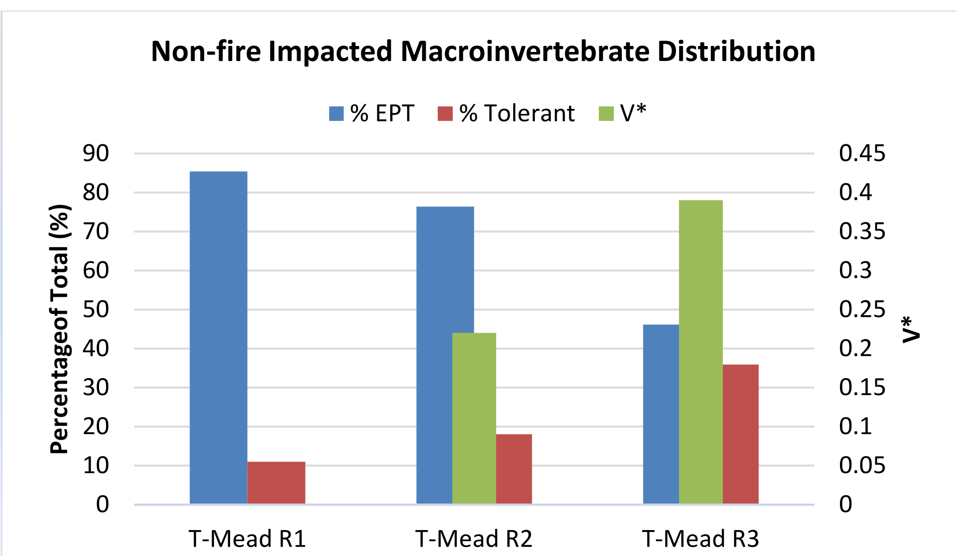

Figure 8: Distribution of macroinvertebrates by reach in Tuolumne Meadows (not impacted by fire) in relation to sediment deposition as measure by V*.

In the fire-impacted section of the Tuolumne watershed near the Clavey River confluence, the macroinvertebrate distribution was similar to the trends observed upstream in Tuolumne Meadows. The mainstem Tuolumne sites, which were sediment-impacted with high V* measurements (Figure 4), had macroinvertebrate samples containing less than 20% EPT taxa (Figure 8). At the Clavey River sites, the percentage of EPT taxa ranged from 44% to 65%. While the percentage of sediment tolerant macroinvertebrate orders was lower in mainstem Tuolumne than in the Clavey river, they were relatively more abundant in comparison to EPT taxa in the more sedimented mainstem Tuolumne.

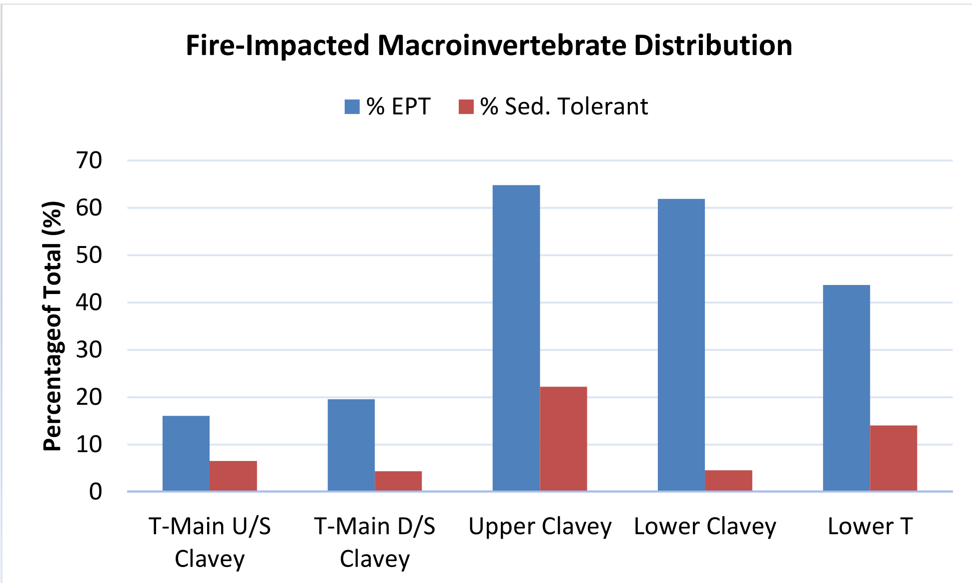

Figure 9: Percentage of sensitive EPT taxa versus percentage of tolerant taxa in different fire-impacted locations near the Tuolumne-Clavey River confluence.

Conclusions:

Based on the results of this case study, there is evidence that the Rim Fire did increase sediment deposition along burned sections of the Tuolumne River watershed. This deposition consequently altered stream bed structure by increasing cobble siltation and organic matter content. In affected stream reaches, the abundance of sensitive macroinvertebrates with low sediment tolerance decreased in relation to more tolerant taxa. These results support the expectation that fine sediment deposited by the Rim Fire altered the composition and distribution of macroinvertebrates in the Clavey and mainstem Tuolumne rivers.

Fire Management for the Future

Although the Rim Fire had substantial impacts on the ecosystem, it offers a unique opportunity to approach restoration efforts of burned landscapes differently. In the 1980s, fires affected the same area, and forest managers planted new trees that were burned by the Rim Fire and may have even contributed to its intensity (Howard, 2014). Possible alternatives to restoring the region include leaving areas to revert back to forest on their own, replanting trees such as conifer seedlings, and changing the notable controversial practice of salvage logging (Lopez, 2014).

To prevent large-scale fires like the Rim Fire, fire managers often use three primary tools to mimic fire's natural function within the ecosystem: prescribed fires, mechanical thinning, and wildland fire use. Prescribed fires are small-scale carefully managed burns with the intent of clearing any unsafe accumulation of dead or fallen wood. Mechanical thinning removes smaller trees with tools such as chainsaws to provide safer conditions for firefighters. Wildland fires are generally caused by lightning and burn naturally under close surveillance to support natural ecosystem processes (NPS, 2014). The Forest Service has implemented mechanical thinning within close proximity to houses and buildings to reduce fuel and fire temperatures. The National Park Service has also recently begun experimenting with letting some lightning fires burn in parts of Yosemite (Howard, 2014). Naturally occurring fires not only allow forests to be thinned, but also open the canopy, recycle nutrients, and reduce the amount of dead woody debris (NPS, 2014).

The California Department of Forestry and Fire Protection (CAL FIRE) is the California state agency responsible for fire protection of California's wilderness. CAL FIRE is the largest fire department in the state and has a long history of providing fire prevention, safety, and education programs for the citizens and visitors of California. Their education programs include school lessons, fair exhibits, flyers, posters, radio and television spots, community meetings, and one-on-one contacts with homeowners. Fire safety education is an important tool utilized to reduce the chances of human-caused wildfires and to provide residents with the information necessary to protect themselves, their families, and belongings (Wallechinsky, 2014). Although smoke from a fire can be harmful to resident's health due to the release of particulate matter, there is usually less smoke from a prescribed burn than from a wildfire burning over the same area. Residents may oppose the smoke generated from controlled burns; however, they may help reduce the risk to target groups such as asthmatics, the elderly, and youth populations by decreasing the probability of a larger more intense and smoky fire (Monroe, 2013).

Today we can use fire as a tool to balance the amount of fuel load available and foster an environment of continued rebirth. By enacting an adaptive management strategy towards fire management, wildfires can provide opportunities for learning and moving away from "the status quo" (Gunderson, 2006). A broad adaptive management strategy would provide an opportunity to conduct structured studies on the impacts of fire on the Sierra Nevada region and assess how these impacts will change over time in relation to additional factors such as increasing temperatures due to climate change, population growth, and natural ecosystem changes.

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