Building Climate Resiliency in a Warming World: from beaver dams to undergraduate education

by

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Abstract

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Building Climate Resiliency in a Warming World: from beaver dams to undergraduate education

Dissertation directed by Professor Eric E. Small

As climate changes and global temperatures rise, we are faced with unique new challenges to our land, ecosystems, livelihood, and infrastructure. One way of dealing with the impacts of climate change is to build climate resiliency – or the ability to resist or recover from climate change-driven disturbances. This dissertation explores two avenues for building climate resiliency in a warming world. Chapters 2 and 3 focus on the physical earth and creating resilient landscapes through the natural impacts of beaver damming. Chapter 4 focuses on building a more diverse geoscience workforce to creatively tackle the challenges presented by climate change.

In Chapter 2 I investigate one potential consequence of beaver-related water storage in the landscape – drought buffering. Using remotely sensed Normalized Difference Vegetation Index (NDVI) and modeled evapotranspiration (ET) data, I compare riparian areas with beaver to riparian areas without beaver on two creeks in semi-arid Nevada during both seasonal and multiyear droughts. The beaver-dammed riparian areas had ET and NDVI signatures more similar to that of irrigated cropland than to riparian areas without beaver. This suggests that the drought-buffering is likely stemming

from the unique storage and distribution of water in beaver-dammed landscapes.

In Chapter 3 I push the bounds of beaver-driven climate resiliency determine whether or not beaver wetlands are uniquely resistant to wildfire. To do this, I use remotely sensed NDVI data to quantify the riparian vegetation response during five large wildfires along creeks that have variable amounts of beaver damming. Through comparison of NDVI before, during, and after fire in riparian areas with beaver damming to riparian areas without beaver damming, I show that beaver-dammed riparian areas are uniquely resistant to wildfire.

In Chapter 4 I explore a different approach to building climate resiliency and focuses on the people solving climate issues, not the impacts of climate change on the physical earth. My research establishes that even infrequent training on accessibility and inclusivity can measurably change undergraduates' feelings of inclusion and connection to their academic department. That inclusion and connection is an integral component of retaining these students throughout their undergraduate careers.

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Chapter 1: Introduction

Beavers are the archetypal ecosystem engineer – they build dams, which in turn create ponds and lead to a cascade of geomorphic, ecologic, and hydrologic changes in the landscape around them. Some of the key ecohydrologic impacts of beaver damming reported either anecdotally in popular media or documented in the scientific literature are as follows:

- **Storage of water in the surface in ponds and channels** ([*Gurnell*, 1998; *Karran et al.*, 2017b; *Rosell et al.*, 2005])
- **Storage of water in the subsurface as soil moisture, groundwater, and hyporheic flow** ([*Briggs et al.*, 2013; *Briggs et al.*, 2012; *Janzen and Westbrook*, 2011])
- **Locally elevated water tables** ([*Dittbrenner et al.*, 2018; *Feiner and Lowry*, 2015; *Karran et al.*, 2017a; *Lowry*, 1993; *Puttock et al.*, 2017; *Westbrook et al.*, 2006])
- **Attenuation of peak flows** ([*Hillman*, 1998; *Law et al.*, 2017; *Puttock et al.*, 2017])
- **Increased water residence times** ([*Briggs et al.*, 2013])
- **Increased hydrologic connectivity in the landscape** ([*G A Hood and Larson*, 2015; *Wegener et al.*, 2017]
- **Increased pond and wetland habitat area** ([*Brown and Fouty*, 2011; *Cunningham et al.*, 2006; *Law et al.*, 2017; *Little et al.*, 2012; *McKinstry et al.*, 2001; *Müller-Schwarze and Sun*, 2003; *M. M. Pollock et al.*, 2015;

Sturtevant, 1998])

- **Buffering drought effects on nearby riparian vegetation** (Chapter 2, anecdotal, [*G A Hood and Bayley*, 2008])
- **Protecting ecosystem from wildfire** (Chapter 3, anecdotal)

In addition to their ecohydrologic impacts, beaver damming also creates large geomorphic (sediment aggradation, floodplain connection, channelization of riparian zone), geochemical (denitrification, development of anoxic sediments, methane release, reduction of downstream pollutants), and ecologic (tree-cutting, wet meadow development, increased biodiversity) impacts [M. M. Pollock et al., 2015]. Beavers are thought to be second only to humans in their ability to modify the physical environment to suit their needs. Despite the enormous scale of their impacts, much of the existing literature on the impacts of beaver damming is done at the single-pond or few-pond scale and relies heavily on field work.

The first goal of my research is to assess the ecohydrologic role beaver damming plays in building climate resiliency at the landscape scale using primarily remote sensing and modeling. In this dissertation, I present (Chapter 2) an investigation into whether beaver dammed riparian areas are better buffered against droughts than areas without beaver, and (Chapter 3) documentation and quantification of beaver damming increasing the fire resistance of riparian vegetation during wester US wildfires. In this research, I provide the scientific community as well as land managers with a better understanding of how beaver damming can play a role in building climate resiliency at the landscape scale.

The second goal of my research is to develop impactful techniques for increasing the diversity of the future geoscience workforce. Geosciences are the least diverse STEM discipline at all education levels according to NSF statistics. Dismantling the systematic barriers faced by future geoscientists from underrepresented groups is a necessity if we want our society as a whole to be resilient to climate change. The dominant schools of thought and problem-solving strategies have not succeeded in stopping, slowing, or mitigating climate change so far. Retaining more diverse undergraduate students not only benefits the students who have been historically excluded from the field, but also benefits the scientific community as a whole. The progress of science has been slowed by excluding various populations from the conversation for hundreds of years. We can't reverse the damage that has already been done, but we can set course on a better path for the future – and that starts with our instructors. Teaching Assistants (TAs) are often the first authority figure college students interact with at large research-focused universities. In Chapter 4, I design, implement, and assess a novel training for TAs on inclusivity and Universal Design for Learning. My research establishes that even infrequent training on accessibility and inclusivity can measurably change undergraduates' feelings of inclusion and connection to their academic department. That inclusion and connection is an integral component of retaining these students throughout their undergraduate careers, and in this research I provide foundational resources for other academic departments around the world to follow suit an improve their own inclusivity through TA trainings.

Chapter 2: Using Remote Sensing to Assess the Impact of Beaver Damming on Riparian Evapotranspiration in an Arid Landscape

2.1 Background

Through their construction of numerous dams, beavers create and maintain riparian ecosystems throughout the American west [*Naiman et al.*, 1986; *M. M. Pollock et al.*, 2014; *Rosell et al.*, 2005] – including in desert climates [*Andersen and Shafroth*, 2010; *Carillo et al.*, 2009; *Gibson and Olden*, 2014; *Gibson et al.*, 2015]. The hydrologic and geomorphic structure of these beaver-dammed riparian areas differs significantly from undammed riparian areas [*Green and Westbrook*, 2009; *Janzen and Westbrook*, 2011; *Michael M. Pollock et al.*, 2007]. Beaver dams create deep ponds which store large volumes of water on the surface and in the subsurface, and they help connect incised streams back to their floodplains [*Karran et al.*, 2017b; *Lautz et al.*, 2006; *Levine and Meyer*, 2014; *M. M. Pollock et al.*, 2015; *Polvi and Wohl*, 2012]. Furthermore, beaver ponds provide the hydrologic benefit of buffering peak flows and flood waves [*Burns and McDonnell*, 1998; *Butler and Malanson*, 2005; *Hillman*, 1998; *Rosell et al.*, 2005]. In this paper we investigate another possible, less studied hydrologic benefit of beaver damming: drought buffering. For the purpose of this study, drought buffering refers to the ability for vegetation to produce a typical season arc in evapotranspiration similar to that predicted by the Penman-Monteith equation for potential evapotranspiration (PET) [*R Allen et al.*, 1998], and avoid senescence despite little to no precipitation. For example, vegetation that is well-buffered against droughts would have a transpiration signal more similar to irrigated crops than to more precipitation-dependent vegetation in the landscape.

To buffer flood waves, beaver dams slow down and store large volumes of rapidly incoming water over a large area, and then gradually release it over a period of days-to-months. Our proposed mechanism of beaver-dam-induced drought buffering is very similar to the mechanism behind beaver-dam-induced flood buffering: beaver ponds formed upstream of each dam retain water during wetter periods and then release it gradually over drier ones. Since beaver ponds have been shown to locally elevate the water table [*Lowry*, 1993; *Westbrook et al.*, 2006], any pond water that enters the banks will flow both vertically and laterally along the phreatic surface and out into the broader riparian zone [*Briggs et al.*, 2013; *Jin et al.*, 2009]. Here the pond water is accessible to the roots of riparian vegetation, acting similar to a subsurface irrigation system [*Gurnell*, 1998; *Hammerson*, 1994].

Given that productive plants are foundational to the trophic webs of most terrestrial ecosystems and that riparian zones are the main source of wetland habitat in arid and semi-arid landscapes [*Kauffman et al.*, 1997; *Knopf et al.*, 1988; *W. W. Macfarlane et al.*, 2016; *Naiman et al.*, 1993; *Pettorelli et al.*, 2005], creating and preserving patches of consistently productive vegetation is crucial to wetland conservation efforts. However, due to their strong dependence on water availability, riparian ecosystems in general are particularly sensitive to droughts [*Kauffman et al.*, 1997; *Knopf et al.*, 1988]. The relationship between riparian restoration and drought buffering was recently assessed at a location with beavers [*Huntington et al.*, 2016], but the role that beaver damming plays and how strong of an influence it has on riparian ET and plant productivity has not been studied in depth. We hypothesize that beaver dammed riparian ecosystems are better buffered against droughts than riparian areas without beaver activity. To test this hypothesis, we compared the evapotranspiration and greenness of riparian vegetation – two indicators of plant productivity – along creeks with differing levels of beaver damming during both seasonal and multiyear droughts. If beaver dammed riparian areas are better buffered against droughts than areas without beavers, then the promotion of beaver dam building activity should be considered in management plans for riparian areas in arid and semi-arid landscapes.

2.1.1 Assessing Vegetation Productivity: ET and NDVI

Modeled evapotranspiration (ET) and satellite-derived Normalized Difference Vegetation Index (NDVI) are used in this study to estimate the density and vigor of vegetation across the landscape. These indicators can then be interpreted as an approximation of the overall productivity of the riparian ecosystem [*Carlson and Ripley*, 1997; *Fisher et al.*, 2011; *Pettorelli et al.*, 2005]. ET is the combination of evaporation of water directly from soil, water, and plant surfaces, and transpiration by plants, and in general correlates to greater species richness [*Hawkins et al.*, 2003]. Although both evaporation and transpiration are dynamic, we assume that the changes in the evaporation component of ET are relatively consistent over a given landscape. We believe this assumption is valid considering the main variables driving evaporation -incoming radiation, temperature, wind speed, and relative humidity – do not vary significantly on the spatial scale of this study. If changes in evaporation are consistent across the entire landscape, then relative spatial or temporal changes in the ET signal between any two areas will be primarily due to changes in plant transpiration. During the growing season, ET values close to the maximum potential evapotranspiration (PET) indicate that plants are transpiring at their maximum potential rate. ET values less than the PET indicate that plant growth is being limited by something – typically lack water in semi-arid and arid landscapes [*Laio et al.*, 2001; *Porporato et al.*, 2001]. If water-stress is extended, plants may undergo senescence – the strategic die off of plant tissue and slowing of growth rates designed to increase likelihood of long-term survival [*Munné-Bosch and Alegre*, 2004]. NDVI is an indicator of photosynthetic activity by plants [*Carlson and Ripley*, 1997], and when used in conjunction with ET can distinguish high ET signals due to increased plant transpiration from high ET signals due to open water or soil evaporation.

NDVI is calculated directly from remotely sensed surface reflectance data (such as from the Landsat satellites) [*Tucker*, 1979]. ET is estimated using a combination of remote sensing and modeling. We used Landsat acquired images for the remote sensing portion, and for the model we used the METRIC (**M**apping **E**vapo**T**ranspiration at high **R**esolution with **I**nternalized **C**alibration) model [*Richard G. Allen et al.*, 2007a]. METRIC combines Landsat satellite imagery and local or modeled meteorological data to calculate the ET of a landscape. METRIC has been previously validated with field observations [*R. G. Allen et al.*, 2005; *Richard G. Allen et al.*, 2007b; *French et al.*, 2015; *Paço et al.*, 2014], and has also been used without ground-based validation [*Santos et al.*, 2012; *Trezza et al.*, 2013]. A recent study by Liebert et al. used both modeled data from METRIC and ground-based eddy flux tower data to estimate the ET and a vegetation index of broad riparian areas in southeast Nevada which were impacted by leaf beetles [*Liebert et al.*, 2016]. The METRIC calculations were validated by the eddy flux tower data in their study. That being said, eddy covariance field measurements of ET are prone to large uncertainties and errors when applied to very small, narrow areas like riparian corridors due to advection and flux divergence [*Blanken et al.*, 1997; *Steinfeld et al.*, 2006; *Wilson et al.*, 2002]. Furthermore, deploying eddy towers is quite expensive and time intensive. Given the similarity between our area of interest and previous field validations of METRIC as well as how resource intensive, non-representative, and uncertain eddy covariance results would be for our specific field site, we chose to utilize METRIC data without additional ground-based validation.

2.1.2 Region of Interest

This study uses Maggie and Susie Creeks, located in northeastern Nevada, as case studies for beaver-dam-induced drought buffering (Figure 1). Maggie and Susie Creeks are in a region of Nevada that is classified as an arid climate, according to the Köppen-Geiger Climate Classification system [*Kottek et al.*, 2006], and receive 29 cm of precipitation annually [*NCEI*, 2010]. Maggie Creek drains 1029.2 square kilometers, and Susie Creek drains 476.7 square kilometers, both emptying into the Humboldt River. Both creeks run dry or near-dry from approximately late June/early July through October every year according to USGS streamflow data collected at the lowermost section of each creek [*USGS*, 2016].

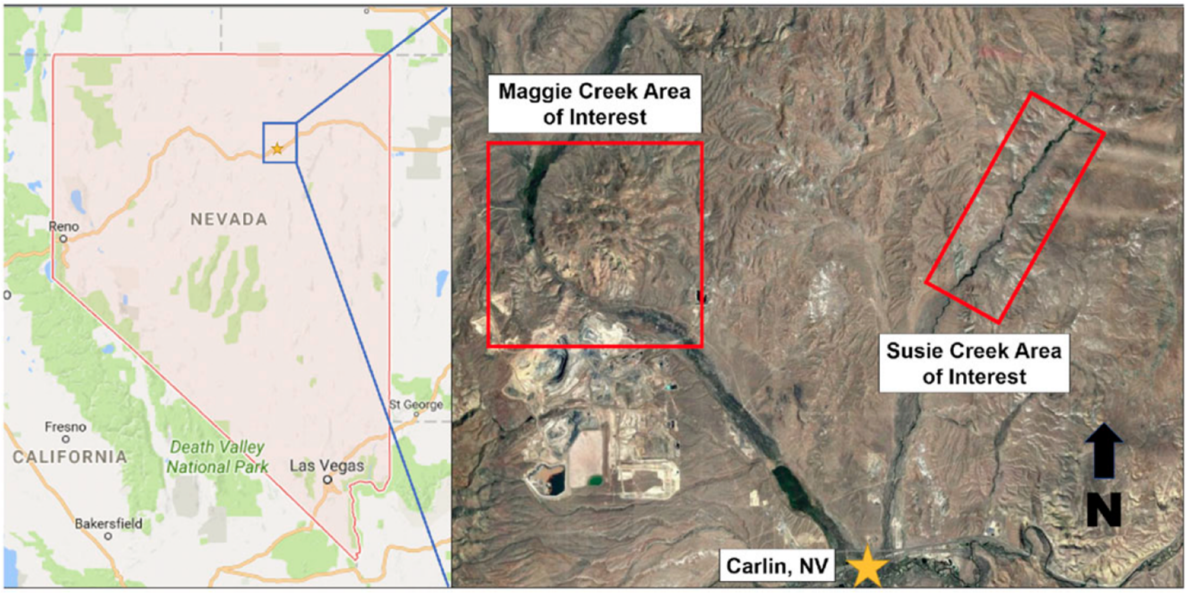

Figure 1: Susie and Maggie Creeks, NV. The water in the creeks runs from north to south, ultimately draining into the Humboldt River at the very bottom of the image where the creeks nearly converge in the town of Carlin, NV. Both creeks have significant beaver activity. The areas of interest on Susie and Maggie Creeks are outlined with red boxes. An irrigated alfalfa field is outlined in a blue box, and the remaining landscape is largely sparsely vegetated hillslopes.

For much of their recent history, these creeks were significantly incised due to overgrazing by cattle. A restoration effort began in 1993 in which grazing was limited and the creeks were allowed to return to a more natural state. A byproduct of this restoration was the unintentional colonization of the creeks by beaver in the early 2000's. Since 2003, beavers have built hundreds of dams on the creeks.

Figure 2 shows transformation of the creek during the restoration process through a series of photographs taken by the Elko Bureau of Land Management [*Swanson et al.*, 2015].

The region has sparse vegetation except in the riparian areas and in irrigated alfalfa crops along the lowermost section Maggie Creek (Figure 1

). The 2011 Elko Bureau of Land Management (BLM) Environmental Assessment Report indicated that a recent survey found that the dominant species of riparian vegetation in the area are Coyote willow (*Salix exigua*), common threesquare bulrush (*Scirpus americanus*), baltic rush (*Juncus balticus*) and spikerush (*Eleocharis spp)* [*BLM*, 2011]. During periods of drought – including the annual summer dry season – the productivity of hillslope vegetation is limited by water stress. We expect this to result in low ET and NDVI during peak drought months compared to early growing season months when water is more plentiful. The alfalfa crops, however, should maintain high ET and NDVI throughout periods of drought for as long as whoever manages that land continues to irrigate them. Although narrow riparian areas surrounded by arid landscapes can experience advection and have negative sensible heat fluxes and result in ET values higher than even the PET, the alfalfa fields in the study area are also relatively small and located along the stream. Thus, they should experience similar advection. It then follows that the ET of the riparian areas – both with and without beaver – should fall somewhere between the values calculated with METRIC for the streamside alfalfa fields and for the hillslopes.

Figure 2: A riparian area along Susie Creek from 1991 (pre-restoration) to 2014. Restoration efforts began in 1993, and beavers moved into the creek in the early 2000s. Note the change in water volume, vegetation density, and vegetation greenness in the riparian areas as restoration and beaver colonization took place. Photos from the Elko Bureau of Land Management

2.1.3 Seasonal and Long-Term Droughts on Susie and Maggie Creeks

Maggie and Susie Creeks experience seasonal droughts every summer, as well as occasional multi-year droughts. The study area has a Mediterranean-type climate which alternates between hot, dry summers and cold, wet winters. Similar to previous ecohydrology studies, we consider the summer dry season a seasonal drought [*Baker et al.*, 2008; *Condit et al.*, 2013; *Sala and Tenhunen*, 1995; *Shafroth et al.*, 2002; *Stella and Battles*, 2010; *Wright*, 1991; *Wright and Cornejo*, 1990]. During seasonal droughts, the water demands of vegetation exceeds the amount of precipitation for an interval of several months. Under these conditions, vegetation must rely on streamflow, groundwater, and soil moisture to meet its water needs. If these water resources become depleted or are absent altogether then a common evolutionary response to the drought stress is for the vegetation to undergo senescence and reduce evapotranspiration [*Amlin and Rood*, 2002; 2003; *Munné-Bosch and Alegre*, 2004; *Pereira and Chaves*, 1995; *Rood et al.*, 2000; *Zha et al.*, 2010]. Although senescence is a natural part of the life cycle of vegetation, extended vegetation senescence can have negative impacts on the riparian ecosystem as a whole [*Perry et al.*, 2012; *Shafroth et al.*, 2002; *Vivian et al.*, 2014]. Furthermore, if drought stress persists then soil moisture can drop below the wilting point of the vegetation and lead to total plant death [*Cassel and Nielsen*, 1986]. Wetlands plants tend to have the majority of their root system located in the top 15-45 cm of the soil, and as such can reach the wilting point within a matter of weeks during a drought if no new water is entering the soil [*Sipple*, 1992].

Seasonal droughts in the study area were identified by comparing the calculated potential evapotranspiration, or PET, of the landscape to the incoming water from precipitation. PET is a measure of the maximum possible total water losses to both plant transpiration and evaporation from the soil and open water surfaces if the system was not water-limited. PET is commonly calculated with the Penman-Monteith equation [*R Allen et al.*, 1998], and is calculated this way for this study using values for an alfalfa reference crop. During the summer and early fall (June through August), the PET at Maggie and Susie Creeks is much higher than the incoming precipitation, and thus we consider it a seasonal drought. It is over these months that the shallow groundwater storage from beaver ponds should have the most pronounced effect on the ET of nearby riparian vegetation. These effects should be noticeable in both normal precipitation years and during multi-year droughts, at least until the ponded volume of water is completely depleted. For this reason, data from all years – both wet and dry - were included in assessing the role of beaver damming in buffering ET during the seasonal droughts that occur predictably each summer.

To identify long-term droughts, we used the Standardized Precipitation Evapotranspiration Index (SPEI) [*Vicente-Serrano et al.*, 2010]. The SPEI calculates the difference between the current precipitation amounts and the historical long-term averages, subtracts out the potential evapotranspiration (PET), and is standardized. The resulting value indicates a water surplus (+) or deficit (-) for the time period considered. The inclusion of potential evapotranspiration in the drought index calculations simply helps account for the fact that different areas have different water needs, and those with higher water needs will experience negative effects of decreased precipitation more strongly than those with low water needs. The SPEI for Maggie and Susie Creeks was calculated for each water year (Oct 1 – Sept 30) from 1996-2016 based on meteorological data collected at the nearby Elko Regional Airport (Figure 3).

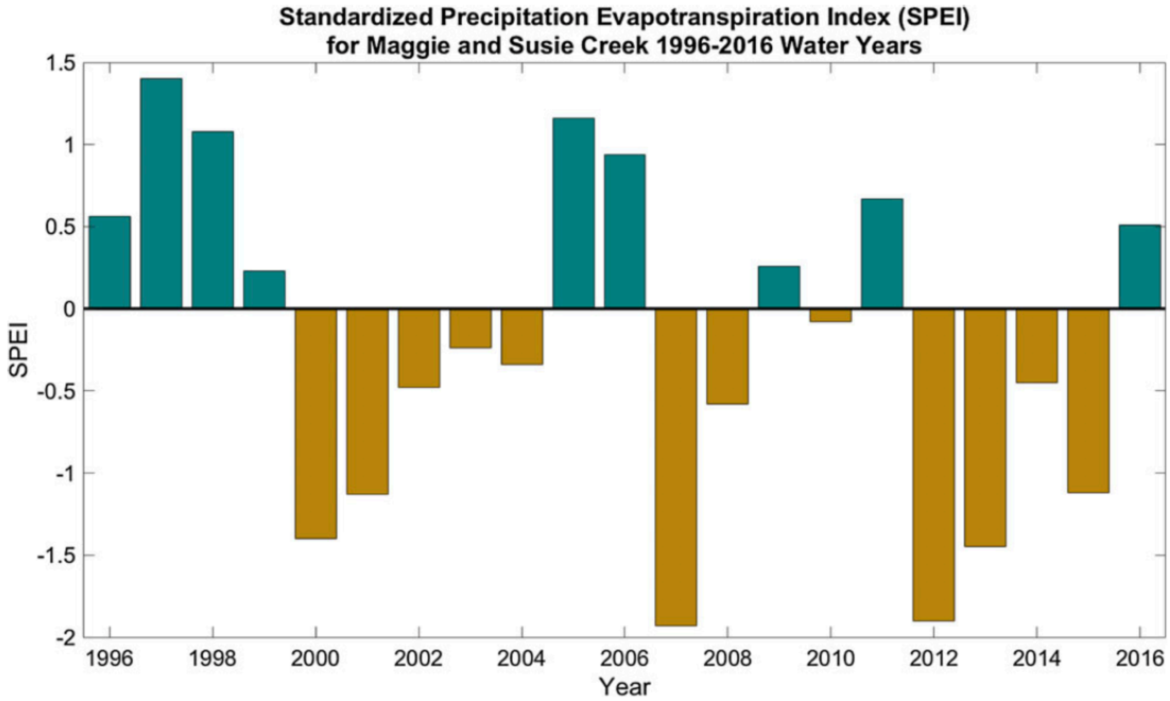

Figure 3: Standardized precipitation evapotranspiration index (SPEI) for Maggie and Susie Creeks in Nevada. Negative SPEI values indicate abnormally dry water years and are coloured yellow, whereas positive SPEI values indicate abnormally wet water years and are coloured teal. SPEI less than −1.00 is considered a moderate or greater intensity drought.

It is clear from Figure 3 that the creeks had three distinct multi-year droughts in the last two decades: 2000-2004, 2007-2008, and 2012-2015. We look at the effects that beaver damming has on ET from 2013-2016. Including three drought years and one normal precipitation year allows us to quantify the impact of beaver damming on ET during seasonal droughts and assess the extent to which the ET of beaver dammed riparian areas vs undammed riparian areas are impacted by multiyear droughts.

2.2 Methods

2.2.1 Remote Sensing with Landsat

This study utilizes Landsat 8 imagery, which is available from April 2013 through the present, has bands with 30-100m resolution, and a 16-day recurrence interval [*Anderson et al.*, 2012; *Roy et al.*, 2014]. The Landsat flyover time at Susie and Maggie Creeks is ~11:30am Pacific Time. Beaver ponds and the nearby riparian areas are relatively small landscape features, so the high resolution of Landsat 8 made it a better choice than other popular ways to measure evapotranspiration remotely, such as MODIS (Moderate Resolution Imaging Spectroradiometer) which has much coarser 1-km resolution [*Mu et al.*, 2007]. Additionally, the timing of available of Landsat 8 imagery includes the last 3 growing seasons (April – October) of the 2012-2015 drought, and 1 growing season during a non-drought year (2016) which allows us to evaluate the impact that beaver ponds have on ET during both multi-year and seasonal droughts. Only images with <10% cloud cover were included in analysis. A table of the Landsat 8 images used in this study are summarized below (Table 1).

Table 1: Dates of Landsat images used in analysis.

2013	2014	2015	2016
4/11	4/14	4/17	4/19
5/13	6/1	5/3	6/6
6/30	7/19	6/20	6/22
8/1	8/20	8/23	7/8
8/17	10/7	9/8	7/24
9/18		10/10	8/9
			8/25
			9/10
			9/26

When using the Landsat imagery to make comparisons between dammed and undammed sections of creek, we were careful to exclude any mixed pixels that contained both riparian area and hillslope. Exclusion of pixels was done manually using the Google Earth images [*Google*, 2018] overlaid with the Landsat pixel outlines. Any pixel containing observable hillslope was removed from analysis. Hillslopes are less vegetated than the riparian areas and not in contact with the stream or ponded water, so any inclusion of pixels containing hillslope would have resulted in underestimation of both ET and NDVI for the riparian area.

Although we calculated ET and NDVI for each of the dates listed in Table 1, in the interest of being concise the figures containing maps of ET and NDVI in this paper feature four representative dates: April 14th and July 19th of the 2014 drought year, and on April 19th and July 24th of the 2016 non-drought year. These dates were chosen for two reasons. First, the timing of the two scenes each year is very similar – April 14th and 19th, July 19th and 24th. The similarity in day-of-year allows us to make direct comparisons between the drought and non-drought year without needing to adjust for the timing of the image. Second, looking at both April - before the seasonal drought, and July – the peak of the seasonal drought and also when streamflow is at an annual low point meaning the beaver ponds are the major water source along the creeks [*USGS*, 2016] enables us to see if the relationship between beaver damming and ET changes as the seasonal summer drought progresses. All figures not containing maps of ET and NDVI utilize the full time series of data.

2.2.2 Ground-Based Meteorological Data

The meteorological data collected for use in METRIC is from the Elko Regional Airport, located approximately 30km east of Susie Creek. The weather station is at 1533m elevation, and the sections of creek studied range from 1524m – 1544m elevation. This weather station has over 100 years of continuous hourly weather observations of almost all the meteorological parameters required by METRIC – temperature, relative humidity, and wind speed. Wind speed was adjusted from the sensor height of 10m to the 2m height required by the Penman-Monteith formulation and METRIC using the wind profile power law and a coefficient of 0.143 for neutral stability conditions [*Justus and Mikhail*, 1976]. The only parameter missing is incoming clear sky solar radiation at the time of overpass, $\boldsymbol{R_{s\downarrow}}$ (W), which was modeled based on the latitude of the station as shown in Eq. 1 below,

$$\boldsymbol{R_{s\downarrow}} = \frac{\boldsymbol{G_{sc} cos\theta_{rel} \tau_{sw}}}{\boldsymbol{d^2}} \qquad \text{Eq. 1}$$

where $\boldsymbol{G_{sc}}$ is the solar constant (1376 Wm^{-2}), $\boldsymbol{\theta_{rel}}$ is the solar incidence angle in radians, $\boldsymbol{\tau_{sw}}$ is the atmospheric transmissivity, and $\boldsymbol{d}$ (m) is the relative Earth-Sun distance [*Richard G. Allen et al.*, 2007a]. The clear sky solar radiation model is an acceptable model for our study because the Landsat images were selected to be at least 90% cloud free, and as such are clear sky images. Atmospheric transmissivity, $\boldsymbol{\tau_{sw}}$, was held at a constant value calculated for the elevation of the scene according to Eq. 2,

$$\boldsymbol{\tau_{sw}} = \boldsymbol{\tau_o}^{(\frac{\boldsymbol{P}}{\boldsymbol{P_o}})} \qquad \text{Eq. 2}$$

where $\boldsymbol{\tau_o}$ is the clear sky transmissivity at sea level (0.84), P is the pressure at the current elevation, and P_o is the pressure at sea level [*Cuffey and Patterson*, 2010]. Because of the similarity in elevation between the weather station and the creeks studied, no elevation adjustments were made to the meteorological data gathered.

2.2.3 Calculations of ET and NDVI

Normalized Difference Vegetation Index (NDVI) is calculated from Landsat acquired reflectivity data according to Equation 7 [*Tucker*, 1979],

$$NDVI = \frac{(\rho_4 - \rho_3)}{(\rho_4 + \rho_3)} \qquad \text{Eq. 3}$$

where ρ_4 is the near-infrared band reflectivity (Landsat 8 band 4) and ρ_3 is the red band reflectivity (Landsat 8 band 3). The Landsat images used were USGS Level-2 Surface Reflectance images and have already had atmospheric corrections applied. All images came with a quality assessment statement regarding whether the integrity of data had been affected by instrument artifacts or atmospheric conditions. None of the images used in this study had any quality issues. We use NDVI to assess vegetation health both on seasonal and multi-year drought timescales and is thus a measure of drought buffering.

Evapotranspiration (ET) is calculated as the residual of a surface energy balance. For each pixel in a Landsat 8 scene, METRIC calculates the latent energy (LE) according to Equation 4 below [*Richard G. Allen et al.*, 2007a]:

$$LE = R_n - G - H \qquad \text{Eq. 4}$$

Latent energy (*LE*), net radiation at the surface (R_n), the ground heat flux (*G*), and the sensible heat flux (*H*) are calculated as Wm^{-2}. METRIC uses the narrow-band reflectance and surface temperature collected by the Landsat 8 satellite to calculate R_n, estimates G from R_n and the vegetation indices - including NDVI, and estimates H from surface temperatures, surface roughness, and wind speed. METRIC is internally calibrated by anchor pixels selected at hot and cold points in the scene. Hot pixels correspond to low ET areas – such as bare, dry dirt; cold pixels correspond to high ET areas – such as irrigated alfalfa. The hot and cold pixels were chosen using the CITRA-MCB automated process [*Olmedo et al.*, 2015]. In the CITRA-MCB process, the code walks through all the pixels in the scene and finds a user defined number of the hottest and coldest pixels. To find hot pixels, it looks for pixels that both maximize surface temperature and minimize leaf area index (LAI). To find cold pixels, it looks for pixels that minimize surface temperature and maximize LAI. To ensure that the automated pixel selection made sense, pixel locations were overlaid on a Google Earth satellite image [*Google*, 2018] and checked that they corresponded to bare soil (hot pixels) and lush, green vegetation (cold pixels).

The instantaneous ET (ET_{inst}, mm/hr) at the time of Landsat overpass is calculated by dividing the latent energy at each pixel by the density of water, ρ_w, and the latent heat of vaporization of water, λ, then multiplied by 3600 to convert from seconds to hours:

$$ET_{inst} = 3600\frac{LE}{\rho_w\lambda} \qquad \text{Eq. 5}$$

It is then divided by the Penman-Monteith modeled instantaneous ET (mm/hr) for a 0.5m tall alfalfa reference crop (ET_r) given the same meteorological parameters [*R Allen et al.*, 1998]. In our study, these meteorological parameters were the ones gathered from the Elko Regional Airport MET station. The resulting value is the fractional ET, ET_rF, as shown in Equation 6.

$$ET_rF = \frac{ET_{inst}}{ET_r} \qquad \text{Eq. 6}$$

It is assumed that instantaneous ET_rF computed at the image time is the same as the average ET_rF over the 24-hr period [*Richard G. Allen et al.*, 2007a]. From the fractional ET, METRIC calculates the daily ET by multiplying the fractional ET by the 24-hr cumulative reference ET for the 0.5m alfalfa crop

(ET_{r_24}) (mm/day) and a correction factor for sloping terrain, C_{rad}, calculated from an input digital elevation model.

$$ET_{24} = C_{rad}(ET_rF)(ET_{r\_24}) \qquad \text{Eq. 7}$$

Although METRIC has been shown to have a larger error on steep slopes (~30%) – such as some of those nearby to Maggie Creek – the error is small on low slopes and flat lands (< 5%) [*Richard G. Allen et al.*, 2013]. The actual riparian areas we studied are located on low and flat slopes, so the error in our calculations for these areas is expected to be small. It is possible that there is some unaccounted-for advection in the ET results, but this advection and the resultant negative sensible heat flux would be expected to occur throughout the riparian zone as well as in the streamside alfalfa. It is also expected to be small in value. The hillslope ET calculations should not have any advection bias. The calculations of daily ET are used to in our analysis to assess water access and use by riparian vegetation on both seasonal and multi-year drought timescales and is thus a measure of drought buffering.

2.2.4 Classification of Dammed and Undammed Riparian Areas

To assess the extent of beaver activity, beaver dams along both creeks were identified, measured, and categorized as active or inactive based on satellite images acquired through Google Earth [*Google*, 2014]. Dammed vs undammed riparian areas on Maggie and Susie Creeks were identified visually using the Google Earth imagery. The width of the riparian areas was determined based on transitions between riparian vegetation species and grasses found on the drier hillslopes and changes in elevation greater than 2m from the stream. For both creeks, only riparian areas with similar average widths were compared against one another.

The spacing and density of dams along Susie Creek is variable. There are no large sections that are distinctly dammed or undammed. We utilized this variability in damming to investigate the degree of correlation between increasing beaver activity and increased ET. In order to quantify the variable beaver damming on Susie Creek, we defined damming intensity as the total length of dams within a 500-m length of creek. The total length of the stream in the area of interest (Figure 1) was broken into 500-m blocks, and the total length of beaver dams within each block was measured. The downstream point of the creek in the area of interest is the start of Block 1, and Block 25 ends at the most upstream point of the creek (12.5 km upstream).

Maggie Creek, on the other hand, is essentially broken into two large sections: a heavily dammed riparian area, and a completely undammed riparian area. The stark contrast in beaver activity in the riparian areas on Maggie Creek allowed us to assess the role beaver damming plays in elevating and maintaining the riparian evapotranspiration by comparing the two sections against one another without needing to control for varying intensity of damming.

2.3 Results

2.3.1 Intensity of Damming vs ET on Susie Creek

Along the stretch of Susie Creek examined, the ET signal from the riparian area is non-uniformly elevated (Figure 4).

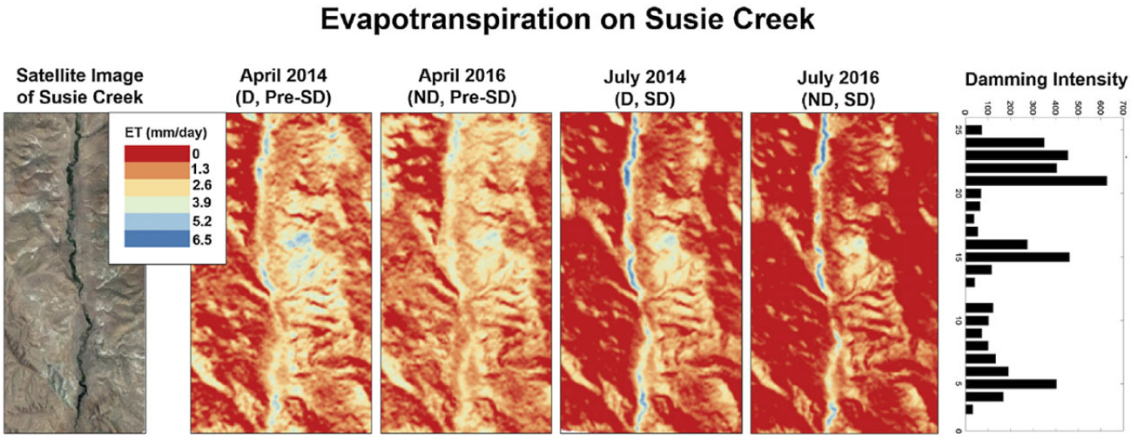

Figure 4: Evapotranspiration (ET) data from Susie Creek for April 2014, April 2016, July 2014, and July 2016. "D" signifies it was a drought year, "ND" signifies a non-drought year, "Pre-SD" is pre-seasonal drought, and "SD" is seasonal drought. Note that in all months, it visually appears that there are ET hotspots near where there is the most intense beaver damming.

The portions of creek with most intensely elevated ET visually corresponds to the portions of creek with the most intense beaver damming, while areas with lower ET correspond to stretches of creek with relatively little beaver damming. Small day-to-day variations in ET are expected - air temperature, humidity, and wind speed all vary slightly on a daily basis within a given month. These day-to-day variations are much smaller than monthly or seasonal variations in ET. The contrast between the beaver dammed sections of Susie Creek and the rest of the landscape are greatest in the July images, but the correlation between damming and elevated ET appears to be present to some extent in all four images. Extracting the average ET in each 500m section of creek and plotting it against the damming intensity shows this correlation more quantitatively (Figure 5).

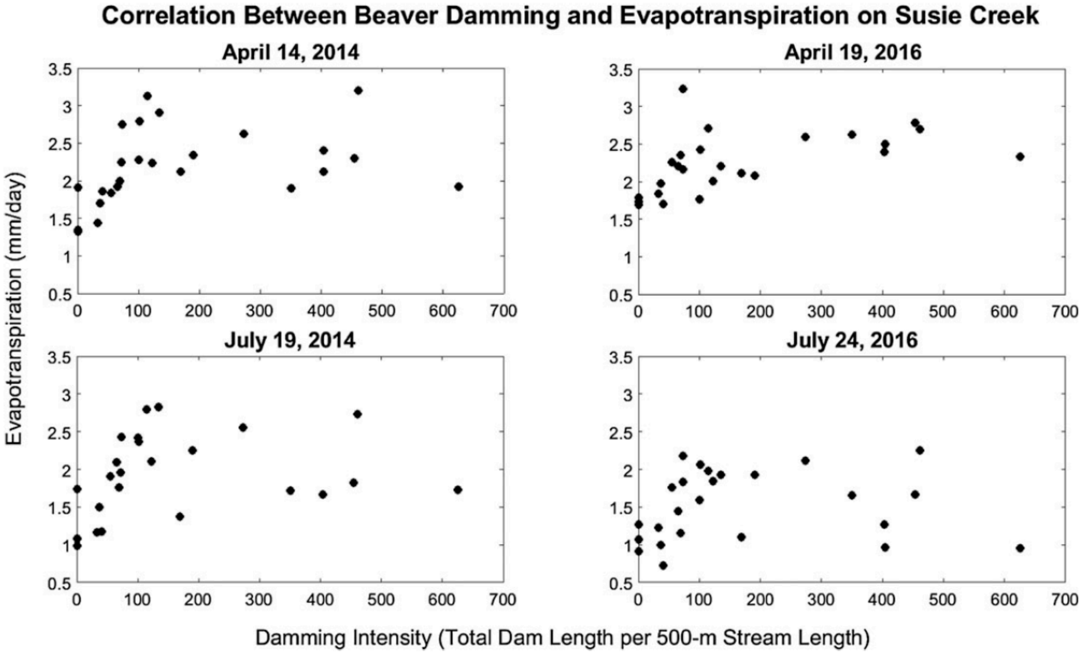

Figure 5: Evapotranspiration as a function of damming intensity. Going from no damming (0-m dam length/block) to light/moderate damming (~150-dam length/block), there again appears to be a positive correlation between the two variables. However, beyond ~150-m-total dam length, the evapotranspiration signal stops increasing and has more variability. Linear models were fit to the data with <150 total dam length per block.

The data shows a positive correlation between increased damming and elevated ET going from no damming (0 meters dam length per block) up to low/moderate damming (~150 meters dam length per block). Additional damming beyond ~150m/block seems to have little additional effect, if any, on the ET. Instead, the ET values level off and have more variability as damming intensity continues to increase. We fit a linear model to the data up to 150m/block damming intensity for all dates examined, although only four representative dates are shown in Figure 5. The average correlation coefficient between damming intensity and ET up to 150m/block was 0.56. Overall, the results from the Susie Creek damming intensity analysis indicate that increased beaver damming is associated with increased ET, but that the relationship is not perfectly linear and there is possibly a threshold where the effects of beaver damming and water availability on ET are no longer the main limiting factor in evapotranspiration.

2.3.2 ET and NDVI of Dammed and Undammed Riparian Areas on Maggie Creek

Unlike Susie Creek's varying intensity of damming, Maggie Creek is heavily dammed on its upper stretch (>150m dam length per 500m steam length) and has no damming at all on the lower stretch. This makes comparing dammed and undammed riparian areas straightforward and eliminates the need to control for extent of damming. The two creeks are otherwise similar in terms of vegetation type, topography, and riparian area width. Our results from Susie Creek suggest that any differences in the ET between the upper and lower sections of Maggie Creek are most likely associated with the difference in beaver activity between them.

The ET images show a stark difference between the dammed and undammed portions of Maggie Creek (Figure 6, left). ET is clearly elevated where the creek has been dammed by beavers, and that signal is more prominent during the summer. Although the ET values on the slopes immediately adjacent to the Maggie Creek riparian areas are likely calculated as too high due to the sensitivity of METRIC to steep slopes, the riparian areas are located on low slopes (< 5%) and as such have relatively low errors. In the drought year (2014), the undammed riparian area has very low ET and looks more similar to the surrounding landscape than the riparian area with beavers. In the wet year (2016), the undammed riparian area is still lower ET than the dammed riparian area, but there is a streak of high ET through the middle nearest to the creek which resembles the ET of the dammed riparian area. This suggests that given more precipitation, the difference in ET between undammed riparian areas and dammed riparian areas may be smaller.

The riparian area with beavers is heavily dammed and may have more standing water, which could produce a high ET signal just from evaporation off the water surface. To determine whether the higher ET signals in the beaver dammed riparian area were primarily from increased plant transpiration or increased water evaporation, NDVI was calculated (Figure 6, right). The differences between dammed and undammed riparian areas are even more stark in the NDVI results than in the ET results, implying that the differences are more likely due to plant transpiration. To quantitatively test whether the increased ET in the riparian areas was due to increased vegetation transpiration or to increased open water/soil evaporation, we plotted NDVI against ET for both the beaver dammed riparian area and the undammed riparian area (Figure 7). In the data analysis, pixels with a negative NDVI value were assumed to be open water and were excluded.

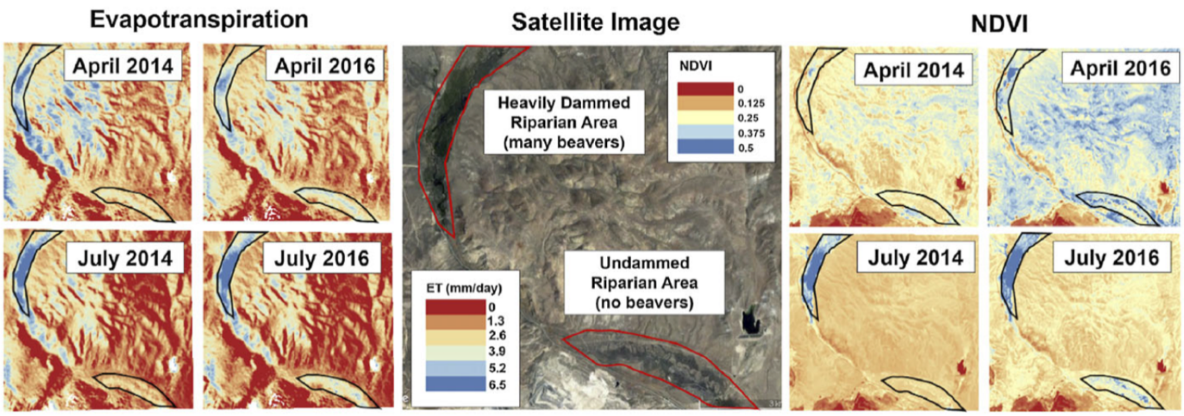

Figure 6: Center: A satellite image of the area of interest on Maggie Creek with the dammed and undammed riparian areas outlined in red. Left: Evapotranspiration (ET) images of Maggie Creek during the spring (April) and summer (July) of both a drought year (2014) and a normal precipitation year (2016). Note that in all years, the beaver-dammed area has a higher ET than the undammed area and that difference peaks in the summer and during the drought. Right: Same for normalized difference vegetation index (NDVI).

If the evapotranspiration increase had been from mostly evaporation, NDVI would have remained constant while ET increased. The positive linear relationship observed between NDVI and ET in Figure 7 confirms that the elevated ET signals coming from the beaver-areas are very likely due to more dense and healthier vegetation transpiration as opposed to open water or soil evaporation.

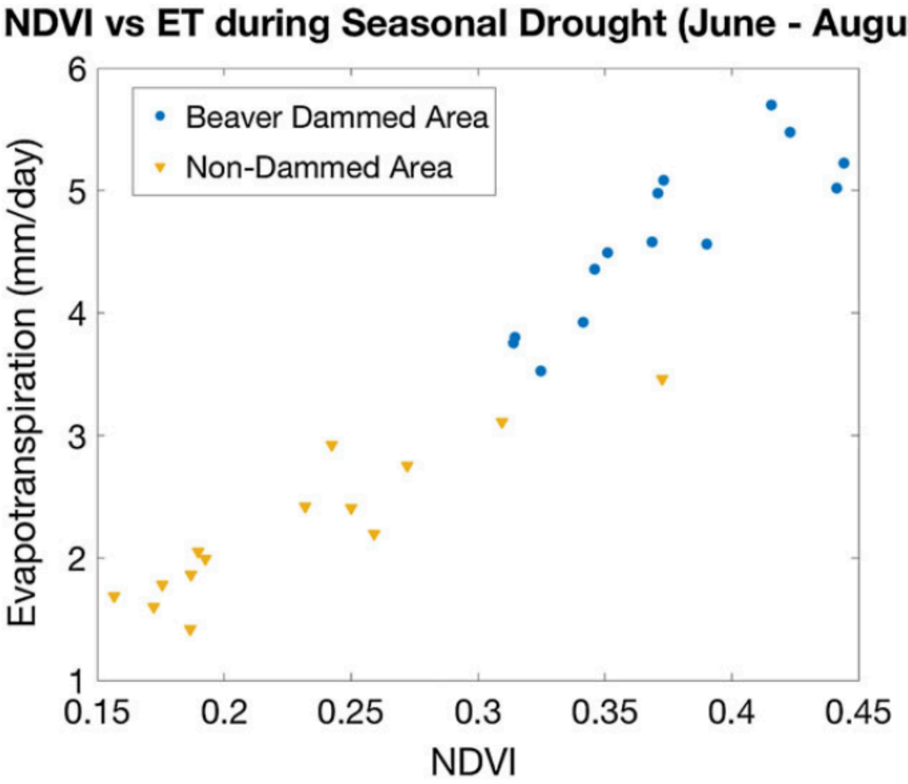

Figure 7: Normalized difference vegetation index (NDVI) versus evapotranspiration (ET) for both dammed and undammed riparian areas. The positive linear relationship indicates that the increased ET signal observed is coming from healthier or more dense vegetation transpiration, not open water or soil evaporation.

3.3.3 ET and NDVI in the Context of the Landscape

We compared the ET from riparian areas that have been dammed by beavers to the ET of several other vegetated elements of the landscape – the undammed riparian areas, an irrigated alfalfa field, and the vegetation on hillslopes – over the 2013-2016 period (Figure 8). The Penman-Monteith PET is shown as well for comparison.

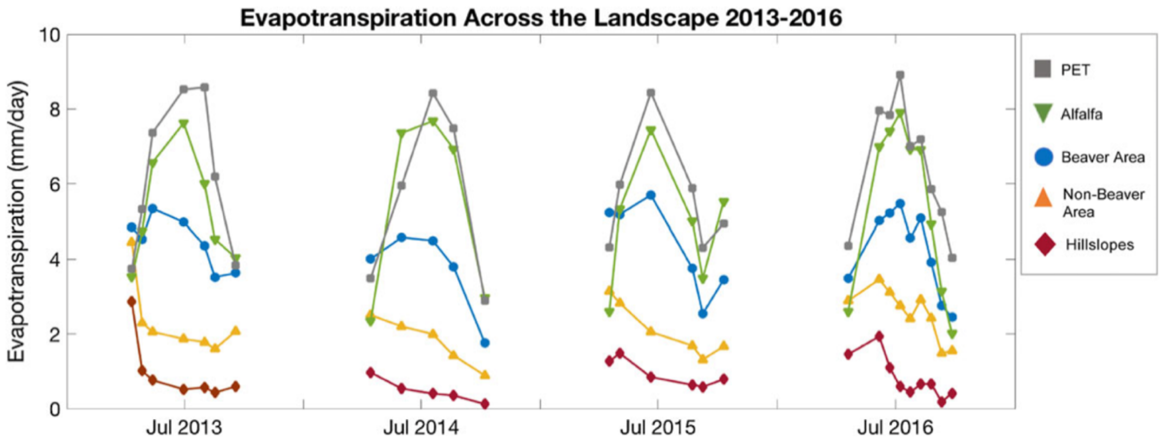

Figure 8: Evapotranspiration of beaver-dammed riparian areas put in the context of other landscape elements: undammed riparian areas, irrigated alfalfa, and hillslopes disconnected from the streams. Potential evapotranspiration (PET) is shown for comparison as well

Figure 8 shows that beaver-dammed riparian area and irrigated alfalfa are most similar in shape and magnitude of ET through time, while the undammed riparian area appears more similar to the hillslope vegetation. Beaver-dammed areas and alfalfa have a seasonal arc in ET, peaking in June/July, then decreasing into the fall. The alfalfa ET calculated with METRIC never quite reaches the PET despite the fact that our PET was calculated for an alfalfa reference crop. We attribute this to imperfect irrigation practices and crop spacing producing slightly lower ET than predicted. It is also possible that because the Landsat thermal pixels are 100m x 100m, there are still some edge effects impacting the results even after the manual mixed pixel exclusion process. We expect these errors to be small and not impact the overall trend of the data. Areas without beaver damming and hillslopes had a tendency to just decrease throughout the growing season – likely due to increasing water stress. The NDVI calculations over the same time period show similar results (Figure 9).

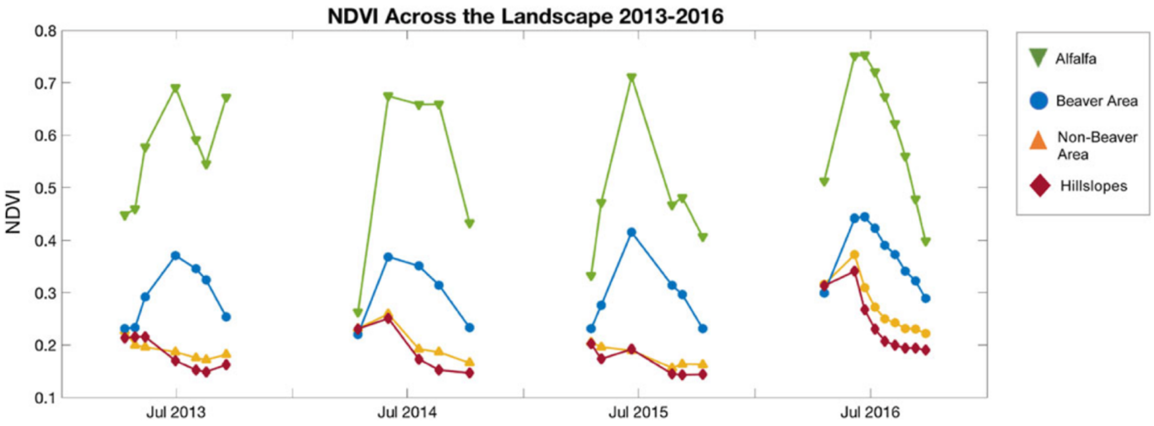

Figure 9: Normalized difference vegetation index (NDVI) of beaver-dammed riparian areas put in the context of other landscape elements: undammed riparian areas, irrigated alfalfa, and hillslopes disconnected from the streams

In Figure 9, the NDVI of each landscape element has a similar shape to the respective ET in Figure 8. This again confirms that observed differences in ET between the four landscape elements (dammed riparian areas, undammed riparian areas, irrigated alfalfa, and hillslopes) is largely due to differences in vegetation transpiration as opposed to soil or open water evaporation. Additionally, it shows that beaver dammed riparian areas are more similar in vegetation health and/or density to the irrigated alfalfa than to either the non-beaver riparian areas or the hillslopes.

2.3.4 Seasonal and Multiyear Drought Analysis

The data from 2013-2016 showed that both measures of drought buffering (ET and NDVI) were consistently higher in the riparian areas with beavers than in those without beavers (Figure 10).

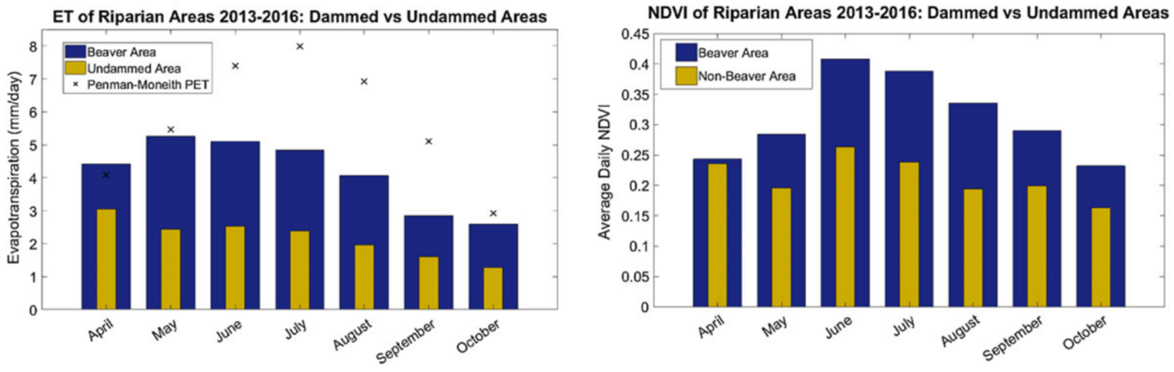

Figure 10: Left: The evapotranspiration (ET) of riparian areas with beaver versus riparian areas without beaver. Right: The normalized difference vegetation index (NDVI) of dammed and undammed riparian areas. PET: potential evapotranspiration

We found that the ET of riparian areas with beaver damming was 50-150% higher than the ET in riparian areas without beaver damming, and that NDVI in dammed riparian areas was 6-88% higher than in undammed areas. The difference between the dammed and undammed areas peaks in the summer – the time when water needs are highest and water availability is lowest. Figure 10 also shows that for both ET and NDVI the greatest difference between the two areas is June-August - the seasonal drought. This suggests that on Maggie Creek, beaver-dammed riparian areas are better buffered against seasonal droughts than riparian areas that do not have beaver damming.

Although the beaver dammed riparian areas clearly maintain vegetation health better than the riparian areas during seasonal droughts, the question remains as to whether the drought buffering was more pronounced during the drought years (2013-2015) than the non-drought year (2016). Figure 11 shows the data from each year plotted on top one another to allow for direct comparisons between drought and non-drought years for the beaver dammed and undammed riparian areas.

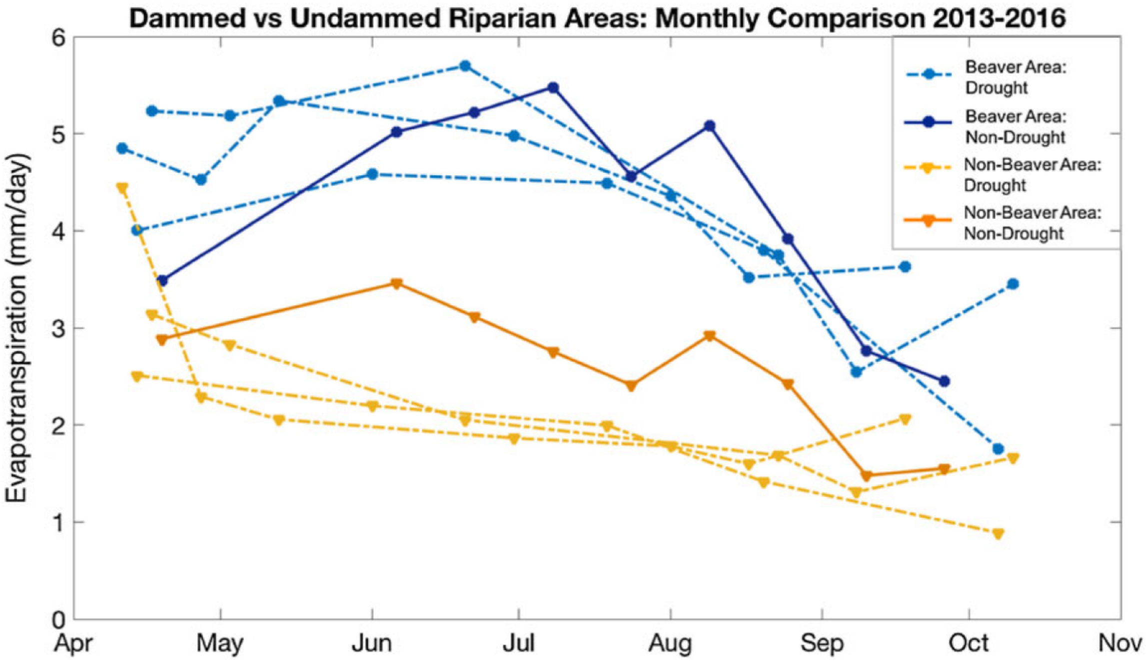

Figure 11: Evapotranspiration of riparian areas with and without beaver. Each year from 2013 to 2016 is individually plotted and colour coded by beaver versus no-beavers (blues vs. yellow) and drought versus nondrought (light dotted line vs. dark solid line)

For the beaver dammed riparian area (blue, Figure 11), the drought (dashed line) and non-drought (solid line) data do not have distinctly different shapes or magnitudes. There are two takeaways from this: first, this shows that the drought buffering capacity of the beaver-dammed riparian area did not diminish significantly over during the studied multiyear drought. Second, vegetation in the beaver-dammed riparian area did not fare any worse during the multiyear drought that it did during the normal precipitation year. This indicates that the extent of beaver damming on Maggie Creek was enough to fully buffer the effects of the multiyear drought on the riparian vegetation.

For the riparian area without beaver damming (yellow, Figure 11), the drought (dashed line) and non-drought (solid line) data have different shapes and different magnitudes. All the data from the drought years essentially just decrease from a high value in April – likely due to the vegetation undergoing senescence at the beginning of the summer and staying senesced throughout. The shapes of the drought year data have no arc, and do not look similar to the beaver dammed area's drought data. During the non-drought year, however, the shape of the ET for the riparian area without beaver damming was similar to the riparian area with beaver damming, and no longer had the monotonously decreasing shape like it did during the drought years. Vegetation in the undammed area likely still underwent senescence, but it appears to be for a shorter duration and begin later in the summer than it did during the drought years. Additionally, it was higher in magnitude than the three drought years. This suggests that the riparian area without beaver damming was sensitive to multiyear droughts.

In summary, these results showed that beaver dammed riparian areas had largely the same ET signal for drought years and the non-drought year, implying that they are well-buffered against extended periods of drought. Riparian areas without beaver, however, appear to have been affected by the multiyear drought and appeared to begin senescing very early in the summer, implying that they are not as well-buffered against extended periods of drought.

2.4 Discussion and Conclusions

We proposed that beaver-dam-induced drought buffering occurs via water seepage from the beaver ponds into the nearby soil, where it is accessible to the roots of riparian vegetation. Our data showed that within the context of the landscape, the beaver dammed riparian areas have ET and NDVI signals more similar to irrigated crops than to either undammed riparian areas or hillslope vegetation. This similarity supports the idea that the drought buffering mechanism associated with beaver damming works like an underground irrigation system for the riparian vegetation, in which water seeps from the beaver ponds into the shallow subsurface.

We demonstrated that increased beaver damming is associated with elevated ET signals using the data from Susie Creek. We found a linear positive relationship between damming intensity and ET going from no beaver damming to ~150m dam length per 500m stream segment. However, beyond 150m dam length/500m stream segment the effects of increased damming failed to produce increasingly higher ET values. This suggests that there is a threshold beyond which some other factor limits ET more than the availability of ponded water. We suspect that this threshold may be associated with physical characteristics of the riparian area – such as soil drying rate, soil porosity, shape of the hyporheic zone, and maximum vegetation density.

We hypothesized that the drought buffering mechanism associated with beaver damming is at least sustainable on seasonal timescales, where the beaver ponds are refilling each winter/spring with precipitation and slowly releasing it through hot, dry summers. This hypothesis was confirmed by our results, which showed that beaver-dammed riparian areas have consistently higher ET during seasonal droughts than undammed areas. Our NDVI calculations indicated that the increase in ET was more likely due to increased plant productivity and/or density rather than more open water or soil evaporation. Furthermore, we predicted that as long as there was water remaining in the beaver ponds, the drought buffering would be able to persist through multiyear droughts. Our results did not show a significant decrease in the ET of the beaver dammed area as the multiyear drought progressed. The riparian area without beaver damming, on the other hand, was negatively impacted by the multiyear drought and showed a regain of vegetation health once the drought ended. This supports the idea that drought buffering associated with beaver damming can be effective on multi-year timescales in additional to seasonal ones.

A major limitation of this study is that it is a site-specific case study, and although we suspect the results may be more generalizable we do not currently have data to support that claim. Additionally, because of the transient nature of beaver damming (beaver dams come in and out of repair and beavers move up and down stream looking for fresh food [*Neff*, 1957; *Ruedemann and Schoonmaker*, 1938; *Woo and Waddington*, 1990]) and lack of a detailed long-term record of dam locations and sizes along the creeks we were only able to justify using the 4 years of Landsat data centered around a dataset of known beaver dam distribution data. Although we chose a field site where we expected differences in topography, geology, and soil hydraulic parameters to be minimized, it is likely that the undammed riparian areas are not completely analogous to the beaver dammed riparian areas. For example, it is known that beaver ponds accumulate sediment –

particularly fine sediments and organic matter – and can transform streams into true wetlands and wet meadows. We did not attempt to separate out the effects that changes in soil properties, connection to floodplain, vegetation type changes would have caused – they were all considered beaver related effects and discussed as an innate difference between dammed and undammed riparian areas.

Despite the limitations of this study, we have shown that these particular beaver-dammed riparian areas are better equipped to thrive during droughts than riparian areas without beavers. Our results are not easily explained by any process that would be site-specific and only applicable at Maggie and Susie Creeks – such as a beetle kill, high variation in soil type or plant species along the creeks, etc. We expect that further research will show similar results in arid watersheds across North America.

All of the arid and semi-arid states in the western USA have lost a huge percentage of wetland habitat since the 1700's – with California having lost 91%, Nevada 52%, Idaho 56%, and Colorado 50% [*Mitsch and Gosselink*, 1993]. These same states also have extensive habitat that could be colonized by beaver in the coming decades [*William W. Macfarlane et al.*, 2015], potentially restoring some of the lost wetland habitat in a way that is more resilient to future stressors like drought. Our study showed that beaver dammed riparian areas may be better buffered against droughts than riparian areas without beaver, and so we encourage land managers to consider encouraging beaver dam building activity in future management plans for arid and semi-arid landscapes. Further modeling, remote sensing, and field work is necessary to fully characterize the role that beavers will play in the future of wetland habitat creation and maintenance in arid and semi-arid climates, but we believe our study shows the potential for their impacts to be important and worth consideration.

Chapter 3: Refuge in the Inferno: Beaver Wetlands Emerge from Western Wildfires Unscathed

3.1 Background

Beavers are present in and native to most of North America – from the northern portions of Mexico up to the Canadian Arctic; from the east coast to the west coast and everywhere in between [*Beedle*, 1991; *Beier and Barret*, 1987; *Bigler et al.*, 2001; *Burchsted*, 2013; *Butler and Malanson*, 1995; *Carillo et al.*, 2009; *Cavin*, 2015; *Cunningham et al.*, 2006; *Gibson and Olden*, 2014; *Goldfarb*, 2018; *Hammerson*, 1994; *W G Hood*, 2012; *Johnston*, 2017; *Lanman et al.*, 2013; *Morgan*, 1868; *Müller-Schwarze and Sun*, 2003; *Naiman et al.*, 1988; *M. M. Pollock et al.*, 2015; *Rybczynski*, 2007; *Tape et al.*, 2018]. Through their construction of dams and channels, beavers create and maintain vast wetlands along riparian corridors throughout the continent [*Gurnell*, 1998; *Rosell et al.*, 2005]. The geomorphic, ecologic, and hydrologic impacts of beaver are many, but one that has garnered recent attention in popular media is the ability for beaver damming to buffer their wetlands against the effects of climate change [*Hyslop*, 2013; *Mullen*, 2018; *Osborne*, 2014; *Worrall*, 2018]. The potential for beaver damming to play a significant role in building climate resiliency has not gone unnoticed in the scientific community – beavers have been documented buffering drought effects [*Fairfax and Small*, 2018; *G A Hood and Bayley*, 2008] and were discussed in the Fourth National Climate Assessment as a way to rewet drying landscapes [*Vose et al.*, 2018].

The mechanisms and processes behind beaver-induced climate resiliency are founded in the beavers ability to slow down and store large volumes of water in both the surface and subsurface, and then to spread that water out into the surrounding landscape via channels they dig from their ponds [*Burchsted et al.*, 2010; *Burns and McDonnell*, 1998; *Dittbrenner et al.*, 2018; *Feiner and Lowry*, 2015; *Janzen and Westbrook*, 2011; *Karran et al.*, 2017a; *Karran et al.*, 2017b; *Lowry*, 1993; *Pilliod et al.*, 2017; *Wegener et al.*, 2017; *Westbrook et al.*, 2006]. Although it has been discussed anecdotally and compelling photographs are available in popular news (https://blog.nwf.org/2018/10/beavers-water-and-fire-a-new-formula-for-success/), it has not yet been studied whether the beaver-induced climate resiliency in a landscape extends to wildfire. We hypothesize that by rewetting the soil and buffering riparian vegetation against drought, beavers create more fire-resistant riparian corridors than would otherwise naturally occur.

Wildfires are a growing concern in much of the western United States as climate warms and droughts become more frequent [*Abatzoglou and Williams*, 2016; *Marlon et al.*, 2009; *McKenzie et al.*, 2003; *Mutch*, 1970; *Westerling and Bryant*, 2007; *Westerling et al.*, 2006; *Westerling et al.*, 2003]. This hotter, drier climate increases the duration and intensity of fire season each year. It is widely accepted that fuel moisture is a large driver of wildfire – with drier fuels (vegetation) leading to larger, more intense burns [*Nolan et al.*, 2016; *Rothermal*, 1972]. Given that beaver have been shown to keep soil wetter and vegetation lusher through their storage of water in the surface and subsurface, it makes logical sense that they would also be creating uniquely fire-resistant patches in the landscape. Beaver-dammed riparian areas are, however, relatively small landscape features when compared to the size of most wildfire burn scars. It is not unreasonable to think that given their size relative to the size of wildfires, the vegetation near beaver ponds may be much wetter than other vegetation but is still small enough in area that the fires could consume it regardless.

In this study we use satellite-derived Normalized Difference Vegetation Index (NDVI) data of beaver-dammed riparian areas collected before, during, and after large wildfires to determine whether or not beaver-dammed riparian areas are more fire-resistant than riparian areas without beavers.

3.2 Methods

3.2.1 Wildfire Locations and Information

We examined 5 recent large wildfires located in 5 different western U.S. states: Colorado, California, Oregon, Idaho, and Wyoming. The approximate location of each wildfire is marked with a red circle in Figure 12.

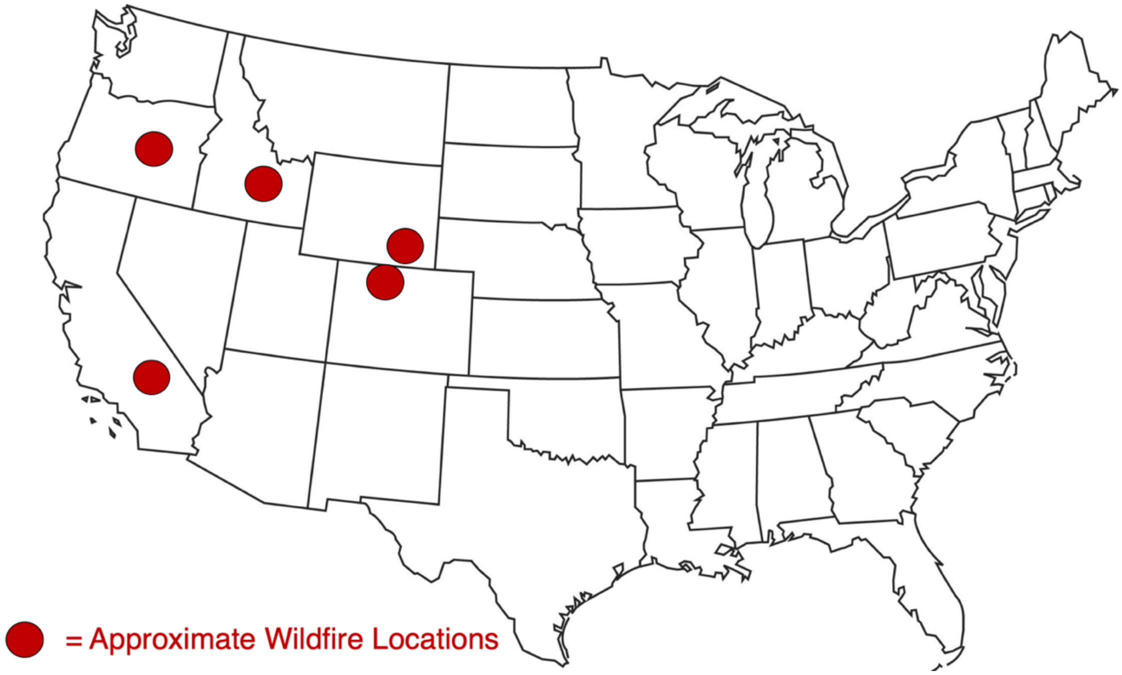

Figure 12: Location of each wildfire included in this study. Fire locations are marked with a red circle.

The burn area for each fire is shown highlighted in red overlaid on Google Earth satellite imagery in Figure 13.

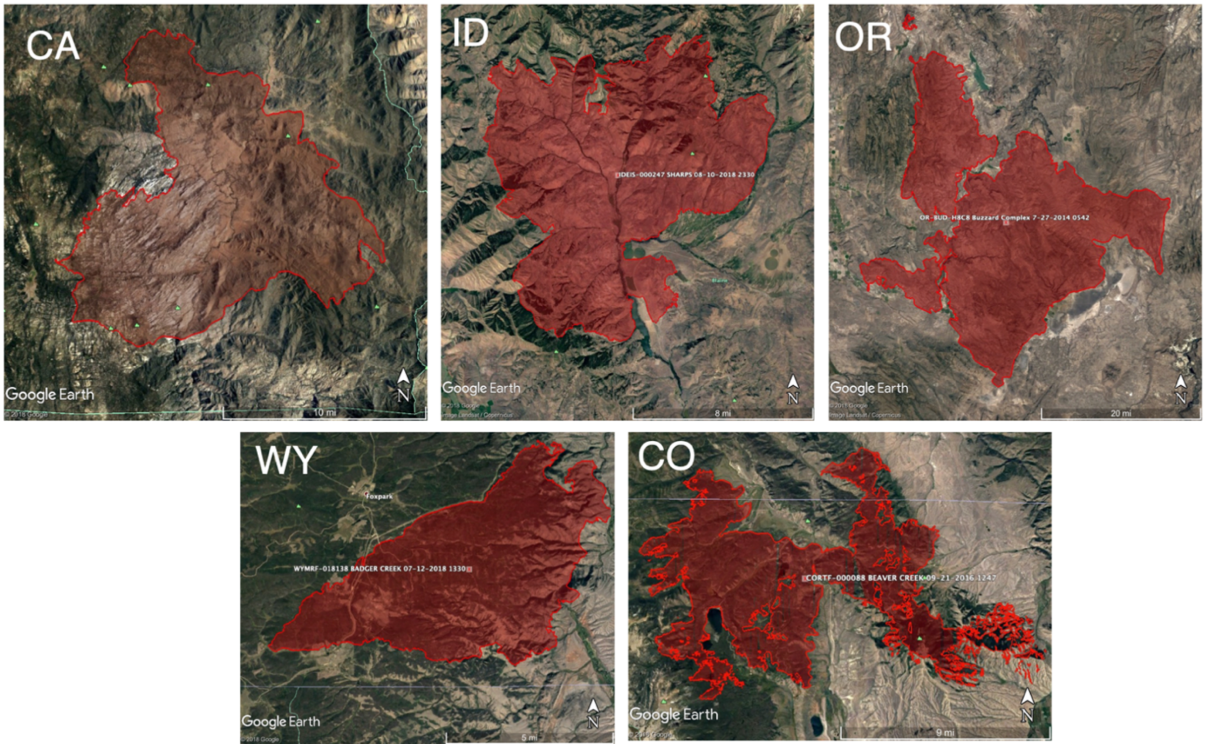

Figure 13: Burn perimeters for each fire shaded red and overlain on Google Earth imagery.

These fires all affected creeks with variable amounts of beaver damming located within the burn perimeter as determined by reviewing the Google Earth satellite imagery in each location [*GoogleEarth*, 1995; 2002; 2014a; b; 2016; 2017]. Identification and mapping of beaver dams and ponds via Google Earth imagery is described in section 2.2.2.

We selected fires for the study that had differing topographies and landcover to help determine the generalizability of beaver-wildfire impacts in the American West. The wildfires occurred in both alpine and lowland settings, in forests and in semi-arid shrubland/grassland. With the exception of Idaho and Wyoming, smoke/cloud-free Landsat satellite imagery is available for all fires used in this study the on the approximate date of the burn in the year before, of, and after the fire. The fires in Idaho and Wyoming burned in the summer of 2018, so the following year's NDVI data does not exist yet. In these cases, we only used pre-fire and during-fire data. These satellite data are used to calculate the NDVI as described in Section 3.2.2. The details of the fires examined - including fire ID, fire name, approximate burn start and end dates, approximate burn duration, area burned, and number of beaver dams present - is summarized in Table 2. These data and fire perimeters were compiled from the USGS GeoMAC Wildland Fire Support database [*USGS*, 2019].

Table 2: Wildfire Information

State	**Year**	**Fire Name**	**Fire ID**	**Burn Start**	**Burn End**	**Burn Duration (days)**	**Burn Area (acres)**	**# of Beaver Dams**	**# of Creeks**
California	2000	Manter	n/a	7/28/00	8/28/00	~30	79182	57	2
Colorado	2016	Beaver Creek	CORTF-000088	6/19/16	9/21/16	94	38380	364	4
Idaho	2018	Sharps	IDEIS-000247	7/29/18	8/10/18	12	64811	62	2
Oregon	2014	Buzzard Complex	ORBUD-H8C8	7/13/14	7/27/14	14	395348	48	1
Wyoming	2018	Badger Creek	WYMRF-018138	6/10/18	7/12/18	32	21322	190	3

3.2.2 Identification and Mapping of Beaver Dams

To determine where beavers were influencing riparian corridors along the creeks in our study, we mapped out beaver dams, ponds, and beaver-dug channels on each creek using satellite images acquired through Google Earth [*GoogleEarth*, 1995; 2002; 2014a; b; 2016; 2017]. Beaver dam, pond, and channel mapping is done based on a set of criteria previously developed and tested by the authors of this study. Beaver dams are often visible in satellite imagery as they are often 10's – 100's of meters long. To date, the primary author of this study has mapped out and/or identified over 2500 beaver dams in satellite imagery and ground-truthed more than 200 beaver dams. None of the ground-truthed beaver dams were determined to be falsely classified. Based on our history with positive identification of beaver-related landscape features in satellite imagery, we expect the error on our classification of beaver dams and ponds to be less than 1%. To be classed as a beaver pond, a feature must have: a visible dam that conforms to typical dam shapes observed in the field, a visible beaver lodge within 1-kilometer, ponded water upstream of the dam. Channels must originate from ponds and spread into the riparian zone in the general direction of nearby food or building materials. An example of a beaver-impacted landscape in Wyoming pre/post mapping out beaver ponds is shown in Figure 14.

Figure 14: A beaver-impacted landscape in Wyoming, USA pre (left) and post (right) mapping out the ponds. Ponds are outlined in white in the image on the right.

We used imagery taken as close to the date of the fires as possible in our beaver-related feature mapping. Beaver dams and ponds can persist in a landscape for decades, and can also be freshly constructed in weeks. To make a best estimate of which dams were present during the fires, we examined imagery as close to the burn dates as possible, but also prior to burn date and well after the burn date. If dams were present before and after the fire, we assumed they were also present during the fire. In cases where no high-resolution imagery was available after the fires, we only counted beaver dams that had been in the landscape for at least 2 years' worth of images. This was done to limit our analysis to well-established beaver wetlands which are what we assume would continue to persist in the landscape into the fire years barring blowouts during large flood events or destruction of dams by humans.

3.2.3 NDVI Calculations and Creek NDVI Fire Severity Scores

Beaver ponds and riparian corridors are relatively small landscape features, so to calculate NDVI via remote sensing we needed satellite data with red and near-infrared imagery and relatively high spatial resolution. With the exception of the 2000 Manter Fire, we calculated NDVI from Landsat 8 imagery. Landsat 8 imagery is available from April 2013 through the present, has bands with 30m resolution on its red and near-infrared bands, and a 16-day recurrence interval [*Anderson et al.*, 2012; *Roy et al.*, 2014]. For Manter Fire, I used Landsat 7 imagery. Landsat 7 imagery is available from April 1999 through present and also has 30m resolution on the red and near-infrared bands, and a 16-day recurrence interval. The Scan Line Corrector on Landsat 7 failed in 2003, which lead to a loss of ~22% of data per scan [*NASA*, 2019]. The data used for the Manter Fire in this study was collected prior to the failure (1999, 2000, 2001) and thus is not impacted by that data loss.

NDVI is calculated from Landsat acquired reflectivity data according to [*Tucker*, 1979],

$$\mathrm{NDVI} = \frac{(\rho_4 - \rho_3)}{(\rho_4 + \rho_3)} \qquad \text{Eq. 8}$$

where ρ_4 is the near-infrared band reflectivity and ρ_3 is the red band reflectivity. The All images came with a quality assessment statement regarding whether the integrity of data had been affected by instrument artifacts or atmospheric conditions. None of the images used in this study had any quality issues. Only images with no cloud cover over the area of interest were used in this study to avoid introducing error or obscuring data.

The literature indicates that NDVI can be used as a proxy for overall riparian vegetation health, and that it can be estimated from remotely sensed NDVI [*Fairfax and Small*, 2018; *Kauffman et al.*, 1997; *W. W. Macfarlane et al.*, 2016]. High NDVI (values close to 1) generally indicated lusher, greener vegetation while very low NDVI (values close to 0 or negative) generally indicate unhealthy, senesced, or dying vegetation. However, NDVI depends on both the photosynthetic activity of the plants as well the number of plants per area. Thus, a low NDVI could be indicative of relatively few plants that may still be healthy and have high productivity – this is the case in shrublands where an NDVI of 0.2-0.3 could be expected for a healthy, but sparsely vegetated shrubland [*DeFries and Townshend*, 1994]. In more densely vegetated areas – including riparian zones – an NDVI below 0.3 is generally considered to be indicative of low plant health and productivity [*Donnelly et al.*, 2016; *Esau et al.*, 2016; *Nagler et al.*, 2001; *Silverman et al.*, 2019]. Riparian vegetation is well adapted to disturbances, so we assume that the NDVI in the post-fire year should be very similar to the pre-fire year if the system recovered - if the NDVI is slightly lower in the post-fire year, it can be due to normal annual fluctuations in NDVI or due to the pre-fire NDVI being artificially high from an excess of fuel build up [*Pettit and Naiman*, 2007].

In this study, we use the 0.3 NDVI threshold to determine whether or not there is riparian vegetation present. Other than that threshold, we do not attempt to quantify the absolute vegetation health or condition at any single moment in time as this would require more detailed ground surveys and are beyond the scope of this project. Instead, we primarily focus on the change in NDVI in a given area over time to quantify how the riparian corridor was impacted by fire in this study. For example, if a given pixel changes from an NDVI of 0.7 to 0.4 during a fire, that indicates the vegetation health in that area suffered. If a given pixel had an NDVI of 0.4 both before and during the fire, then we interpret that as the vegetation health not suffering because of the fire, even though it had a fairly low absolute value. That low NDVI area may or may not have had much riparian vegetation prior to the fire, but because it did not change we interpret that to mean it was not significantly impacted by the fire.

We use NDVI to assess changes in riparian vegetation health within the burn perimeters on approximately the same day of year in the years before, of, and after the fire when possible. This is done to ensure vegetation is at approximately the same point in the growing season for each image. The exact same day of year is not always possible because of weather, shifts in flyover date, and smoke. The year and day of year (YYYY-DOY) of imagery used in this study are listed in Table 3 for each fire.

Table 3: Landsat Imagery Used for NDVI Calculations

State	**Fire Name**	**PreFire**	**Fire**	**PostFire**
California	Manter	1999-231	2000-218	2001-236
Colorado	Beaver Creek	2015-234	2016-244	2017-246
Idaho	Sharps	2017-217	2018-220	NA
Oregon	Buzzard Complex	2013-204	2014-207	2015-201
Wyoming	Badger Creek	2017-230	2018-210	NA

NDVI was calculated in the entire landscape for each fire at each point in time. To isolate the impact of beaver damming on NDVI along the riparian corridor, we extracted the value of the NDVI in each pixel along each creek examined. We did not take into consideration the width of riparian zone along the creeks in areas with and without beaver. The NDVI values extracted are only for the cells immediately adjacent to the creek. Because beaver damming often creates wider riparian zones than would otherwise occur on a given stream, our NDVI calculations should be interpreted as a conservative assessment of the potential for beaver to provide wetland habitat refuge during wildfires.

To make fair comparisons of the vegetation health in areas with and without beaver during the fires, we calculated a “creek NDVI Fire Severity Score” along each creek in the study (Eq. 9). The NDVI Fire Severity Score is the difference in NDVI between the fire year and the average of the pre/post fire years for each fire. In cases where no post-fire data exists, the NDVI Fire Severity Score is the difference between the pre-fire NDVI and the fire NDVI.

$$0.5 * (\mathrm{NDVI}_{\mathrm{pre}} + \mathrm{NDVI}_{\mathrm{post}}) - \mathrm{NDVI}_{\mathrm{fire}} = \text{NDVI Fire Severity Score} \quad \text{Eq. 9}$$

To compare areas influenced by beaver damming to areas without beaver damming, we broke each creek into sections designated as with beaver or without beaver. To be considered a section with beaver damming, the pixels in the image must be touching or within 50 meters of either: a beaver dam, a beaver pond, or a beaver-dug channel. The 50m buffer was chosen to help account for the subsurface impact beaver damming has on locally raising the water table and saturating nearby soils [*Feiner and Lowry*, 2015; *Lowry*, 1993; *Westbrook et al.*, 2006]. We calculated the average NDVI Fire Severity Score of each section to determine within a given creek how areas with beaver fared during the fires as compared to areas without beaver.

In order to make comparisons of beaver impact on NDVI during wildfire between locations (both within a given fire and between fires) we calculated a scaled NDVI Fire Severity Score at every pixel along the creeks. The first step to calculate the scaled NDVI Fire Severity Score was determining the maximum NDVI Fire Severity Score excluding any statistical outliers (outliers defined as 1.5x the interquartile range of all NDVI values along each creek profile). All NDVI values along the creek profile were scaled to this maximum value to determine what percentage of maximum NDVI suffering was realized at any point along the creek during the fires (Eq. 10).

$$\frac{\text{NDVI Fire Severity Score at Pixel}}{\text{Max NDVI Fire Severity Score on Creek}} = \text{Scaled NDVI Fire Severity Score}$$

Eq. 10

We used the scaled NDVI Fire Severity Scores from all areas with beaver damming and all areas without beaver damming to quantify the difference between each type of riparian area fared during wildfire.

3.2.4 Two-Sample Kolmogorov-Smirnov (KS) Test

To determine if there was a statistically significant difference between the scaled NDVI Fire Severity Score of areas with beaver damming and areas without beaver damming, we opted to use the Kolgomorov-Smirnov (KS) Test [*Massey*, 1951]. This statistical procedure tests whether two samples come from a single distribution of data or two distinct distributions.

In the KS test, data from each population (areas with beaver damming, areas without beaver damming) are sorted and a cumulative distribution function for each is determined. The KS statistic (*D)* is the maximum distance between the two cumulative distribution functions. In order to get a p-value of 0.05 indicating 95% confidence that the populations are distinct, D must be greater than a critical distance, $D_{crit,95}$. This critical distance is defined in Equation 11.

$$D_{\text{crit,95}} = 1.36 * \text{SQRT}(1/n_{\text{beavers}} + 1/n_{\text{no beavers}})$$ Eq. 11

Where $n_{beavers}$ and $n_{no\ beavers}$ are the number of data points in the populations with and without beavers respectively.

3.3 Results

3.3.1 NDVI in the Burn Perimeters Before, During, and After Fire

For each fire studied, we calculated the NDVI in the entire landscape before, during, and after the fire. Our data from the Manter Fire in California is shown in Figure 15 and is representative of the results we saw across all five fires examined. In all fires, we saw a large decrease in NDVI at the landscape scale, followed by varying amounts of recovery in the year after the fire.

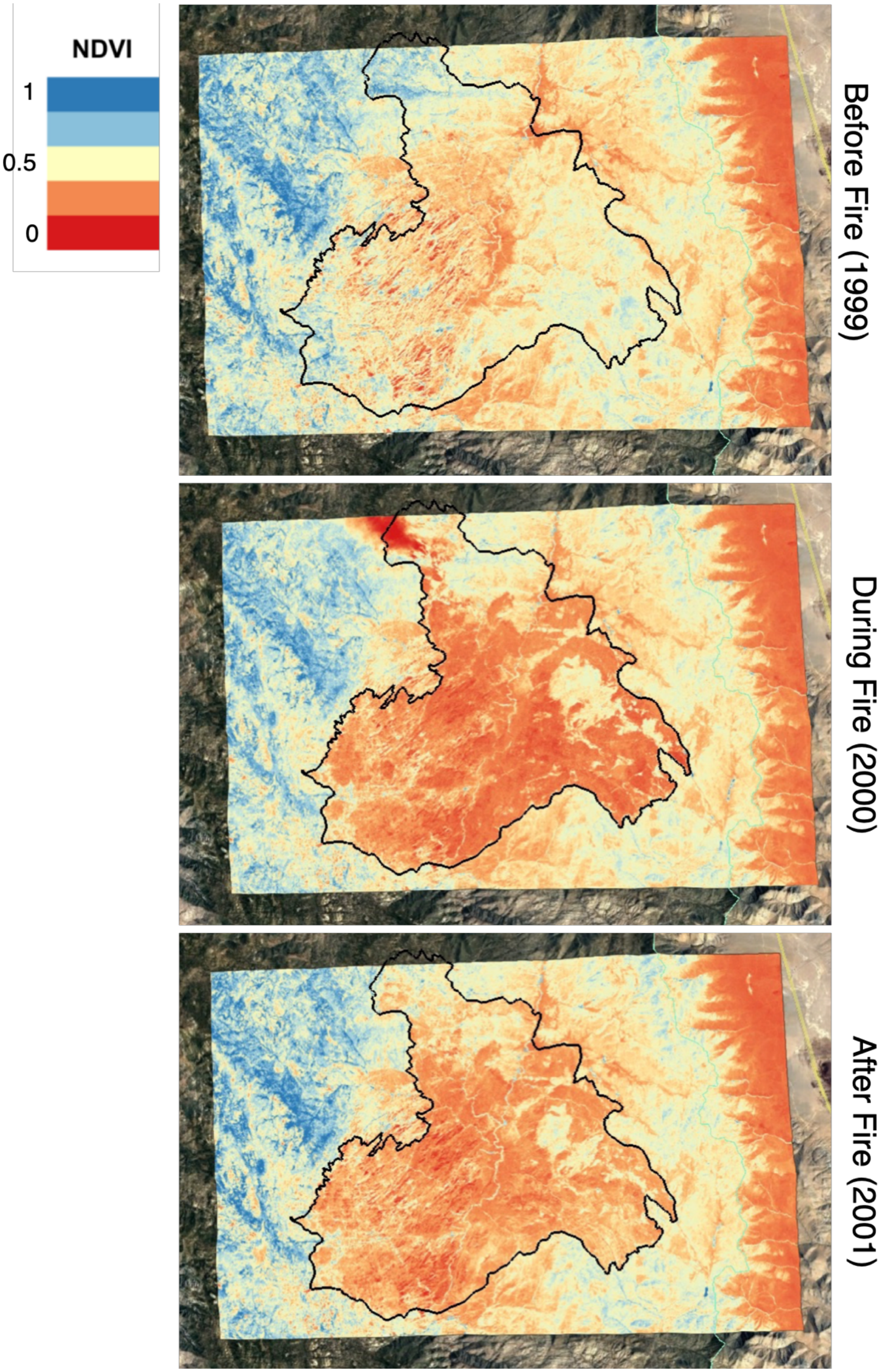

Figure 15: NDVI in the Manter Fire burn perimeter before, during, and after the fire.

We focused our analysis on creeks with variable amounts of beaver damming. The NDVI results zoomed in to the creeks with beaver damming in the Manter Fire perimeter are shown in Figure 16.

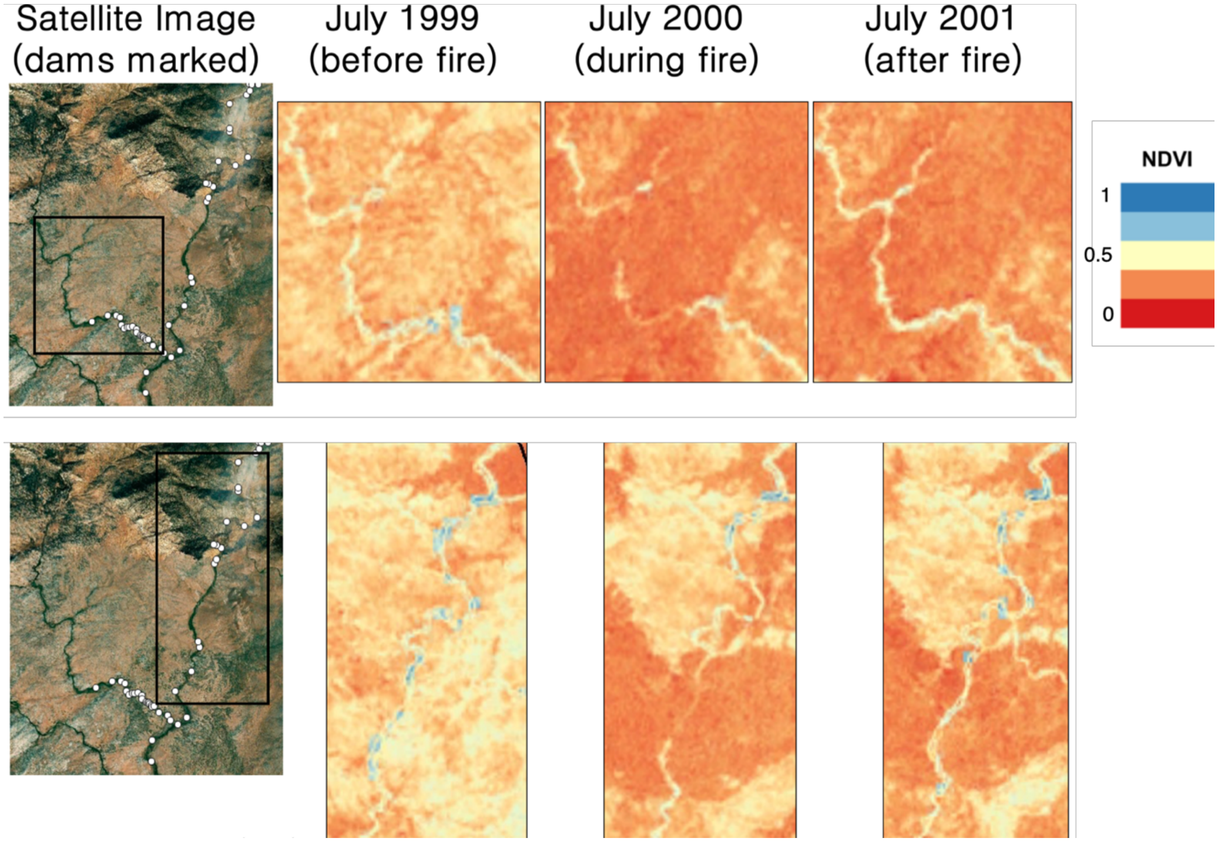

Figure 16: Zoomed in view of NDVI on creeks with variable amounts of beaver damming in the Manter Fire.

In general, we observed loss of vegetation health during the fire primarily in sections of the riparian corridor without beaver damming. This was true even if the area without beaver had higher NDVI than the areas with beaver prior to the fire.

For each creek, we extracted the NDVI values along the riparian corridor and plotted them as a function of stream length for pre, during, and post fire years. A representative plot is shown in Figure 17.

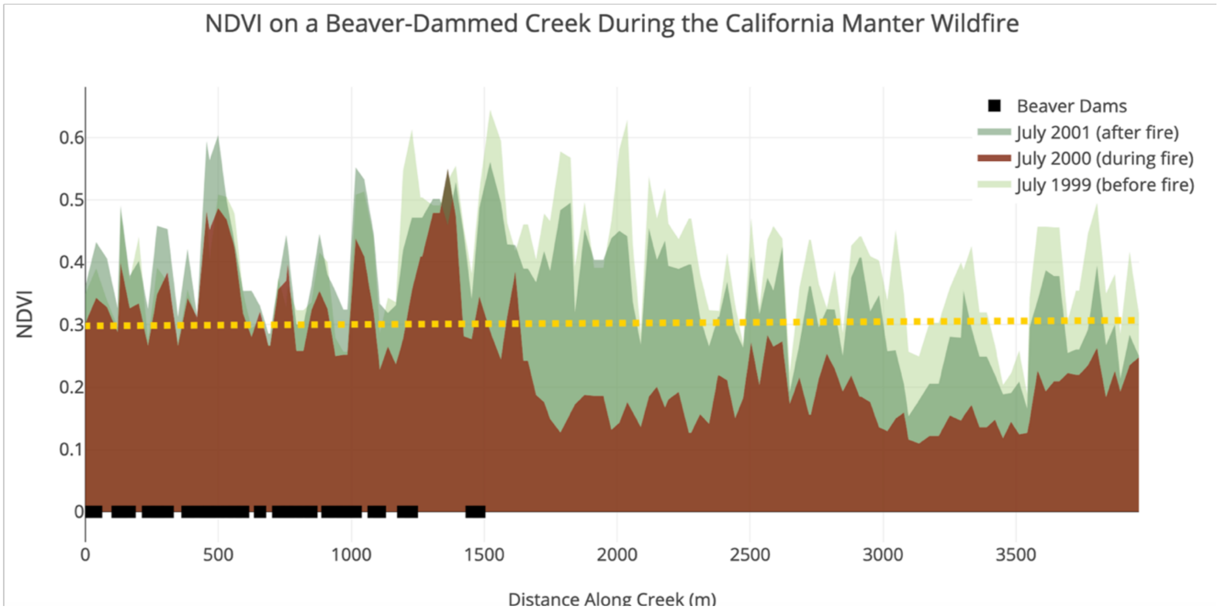

Figure 17: NDVI pre (lightest green), post (light green), and during (brown) the wildfire. Locations of beaver dams are marked with black boxes along the x-axis. The dashed yellow line is at NDVI = 0.3, which is typically indicative of riparian vegetation beginning to wilt, die, or go into senescence.

NDVI of 0.3 is marked with a dashed yellow line in Figure 28 and represents the point at which riparian vegetation would be considered generally unhealthy – it is either wilting, dying, or going into senescence. The locations of beaver dams are marked with black boxes along the x-axis in Figure 17. We observe the areas with beaver damming have smaller differences between the pre/post fire NDVI and the during-fire NDVI. This difference is calculated and plotted as a NDVI Fire Severity Score.

3.3.2 NDVI Fire Severity Scores

For each creek in the study, the difference between pre/post fire NDVI and during-fire NDVI was calculated according to Equation 10 for each pixel along the creek and is referred to as the creek's NDVI Fire Severity Score – a measure of how much the riparian vegetation suffered during the fire according to the NDVI data. A representative NDVI Fire Severity Score derived from the data shown in Figure 17 is given below in Figure 18.

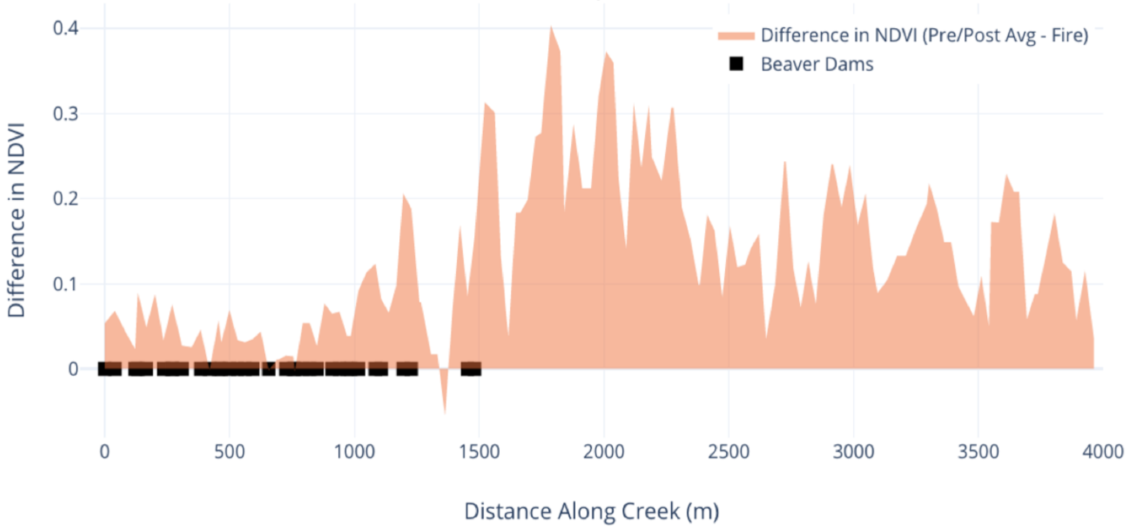

Figure 18: NDVI Fire Severity Score along a creek from the Manter Fire. Black boxes on the x-axis indicate the location of beaver dams

The creeks were broken into sections with and without beaver damming and the average NDVI Fire Severity Score was calculated in each section. These are plotted against the maximum NDVI Fire Severity Score on each particular creek in Figure 19.

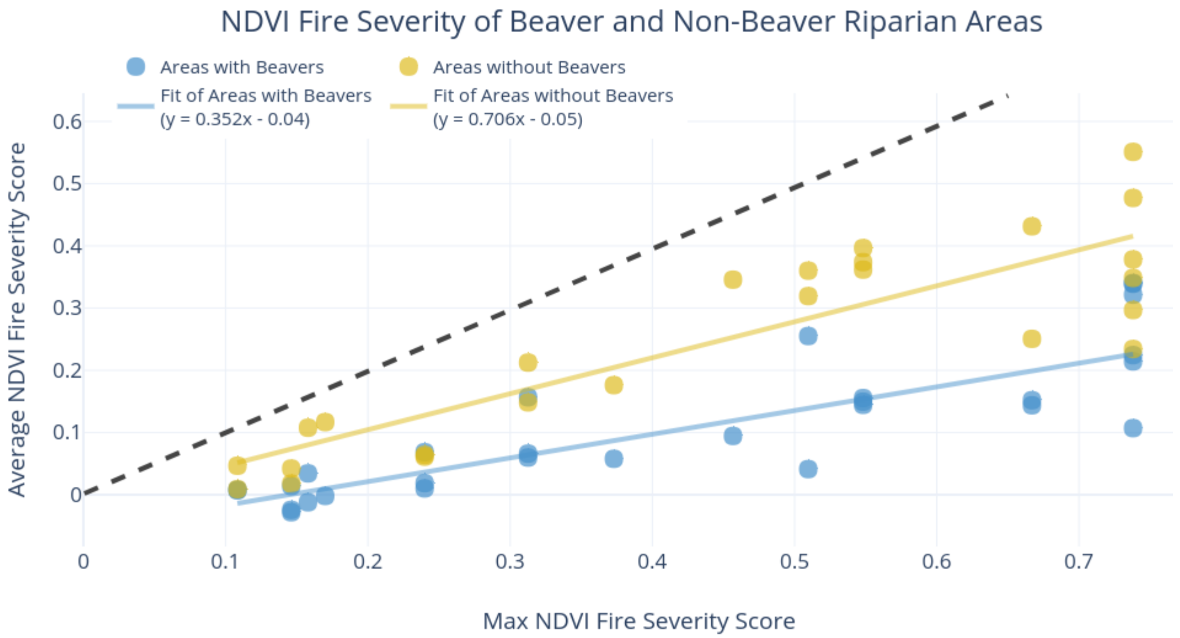

Figure 19: Average NDVI Fire Severity Scores in each section of the creeks relative to the max NDVI Severity Score on that creek. The dashed 1:1 line represents where max severity = avg severity. The further below this line points fall, the more resistant the vegetation was to the effects of wildfire.

The areas with beaver overall fall further below the 1:1 line, indicating that the vegetation in those areas suffers less during the fires than the areas without beaver. We fit the two populations of data with linear models and the slope of the line in areas without beaver was roughly twice as large as the slope of the line in the areas with beaver. This suggests two things: 1) riparian areas with beaver are overall less affected by wildfire, 2) riparian areas with beaver are more resistant to fire effects than areas without beaver – for a single unit change in maximum NDVI Fire Severity Score on the creek, the areas with beaver will only experience half as much increased suffering as the areas without beaver.

3.3.3 Scaled NDVI Fire Severity Scores and the KS Test

To ensure that the response to fire observed in the two populations of data (areas with beaver and areas without beaver) are statistically significant, we scaled the average NDVI Fire Severity Scores from each creek section to the max NDVI Fire Severity Score on that creek and separated the data into two groups. We plotted these groups as violin plots in Figure 20. Violin plots are box and whisker plots surrounded by shading which represents where data points are clumped. Wider shading means more data is at that location.

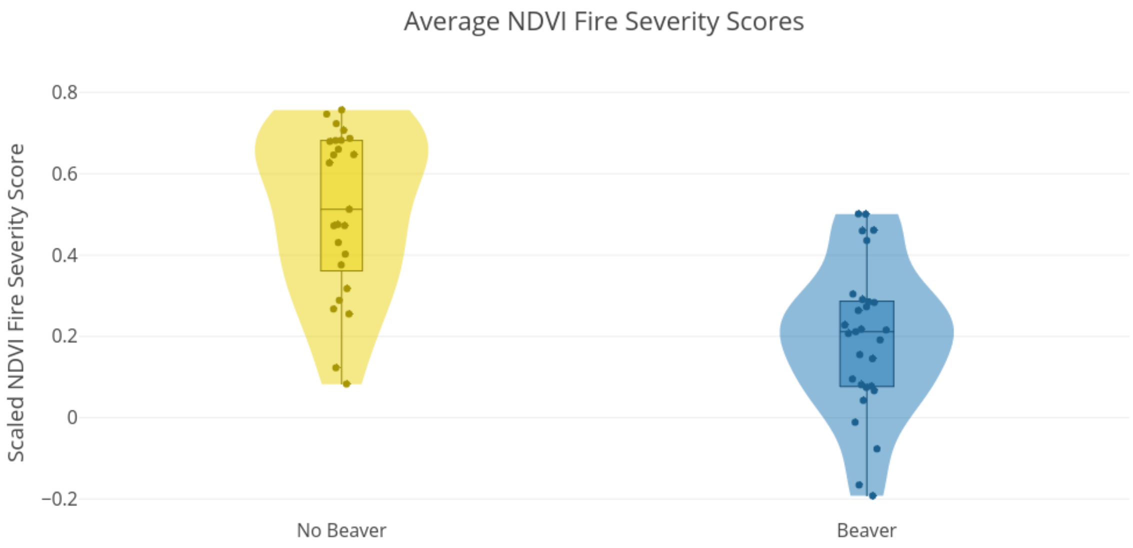

Figure 20: Violin plots of the scaled NDVI Fire Severity Scores for areas with and without beaver damming.

Data points are also shown in Figure 20 and have been jittered for ease of viewing. We observed that the riparian areas without beaver damming were a non-normal distribution skewed toward higher scaled NDVI Fire Severity Scores and is most densely populated with data around a scaled NDVI Fire Severity Score of 0.6 – 0.7. This suggests that most riparian areas without beaver damming would be expected to experience around 60-70% of the maximum suffering observed on the creek. The riparian areas with beaver damming were a normal distribution centered around a scaled NDVI Fire Severity Score of approximately 0.2. This suggests that most beaver dammed riparian areas would be expected to only suffer around 20% as much as the maximum suffering observed on the creek.

We used the KS test to determine whether the two populations of data (riparian areas with beaver, n = 26; and riparian areas without beaver, n=25) were statistically different in how the vegetation fared during wildfire. The cumulative fraction plot of the two populations is shown in Figure 21.

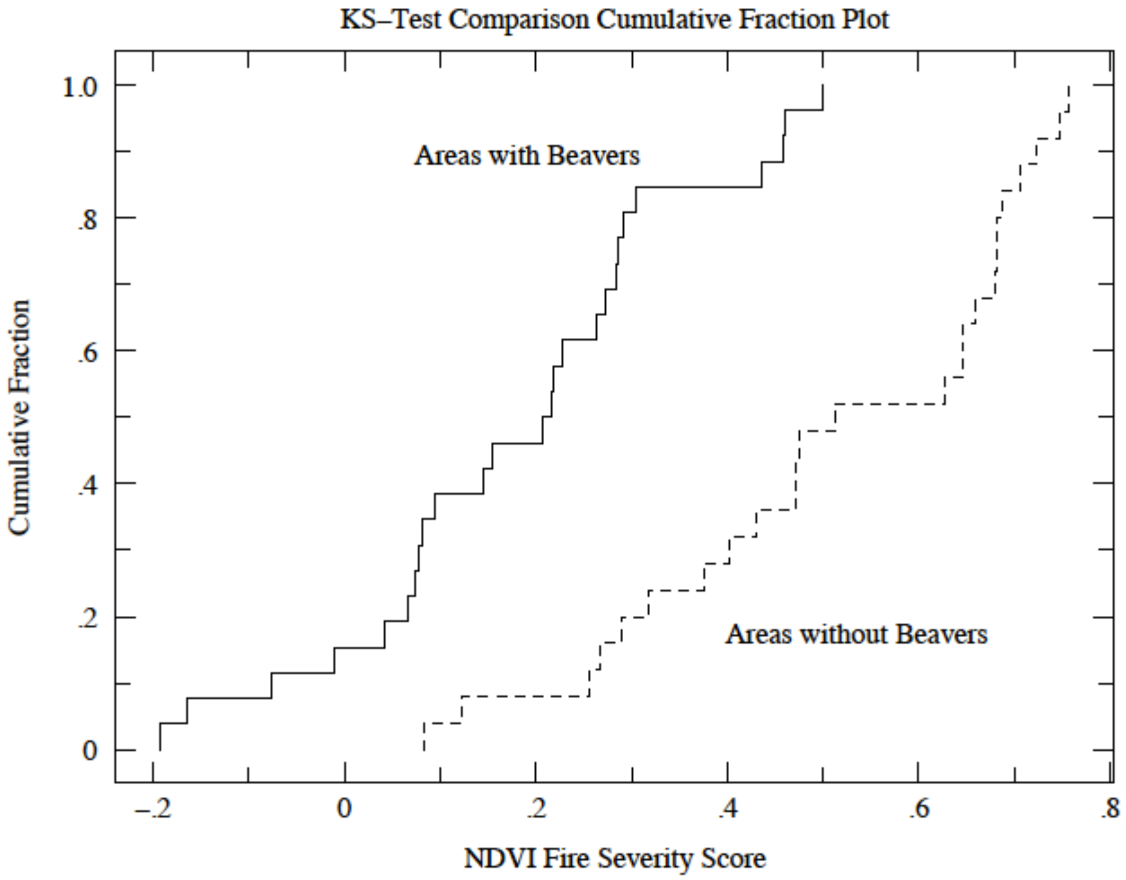

Figure 21: Cumulative fraction plot for the two populations of data. The solid line is the area with beaver damming, the dashed line is the area without beaver damming.

The critical *D* for a p = 0.05, 95% confidence was calculated to be 0.28 given the sample sizes for both populations of data. The KS statistic *D* for the two populations of data in this study was calculated to be 0.65. This corresponds to a p-value of < 0.001, indicating that we can say with high confidence that the two populations are different. This suggests that the way vegetation is affected by wildfire is fundamentally different in riparian areas with and without beaver damming, and that areas with beaver damming are better protected from wildfire than areas without beaver.

3.3.3 Riparian Recovery in Areas with and without Beaver

I calculated the recovery of riparian vegetation for the California, Colorado, and Oregon fires using the NDVI data from the year before the fire and the NDVI data from the year after the fire. Post-fire year data was not available in Idaho or Wyoming. If the riparian vegetation returned to the pre-fire state, the NDVI difference should be 0. If the riparian area had lower NDVI in the post-fire year than the pre-fire year, the NDVI difference is a positive value. If the riparian vegetation had higher NDVI in the year after the fire than the year before the fire, the NDVI difference in a negative value. The two populations – areas with beaver and areas without beaver – are summarized in the Figure 22 below.

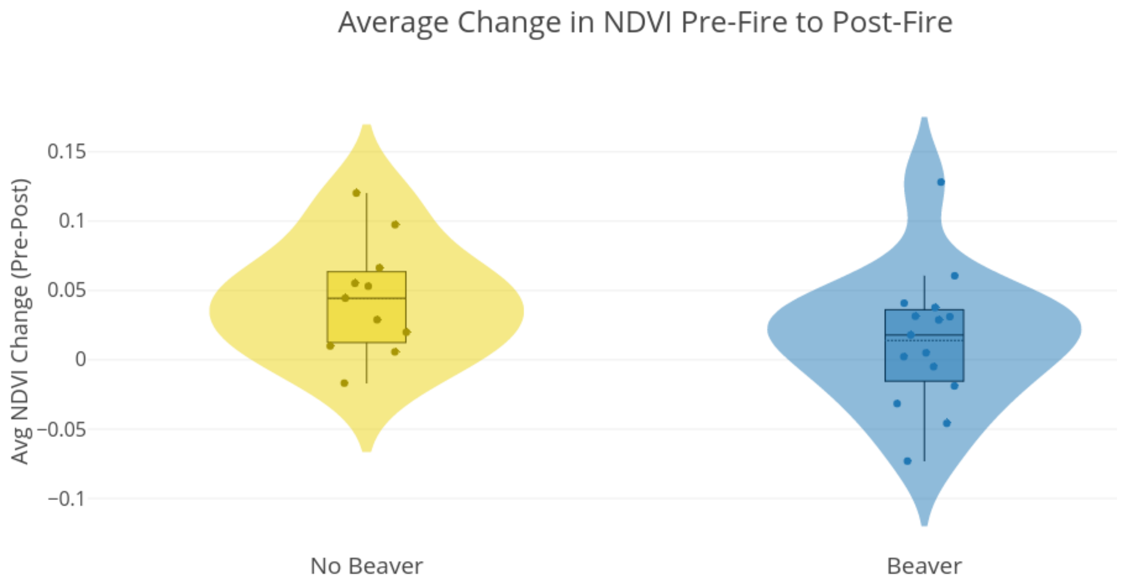

Figure 22: NDVI change between pre and post fire years. A change of zero indicated the riparian vegetation returned to the original state. Positive changes indicate the pre-fire state had higher NDVI, negative changes indicate the post-fire state had higher NDVI.

The mean NDVI change of the area with beavers was 0.01. The mean NDVI change of the area without beavers was 0.04. I also used the KS test on this data to determine statistical significance, the results of which are in Figure 23.

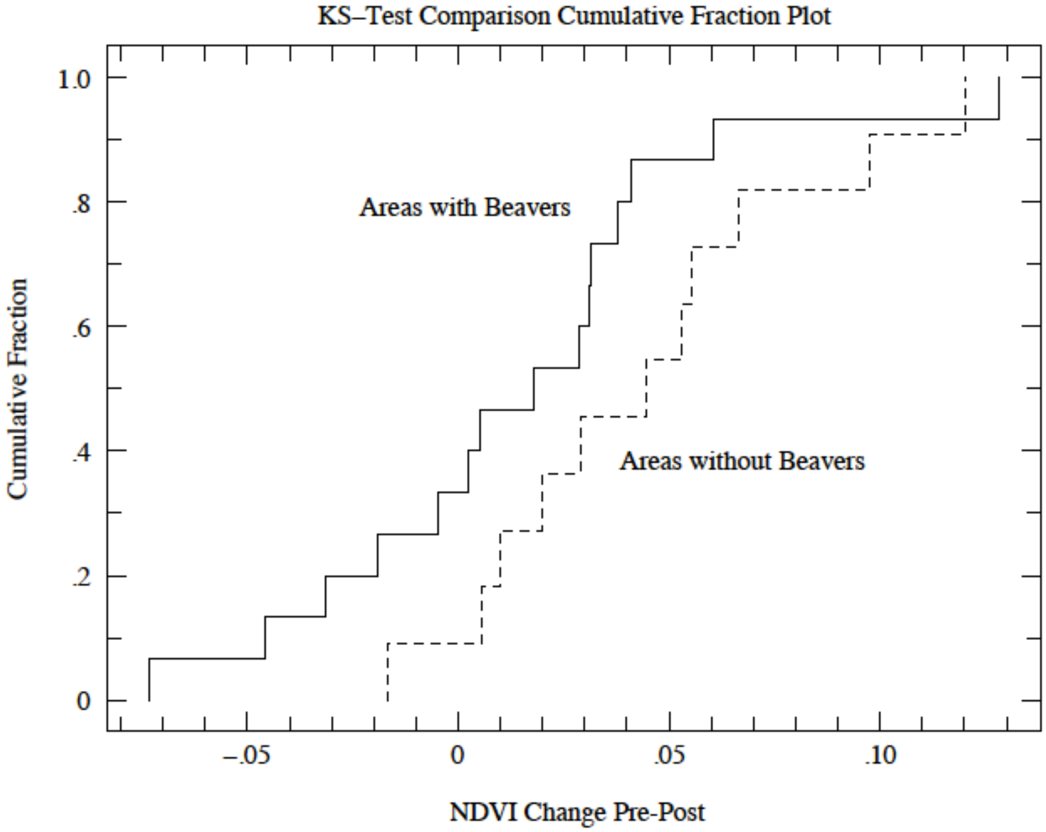

Figure 23: Cumulative Distribution Fraction (CDF) of the NDVI change data for areas with beaver and areas without beaver.

This data produced a p-value of 0.173, indicating that we can say with high confidence that the two populations are likely the same. This suggests that the way riparian vegetation recovers from wildfire is not fundamentally different in riparian areas with and without beaver damming. This reinforces the idea areas with beaver damming are primarily serving as a refuge during the wildfire, but do not have a large impact on the timeline of riparian recovery.

3.4 Discussion and Conclusions

3.4.1 Persistence of Beaver Wetlands Through Fire

The fires considered in this study were large, destructive wildfires – 10's – 100's of thousands of acres burned. On-ground accounts of the fires emphasize how intense they were. A quote given by officials to the LA Times during the Manter Fire in 2000 described the wildfire as follows: "It is a humbling expression of nature. Walls of flame 70 ft high, twice as tall as the nearest tree. Fire leaping through canyons and valleys, at times in five directions at once. Left behind, quite literally, is scorched earth: the fire is so hot it has scarred the soil." (http://articles.latimes.com/2000/aug/02/news/mn-63017) These wildfires are massive, destructive forces of nature. Given the results of our previous work showing that beaver-dammed riparian areas are relatively unaffected by drought compared to riparian areas without beaver [*Fairfax and Small*, 2018], we hypothesized that the vegetation in beaver-dammed riparian areas would fare better through large wildfires than similar riparian areas without beaver.

Using NDVI data from before, during, and after each wildfire, we found that the vegetation in riparian areas with beaver damming suffered on average only half as much as the vegetation in riparian areas without beaver. The riparian areas without beaver damming typically had high NDVI before and after the fires (>0.5), but very low NDVI during the fire (<0.3). In the riparian areas with beaver, a high NDVI (>0.5) was typically maintained before, during, and after the fire. It's important to be clear that fire is a natural landscape disturbance and that beaver ponds do not stop wildfire altogether. Our data clearly shows the riparian vegetation in places with and without beaver returning to similar pre-fire NDVI values just one year after the fires burned. What beaver ponds are doing is maintaining vegetation health and habitat during the fire – they're providing a refuge in the inferno. This preservation of riparian vegetation suggests that the riparian ecosystems with beaver were relatively unaffected by the fire and could potentially provide refuge for fish, amphibians, reptiles, small mammals, and birds that are unable to outrun/swim/fly the spread of flames.

The mechanism behind this preservation of vegetation is likely similar to the mechanism suggested for drought buffering in our 2018 study in Nevada [*Fairfax and Small*, 2018]. The beaver ponds store large volumes of water both in the surface ponds and in the shallow subsurface. This water is spread out into the landscape by beaver-dug channels, acting like an irrigation system. The beaver-dammed riparian areas stay wet even while the surrounding landscape is relatively dry during droughts or fire season. When a fire does ignite, the beaver-dammed riparian areas have enough stored water to make it energetically unfavorable to burn. It's similar to trying to start a fire with a pile of wet leaves vs with dry kindling.

The potential hydrologic and ecologic role these fire-resistant beaver wetlands play in the American west may be greater than previously thought. The western United States has lost the majority of its wetlands over the last three centuries [*Mitsch and Gosselink*, 1993]. It is possible that before most of our wetlands were lost, not only would native wetland species be more protected from fire, but other vulnerable fauna could have easily sought the wetlands out as refuge during fire. Restoration of wetlands in a warming world is increasingly being looked to as a way to build climate resiliency in the landscape and preserve biodiversity. Today, we use engineering to create and restore many wetlands in the west. Our results suggest that instead of relying solely on human engineering and management to create and maintain fire-resistant wetlands, we could benefit from ecosystem engineering by beaver to achieve the same goals. The data clearly shows that beaver-dammed riparian areas are less affected by wildfire than areas without beaver, even during very large, intense fire.

3.4.2 Study Limitations and Future Work

A limitation of this study is that ground-truthing the NDVI of riparian areas during the large wildfires is not currently possible. When the fires are actively burning they present unsafe field conditions. The airspace is often restricted over fires for the safety of air firefighting efforts, which makes collecting drone data challenging. Aerial photographs taken immediately after fires in beaver dammed areas, like those taken by Dr. Joe Wheaton after the Sharps Fire (https://blog.nwf.org/2018/10/beavers-water-and-fire-a-new-formula-for-success/) do show bright green vegetation surrounded by black char. This implies that the vegetation stayed green as the flames surrounded it, but on-site data taken in that moment does not yet exist.

This study establishes that the vegetation in beaver-dammed riparian areas fares better than it does in riparian areas without beaver during large wildfires. We found this to be true in 12 creeks in 5 states. More data is needed to isolate which beaver-driven processes – ponding, channel-spread water, raising the water table, etc. – play the largest role in creating the observed fire resistance. In order to best answer those questions, a wider network of field-instrumented beaver-dammed riparian areas and nearby comparison sites must be established and monitored, and then combined with the type of remote sensing analysis completed in this study once a fire begins. Igniting large wildfires is unethical, so we would need to wait for several of the instrumented sites to be caught in natural fires before we can begin using the data to determine the role that various beaver-driven processes play in building fire resistance. Modeling work can be undertaken in the meantime to begin disentangling the various beaver impacts. Unfortunately, it is notoriously challenging to build landscape scale ecohydrologic models of beaver wetlands due to the variable leakiness of the dams, constantly changing landscape structure as beavers dig new channels, and complex groundwater-surface water interactions [*Feiner and Lowry*, 2015; *Law et al.*, 2017; *M. M. Pollock et al.*, 2015; *Woo and Waddington*, 1990].

Despite these limitations, this study is the first to consider whether beaver damming increases the fire-resistance of riparian corridors. Our quantification of NDVI before, during, and after large fires clearly establishes that this is an observable, measurable phenomenon that merits further investigation. Our results have immediate relevance to scientists and land managers across the western United States – particularly in places with increasing wildfire risk.

Chapter 4: Increasing Accessibility and Inclusivity in Undergraduate Lab Courses Through Scenario-Based Teaching Assistant Training

4.1 Introduction and Learning Goals

Despite the fact that people with disabilities are the largest minority group in the United States [*Olkin*, 2002], national statistics illustrate that the number of individuals with disabilities studying or working in STEM disciplines is dwindling [*NSF*, 2012]. The geosciences are no exception to the underrepresentation of people with disabilities in STEM [*Atchison and Martinez-Frias*, 2012], especially considering that highly physical field work is a common component of geoscience training programs [*Atchison and Feig*, 2011; *Carabajal*, 2017; *Cooke et al.*, 1997; *Hall et al.*, 2004; *Henry and Murray*, 2018]. A number of reasons have been proposed for why there is such low representation of people with disabilities in STEM fields. Students with disabilities were often denied access to higher education before the passing of the Rehabilitation Act of 1973 [*Belch*, 2004], so it is not a stretch to imagine that the stigma associated with people with disabilities likely persists in society today [*McCune*, 2001]. Additionally, it has been suggested that many faculty and instructors are not adequately trained in Universal Design for Learning (UDL) [*Curry*, 2003; *Pliner and Johnson*, 2004] or even in making reasonable accommodations [*Atchison*, 2013]. This lack of training can lead to inaccessible classrooms and curriculum, an unwelcoming environment, and ultimately the perception of non-empathetic instructors [*Carabajal et al.*, 2018; *Hall et al.*, 2004].

Dismantling the systematic barriers and discriminations faced by people with disabilities is no doubt an ongoing, long-term process that must span many institutions over many years. However, every step in the right direction matters. In that spirit, we designed and implemented a training at the university department scale to help begin correcting the lack of training and empathy among geoscience instructors. The training was originally designed for and given to Teaching Assistants (TAs) with the intention of being repeated on an annual basis, although it could be implemented among faculty as well. Our training has five main learning goals:

1. familiarize TAs with the principles of UDL
2. emphasize that all students have differing abilities, regardless of documentation with formal campus disability services
3. instill the notion that UDL benefits all students in a classroom, not just those requiring formal accommodations
4. give TAs experience confronting and navigating accessibility issues in a low-risk, learning-focused environment
5. provide TAs with an Accessibility Statement instead of a Disability Statement to include on their syllabi

The development, implementation, and assessment of our training was a multiyear process that first characterized the accessibility climate – or general attitudes, experiences, and thoughts regarding accessibility held by faculty, TAs, instructors, and undergraduates – of the department at a large, research-focused institution. After gaining a clearer understanding of the accessibility climate in the department via a survey in 2016-2017, TAs were chosen as the best population to begin a training program based on the survey responses. A training was developed and implemented in summer 2017, shortly prior to the start of the 2017-2018 academic year. In fall 2017, assessment of the efficacy of the training program took place via undergraduate surveys and TA pre/post-testing. The remainder of this paper details this process and discusses the implications for our results in the greater context of diversity and inclusion in geoscience.

4.1.1 Universal Design for Learning

Universal Design for Learning (UDL) [*Rose and Meyer*, 2002] is a set of guidelines that are intended to improve the accessibility and overall quality of curriculum and teaching methods [*Curry*, 2003; *Pliner and Johnson*, 2004; *Shaw*, 2011]. To be in alignment with the guidelines of UDL, curriculum and instructional methods should provide:

- multiple means of engagement, i.e. the “why” of learning
- multiple means of representation, i.e. the “what” of learning
- multiple means of action and expression, i.e. the “how” of learning

UDL is often brought up in the context of accessibility and disability, but at its core it is designed to benefit all students regardless of ability level.

4.2 Literature Context

4.2.1 Why Train Teaching Assistants (TAs)?

In 1997, an extensive study was conducted on why undergraduate students switch out of STEM majors [*Seymour et al.*, 1997]. The results indicated that the majority of those surveyed had difficulty getting help from faculty and TAs - a quarter of students that switched out of STEM majors cited this as a concern that contributed to their decision. In addition, loss of interest in the discipline and poor teaching by STEM faculty were main factors contributing to decisions to switch out of STEM majors. Another large survey of undergraduate students on the impact of teaching assistants on retention in the sciences was conducted in 2007 [*O'Neal et al.*, 2007]. The authors found that the climate in lab courses was a main factor with both retention and attrition. For their study, the definition of lab climate includes enthusiasm of the TA, students' anxiety levels, and how welcome students felt in the class. The survey also revealed that students who had experiences in the lab environment they perceived as stressful and frustrating had a decreased interest in science. O'Neal et al. (2007) suggest training for TAs in four main areas: (1) issues of retention, (2) fostering a positive lab climate, (3) modeling possible science careers, and (4) making explicit grading standards and procedures and communicating student progress in the course. In our training, we focused on area (2) fostering a positive lab climate - the area their study indicated TAs have most control over.

Existing research also suggests that creating a more inclusive environment must start at the pedagogical level – e.g. retraining TAs to design inclusive curriculum and implement equitable accommodations for all students (e.g. students with disabilities), and redesigning existing curriculum to be more in accordance with the principles of Universal Design [*Atchison and Feig*, 2011; *Shaw*, 2011]. We present a simplified theoretical positive feedback cycle of low enrollment and retention of people with disabilities, and the lack of instructor training that makes classes inaccessible and unwelcoming for these students. This undesirable cycle is represented graphically in Figure 24.

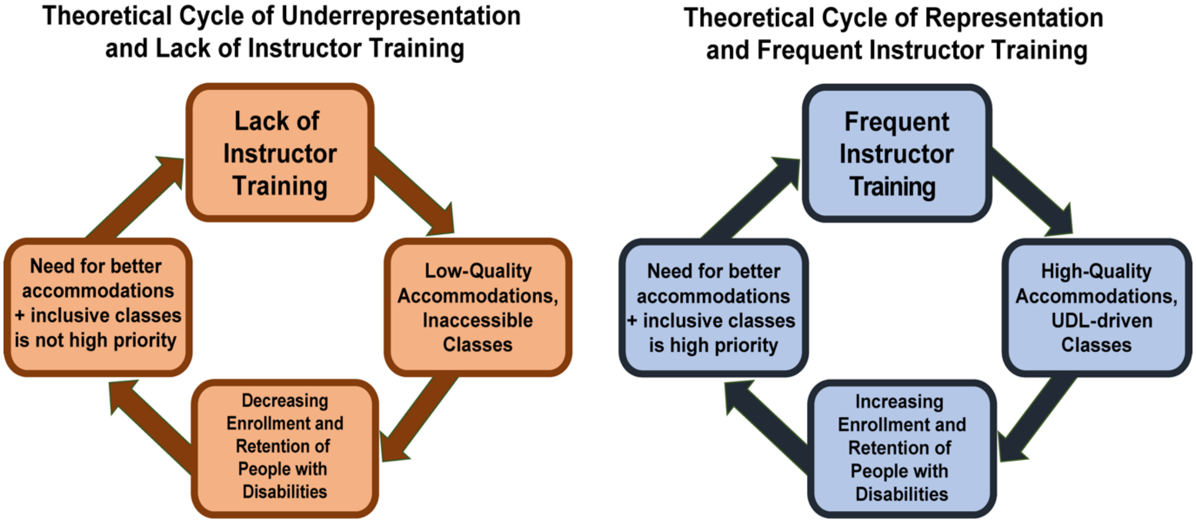

Figure 24: Left, the cycle of underrepresentation of students with disabilities as it relates to lack of instructor training. Right, the cycle of representation of students with disabilities as it relates to frequent instructor training.

Breaking the cycle of low enrollment of people with disabilities and lack of instructor training strategy is along the lines of “build it and they will come.” If the TAs are more conscious of issues in accessibility when designing curriculum, then they are more likely design better labs and classes from an inclusion standpoint [*Ouellett*, 2004; *Silver et al.*, 1998]. Better lab environments and sense of belonging makes for higher retention of students, particularly in the sciences [*Chang et al.*, 2016; *O’Neal et al.*, 2007; *Seymour et al.*, 1997]. This is also a positive feedback loop similar to that in the left-hand side of Figure 24, except the outcomes are more desirable. This more desirable theoretical cycle of instructor training and enrollment of students with disabilities is also represented graphically in the right-hand side of Figure 24.

The motivating strategy behind our training is to disrupt the undesirable cycle of underrepresentation as depicted in Figure 24 by increasing the frequency of instructor training. We model this after the Hollingsworth growth network model of professional development, which states that when a teacher is given information or training, that will influence their practice. That then in turn produces salient outcome and informs the knowledge, beliefs and attitudes of the teacher [*Clarke and Hollingsworth*, 2002].

In our theoretical model we add a connection between instructor knowledge/beliefs/attitude and information/training. When trainings on accessibility in an academic department are not mandatory, we suggest that increasing knowledge of a need (like the need for better accommodations) would push an academic department to respond with new or more frequent instructor trainings. Our overarching goal is to create a self-sustaining need for frequent instructor trainings as a result of increasing enrollment and retention of students with disabilities in introductory geology labs.

4.2.2 What are Best Practices for Training TAs?

Given the importance of training TAs for retention of students from underrepresented backgrounds, grounding new trainings in established best practices is of utmost importance. A 2017 literature analysis of studies on TA trainings identified 48 existing articles that were published in peer-reviewed journals between 1990 and 2016, described or evaluated a professional development program for TAs, and contextualized it within a STEM discipline [*Bitting et al.*, 2018]. Some of the studies considered were based on practitioner wisdom, some were case studies, and some were the results of multiple iterations of a study. Overall, Bitting et al. found that 34 of 48 studies had only low-moderate strength of evidence for their claims about best practices in TA training. In response, we critically considered all claims of best practices before including selecting which to include in our training.

It was established decades ago that TAs prefer to learn through scenario-based training. In 1980, Schade and Bartholomew found that 85% of the TAs they trained found engaging in scenario-based learning by watching and discussion videotaped educational scenarios “acceptable and enjoyable” [*Schade and Bartholomew*, 1980]. Involving graduate students or postdocs in the implementation of the training was indicated as a best practice in a study on TA training at the University of Washington [*McManus*, 2002]. Additionally, it was suggested that the training be developed specifically for the department and grounded in issues that have arisen in the past. In a more recent study, Dotger found that pushing TAs to think about the “why” and “how” of their teaching, not just “what” they are teaching [*Dotger*, 2011]. The intention is to get them thinking more about designing instructional methods, not just implementing them.

4.2.3 Why Use Scenario-Based Instructional Methods?

Experiential learning, scenario-based learning, hands-on learning, etc. are all variations of immersive active learning and have been shown to increase knowledge gain and retention among students [*Beard and Wilson*, 2002; *Errington*, 2003; *Hmelo-Silver*, 2004; *A Y Kolb and Kolb*, 2005; *D A Kolb*, 2014]. We designed an hour-long scenario-based segment of our training in order to accomplish Learning Goal 4 and to build upon the success of the video-based scenarios in Schade and Bartholomew (1980). Our scenarios introduced the TAs to potentially sensitive and difficult accessibility problems in a safe, learning-focused environment instead of in real-time on-the-job. In doing so, we intended to not only give the TAs hands-on practice working through these kinds of situations, but also to increase the confidence and comfort of the TAs so that they can be a more empathetic instructor.

4.3 Materials, Implementation, and Evaluation

This project had three core steps: 1) understand the accessibility climate in the department studied; 2) develop and implement a training to improve accessibility; and 3) evaluate the effectiveness of the training. We primarily used anonymous or semi-anonymous surveys (named redacted and replaced with a unique identifier for each individual prior to analysis) for all three core steps. This was done for several reasons, including:

- low level of disruption in undergraduate classes
- relatively simple response formats (multiple choice, Likert scale, short free-

response)

- ability to reach a broad audience in a short amount of time
- very low risk for privacy violations for participants
- low time/effort required for participants to complete

Copies of the survey items for used for all portions of this project can be found in the supplemental material.

4.3.1 Characterizing the Accessibility Climate

The first step of our process was to survey the faculty, instructional staff, post-docs, TAs, and undergraduate students about their experiences with and perceptions of accessibility in the department. We deployed two different surveys using the software Qualtrics in the spring semester of 2017. The survey items were written by the authors of this study and reviewed and edited by research faculty in the Graduate Teacher Program at the university prior to being administered.

Instructor Survey for Accessibility Climate Characterization

One survey was given to anyone in the department who had taught an undergraduate class in the last 5 years. This included the faculty, instructional staff, post-docs, and TAs. The goal was to gain an understanding of how our instructional staff in general perceived accessibility and disability in geoscience. The survey had 22 items, of which the 9 are directly relevant to this study. The 9 relevant survey items are included in the appendix. We advertised the survey to the department via emails, presentations at faculty meetings and graduate student meetings, and by word of mouth. We then aggregated the anonymous data and reviewed it for trends amongst the various populations of respondents.

Undergraduate Student Survey for Accessibility Climate Characterization

The other survey was given to all of the undergraduate students in the department. This included students with formally declared geology majors as well as students in introductory geology classes, for a total population of approximately 800. The survey had 32 items, of which 6 are directly relevant to this study. These items are included in the appenix. The survey was advertised to the undergraduates via emails, presentations in classes, and by word of mouth. Data was aggregated anonymously and reviewed for trends.

4.3.2 Design and Implementation of TA Training

The TA training was designed by the authors of this study after attending several trainings and workshops on UDL offered through the Graduate Teacher Program at the university. Additionally, we incorporated the best practices in training TAs that were discussed in the introduction. For example, because the literature suggested fellow graduate students or postdocs should be the ones to administer the training, we opted to administer it ourselves instead of requesting it be run by a tenure-track faculty or member of the department. To tailor our training to the department, we focused the lecture portion on examples relevant to geoscience and used real accessibility issues encountered by the authors in previous years as a foundation for the scenario-based portion. We used a scenario-based format for part of the training based on previous studies showing success with this format for training TAs and also on the broader literature surrounding the benefits of experiential learning.

Our TA training was designed to be completed in 2 hours – a 45-minute lecture/discussion segment on UDL, a 15-minute break, and an hour-long facilitated small group scenario-based segment. We include a 45-minute lecture/discussion segment in our training on the guidelines and implementation of UDL as a way to accomplish Learning Goals 1-3. The training was led and facilitated by the authors of this study in August 2017, immediately prior to the start of the fall semester.

The general steps to implement our training are as follows:

Prior to Training

We ran this training with two facilitators (the authors of this study). Both had attended previous trainings on UDL and were comfortable with all of the content in the presentation materials. Two copies of the pre/post-test were printed for each person attending the training so that we would be able to quantify learning gains. Our training took place from 4:30-6:30pm, so we arranged for dinner to be provided during the training.

During Training

The facilitators introduce themselves and briefly explain the goals of the training – to increase knowledge of and comfort with ways to make our classes more inclusive and accessible. We then handed out the pre-test and asked everyone to fill it out to the best of their ability. We did not provide any definitions or information about UDL, ADA, or specific strategies before administering the pre-test. When everyone was finished, they placed their pre-tests in a large envelope.

The training began with a discussion of community standards for the training. Important guidelines covered included assuming positive intent, keeping what the experiences of others that you hear in this room confidential unless you are explicitly told otherwise, accepting feedback and learning from mistakes, and when disagreement arises making sure to argue with ideas and not people. After reaching agreement on the community standards, we started the content of the training with a 45-minute lecture-style session that covers key definitions, concepts, and applications of UDL. Also included in these slides was an example Accessibility Statement to use as an alternative to a Disability Statement (Learning Goal 5). All slides used in the training are included in the supplemental material for this article. During the lecture session, we encouraged participants to stop us and ask questions if anything was confusing. We informed them that after the lecture portion would be a scenario portion in which they would be solving accessibility issues in “real-time.” Other than a couple requests to repeat statements, no questions were asked during this part of the training.

We took a 15-minute break for participants to start eating the provided dinner and to ask us more questions. During this break several participants approached us with additional questions and comments about the lecture portion. Participants also used the break to socialize with the people around them – many did not know each other since they were primarily new graduate students. We consider this break period important because it gives participants a chance to build rapport with the facilitators and their peers prior to beginning the scenario portion of the training.

We began the scenario-portion of the training by explaining the format and goals of each scenario. Participants would work in small groups (3-5 people) to discuss the scenario projected on the screen and respond to the following prompts: 1) What are the possible issues in this scenario? 2) How can you adapt to the situation to make sure the student still learns? and 3) How could this scenario have been avoided? We informed participants that they were welcome to use their notes or flag over the facilitators if they have any questions during the scenarios. We planned to give groups 7-10 minutes to unpack and discuss each scenario but were flexible with timing based on the observed discussion progress. All scenarios used in our training are based on real accessibility issues that have arisen in the experience of the facilitators or were experiences of others in the department and used with permission.

After each scenario we debriefed the content of the scenario and the discussions that each group had. This included discussing how to identify accessibility issues that may not be obvious at first glance as well as strategies for making accommodations and for redesigning the curriculum to be more inclusive from the start. Each debrief took between 5 and 10 minutes depending on the complexity of the scenario. In our training, we got through 4 of the 8 prepared scenarios.

We ended the training by administering the post-test in the same manner as the pre-test. We also provided participants with a link to a Google Drive folder that contained the training slides, a sheet with links to more information and resources on accessibility, a copy of the Accessibility Statement, and our contact information. These materials are included in the supplemental material for this article. We encouraged participants to follow up with us if they had additional questions or needed assistance with accessibility issues in their classes throughout the year.

After Training

Later in the semester after the training, two participants approached the facilitators for guidance in accommodating students in their classes. One of the participants couldn't remember how to determine whether figures are readable with red/green colorblindness, and the other needed more in depth help with 3D-printing landscape models and redesigning assignments and exams for a student who is blind. The facilitators assisted both of the participants in making their classes accessible.

4.3.3 Evaluation of TA Knowledge Gain and Retention

Prior to beginning the training, TAs were given a 1-page survey/pre-posttest to complete about their knowledge and experiences with accessibility and UDL. The same survey/pre-posttest was administered immediately after the training, halfway through the semester, and at the end of the semester. Surveys during the training were administered by the authors, although we stepped out of the room and had the responses placed in an envelope prior to returning to the classroom. TA names were removed from the surveys/pre-posttests and replaced by a numeric identifier by a third party not affiliated with the department in order to track learning gains while maintaining survey respondent privacy.

4.3.4 Undergraduate Experiences in Labs with Trained TAs

To quickly and unobtrusively evaluate the general feelings of inclusion within the undergraduate population, minute papers were given to the students enrolled in lab sections taught by the trained TAs three times throughout the semester: once at the beginning of the semester, once halfway through the semester, and once at the end of the semester. The minute paper questions were written by the authors of this study and were reviewed by research faculty in the Graduate Teacher Program at the university prior to being administered. The students were asked to Strongly Agree/Agree/Disagree/Strongly Disagree with the four statements about feeling comfortable and included in the department. These can be found in the appendix. Students were then given the opportunity to provide additional written feedback if they desired. The minute papers were anonymously collected in an envelope while the instructor was out of the room, and then returned by a student in the class to one of the authors' mailbox.

4.4 Study Population and Setting

This research was conducted at a large, research-focused university in the United States. The university is located in a relatively high-income area, and typically enrolls 20,000-30,000 undergraduates. Participants were not asked their age in the surveys, but all indicated they were above the age of 18 years old on the consent forms administered prior to collecting data.

Information regarding the demographics of our study populations are summarized in Table 4. Although we do no use race, ethnicity, or gender demographics in the analysis of this study, we present it here for availability and use in future follow-up studies or literature analyses.

Table 4: Demographic Information for Study Participants

		Characterizing Accessibility Climate Survey: Undergraduates	Characterizing Accessibility Climate Survey: Instructional Faculty	TA Knowledge Gain and Retention Testing	Undergraduate Experiences in Labs with Trained TA Minute Papers
Population Size	*Population Size Contacted*	800	130	12	505
	Number of Participants	77	45	8 -12	364 - 436
	Response Rate	9.60%	34.60%	75% - 100%	72% - 86%
Ethnicity	*Hispanic / Latino*	2.50%	2.50%	not collected	not collected
	Not Hispanic / Latino	93.50%	85%	not collected	not collected
	Prefer Not to Answer	4%	12.50%	not collected	not collected
Race	*Alaskan Native / American Indian*	2.50%	2.50%	not collected	2%
	Asian	13%	5%	not collected	3%
	Black or African-American	1.30%	2.50%	not collected	2%
	White	81.80%	77.50%	not collected	68%
	Multiracial or Biracial	0%	2.50%	not collected	not collected
	Other	2.50%	5.00%	not collected	17% (International)
	Prefer Not to Answer	5.20%	15%	not collected	not collected
Gender	*Male*	48%	42%	not collected	55.30%
	Female	48%	58%	not collected	44.70%
	Transman	1%	0%	not collected	not collected
	Transwoman	0%	0%	not collected	not collected
	Non-conforming / Non-Binary	1%	0%	not collected	not collected
	Prefer Not to Answer	1%	0%	not collected	not collected

For the Characterizing the Accessibility Climate surveys, we contacted all undergraduate geology majors and students enrolled in introductory geology classes at the university, and sent recruitment emails to the faculty, graduate student, post-doc, and researcher listservs. For the TA training testing, the training was mandated for new TAs and optional for returning TAs and this information was provided to all graduate students in the department via email listserv. Nine of the participants were new TAs and three were returning TAs who asked to join. For the undergraduate experiences in the labs with trained TAs, participants were enrolled in at least one of twenty lab sections taught by the trained TAs (including the 1000-level introduction to field geology; 2000-level introduction to geoscience and introduction to earth materials; and 3000-level structural geology, paleontology, and mineralogy courses). The demographics of the undergraduate population were expected to follow the general demographics of the university's undergraduate population which are summarized in Table 4. Additionally, based on University diversity reports, we expected 6.6% of undergraduates to be formally registered with Disability Services.

4.5 Results

4.5.1 Characterizing the Accessibility Climate

The results from our survey characterizing the Accessibility Climate in the department broadly indicated that undergraduates felt that some of the classes or components of classes in the department are inaccessible, and that accommodations are not being made satisfactorily. Students reported being reluctant to approach their instructors and seek accommodations.

Analysis of the instructional faculty responses showed that TAs were the sub-group of instructors with the highest potential to be impacted by an intervention. Of the various instructor types (tenure-track faculty, post-doc, etc.), they had the least previous training, felt the most strongly that the department was not accessible, and had the largest percentage take ownership of the inaccessibility – i.e. they felt it was their responsibility to make their classes more accessible. We wanted to test our training on a population of instructors that would be receptive to training and likely to make immediate changes in their classes. For these reasons, we focused our analysis and subsequent training on TAs.

Teaching Assistant (TA) Responses

Seventeen TAs responded to the survey characterizing the accessibility climate. Our key results are summarized below. We asked TAs about whether or not the number of undergraduates in the department was representative of the university-wide demographics as one way to determine whether or not they perceive an issue with regards to accessibility in the department. The majority of TAs (16 out of 17) thought that it was not representative and that there were fewer students with apparent or disclosed disabilities in the department than would be expected. Given that not all disabilities are apparent, the TAs answers were likely primarily informed by observing the presence of students with apparent disabilities around the building and/or by being made aware of non-apparent disabilities of students in their classes who have disclosed their disability to Disability Services.

In order to quantify the current representation of students with disabilities in the department, TAs were asked how many students with either long-term or short-term disabilities they had enrolled in their classes in an average year. TAs reported few – if any – students with long-term disabilities enrolling in their classes - 13/17 typically had no students with long-term disabilities in their classes (Figure 25, left). In a typical lab class size of 24 students at this university, each class should have 1-2 students in each class with documented permanent disabilities. This estimate does not include the population of students who have disabilities but choose not to disclose them to Disability Services.

TAs reported relatively higher numbers of students with approaching them with temporary disabilities – 13/17 typically had at least one student with a temporary disability in their classes (Figure 25, right). Temporary disability at this university are not documented by Disability Services and that any accommodation is at the discretion of the instructor. Some of the comments provided in this section indicated that concussions and broken bones were common short-term disabilities that students brought up and that these were expected by the TAs given the athletic and outdoors-focused culture of the campus.

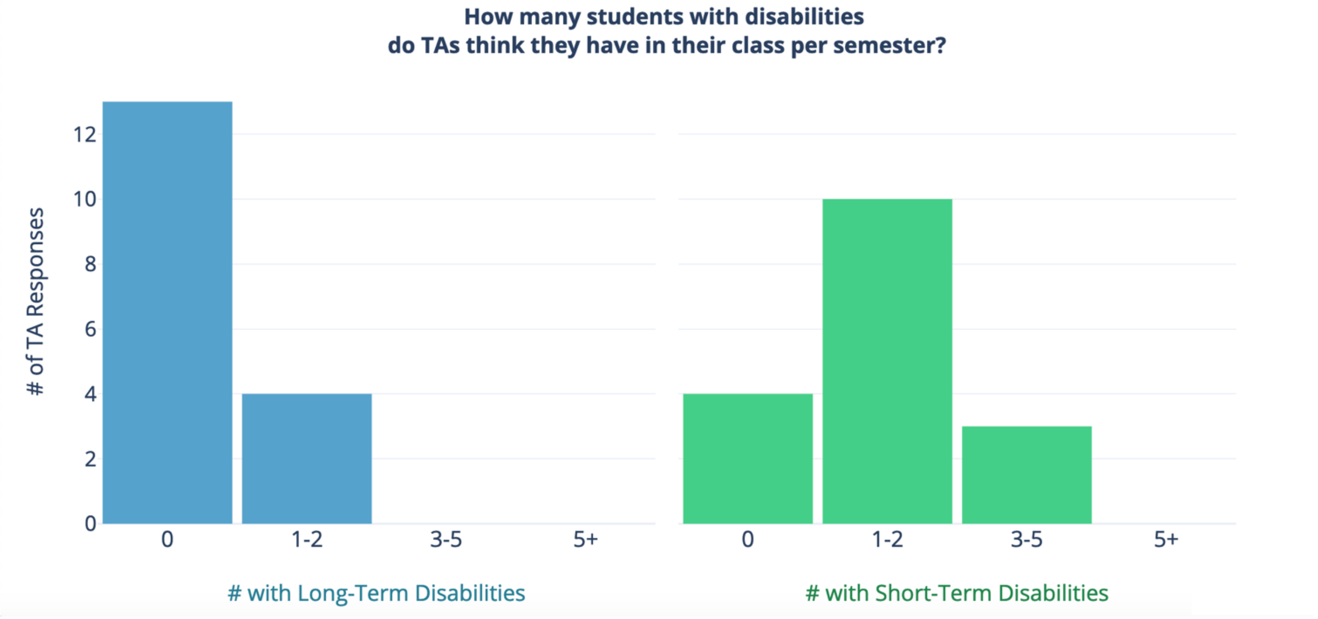

Figure 25: TA estimates of numbers of students with long-term (blue bars, left) or short-term (green bars, right) disabilities enrolled in their classes in a typical year.

The TAs acknowledged that classes and labs were not accessible. The majority of respondents (12/17) disagreed with the statement “the labs I teach are accessible.” The majority of TAs (13/17) did not feel like they had control over content/curriculum in the classes they teach, but most (16/17) felt that they did have control over the pedagogy/methods with which they teach. The majority of TAs expressed being unfamiliar with the principles of UDL (14/17 unfamiliar or unsure), ADA (14/17 unfamiliar or unsure), and with what Disability Services offers (11 unfamiliar or unsure) (Figure 26, left). Additionally, only 3 had ever been trained on accessibility (Figure 26, right).

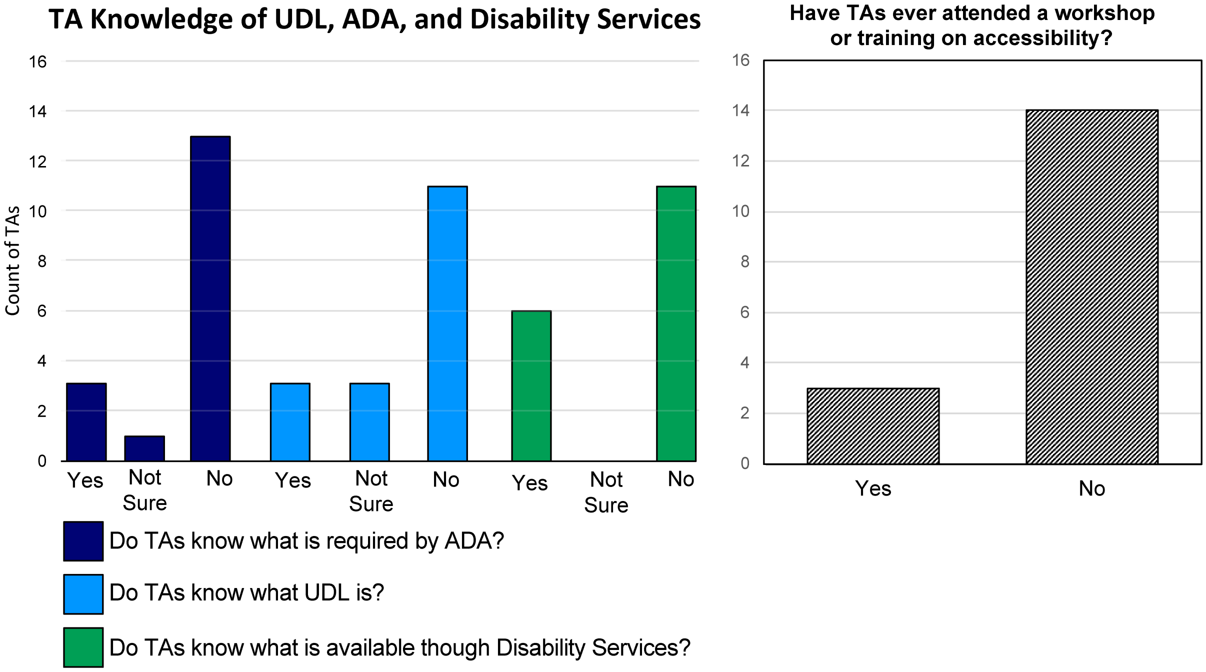

Figure 26: TA knowledge on ADA, UDL, and Disability Services on campus (left), and whether or not they had ever participated in an accessibility-focused training or workshop (right).

Acknowledging a problem in accessibility is one thing, but little change is likely to result from a training unless TAs take some ownership of that problem. To that end, we asked TAs about who is responsible for making alternate assignments and their agreement with the statement that creating alternate assignments is difficult. The majority of TAs felt that they were personally responsible for making alternate assignments (15/17), but many (14/17) also reported feeling that making those assignments was difficult since there are many types of accommodations and accessibility needs that can come up in a class.

Undergraduate Responses

Of the approximately 300 majors and 500 non-majors sent the accessibility survey via email, 91 responses were collected, of which 77 followed through to the completion page. It should be noted that every student answered every question – they had the option to leave any question blank that they did not wish to answer. We used data from all surveys in which the students followed through to the completion page, even if they did not answer all the questions.

Our first portion of questions was only given to a subset of our total undergraduate population. We asked undergraduate students whether or not they had a disability that requires accommodation in any course. If they did, then we followed with a question about whether or not they sought accommodations. Undergraduates were presented with check-box selections describing different things that may be considered either a short or long-term disability (e.g. sensory limitations, mobility limitations, mental illness, chronic illness, or temporary mobility limitation). Twenty-one students indicated that they considered themselves as having one or more of the above options. Those 21 students were then routed to a follow-up question asking them whether or not they had a disability that required accommodation in any class. Only 8 students out of the 21 responded that they had an accommodation-requiring disability. When asked why they did not feel like they needed accommodations, responses tended to fall in two broad categories: not believing their needs merit an accommodation and not believing the instructor would make an accommodation. Some of their responses are quoted here.

Belief That Needs Do Not Merit Accommodation

"I try to stick to deadlines and accomplish what I need to on the same terms everyone else does."

"My health problems do not distract me from learning, nor should they."

"The process seems daunting and my disabilities don't feel "real" enough even though they are."

"If I tell myself I have a problem, [i]t will become a bigger problem than just living with it."

"Want to be like everyone else"

Belief That Instructors Would Not Make Accommodation

"I don't believe my teacher would be accommodating to my needs"

"Don't believe teach[er] would make accommodations"

Returning to the entire population of undergraduates surveyed, we asked their thoughts on the accessibility of four different class types: lectures, seminars, labs, and field trips (Figure 27). It is important to note that the lab sections for many of the introductory geoscience courses in the department have frequent field trips that last the entire duration of the class period. The field trips take place at a series of outdoor locations within a one-hour drive of the institution. The terrain students are expected to navigate on the field trips ranges from steep trails to paved roads. They occur throughout the semester and typically are 3-4 hours in duration.

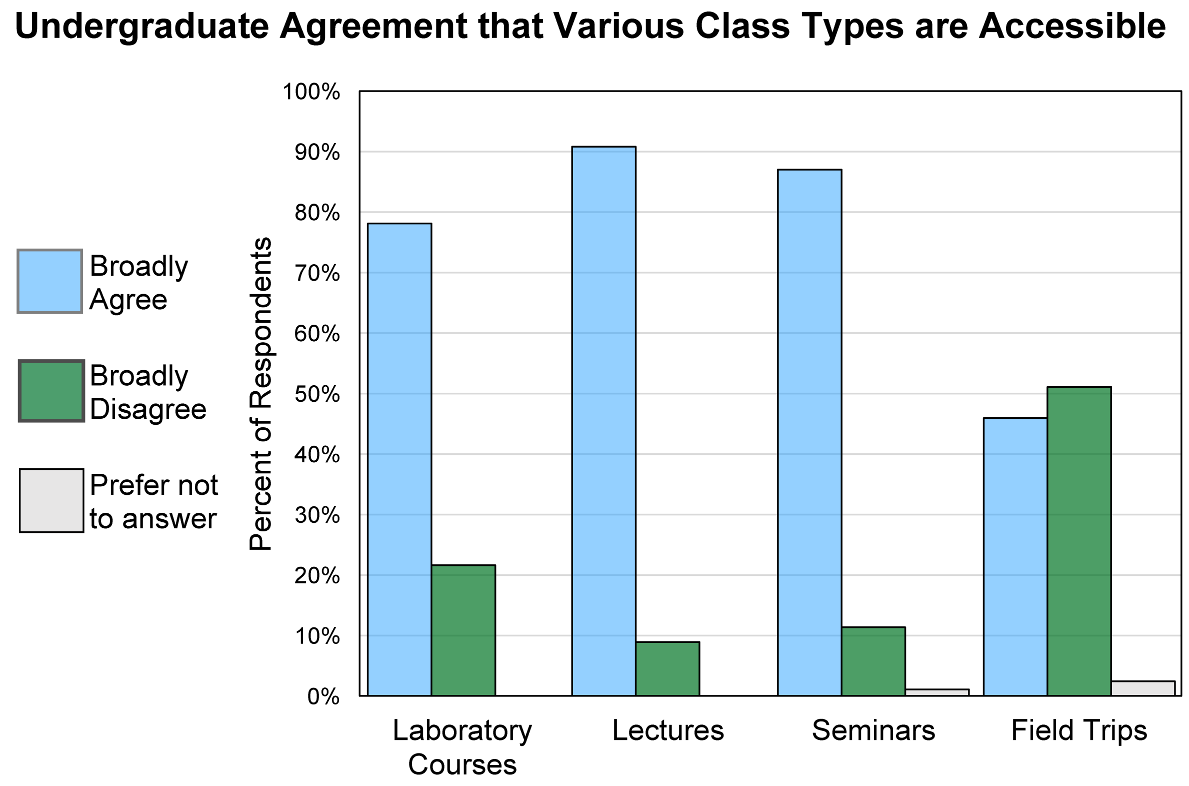

Figure 27: Undergraduate agreement that various class types (lecture, seminar, lab, field trip) are accessible. Blue bars indicate agreement, green bars indicate disagreement.

Figure 27 shows that a persistent population of undergraduates (~10%) consider all class types to be inaccessible. About 20% consider lab courses to be inaccessible, and a little more than 50% consider field trips in general to be inaccessible. These results show that the majority of undergraduate students enrolled in introductory geology courses consider field trips to be inaccessible even though less than a quarter of respondents identified as personally having a disability. The next series of questions asked for more details about the accessibility of field trips that happen in lab courses: are field trips in labs accessible, can everyone participate in outdoor field trips, and if there are people who cannot participate do instructors make reasonable accommodations. Their responses are summarized in Figure 28.

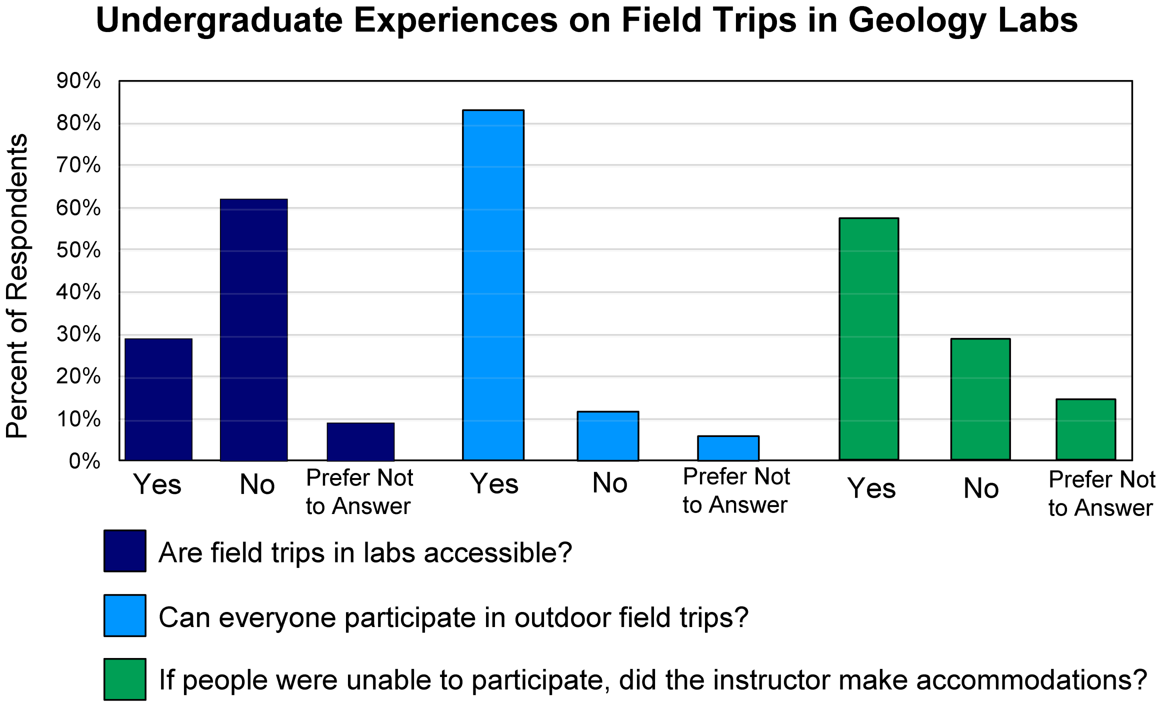

Figure 28: Undergraduate experiences on field trips in labs with regards to accessibility. Thoughts on lab field trip accessibility are the dark blue bars, thoughts on ability for people to participate are light blue bars, and whether or not instructors made accommodations are the green bars.

These results clearly show that the majority of undergraduates (62%) do not think field trips in lab courses are accessible. Despite that, most undergraduates (83%) reported that they thought everyone was able to participate in outdoor field trips. Of the undergraduates who responded that not everyone could participate in outdoor field trips, 29% said that in their experience instructors did not make accommodations for the student(s) who were unable to participate. Again, their acknowledgement of the inaccessibility of classes but lack of actually seeing people be unable to perhaps relates to the underrepresentation of people with disabilities in the department's introductory geology classes.

Overall, our results from the undergraduate portion of characterizing the accessibility climate emphasize the need for more accessible field trips and labs as well as for more instructor training.

4.5.2 TA Knowledge Gain and Retention

Twelve TAs participated in the training. The response rates for the pre-training, post-training, middle semester, and end of semester testing are respectively as follows: 12, 12, 8, 8. Participation in our follow up survey was optional, and we suspect the decline in response rate simply reflects some of our TAs having a lot of other work to do and not having time to continue following up with us. In this section we summarize the results of their knowledge gain and retention on accessibility-related topics.

First, TAs were asked about their familiarity with UDL and then asked to define it. We graded the TA responses as either broadly correct or broadly incorrect. To be correct, the TAs had to mention a goal of accessibility for all students and designing courses to be accessible from the start instead of making accommodations as issues arise. The TAs were also asked whether or not they knew what was required by the ADA. A summary of their responses to these three questions is shown in Figure 29.

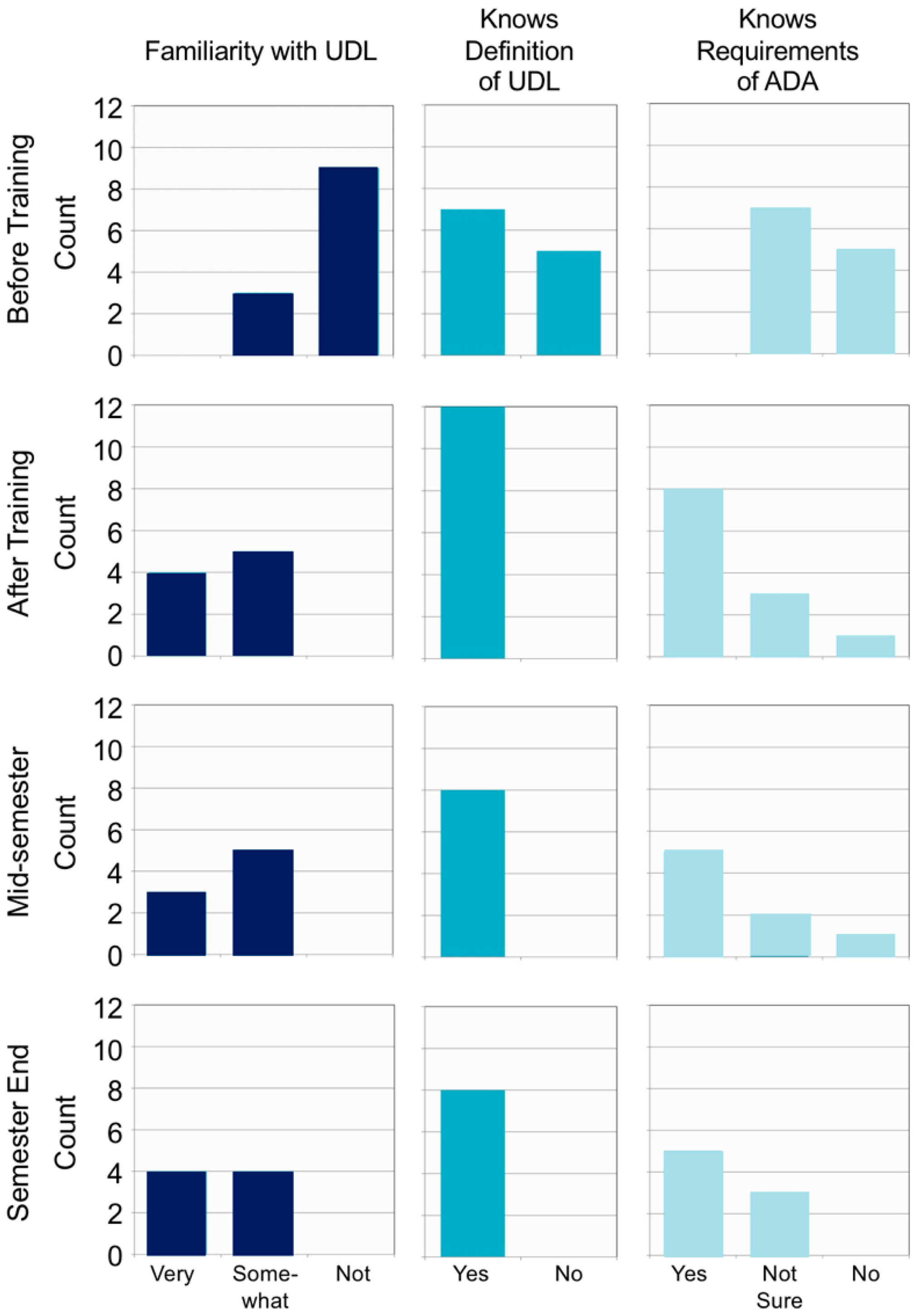

Figure 29: TA knowledge of UDL and ADA tracked throughout the semester. The left column (dark blue) is familiarity with UDL, the middle column (medium blue) is whether or not they can correctly define UDL, and the right column (light blue) is whether or not they feel they know what is required by ADA.

The majority of TAs (9 out of 12) reported being unfamiliar with UDL prior to training, but 7 out of 12 were still able to correctly define it. Additionally, none of the TAs reported knowing what was required by ADA prior to the training. After the training, all the TAs reported having at least some familiarity with UDL and all were able to correctly define it. This learning gain persisted throughout the course of the semester. The learning gains with regards to ADA were less dramatic – some TAs (4/12) still felt unsure of what was required by ADA after the training and 3 out of 4 never fully gained familiarity with the topic.

We also monitored the TAs feelings of control over the curriculum in the classes they teach and over their teaching methods throughout the semester (Figure 30). We noted that in both domains of control – curriculum and teaching methods – the general center of the data shifted toward being in more control.

Figure 30: TA feelings of control over curriculum (left column) and teaching methods (right column) over the course of the semester.

Finally, we asked TAs about how they changed their classes and whether or not they were approached by students with accessibility needs. In the single semester of having trained TAs, there were 5 unique undergraduates seeking accommodations which corresponded to 5 out of 12 (42%) of the TAs being approached for accessibility needs. Survey responses indicated that the discussion of accessibility between the students and the TAs was ongoing throughout the semester – the type of accommodations and conversation evolved as the class progressed, suggesting that TAs responded to the initial request for accommodations in a way that built the students trust and encouraged them to come back and continue the conversation as needs change. In our characterization of the accessibility climate prior to the TA training, 13 out of 17 (76.5%) of TAs stated that they had **never** been approached for accommodations in their classes. In a single semester of training, we saw the percent of TAs being approached by undergraduates for accessibility needs nearly double.

TAs were also asked whether they had changed their curriculum or teaching methods in a way to increase accessibility or incorporate any of the principles of UDL, regardless of whether or not students requested accommodation. There were 16 unique attempts to increase accessibility of the introductory labs by TAs, and 8 out of 12 trained TAs (the 8 who continued to respond to our survey throughout the semester) reported using UDL to adjust their class. Of the 4 who did not respond to our survey later in the semester, all four did indicate on the pre-semester survey that they intended to adjust their classes to better align with UDL – however we do not have data to confirm that they followed through on that intent. The most frequently mentioned strategies implemented were: removing/replacing red-green color schemes, making documents screen-reader accessible, building in more group work, adding visuals to text or oral instruction, and adding captions to figures.

4.5.3 Undergraduate Experiences in Labs with Trained TAs

As a final way to assess the effectiveness of the TA training on improving the accessibility climate of the undergraduate labs, we surveyed the undergraduate students enrolled in lab courses with the trained TAs. The undergraduate students were asked to respond to four prompts on a scale of Strongly Agree (SA, =1) to Strongly Disagree (SD, =4). The average of their responses for each of the four prompts over the three administrations of the survey (R1 = round 1, beginning of semester; R2 = round 2, middle of semester; and R3 = round 3, end of semester) are summarized below. The four prompts they responded can be found in the supplemental material for this article.

A summary of the results from the four prompts (Q1-Q4) over the course of the semester (R1-R3) are in Figure 31.

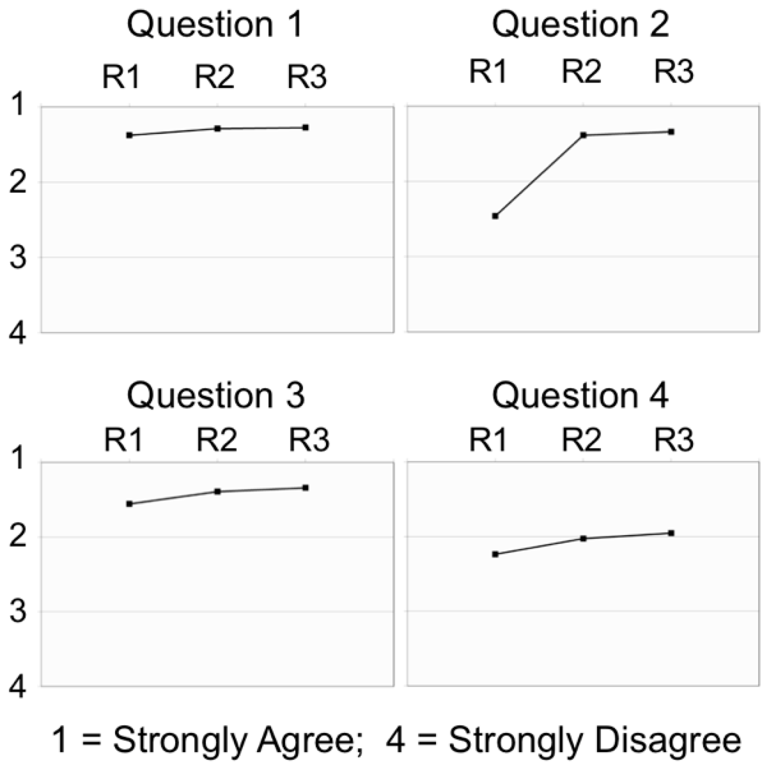

Figure 31: Undergraduate ratings of: Q1 - comfort approaching TA, Q2 – whether TA knows student's name, Q3 – TA care for learning of individual, and Q4 – connection to geology department.

These results indicate that the TAs started the semester off highly rated in all four prompts and continued to improve slightly throughout the semester. Finally, undergraduates were also given the opportunity to leave additional comments or feedback. Students left overwhelmingly positive comments for their TAs, praising their enthusiasm, effort, and attitude. The negative comments that were received were in general directed toward department or faculty level issues that are not within the scope of this study but are still important to take note of for future work.

4.6 Interpretations and Discussion

4.6.1 Accessibility Climate

Our results showed that there was definite room for improvement in the accessibility climate in the department.

From the instructor survey, our main interpretation is that TAs acknowledge there is room for improvement with respect to accessibility in the department and feel like they have the most control over how they teach as opposed to what they teach. We determined that the other sub-populations of instructors were less likely to be impacted by a training because larger percentages of the populations 1) either didn't acknowledge or have awareness of underrepresentation of people with disabilities in the department, 2) had already been trained on accessibility recently, or 3) thought the classes they taught were already accessible. These results helped define the need for increased training that focused on TAs that were teaching introductory lab courses.

From the undergraduate survey, we found that undergraduate students also feel that the department has room to improve with regards to accessibility. Field trips in particular were identified as being inaccessible, and some undergraduates reported that instructors did not make reasonable accommodations. We suspect that this is due, at least in part, to inexperience and lack of knowledge on how to make high quality accommodations for a variety of accessibility needs.

When a subpopulation of students who reported having accessibility needs was asked whether or not they sought accommodations and why, a disturbing number of responses indicating negative attitudes towards disabilities in general surfaced. For example, students didn't feel their needs were real enough, didn't think instructors would make accommodations, or didn't want to be singled out as different. This indicated to us a systematic, cultural problem within the department or possibly university as a whole. This phenomenon has been observed elsewhere for decades and is thought to be in part due to lack of high-quality training and/or awareness [*A Lombardi et al.*, 2013; *A R Lombardi and Murray*, 2011; *Matthews et al.*, 1987; *Newman*, 1976; *Rao and Gartin*, 2003]. Based on the comments the undergraduate students made, we conclude that many did not feel like approaching the instructors to seek out accommodations would be beneficial and/or productive. The results from this subset of the undergraduate population reveal a pervasive negative attitude toward accessibility and disability. It is not wholly unsurprising that stigma persists given the relatively recent advances in equitable higher education for people with disabilities [*Belch*, 2004; *McCune*, 2001]. We were saddened, but not surprised, to see students who identify as having disabilities make statements that their disabilities either don't need or shouldn't require an accommodation.

These sentiments are reflective of the differences between the Individual and Social Models of Disability. In the Individual Model disability is defined as an individual's deficit – it is the student's medical impairment that makes them have disability. The students who felt that they were responsible for managing their disability on their own align more closely with this model. In the Social Model, the student's disability is instead a product of the relationship between their impairment and a disabling society. Here students with impairments can still participate fully in activities if the society takes ownership of removing systematic barriers, bias, and discriminatory practices [*Oliver*, 2013; *Shakespeare*, 2006]. One of the goals of our training was to shift the conversation from student disability to instructor-driven accessibility, highlighting that making an accessible classroom is not about managing specific impairments but is instead about removing non-inclusive practices altogether. We also emphasized that every single student should feel comfortable approaching our instructional faculty when the class isn't accessible to them – regardless of whether or not they are registered with Disability Services. They should feel confident that our teaching staff will be open to discussing the student needs and helping build the path forward.

Overall, the results from this portion of the study indicate that accessibility is a complex issue and there is no quick fix to making a department more accessible. Field trips are clearly a type of class that tends to have more accessibility issues than lectures, seminars, or labs in this department. We acknowledge that although many field trips can be easily made accessible through small curriculum or instruction changes, some require more significant curricular overhauling beyond the scope of TA responsibilities. However, we firmly believe that instructors should always create a classroom environment where students are comfortable bringing up their accessibility needs and be able to create a high-quality accommodation for the student. From large surveys like this a department can gather evidence of accessibility issues affecting their student population and then identify which instructor populations that have the potential to make high-impact changes given the right training and information. In our case this was TAs, but in other departments it may be a different population.

4.6.2 TA Training

One of the main goals of doing scenario-based training was to empower the TAs to make changes and feel like they had control over how they respond to various situations, i.e. their control over teaching methods, and the knowledge to inform their responses. We did not explicitly try to increase TA feelings of control over curriculum because in this department the TAs realistically do not have a large amount of control over the curriculum in their labs. Despite that, we saw a shift toward greater feelings of control starting immediately after the training and continuing as the semester progressed. We briefly mentioned during our training that very small curriculum changes can greatly improve accessibility in a classroom. However, we mainly focused on teaching techniques and pedagogy since that is what TAs previously reported feeling that they have control over. We think the gains in feelings of control – both in terms of curriculum and pedagogy - are likely due to a combination of feelings of empowerment from the scenario-based aspect of the training, general increasing confidence of the TAs, or to TAs considering making small alterations to assignments to improve accessibility as having control over the curriculum.

We saw large, persistent learning gains with regards to UDL, but the gain regarding ADA were not as strong. We think that this likely stems from our training being heavily focused on UDL, with less in-depth discussions of ADA. We received oral feedback from the TAs in the training that ADA was still confusing because they are “not lawyers” and can’t really be sure what is legally required and what legally counts as reasonable accommodation. Overall, our results from this portion of the study indicate that our training is an effective way to increase knowledge, familiarity, and feelings of control regarding accessibility issues in the classroom amongst TAs, and that those effects persist for at least a semester.

4.6.3 Undergraduate Experiences in Trained TA Labs

The results from our undergraduate minute papers were straightforward – students reported feeling comfortable with their TAs, thought TAs genuinely cared about their learning, and felt connected to the department. We did not want to explicitly ask about accessibility or disability in this round of surveying. We suggest that if students report feeling more comfortable and the TAs also report being approached more for accessibility needs, then this demonstrates the connections between training TAs, awareness of the need and willingness to teach inclusively, and tangible impacts on the undergraduate population.

As the semester progressed, the undergraduate responses became progressively more positive. Increasing numbers of students reported that they felt comfortable and welcome in their classes at each administration of the minute papers. We interpret this to mean that TAs continued to create a positive climate in their classrooms for many weeks after the training ended. These results are in contrast to the kinds of responses in the first characterization of the accessibility climate in the department where undergraduates felt that instructors in general would not make accommodations and would be unsympathetic to accessibility needs. We think this reinforces our result from the TA knowledge gain study that the trained TAs didn't just go back to old habits immediately after the training ended. The effects of the training were able to last at least a semester.

That being said, undergraduates still took the time to use the free-response open comment section of their minute papers to express negative feelings toward tenure-track faculty, curriculum, and department-scale issues. Although negative feelings themselves are not a good thing, we think this emphasizes that the positive feelings were tied to the trained TAs themselves, not something else going on within the major or department. We plan to use these negative, non-TA related comments as the foundation for additional follow-up studies on how to improve inclusivity at the department scale. Overall, our results from this portion of the study indicate that undergraduates enrolled in classes with trained TAs feel comfortable with and included by their TAs, and also felt connected to the department as a whole.

4.7 Limitations and Implications

The main limitations of this study are the sample size and the experimental design. This was a case study with no true control group, and because it took place in a single department the number of respondents for each portion of the study was relatively small. Additionally, just as the accessibility climate would be expected to vary from department to department, so would the effectiveness of the training. We think that our training was particularly effective because the TAs had never been trained before and because they were aware of and interested in improving accessibility in the department. If TAs felt that classes and labs were inaccessible but had already been trained in UDL, then it is possible that training them again with the training we developed would not improve the accessibility climate. Our results overall suggest that implementing our training – or a similar one - would be an effective first step in improving accessibility in departments that currently lack a dedicated, earth-science-specific accessibility training.

In conversation about accessibility prior to beginning this study, we often heard statements along the lines of, "I've never had a student need accommodation in my classes, so my classes must be accessible" from some members of the instructional faculty. The results from this study suggest that statement is inaccurate. Instead, we think that undergraduates didn't feel comfortable seeking accommodations despite needing them. However, if TAs are trained to be more sensitive and open to accessibility needs, then the undergraduates will be more inclined to come forward seeking accommodation. A hidden need is still a need. Although bringing that need to light may make the situation look worse, that is the only way that it can ultimately be supported.

We recommend that other departments follow a similar approach as we did in this study: first characterize the accessibility climate in the department at hand to identify common issues and instructor populations that are open to being trained;

then based on those survey responses (in particular awareness of underrepresentation of people with disabilities, record of previous trainings, recognition of responsibility for making accessible curriculum) identify and train the highest impact population on UDL in an empowering, safe scenario-based setting. For example, the TAs were the highest impact population to train at the university in this study because they responded that they had never been trained and had little to no knowledge of UDL but agreed that it was their responsibility to make accessible curriculum and that students with disabilities were underrepresented in the department. This signaled to us that they would be receptive to a training and were likely to apply what they learn at the training in their classes. Finally check in throughout the following semester with the undergraduates and the instructors to get an idea of how well the training worked. If it worked well, repeat on an annual or semester basis. If it didn't have a large effect, revisit the results of the accessibility climate survey and see if there are other areas for improvement that can be addressed in a different way.

Improving the accessibility of undergraduate labs and departments as a whole is a never-ending process. There is always room for improvement, and so we recommend an accessibility focused training simply as one of many interventions that can and should be implemented. Improving accessibility and incorporating UDL benefits all students, and we are optimistic that following the steps outlined in this study can initiate the theoretical cycle of representation we proposed in Figure 1. The cycle has already been initiated in the department examined in this study: since our first implementation of the training, the department has adopted it as part of its standard TA training offered on an annual basis. Future studies will be able to determine whether or not increasing the frequency of instructor training on accessibility will have a measurable impact on the quality of accommodations offered or the enrollment of students with disabilities.

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Appendix

Relevant Items from Characterizing Accessibility Climate Survey: Instructional Faculty

1) What is your familiarity with the principles of Universal or Inclusive Design?
2) Briefly explain in your own words the principles of Universal Design.
3) Do you think that the number of students with physical disabilities enrolled in geology classes at [University] is representative of the demographics of the general undergraduate population?
4) In an average year, how many students do you have enrolled in your courses that have permanent/long-term physical disabilities (paraplegic, quadriplegic, chronically ill, blind, deaf, etc.)?
5) In an average year, how many students do you have enrolled in your courses that have short-term physical disabilities (broken leg, concussion, etc.)?
6) Rate your agreement with the following statements about teaching:
    a. The lectures I teach at [University] are accessible to students with physical disabilities.
    b. The labs I teach at [University] are accessible to students with physical disabilities.
    c. I feel that I have control over the design/curriculum in the courses I teach.
    d. I feel that I have control over the pedagogy/methods I use to teach.
7) Rate your agreement with the following statements about accommodations:

    a. I know what kinds of accommodations are available at [University] through Disability Services
    b. When a student tells me they cannot participate in a lab or activity, it is okay to just waive it as long as they are a good student.
    c. When a student tells me they cannot participate in a lab or activity, it is my responsibility to create an alternative assignment.
    d. When a student tells me they cannot participate in a lab or activity, it is someone else's responsibility to create an alternative assignment.
    e. It is hard to have alternative assignments prepared for all the different kinds of disabilities that I might encounter as an instructor
    f. It is particularly hard to create accommodations for students with physical disabilities in geology
8) Do you know what is required by the Americans with Disabilities Act for students with physical disabilities enrolled in geology classes?
9) Have you ever attended a workshop or training specifically on making STEM and/or geology curriculum accessible?

Relevant Items from Characterizing Accessibility Climate Survey: Undergraduate Students

1) Do you have a disability that requires accommodations in any course?
2) Have you sought accommodations in your classes?
    a. What accommodations?

OR

b. Why not?

3) In your opinion, are field trips accessible to a student with a disability?
4) In classes with outdoor field trips, was everyone able to participate fully in the trip?
    a. If no, were accommodations made by the instructor?
5) Please rate your level of agreement/disagreement. Each of these types of courses at [University] are accessible to everyone:
    a. Laboratory Courses
    b. Lectures
    c. Seminars
    d. Field Trips
6) Are appropriate course accommodations available at [University]?

Undergraduate Inclusion Minute Paper Items

1. I feel comfortable approaching my teaching assistant (TA) about issues affecting my performance in class.
2. My teaching assistant (TA) knows my name.
3. I feel like my teaching assistant (TA) genuinely cares about my learning as an individual.
4. I feel connected to the geology department.