BEAVER MODERATED FIRE RESISTANCE IN THE NORTH CASCADES AND POTENTIAL FOR CLIMATE CHANGE ADAPTATION

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ABSTRACT

Climate change and fire suppression have altered historic fire regimes, creating conditions for larger, more intense fires. Intense burns can alter watershed hydrology, increasing the potential for harmful channel incision, which impairs riparian ecosystem function by lowering the water table, disconnecting floodplains from aquatic environments. However, wetlands and functioning riparian zones can reduce burn intensity. Beaver, with their unique ability to build dams, can restore incised and degraded streams, store water, and expand wetland environments, potentially decreasing wildfire intensity, fire spread and create fire breaks across the landscape. My objective was to test the hypothesis that beaver impoundments increase landscape resistance to wildfire by increasing soil and fuel moisture in riparian zones and surrounding uplands, hindering fuel ignition and fire rate of spread. To test this hypothesis, beaver impounded sites and paired undammed reference reaches were compared using field moisture surveys, GIS analysis of burn severity, and remote sensing of plant water stress via drone. Soil and fuel moisture samples were collected at repeated times throughout the fire season, above, within and below ten beaver impounded streams and ten non-impounded reference reaches within the Methow Watershed, WA, USA. The six of these paired sites that had recently burned, and an additional eight paired burned reaches (n=14 pairs) were selected for GIS analysis comparing post fire burn severity, measured as dNBR, within valley bottoms and upland zones. Potential plant water stress of riparian grasses, shrubs, and upland conifers was compared at one site and a paired reference reach at the beginning, middle and end of the fire season using NDVI analysis of drone survey imagery. GIS analysis of historically burned beaver sites showed that beaver dams, slope, and solar radiation interacted to affect fire intensity in beaver impounded riparian zones, but not their adjacent uplands. Soil and fuel moisture sampling showed that beaver impounded sites had higher average soil and dead fuel moistures than non-impounded sites during the driest times of the year, however beaver dam presence was not associated with increased live fuel moisture content. NDVI analysis revealed increased fluorescence in riparian grasses and upland conifers in beaver impounded riparian zones throughout the fire season. These results support my hypotheses that beaver impounded riparia have a higher resistance to burn events compared to non-impounded riparian zones, indicating that beaver can play a key role protecting river networks from burn events, increasing landscape resistance to wildfire.

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INTRODUCTION

Once ubiquitous across North America, beavers (*Castor canadensis*) are known ecosystem engineers and a keystone species (Naiman et al. 1988). Their damming behavior impounds surface water, creating complex aquatic and riparian systems that support an exceptional number of plants and wildlife (Wright et al. 2002). Beaver dams provide drought relief through increased water storage, which can help ameliorate the impacts of climate change, such as reduced precipitation, snowpack, and lower base stream flows (Baldwin 2015). They can also increase ecosystem resilience to wildfires by trapping sediment and accelerating recovery from channel incision (Pollock et al. 2014, Martin et al. 2015, Whipple 2019). With drought and wildfires increasing in frequency and intensity across the western United States (Westerling 2016)land managers have been exploring ways to create more burn resistant landscapes (Miller and Thode 2007, Schoennagel et al. 2017)). It is possible that beaver damming may increase wildfire resistance by storing water, increasing flooding, and creating extensive drought resistant wetlands that diminish the effect of burn events throughout the watershed.

Climate Change, and Wildfire Activity

Climate change is altering precipitation regimes, diminishing snowpack, and increasing the frequency of drought events, and the length of the fire season across the American West (Westerling et al. 2006, Moritz et al. 2014). Wildfires are becoming larger, more frequent, and intense due to climate change and increased fuel loads resulting from fire suppression (Abatzoglou et al. 2017, Schoennagel et al. 2017). High intensity burns denude the landscape of vegetation, alter hydrologic regimes, and potentially cause mass wasting of harmful sediment (Beyers et al. 2005, Neary et al.

2011).

Wildfires do not burn uniformly and are influenced by topographic factors such as fuel type, slope, aspect, elevation, and distance from waterbody (Halofsky and Hibbs 2008, Rogeau et al. 2018), leaving a mosaic pattern of burned habitats (Pyne 1984). Wetlands and riparian zones contribute to that mosaic effect due to water's high specific heat and vaporization threshold (Byram and Jemison 1943, Kreye et al. 2018, Rossa and Fernandes 2018) making wetlands and functioning riparian zones naturally resistant to fire (Camp et al. 1997, Dwire and Kauffman 2003, Beyers et al. 2005). Functioning riparian areas can act as firebreaks that diminish the severity of burn events, provide refuge for plants and animals, and provide vital post fire habitat (Pyne 1984, Camp et al. 1997, Pettit and Naiman 2007). A similar effect is observed in boreal systems where proximity to lakes and wetland habitats are associated with fire refugia (Araya et al. 2016, Nielsen et al. 2016). Water availability is often one of the highest predictors of diminished fire severity and locations of fire refugia (Keeton and Franklin 2004, Araya et al. 2016, Rogeau et al. 2018) as it directly influences the probability of ignition, rate of combustion and fire spread (Agee et al. 2002, Jolly and Hadlow 2012, Rossa and Fernandes 2018).

Beaver History and Ecology

Beavers are uncanny ecosystem engineers and a keystone species (Naiman et al. 1988). They help shape North American waterways by damming, ponding, and diverting water, creating dynamic stream systems and diverse riparian habitat (Johnston and Naiman 1990, Grudzinski et al. 2020). Formerly numbering in the tens to hundreds of millions across North America, beavers were trapped to near extinction for the fur trade (Baker and Hill 2003, Goldfarb 2018). European settlement of North America also contributed to beaver decline through development and conversion of desirable stream and riparian forest habitat, of which less than one third remains in the contiguous United States (Swift 1984, Naiman et al. 1988, Jones et al. 2010) . Current beaver populations are estimated to be 10% of historic levels, with significant consequences for stream ecosystem function across North America (Jones et al. 2010, Wohl 2020).

The ecological benefits of beavers are well documented (Naiman et al. 1988, Olson and Hubert 1994, Brown and Fouty 2011, Ecke et al. 2017). Beavers dam streams, forming a series of ponds and wetlands (beaver complexes), which protect them from predators and increase their access to forage (Collen and Gibson 2000). In doing so, beaver create extensive riparian and wetland habitat, supporting a disproportionate number of plants and wildlife, including 43% of North America's threatened and endangered species (Flynn 1995, Willby et al. 2018). Additionally, beaver dams provide flood mitigation, sequester sediment and pollutants (Martin et al. 2015, Whipple 2019), and hasten the recovery of degraded stream systems (Beechie et al. 2007, Pollock et al. 2014, Whipple 2019). Beaver dams divert water laterally, forcing stream flows to overtop their banks and spread over the floodplain. This causes flow velocity to decrease and allows sediment to aggrade, raising the stream bed and the water table (Pollock et al. 2014).

Across the American West, historic land use such as overgrazing, logging, and mining have left streams incised and disconnected from their floodplain, leading to loss of riparian ecosystem function and the conversion of riparian areas to a xeric state (Rood et al. 2005, Pollock et al. 2012, Wohl and Beckman 2014). Beaver can accelerate the recovery of incised and degraded streams from centuries to decades and provide land managers with a contemporary tool for aquatic and riparian habitat recovery and expansion (Pollock et al. 2014, Bouwes et al. 2016, Whipple 2019); Figure 1).

Beaver and Fire Adaptation

Although the relationship between increased fuel moisture and decreased burn severity is well documented, there is little research assessing the relationship between beaver presence and increased riparian burn resistance. Two recent studies by (Fairfax and Small 2018) and (Fairfax and Whittle 2020), found that arid riparian areas impounded by beaver had significantly higher evapotranspiration and plant productivity rates, measured as normalized difference vegetation index (NDVI), than areas without beaver dams, suggesting reduced water stress on riparian vegetation and potentially increased resistance to wildfire. However, there has not been any research explicitly linking beaver dams to reduced wildfire intensity, and beaver reintroduction remains controversial due to potential impacts of beaver dams on endangered anadromous fish (Lokteff et al. 2013), misconceptions about beavers' impact on water availability (Goldfarb 2018) and potential for conflicts with human infrastructure (Siemer et al. 2013). If beaver complexes were shown to decrease fire severity and drought tolerance, public perceptions about beaver reintroduction may improve, and land managers would have another resource for increasing drought and fire-resistance in natural landscapes.

The Methow Valley, located in north central Washington State (Figure 2), is an ideal location to test the relationship between beaver and fire resistance. The Methow

Valley encompasses the watershed of the Methow River, which flows from its headwaters in the North Cascades south east towards the Columbia River. This watershed has been subject to two of the largest wildfires in state history, with over 42% of the drainage burned since 2006. These two record-breaking wildfires, the Carlton Complex (2006) and Tripod Complex Fires (2014), consumed over 430,000 acres combined. The Methow Valley is also home to the Methow Beaver Project (MBP), an organization dedicated to the live removal and relocation of beaver in conflict with human infrastructure. The staff at the MBP have been capturing, tagging, and relocating "nuisance" beaver for over a decade, and harnessing their ability to create ponds to increase water storage and support juvenile salmon habitat (Pollock et al. 2004). The abundance of known beaver populations (Figure 2), both historic and present, extensive local knowledge, and agency partnerships provided by the MBP, as well as copious burn events, make the Methow Valley an ideal location to study the effects of beaver dams on fire behavior.

Study Objectives

This study aims to test the hypothesis beaver complexes can increase wildfire resistance in riparian zones and the surrounding landscape. Specifically, I predicted that stream reaches with beaver impoundments have higher soil and fuel moisture, and hence reduced wildfire intensity than reaches without beaver dams. I tested these predictions with a three-part study. First, I compared fire severity of historic burns in stream reaches with beaver dams and comparable reference reaches without dams in a geographic information system (GIS). I predicted that there would be lower average differenced Normalized Burn Ratio (dNBR) in beaver impounded riparian areas compared to sites without beaver. Second, I compared soil and fuel moisture in beaver impoundments and undammed reference sites. Differences in soil and fuel moisture availability can be used to forecast potential fire behavior and riparian resistance to wildfire. I predicted that soil moisture, riparian vegetation and dead fuel associated with beaver dams retain moisture at higher levels longer into the fire season than in undammed areas. Third, I documented plant water stress throughout the fire season in one beaver impounded riparian zone and one reference site using near infrared (NIR) aerial imagery captured with a modified DJI Phantom 4. I predicted that vegetation in beaver impounded riparian zones and adjacent uplands would exhibit less water stress than areas without beaver.

METHODS

Study Area

The Methow River Watershed (Methow Valley) is located in northcentral Washington, on the eastern slope of the Cascade Range, and encompasses an area of 4,727 km^2. Its primary waterbody, the Methow River (129 km), runs southeast from its headwaters in the Cascades to its confluence with the Columbia River and has two primary tributaries: the Twisp and Chewuch Rivers (Figure 2). Climate varies dramatically over the Methow Watershed due to the large change in elevation from the peaks of the Cascades in the west (~ 1,700 m) to the low valleys at the edge of the Channeled Scablands (~ 240 m) in the southeast (Marshall 1915). Categorized as high desert, the Methow Watershed is subject to dry climate with primary precipitation accumulating as snowfall (November to March), ranging from 200 cm/year in the headwaters of the Methow River to ~ 25 cm per/yr at its confluence with the Columbia

River (MBPU 2005, Whipple 2019). Primary vegetation communities in the Methow Valley consist of ponderosa pine (*Pinus ponderosa*), sagebrush (*Artemisia tridentata*), and antelope brush (*Purshia tridentata*) in the mid to low elevation zones; and subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*) and endangered whitebark pine (*Pinus albicaulis*) forest at high elevations (Hessburg et al. 2005, Whipple 2019). Riparian communities along the Methow River include a diverse group of forbs, sedges, rushes, and grasses as well as deciduous shrubs/trees including aspen (*Populus tremuloides*), cottonwood (*Populus trichocarpa*), alder (*Alnus incana*), river birch (*Betula occidentalis*), red-osier dogwood (*Cornus sericea*), and numerous species of willow (*Salix spp*.) (Hessburg et al. 2005, Whipple 2019).

The climate and vegetation characteristics of the Methow Valley support seasonal wildfire disturbance typical of the intermountain west (Agee 1996). Fire regimes pre-colonial settlement consisted of shorter return intervals (7-15 yrs.) and low to mixed severity burns (Pyne 1984, Agee 1996, Moritz et al. 2014) that "shaped and pruned" understory vegetation and forest structure, favoring established fire adapted plant communities and limiting fuel buildup on the landscape (Agee, 1996). Fire suppression in the Methow has increased fuel buildup, as well as contributed to dense stands of Douglas-fir (*Pseudotsuga menziesii*) capable of spreading understory fire to the canopy (Leuschen 1981), increasing the size and intensity of regional fires (Hessburg et al. 2005)

Analysis of Historic Fire Intensity

I identified and compared burn severity in 14 beaver impounded and 14 paired un-impounded reference reaches during historic burn events in ArcMap (ArcGIS *v* 10.7.1.) (Figure 3). Burn severity maps of fires within the Methow Watershed from 1987-2017 were obtained from the Monitoring Trends in Burn Severity Program website (Finco et al. 2012). These maps were available in the form of a series of raster datasets, with a spatial resolution of 30 meters. The rasters of dNBR, a measure of vegetation loss during burns, were mosaiced together to create a composite raster of dNBR in historic burns across the Methow Watershed. The Methow Beaver Project (MBP) provided beaver activity and beaver release points from 2015-2017. These points were overlaid with the composite burn severity raster layer to locate potential sites for further investigation. Historic aerial imagery provided by the USGS *EarthExplorer* database (Earth Explorer Interface 2020) was used to verify the presence of beaver dams at the time of the fires. Additionally, historic imagery was used to determine the influence of wildland fire fighters on potential study sites. Locations with extensive human development or evidence of fire suppression (e.g., fire breaks, trenches) were excluded from the analysis. Aerial investigation of current and historic beaver complexes within burn boundaries revealed 14 potential sites. Beaver complexes were spatially defined as 30 m below the lowest visible dam to 30 m above the highest visible pond in the impounded reach.

To locate suitable paired un-impounded reference reaches, I created a beaver habitat model using the Beaver Restoration Assessment Tool (BRAT *v*. 3.1) (Macfarlane et al. 2017) (Figure 4). The BRAT model identified the potential dam building capacity per reach (dams/km) based on drainage network characteristics (high/low flows, drainage size), stream gradient, and vegetation cover derived from the National Hydrologic Dataset (NHD; (U.S. Geologic Survey 2018), digital elevation models (DEMs;(USGS 2017) and the USDA Land Fire Database (Rollins 2009) respectively. High flows were calculated using the Region 2 regression equation found in the USGS report, *Magnitude, Frequency, and Trends of Floods at Gaged and Ungagged Sites in Washington* (Mastin et al. 2016). Low flow regression data for the eastern side of the Washington Cascade Range was not available, thus, low flow regression equations were sourced from the eastern side of the Oregon Cascade Range (Region 4) (Risley et al. 2008). Intermittent streams delineated by the NHD were excluded from the model to prioritize sites that would maintain flows year-round.

The resulting dam building capacity model predicted the Methow Watershed hosts nearly 52 km of beaver habitat capable sustaining pervasive damming (15-40 dams/km), 130 km of habitat supporting frequent damming (5-15 dams/km), 201 km of habitat supporting occasional damming (2-5 dams/km) and 269 km habitat supporting rare damming (<2 dams/km) (Figure 4). Additionally, the BRAT model segmented the stream network into 300 m reaches which could be queried using ArcMap's identify tool, detailing reach characteristics such as drainage area (km^2) and slope (%). I compared the locations of the 14 beaver impounded reaches to the streams identified in the BRAT model and then chose nearby reference reaches of similar drainage area, slope, and dam building capacity (Table 1). Beaver impounded sites located in reaches that were not delineated by the BRAT model were identified using the USGS Stream Stats: Streamflow and Spatial Analysis Application (U.S. Geological Survey 2016). Using the interactive map, I compared the locations of beaver impounded sites to nearby reaches and selected references sites based on drainage area (km^2), mean slope of the drainage (%), and canopy cover (%) included in the Stream Stats report (Table 2). Length of reference reaches were matched to their corresponding beaver impounded site (n=14 paired sites) (Tables 1 & 2).

Following selection of beaver impounded sites and reference pairs, the valley bottom of the Methow Watershed was delineated using the Valley Bottom Extraction Tool (VBET;Gilbert et al. 2016). The VBET uses DEMs and the NHD to create a polygon of the valley bottom of the Methow Watershed Figure (Figure 4). I used 0.75 Km and 0.25 Km for my large and medium valley buffer sizes respectively; all other required inputs used the VBET default values. The resulting valley bottom polygon was cut to exclude all but the valley bottoms of beaver impounded and reference reaches, resulting in 28 discrete polygons. Study site polygons were edited for accuracy using the methods defined in the VBET protocol (Gilbert et al., 2016). The final valley polygons for each reach were buffered by 25 m and 100 m to create intermediate and high upland zones of analysis. The erase tool was utilized to remove the area of the valley bottom layer from the 25 m buffer zone and the 100 m buffer to create two concentric zones of analysis around the valley bottom layer (Figure 3).

The presence of beaver dams, solar radiance (Wh/m^2), slope (%) and total area of the feature (m^2) were included as factors for statistical analysis. Solar radiance and slope were calculated using 10 m DEMs for the entirety of the Methow Watershed (USGS 2017). The Zonal Statistics tool calculated the average dNBR values, average slope, average solar radiance, and total area (m^2) from the valley bottom, intermediate, and high upland zones at each site.

The interacting effects of beaver impoundments, average slope, solar radiance, and total area on dNBR were compared using mixed linear models with the nlme package in RStudio (RStudio Team 2021; Pinheiro J. et al. 2021), with paired beaver impounded and non-impounded sites accounted for by nesting treatment (beaver vs. no beaver) within a site pair variable. Type III ANOVAs provided in the car package (Fox and Weisberg 2019) were used to perform a log likelihood test on the linear mixed model. Degrees of freedom were calculated using the difference in the number of parameters between the two models. To aid in understanding interaction effects, generalized least square models (gls) (Pinheiro J. et al. 2021) were carried out on separate beaver and non-beaver subsets of the dataset to test the interacting effects of slope, solar radiance, and total area on dNBR in each group. Scatterplots of the dataset were created in R using ggplot2 (Wickham 2016) to illustrate the potential effects of beaver, slope, solar radiation, and site size on dNBR. All GIS analysis was completed using ArcGIS *v* 10.7.1.

Soil and Fuel Moisture Sampling

Soil and fuel moisture samples were collected from ten beaver impounded sites and ten paired un-impounded reference reaches. Sites were selected from throughout the Methow Watershed using the methods described above and included six sites from the GIS analysis of historic burns (Figure 5). For this analysis beaver sites and the paired reference reaches were not restricted to previously burned areas. Special consideration was given to potential reference reaches in proximity to their dammed counterparts to allow sampling of both sites within an eight-hour time interval (10am – 6pm) and limit lag times between sample collection. Soil and fuel moisture samples were collected a minimum of six times at each site during the fire season (the last week of June to the first week of November), with each site pair visited on average every 14 days.

To survey soil moisture, three transects were established at each site. For beaver impounded sites, transects were located 30 m above the upstream extent of the beaver complex (upper transect), at the midpoint of the complex (middle transect) and 30 m downstream from the most downstream extent of the complex (lower transect). If the location of the middle transect did not provide an accessible floodplain (e.g., excessive ponding, stream meander) it was moved to the two thirds point between the upstream and downstream end of the complex. On undammed reference reaches, the three transects were located 50 m apart over 100 m of the reach. All transects were placed on the side of the stream corresponding with the most south and west facing aspects, where solar radiation and fire potential are heightened (Pyne, 1984; Kreye et al., 2018). Each transect began 0.5 m from the stream/pond edge and extended away from the waterbody perpendicular to the valley (Figure 6). Transects continued across the riparian zone and terminated 20 m into the upland. The transition between riparian and upland zones was established where a noticeable break in elevation occurred in conjunction with a transition to upland plant species. Ten soil sample points (R1-R10) were equally spaced within the riparian zone below the upland transition. An eleventh point (R11), with the same spacing as R1-R10, was placed in the transition zone just above the valley floor, where riparian and upland vegetation coexist. Four additional soil sample points were installed above R11 at 5 m intervals extending 20 m into the upland zone (Figure 6).

At each sample point, volumetric soil moisture measurements (%) were collected using a Vegetronix-VG-200 soil moisture probe. Probes were calibrated according to manufacturer specification before every site visit. Where appropriate, duff was carefully removed to expose mineral soil before sample collection and replaced post collection to avoid altering soil moisture between visits. Due to soil heterogeneity and depth, three measurements were taken to a depth of 10 cm at each point along the transect and averaged for a composite sample.

The effect of beaver impoundments on soil moisture values across the fire season was revealed by comparing dammed and reference sites over time using a repeated measures analysis via the PROC MIXED procedure in SAS (v 9.4; SAS 2021) and plotted in RStudio using ggplot2 (RStudio Team 2021, Wickham 2016). The analysis required site visits to be grouped into sample periods (time blocks) for comparison over the fire season, therefore an interval of 14 days was used to parse the site visits into five time blocks for repeated measures analysis. Due to a rain event on September 7th, 2019, site 20 Mile 2 was only visited five times and removed from the analysis.

Fuel Moisture Sampling

To determine effects of beaver dams on fuel moisture, two types of fuels were sampled, including 10-hour moisture sticks and live fuels. All fuel moisture sampling was conducted at the middle transect of field sites and followed the general protocols listed in the National Fire Behavior Field Reference Guide (Ziel 2017). Fuel sample collections were conducted upon departure of the first site visit and then immediately upon arrival at the corresponding paired site to mitigate diurnal fluctuations in fuel moisture levels. Fuel moisture weights were measured using a portable digital scale and occurred on average 11 days apart throughout the fire season.

10-hour fuel moisture sticks were installed on flat ground, 25 cm above the valley floor and within 3 m of the steam or pond edge (Figure 6). Standing vegetation (grasses/saplings) and debris were cleared within 1 m of fuel moisture sticks to minimize effects of plant respiration or ambient moisture sinks. Shade conditions were mimicked for each fuel moisture stick at the corresponding paired site. Stick weights were recorded in the field, with each gram >100 g corresponding to 1% fuel moisture.

Live fuel moisture samples were harvested from dominant riparian vegetation communities (shrubs & graminoids) throughout the fire season. Nine of the 10 paired sites contained shrubs as their primary fuel types and included willow (*Salix* spp.) alder (*Alnus* spp.) and red-osier dogwood (*Cornus sericea*). Due to the variety of willow species at each site, composite samples were collected. No willow or alder species were available at the Cub Creek reference site; thus, dogwood was collected as an analogous riparian fuel source. The collection of graminoids occurred at 20 Mile-2 and its reference and was comprised of a composite sample of rushes and sedges (*Carex* & *Scirpus* spp.)

All vegetation samples were harvested from plants within 5 m of the stream or pond edge (Figure 6). Samples were comprised of a minimum of 50 g of foliar material and excluded woody growth and seeds. If rain occurred, fuel moisture collection was delayed until fuels were dry to the touch. Vegetation samples were stored in vacuum sealed bags and frozen until the end of the field season where they were dried down for 24 hours at 100 C. Moisture content was calculated using the following formula: (field weight-dry weight/dry weight-container weight)*100. Fuel stick weights and live fuel moisture in beaver impounded and non-impounded sites were compared over the course of the fire season in RStudio (RStudio Team 2021) using linear models (R Core Team 2013). Linear models were plotted using ggplot2 (Wickham 2016).

Drone Surveys to Assess Plant Water Stress

Lightning Creek and its paired reference reach were chosen for remote sensing analysis of plant water stress. Lightning Creek and its reference were selected because of the abundance of well-established dams and similar vegetation communities with minimal overstory due to a recent burn event (Figures 7 a & b). Aerial imagery of each site was captured at the beginning (7/20/2020), middle (8/23/2020) and end (9/25/2020) of the fire season using a DJI Phantom 4 drone equipped with a 16 mega pixel AgroCam NIR camera. Flights were conducted using Drone Deploy mission planning software and flown at 75 m above the valley floor achieving a pixel resolution of 5 cm^2. Infrared and color images were captured with a 75% front and side overlap and at a speed of 7 m/s. Images were uploaded to AgroCam's servers for initial orthorectification. To control for differing reflectance rates between plant species (Xue and Su 2017), three locations were selected for analysis at each site: two in the riparian zone focusing on patches of shrubs and grasses, and one location focusing on upland conifers. Three square polygons (165 m^2) were drawn over each vegetation zone of analysis (Figure 7 a & b).

An enhanced vegetation index (EVI) was conducted on shrubs and grasses to reduce the saturation caused by dense vegetation in the riparian zone (EVI = 2.5*(NIR - Red) / (NIR + 6*Red - 7.5*Blue + 1)) (ESRI, 2020). A soil adjusted vegetation index (SAVI) analysis was carried out to control for soil brightness of open ground in the upland zone from previous burn events, with a soil correction factor (L) of 0.5, as it accommodates most land cover types (SAVI= ((NIR - Red) / (NIR + Red + L)) x (1 + L)), (ESRI, 2020). The zonal statistics tool was used to calculate the mean EVI and SAVI (VI) values for the area bounded by the polygons. Fluctuations in average reflectance of each vegetation group were tracked over the course of the fire season and compared to their reference vegetation group to document responses to water stress. Due to natural variation in photosynthetic rate and plant biomass between sample groups, direct comparisons of VI do not indicate inherent differences in water stress. Instead, the rate of change in VI over the fire season is used to measure potential water stress within plant groups.

RESULTS

Analysis of Historic Burns

The presence of beaver impoundments, solar radiation, average slope, and site size had interacting effects on dNBR in valley bottoms based on GIS analysis of historic burns (Table 4, Figure 8a & b). In unimpounded reference sites, dNBR increased with slope, solar radiance, and total area ($Pr < 0.001$, Table 1, Figure 8a & b), as predicted. In contrast, dNBR in beaver impounded sites shows little increase as slope and solar radiance and total area increase (Table 1, Figures 8a & b). Three unimpounded valley bottoms with high slope average experienced the most intense levels of burning (dnBR > 650; Key and Benson 2006), while no beaver impounded areas burned intensely (Figures 8a & b). In the intermediate upland (25 m) and high upland (100 m) buffer zones, no significant relationship was observed between beaver presence and reduced burn severity.

Solar radiance, average slope and site area had interacting effects on dNBR in the intermediate upland zone (Pr<0.05, Table 5). Slope and total area were positively related with dNBR, while solar radiance had little effect on dNBR except for a 4 sites. In the high upland zone, solar radiance and average slope had interacting effects on dNBR (Pr<0.05, Table 6). Solar radiance and average slope were both positively related to dNBR, however solar radiance had less of an impact on dNBR as slope increased.

Soil and Fuel Moisture

In beaver impounded sites, soil moisture remained an average of 13.9% higher throughout the fire season compared to undammed reference sites, (P <0.0001, Table 7, Figure 9). Soil moisture decreased with distance from water source but was higher at greater distances from the stream channel in beaver impounded sites (P<0.0001, Table 7). As the fire season progressed, beaver impoundments also maintained soil moisture at greater distances from the stream for a longer time than sites without beaver (P<0.0004, Table 7). There was no significant difference in soil moisture among transects within sites, regardless of beaver presence or seasonality (Table 7). 10–hour fuel sticks in beaver impounded riparian zones maintained a higher average moisture throughout the season by nearly 2% (P<0.05, Table 8, Figure 10). No significant difference in live vegetative fuel moisture was observed between beaver impounded and non-impounded sites (Table 9).

Drone Surveys

Vegetative reflectance of riparian grasses and upland conifers at Lightning Creek increased over time and peaked in mid-summer indicating minimal plant stress. In contrast, vegetative inflorescence of grasses and conifers in the undammed reference reach showed steady decline over the course of the fire season. Riparian shrubs in Lightning Creek impounded and non-impounded sites had nearly identical increases in solar reflectance over the fire season (Figure 11).

DISCUSSION

My study results provide evidence that beaver activity increases potential fire resistance of riparian zones in the Methow Watershed. Beaver impounded sites exhibited higher fire resistance during historic burn events and maintained higher fuel and soil moisture at greater distances throughout the 2019 fire season than non-impounded sites. However, potential historic fire buffering capacity provided by beavers was partially dependent on topography and fire conditions and restricted to the riparian zone. The decreased burn severity observed in beaver impoundments during historic burns and the increased fuel and soil moisture retention of beaver dams during seasonal drought are compelling evidence that beaver have the potential to bolster the already fire-resistant characteristics of riparia.

Burn severity (dNBR) in beaver impounded sites did not respond as dramatically to factors that increase fire intensity (e.g. solar radiance, total area, slope) as non-impounded sites (Heyerdahl et al. 2001). This muted response, particularly as slope and site size increases, can potentially be attributed to both beaver activity and topographic factors unique to specific sites. Most sites are relatively small (< 50,000 m^2) with low sloped valley bottoms (<10%) except for 7 sites (2 paired sites and 3 references) (Table 3). Breed, Lightning and 20 Mile-1 are large and relatively low sloped environments with wide riparian meadows and represent ideal beaver habitat that is easy to dam and where flooding or inundation capacity is greatest (Baker and Hill 2003, Curtis and Jensen 2004). In addition to being easily wetted, the size of the floodplain and lack of woody fuel within riparian meadows provides a natural fuel break that can slow the rate of fire spread (Van de Water and North 2011, Green 1977, Agee 1996). However, as sites increase in size, so does the heterogeneity of the landscape within the study area, increasing the amount of fuel types available for combustion and gradients of slope, potentially explaining the increased dNBR in some large sites (Turner et al. 1994, Kolden et al. 2012).

Valley bottom sites with high slope and high solar radiance are likely the least affected by beaver flooding, and first to disconnect from the water table during times of drought (Westbrook et al. 2006, Wohl and Beckman 2014). These narrow ravines often burn more frequently than lower gradient riparia and can serve as fire corridors during drought conditions and large burns given their higher productivity and fuel loads (Pettit and Naiman 2007). Consequently, two reference sites (Moose & Woody) with the highest slopes and relatively small area, burned with the highest severity and may influence trends seen in the dNBR analysis.

My hypothesis that the wetting effects of beaver dams would impact burn severity in the surrounding uplands was not supported by my study. The dampening effects of beaver I observed were concentrated in valley bottom zones, with intermediate (25 m) and high upland (100 m) zones showing no relationship between dNBR and beaver presence in my analysis. Other studies have also found differing fire regimes between riparian and upland environments (Van de Water and North 2011, Dwire and

Kauffman 2003, Pettit and Naiman 2007). However, my inability to detect beaver dam effects on fire in the uplands may be derived from the available resolution of the MTBS dNBR rasters, particularly in narrow sites and in the 25 m upland buffer zone. MTBS rasters have a pixel resolution of 30 m^2 (Finco et al. 2012) which may fail to capture the fine scale differences in burn severity in the smallest sites and upland zone immediately surrounding the valley bottom. Differenced Normalized Burn Ratio is also subject to error in areas with low vegetation prior to the burn. Vegetation types that reestablish quickly after fire, such as shrubs and grasses, may not reflect the true vegetation loss in post fire imagery (Parks et al. 2014, Allen and Sorbel 2008). Additionally, dNBR data is subject to atmospheric error and may fail to capture the severity of burns below overstory vegetation (Kolden et al. 2012, Allen and Sorbel 2008). Expanding the 25 m upland zone of analysis, increasing the sample size, and utilizing a relativized differenced burn ratio (RdNBR) raster in the upland zones would add robustness to datasets, and are recommended for future analyses.

Higher than average rainfall during the study period may have obscured the difference in soil moisture between beaver impounded and non-impounded sites, which is likely greater under drought conditions. Weather station data in Winthrop, WA recorded an increase in precipitation of 47% above seasonal average over the course of the study period (July-Oct - 10.4 cm: NOAA, 2020). September was particularly wet, receiving 5.71 cm of rain, nearly as much precipitation as the combined seasonal average (7.09 cm). Two precipitation events on August 14th and September 18th delivered 0.36 cm and 1.6 cm of rain respectively and are reflected in soil moisture and 10 – hour fuel stick measurements. Elevated seasonal precipitation potentially reduced soil and fuel moisture differential between beaver impounded and non-impounded sites.

Despite the relatively wet conditions, soil moisture in beaver impounded riparian zones began and remained higher than non- impounded riparian zones by nearly 14% over the course of the fire season. After an initial drop in late July, soil moisture in beaver impounded sites increased at a greater rate than their non-impounded counterparts, revealing lower water retention in sites without beaver dams. The greatest difference in soil moisture occurred in time block 4 (~September 7th) and is likely the result of increased seasonal precipitation and the recognized water storage capabilities of beaver dams (Pollock et al., 2014). The heightened soil moisture in beaver dammed sites also decreases the combustibility of soil organic matter and fine fuels (e.g.,duff, leaf litter) (Matthews, 2014) reducing residency time and fire spread (Campbell et al., 1994; Samran et al., 1995).

Additionally, beaver impoundments maintained higher moisture levels at greater distances from the stream channel longer into the fire season than riparian zones without beaver, consistent with other studies documenting that beaver increase wetted width of riparian zones (Naiman et al. 1988) and resistance to drought (Baldwin, 2015). Exact dimensions of effective fire breaks are dependent on topography (e.g., fuel type/density, slope; Fechner and Barrows 1976) and fire conditions (e.g., wind speed/direction; Agee et al., 2000). However, wider fuel breaks are more effective at tolerating radiant heat from the approaching fire and less susceptible to transfer of embers (Agee 1996, Green 1977, Dwire and Kauffman 2003).

My study did not provide evidence that beaver dams affect live vegetative fuel moisture over the fire season. The primary fuel type collected was riparian shrubs (willows, alder, dogwood) which secure ground water via deep tap roots (e.g., as phreatophytes) despite seasonal decreases in surface moisture (Rood et al. 2003, Tron et al. 2015), potentially negating any local differences.in water stress. The absence of significant drought conditions over the study period likely increased live vegetation soil moisture in dammed and undammed riparian zones alike.

Like soil moisture, fuel moisture data collected over the fire season was affected by above average seasonal precipitation. 10–hour fuel stick weights show drastic increases during rain events on August 14th, 2019 and September 18th, 2019, likely due to direct exposure to precipitation, which may have narrowed the average difference in fuel moisture (~2%) between beaver impounded and non-impounded sites. A 2% difference in fuel moisture appears minimal, however, ignition and fire spread are dependent on fuel type and atmospheric conditions that affect moisture sorption rates of fuels (Pyne, 1984). During low and moderate intensity burns and conducive atmospheric conditions (e.g., increased relative humidity), small fluctuations in dead fuel moisture can reduce combustion rates by orders of magnitude (Jolly 2007, NWCG 2020). For example, in a study of fire rate of spread during a controlled burn, a 2% increase in fuel moisture reduced fire perimeter spread by over 0.30 m/min (Curry 1938). Heightened fuel moistures in beaver impoundments likely have a dampening effect on fire combustion and spread during low to moderate severity burn events.

Results from NDVI drone surveys of Lighting Creek are consistent with the contemporary literature surrounding the impact of beavers on riparian plant water stress (Fairfax and Whittle 2020, Fairfax and Small 2018). Similar to my live fuel surveys, riparian shrubs were the only vegetation class that did not show divergent relationships in vegetative inflorescence over the course of the fire season in beaver impounded and non-impounded sites. It is also worth noting that the VI response from shrubs in both non-impounded and impounded sites was nearly identical, when other plant species diverged throughout the season., which may reflect the water acquisition strategies of different riparian and upland plant species (Stromberg 2013, Guswa 2010). In contrast riparian grasses and upland conifers in beaver impounded sites maintained higher rates of vegetative inflorescence than non-impounded sites indicating potential water stress and relative susceptibility to wildfire compared to their beaver impounded counterparts. These results support observations found in my fuel and soil analyses, but are only based on one pair of sites, hence should be interpreted with caution.

Conclusions and Management Implications

In conclusion, my study reinforces the current understanding of ecosystem benefits afforded by beavers by providing evidence that beaver impounded sites have increased resistance to drought and wildfire in the riparian zone, consistent with other research (Wohl 2020, Fairfax and Whittle 2020). Beaver presence reduced riparian burn severity during historic wildfires in the Methow Valley and increased the fire resistance potential of riparian zones during the summer of 2019 by increasing water retention and holding it deeper into the fire season than undammed streams. By increasing the amount of surface and groundwater on the landscape for longer durations into the fire season, beaver increase wetland habitat and functionality of riparian zones in the Methow Watershed, making them potentially more resistant to forest fires.

The potential impact of beaver impoundments on wildfire throughout the Methow Watershed may be limited by current beaver population density. Beaver populations are significantly reduced compared to historic levels (Goldfarb 2018, Wohl 2020). Additionally, the BRAT model (Macfarlane et al. 2017) used in my study identifies over 400 miles of beaver habitat capable of supporting dams throughout the Methow (Figure 1, appendix), most of which no longer host dams or has lower dam densities than predicted by the BRAT model. Given the various topographic conditions of my sample sites and the localized effects of beaver dams on fire potential indicated in my results, further study is required to determine the locations and densities at which beaver complexes are most effective in diminishing the effects of wildfire.

Contemporary tools like the BRAT model can help land managers in the Methow Valley incorporate fire prevention and restoration into beaver management decisions by identifying areas with high dam building capacity and fire buffering potential. However, much of the low gradient, valley bottom habitat capable of supporting extensive damming in the Methow is dominated by human infrastructure, which may make beaver reintroduction infeasible. However, recognition of beavers as a keystone species is growing among the public and scientific community. Organizations like the Methow Beaver Project are growing globally, and beaver are being incorporated into holistic watershed restoration projects (Pollock et al. 2014). As climate change increases the frequency and intensity of drought and wildfires, land managers will be tasked with creating more drought and burn resistant landscapes. Given their historic population density and their ability to modify and restore degraded stream habitat, beaver restoration offers land managers a low-cost approach to increasing landscape resistance to drought and wildfire from confluence to headwaters.

List of Tables and Figures

Table 1. List of sample sites identified and paired using the BRAT model. Site pairs with 0 damming capacity-maintained dams at sample site, despite model predictions. * indicates site used in GIS analysis and field surveys.

Site Name	Drainage Area (km^2)	Slope (%)	Dam Building Capacity (Dams/km)	Distance from Ref. (km)
20 Mile 1*	27.3	0.079	13.0	0.75
20 Mile 1 Ref	32.6	0.064	17.7	
20 Mile 2*	8.7	0.031	13.6	1.4
20 Mile 2 Ref	2.4	0.003	12.9	
20 Mile 3*	15.1	0.039	12.1	0.98
20 Mile3 Ref	18.8	0.056	21.5	
Bear Mountain	33.2	0.04	25.3	3.9
Bear Mountain Ref	34.5	0.03	19.0	
Beaver Creek	340	0.04	0	1.5
Beaver Creek Ref	304	0.06	0	
Benson*	46.0	0.037	10.5	1.8
Benson Ref	42.3	0.041	3.3	
Black Canyon*	312.8	0.075	0	4.6
Black Canyon Ref	207.0	0.050	0	
Bobcat	122	0.04	0	5.1
Bobcat Ref	163	0.09	0	
Breed	19.6	0.095	11.0	1.3
Breed Ref	18.3	0.084	19.1	
Cub	30.3	0.073	18.9	11
Cub Ref	22.7	0.097	16.1	
Little Joe	91.5	0.093	0.0	2.0
Little Joe Ref	113.9	0.145	0.0	
Woody	83.9	0.091	0.0	3.1
Woody Ref	79.7	0.118	0.0	

Table 2. List of sites identified and paired using the USGS Stream Stats application. * indicates site used in GIS analysis and field surveys.

Site Name	Drainage Area (km^2)	Mean Basin Slope (%)	Canopy Cover (%)	Distance from Ref.(km)
Halfway	0.67	28.20	84.90	1.6
Halfway Ref	0.70	28.00	84.80	
Boulder	3.89	33.60	53.10	1.6
Boulder Ref	3.60	34.30	54.60	
Bernhardt	2.28	42.70	52.10	0.63
Bernhardt Ref	2.95	35.30	29.80	
Lightning*	7.10	28.20	70.30	1.2
Lightning Ref	2.82	24.60	66.70	
Moose	1.11	33.30	55.40	2.3
Moose Ref	0.65	32.40	61.10	
Tiffany	1.63	31.40	56.40	1.8
Tiffany Ref	5.41	26.90	54.80	

Table 3. List of sites and factors compared during GIS analysis of burn severity during historic wildfires in the Methow Watershed.

Site Name	Site Code	Avg. Solar Radiance (Wh/m^2)	Avg. Slope (%)	Total Area (m^2)	dNBR
Bernhardt	BHT	494555	3	30487	178
Bernhardt Ref	BHTr	522210	6	41267	354
Boulder	BLD	505290	8	26279	498
Boulder Ref	BLDr	477676	8	27531	484
Breed	BRD	433426	4	55219	549
Breed Ref	BRDr	450844	4	91513	502
Halfway	HFY	506176	5	11380	51
Halfway Ref	HFYr	532933	13	5868	256
LittleJoe	LTJ	405153	14	2769	446
LittleJoe Ref	LTJr	395865	10	3609	170
Moose	MOS	491991	5	17869	118
Moose Ref	MOSr	474051	14	14417	918
Tiffany	TIF	510539	4	34926	270
Tiffany Ref	TIFr	509044	5	49240	335
Woody	WOD	409390	10	16320	62
Woody Ref	WODr	467107	13	8022	828
Benson	BEN	445582	9	7010	-43
Benson Ref	BENr	450765	10	9687	-4
BlkCan	BLK	463129	7	34056	0
BlkCan Ref	BLKr	463355	11	16514	0
Lightning	LTN	492935	4	110877	504
Lightning Ref	LTNr	492910	10	124430	695
20Mile3	TM3	511387	5	16908	205
20Mile3 Ref	TM3r	503413	3	11175	123
20Mile2	TM2	513622	3	13659	156
20Mile2 Ref	TM2r	508085	1	10139	0
20Mile1	TM1	507671	2	98486	153
20Mile1 Ref	TM1r	513652	5	49985	291

Table 4. Results of a linear mixed effects model showing the interacting effects of slope, solar radiance, total site area, and beaver dam presence on dNBR in valley bottom sites. Beaver indicates presence of dams. * Indicates results significant at α=0.05.

Effect	**Chisq**	**DF**	**Pr(>Chisq)**
Beaver	78.85	1	< 0.0001*
Slope	21.73	1	< 0.0001*
Solar Radiance	1.35	1	0.25
Total Area	14.73	1	0.00012*
Beaver Slope	77.81	1	< 0.0001*
Beaver*Solar Radiance	78.32	1	< 0.0001*
Slope*Solar Radiance	20.86	1	< 0.0001*
Beaver*Total Area	8.50	1	0.0035*
Slope*Total Area	14.73	1	< 0.0001*
Solar Radiance*Total Area	16.60	1	< 0.0001*
Beaver*Slope*Solar Radiance	70.47	1	< 0.0001*
Beaver*Slope*Total Area	0.46	1	0.50
Beaver*Solar Radiance*Total Area	7.74	1	0.0054*
Slope*Solar Radiance*Total Area	14.41	1	< 0.0001*
Beaver*Slope*Solar Radiance*Total Area	0.33	1	0.57

Table 5. Results of a linear mixed effects model showing the interacting effects of slope, solar radiance, total site area, and beaver dam presence on dNBR in 25 m buffer zone. Beaver indicates presence of dams. * Indicates results significant at α=0.05.

Effect	**Chisq**	**DF**	**Pr(>Chisq)**
Beaver	2.10	1	0.14
Slope	4.76	1	0.029*
Solar Radiance	6.21	1	0.013 *
Total Area	5.72	1	0.016 *
Beaver Slope	2.29	1	0.13
Beaver*Solar Radiance	2.21	1	0.14
Slope*Solar Radiance	4.34	1	0.037 *
Beaver*Total Area	1.774	1	0.18
Slope*Total Area	5.02	1	0.025 *
Solar Radiance*Total Area	5.75	1	0.017 *
Beaver*Slope*Solar Radiance	2.30	1	0.13
Beaver*Slope*Total Area	1.31	1	0.25
Beaver*Solar Radiance*Total Area	1.72	1	0.19
Slope*Solar Radiance*Total Area	4.80	1	0.028*
Beaver*Slope*Solar Radiance*Total Area	1.07	1	0.30

Table 6. Results of a mixed effects model showing the interacting effects of slope, solar radiance, total site area, and beaver dam presence on dNBR in 100 m buffer zone. Beaver indicates presence of dams. * Indicates results significant at α=0.05.

Effect	**Chisq**	**DF**	**Pr (>Chisq)**
Beaver	0.92	1	0.34
Slope	4.43	1	0.035*
Solar Radiance	2.15	1	0.14
Total Area	2.19	1	0.14
Beaver Slope	1.18	1	0.28
Beaver*Solar Radiance	0.86	1	0.35
Slope*Solar Radiance	4.57	1	0.033*
Beaver*Total Area	1.14	1	0.29
Slope*Total Area	3.46	1	0.063
Solar Radiance*Total Area	2.23	1	0.14
Beaver*Slope*Solar Radiance	1.01	1	0.31
Beaver*Slope*Total Area	1.28	1	0.26
Beaver*Solar Radiance*Total Area	1.11	1	0.29
Slope*Solar Radiance*Total Area	3.54	1	0.58
Beaver*Slope*Solar Radiance*Total Area	1.17	1	0.28

Table 7. Results of a repeated measures analysis showing the interacting effects of distance from water's edge, beaver dam presence, and sampling time block on soil moisture. Beaver indicates presence of dams. * Indicates results significant at α=0.05.

Effect	**Num DF**	**Den DF**	**F Val**	**Pr > F**
Beaver	1	65.5	14.6	0.0003
Time Block	4	2942.0	32.5	<.0001
Beaver*Time Block	4	2942.0	10.4	<.0001
Transect	2	65.5	1.2	0.32
Beaver*Transect	2	65.5	0.20	0.82
Transect*Time Block	8	2980.0	1.2	0.29
Beaver*Transect*Time Block	8	2980.0	1.9	0.058
Distance	1	857.0	651.6	<.0001
Distance*Beaver	1	857.0	25.8	<.0001
Distance*Time Block	4	2946.0	20.8	<.0001
Distance*Beaver*Time Block	4	2946.0	3.87	0.0039
Distance*Transect	2	857.0	0.26	0.77
Transect*Beaver*Distance	2	857.0	0.70	0.50
Transect*Distance*Time Block	8	2983.0	0.82	0.58
Transect*Beaver*Distance*Time Block	8	2983.0	1.22	0.28

Table 8. Results of ANOVA comparing 10-hour fuel stick weights in beaver and non-beaver impounded sites. Beaver indicates presence of dams. * Indicates results significant at $\alpha=0.05$.

	Df	Sum	Sq Mean	Sq F value	Pr(>F)
Beaver	1	122.6	122.64	5.05	0.026*
Time	1	504.3	504.34	20.76	< 0.0001*
Beaver* Time	1	6.1	6.11	0.25	0.62
Residuals	133	3231.2	24.29		

Table 9. Results of ANOVA comparing live fuel moisture in beaver impounded and non-beaver impounded sites. Beaver indicates presence of dams. * Indicates results significant at $\alpha=0.05$.

	Df	Sum	Sq Mean	Sq F value	Pr(>F)
Beaver	1	242	242.2	0.05	0.82
Time	1	928	928.4	0.20	0.65
Beaver* Time	1	1275	1274.5	0.28	0.59
Residuals	121	541364	4474.1		

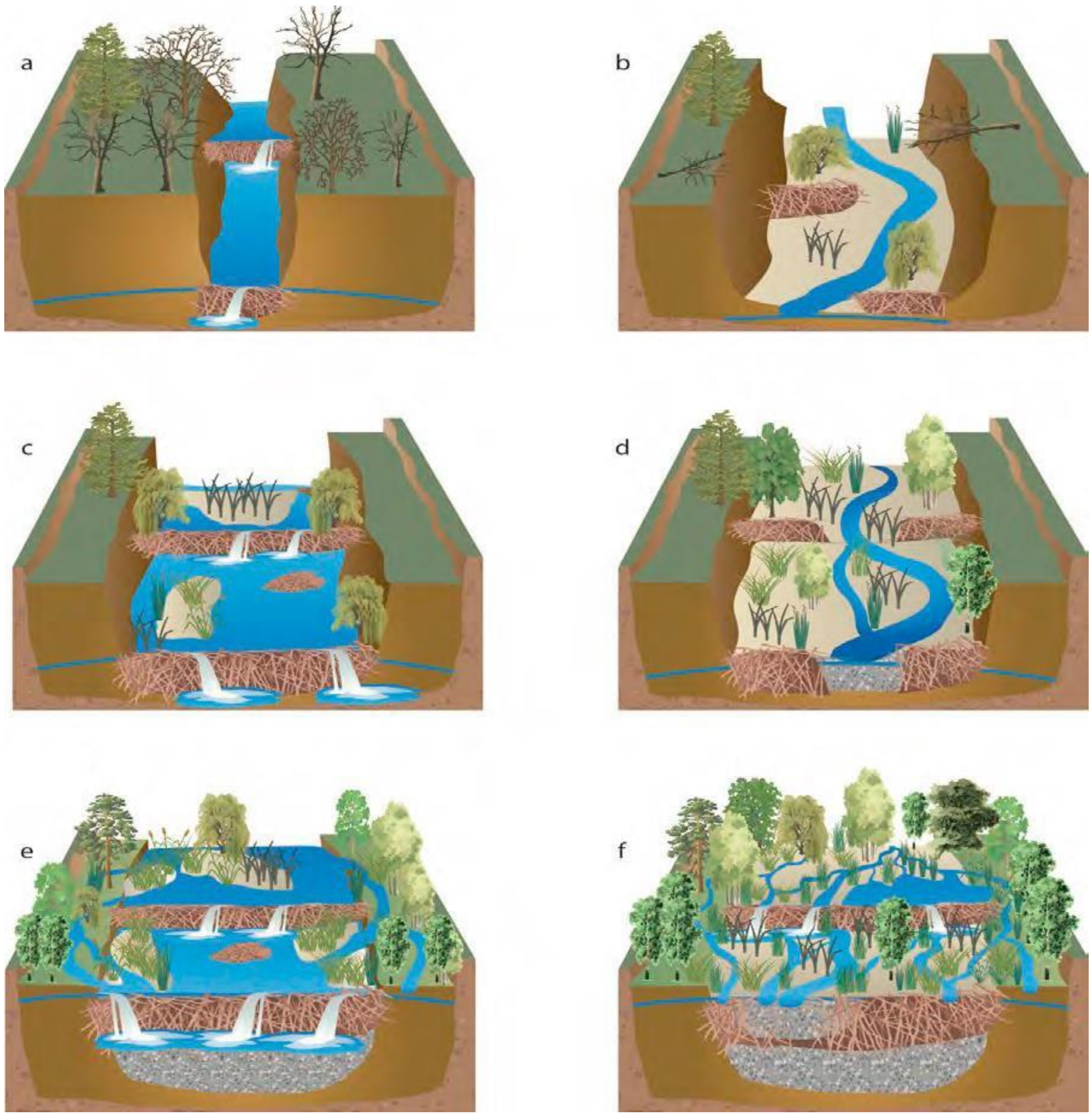


Figure 1. Illustration from Pollock (2014) showing how beaver dams affect the recovery of incised streams: (a) Beaver will dam streams within narrow incision trenches during low flows, but stream power is often too high, which results in blowouts or end cuts that (b) help widen the incision trench, which allows an inset floodplain to form. (c) The widened incision trench results in lower stream power, which enables beaver to build wider, more stable dams. (d) Because streams that have recently incised often have high sediment loads, the beaver ponds rapidly fill up with sediment and are temporarily abandoned, but the accumulated sediment provides good establishment sites for riparian vegetation. This process repeats itself until (e) the beaver dams raise the water table sufficiently to reconnect the stream to its former floodplain. Eventually, (f) vegetation and sediment fill the ponds, and the stream ecosystem develops a high level of complexity as beaver dams, live vegetation, and dead wood slow the flow of water and raise groundwater levels such that multithread channels are formed, often connected to off-channel wetlands such that the entire valley bottom is saturated (Pollock 2014).

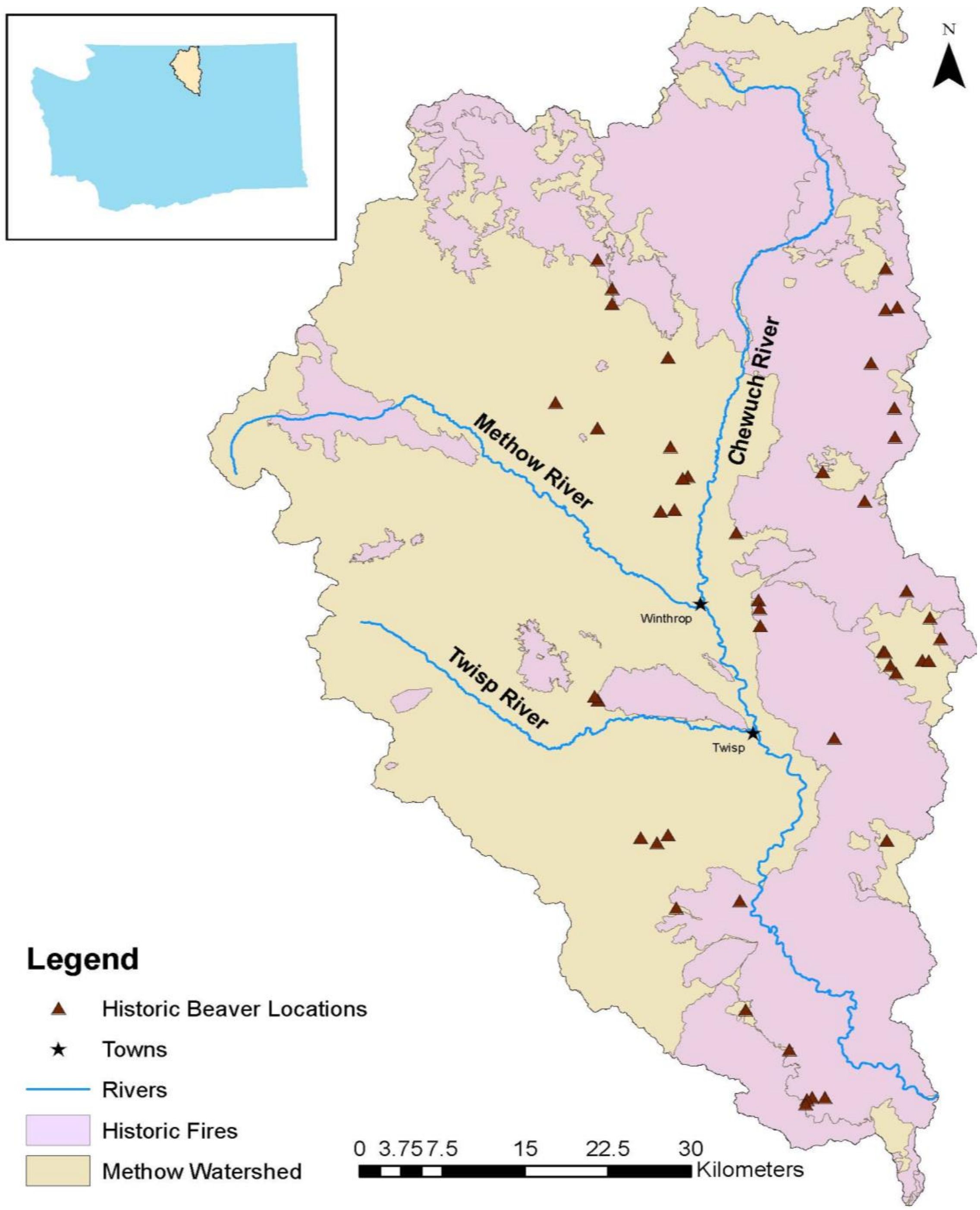


Figure 2. Map of Methow Valley study area detailing locations of beaver activity, historic burn areas, and the potential capacity of beaver damming derived from the BRAT model.

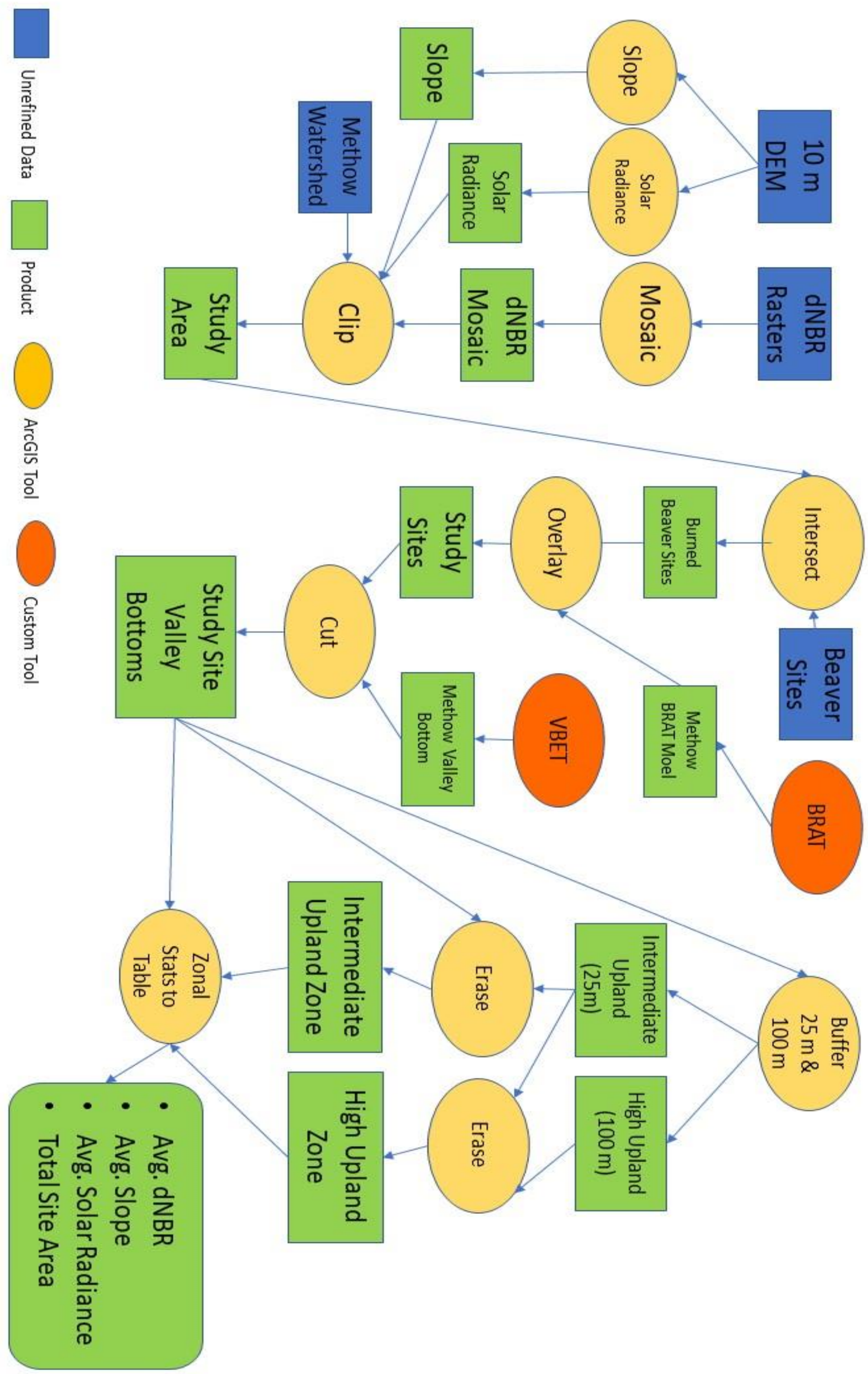


Figure 3. Workflow detailing derivation of valley bottom, intermediate, high upland zones, and extraction of dNBR, slope, solar radiance, and total area.

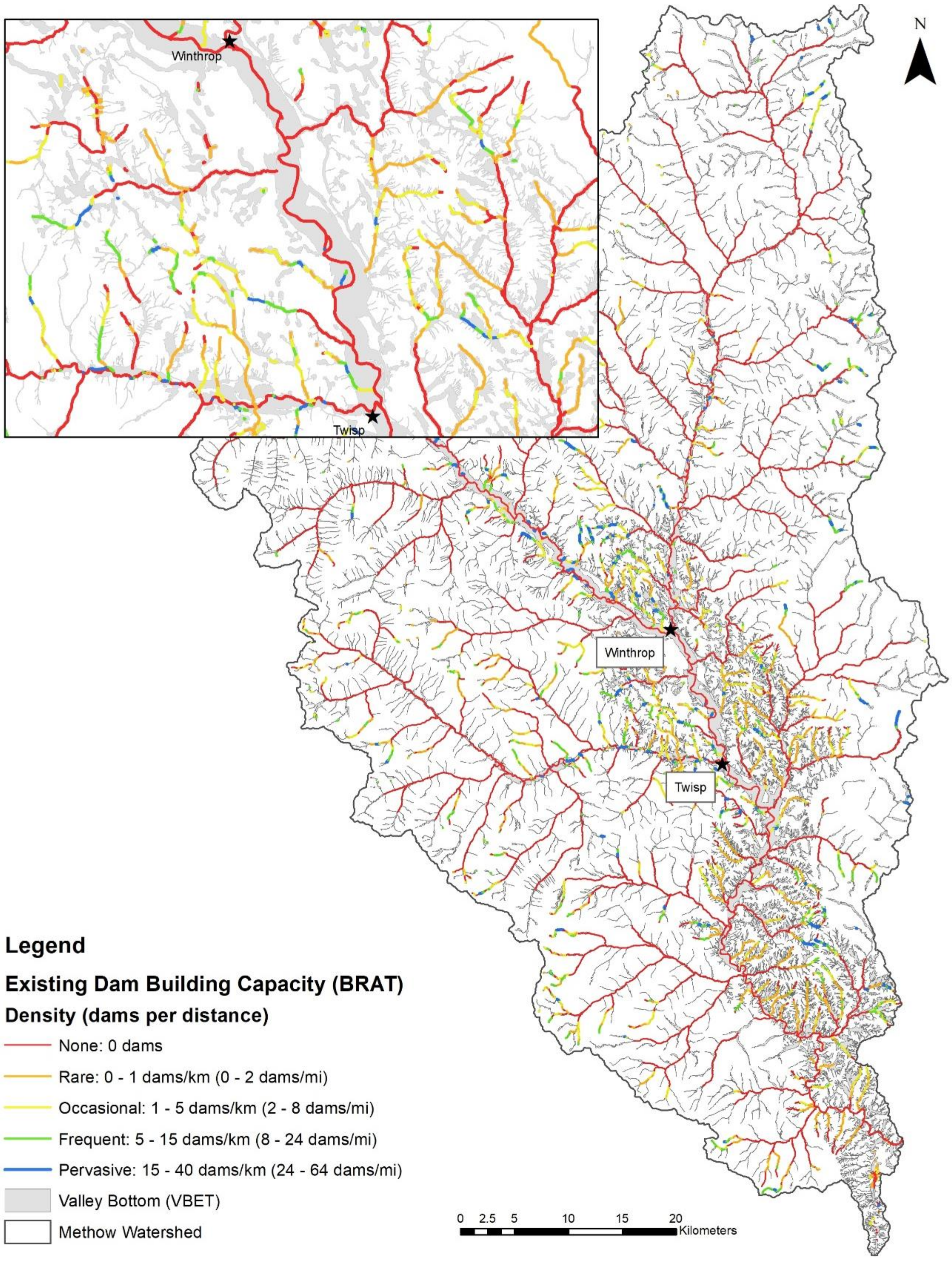


Figure 4. Map featuring dam building capacity of rivers and tributaries and the valley bottoms of the Methow Watershed. Inset map shows the area between the towns of Winthrop and Twisp at finer scale.

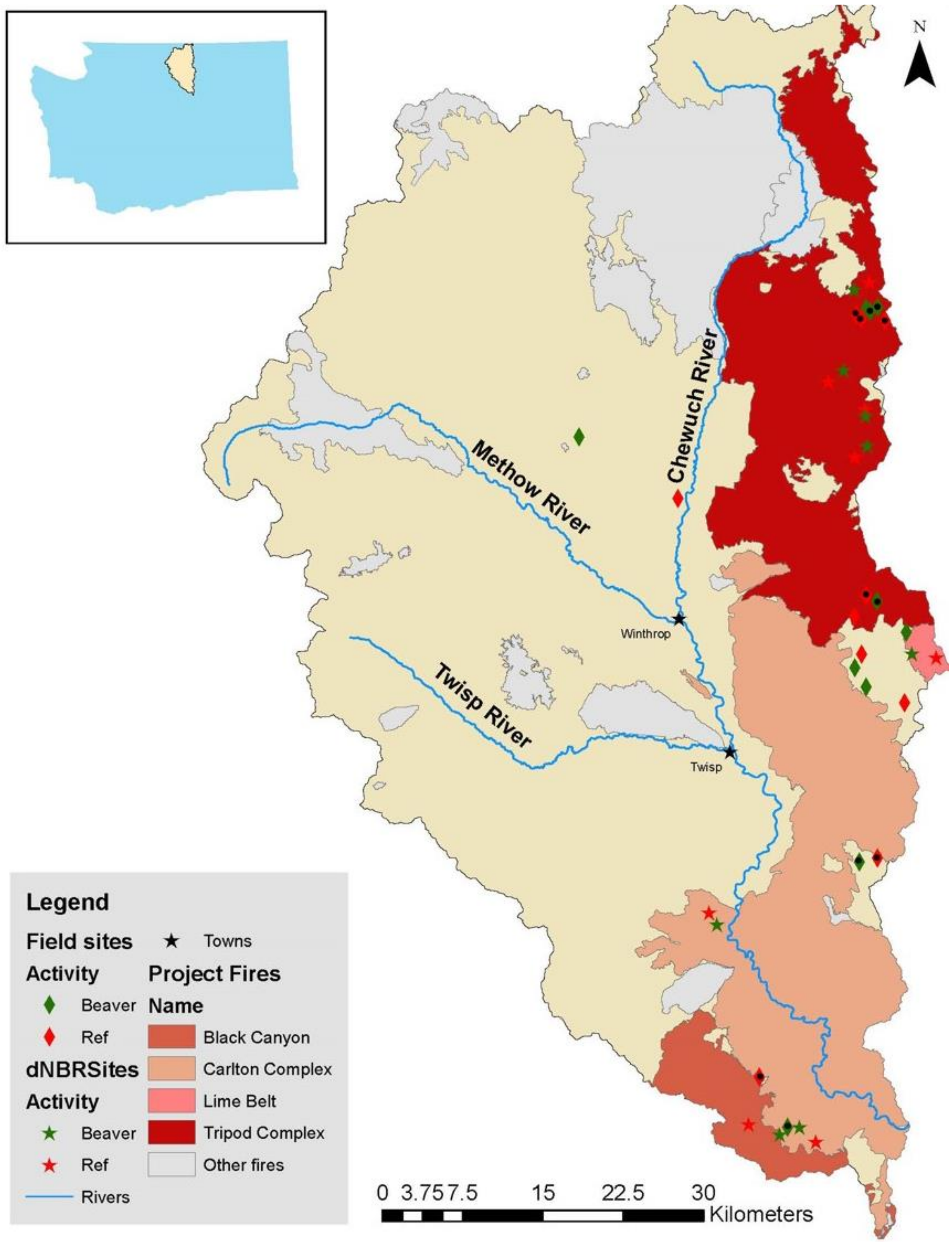


Figure 5. Map of fires and beaver/reference locations utilized in GIS analysis of dNBR and field surveys throughout the Methow Watershed. Field sites with black dots indicate presence in both GIS and field analyses.

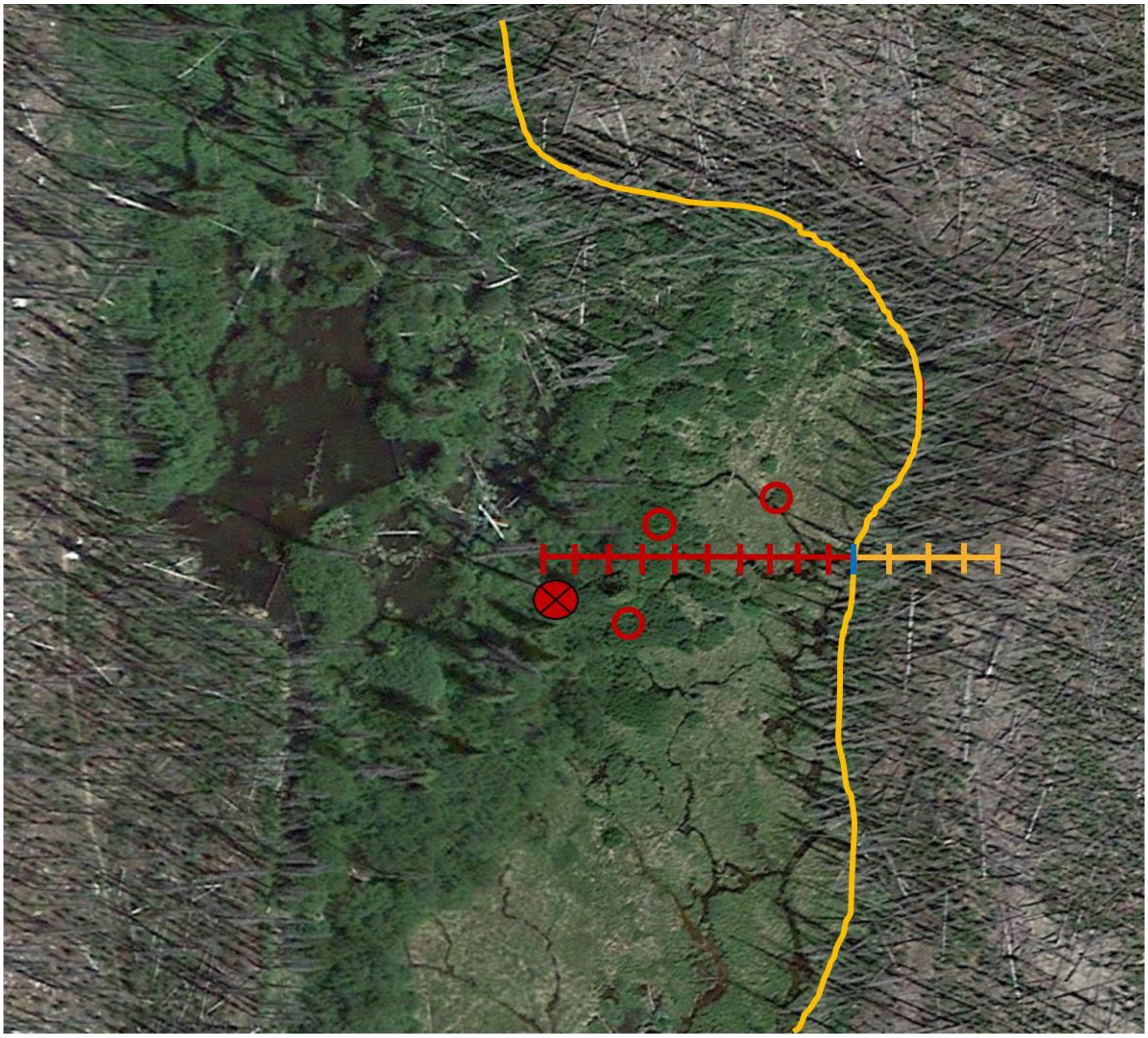
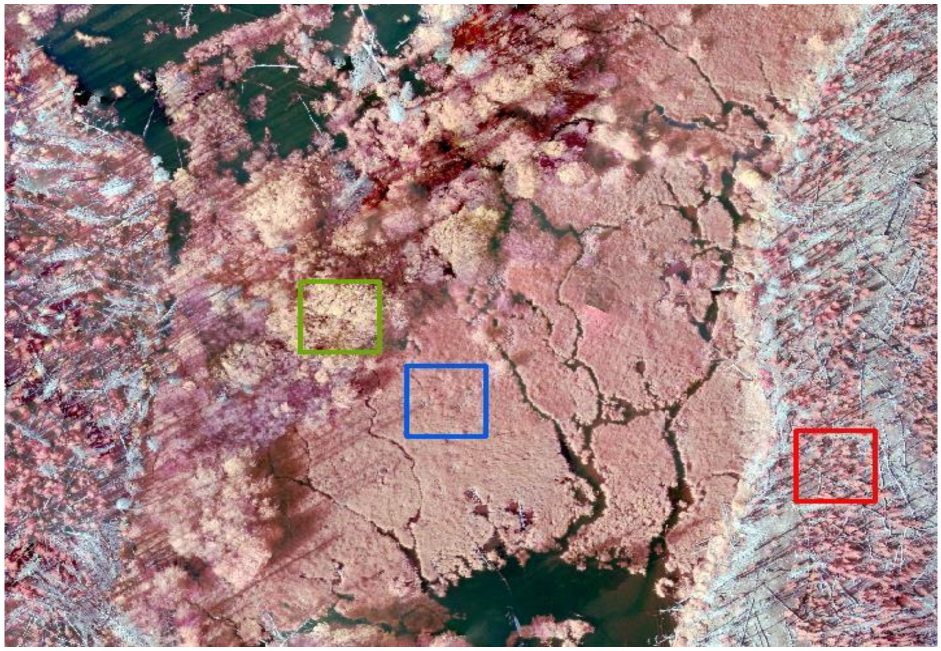


Figure 6. Aerial photo of Lightning Creek beaver complex, middle transect. Red line indicates the location of the riparian soil moisture transect; yellow portion indicates upland zone. Red, blue, and yellow hash marks represent riparian (R1-R10), transition (R11) and upland (U1-U4) soil moisture sample points, respectively. Hollow red circles represent live fuel moisture sample locations, filled circle indicates 10 – hour fuel stick location.

A



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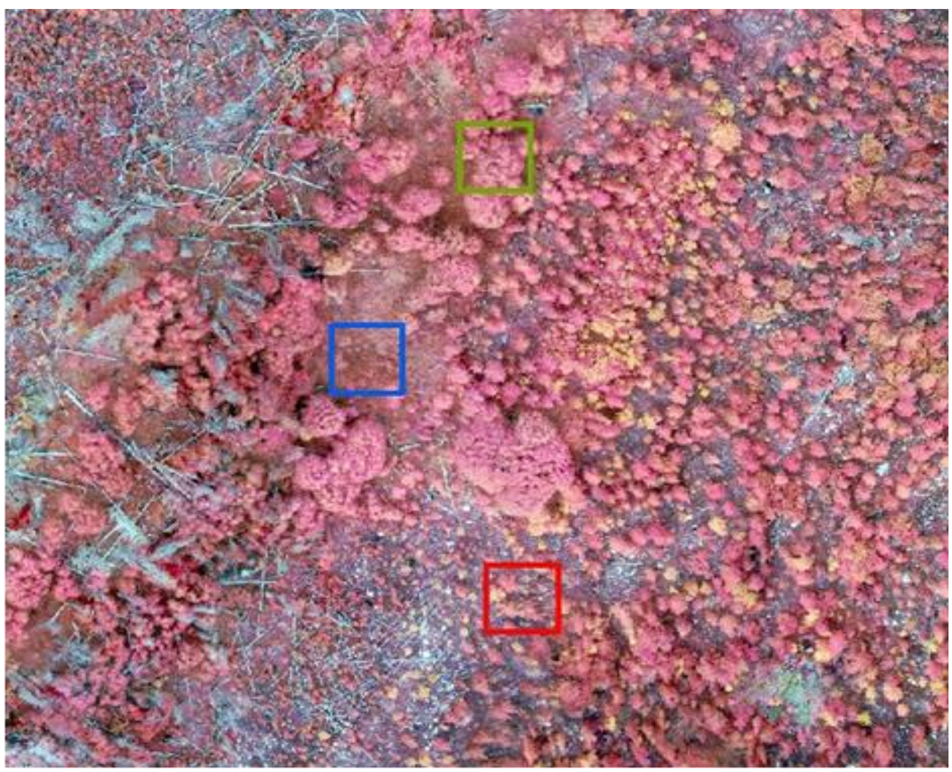
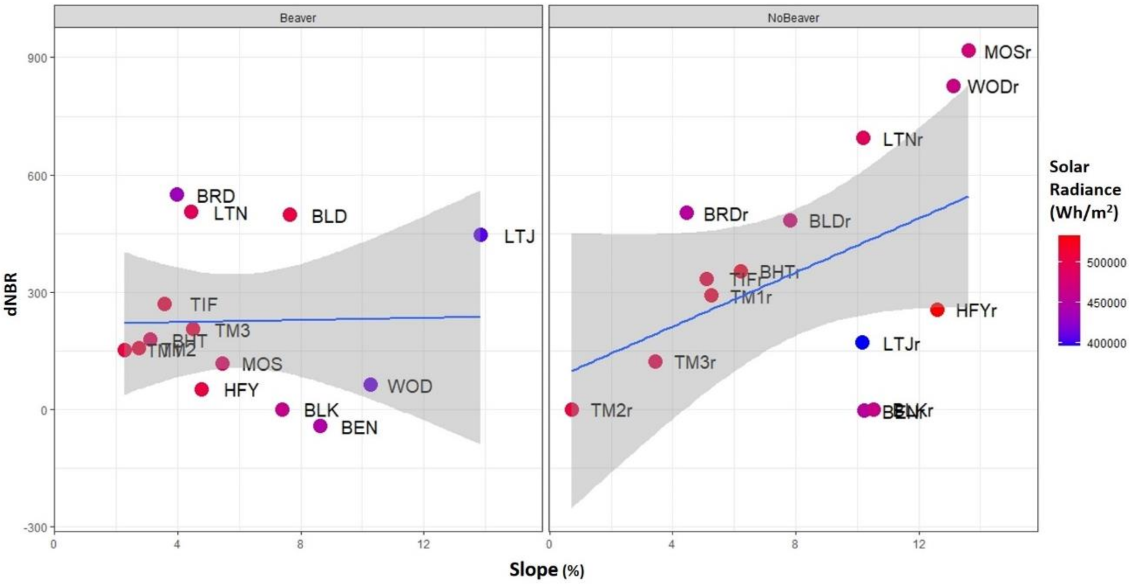


Figure 7. Near infrared aerial image of Lightning Creek (a) and reference site (b) captured via drone (9/25/19). Red, blue, and green boxes indicate NDVI analysis zones of upland conifers, and riparian grasses and shrubs. Boxes are 165 m^2

A



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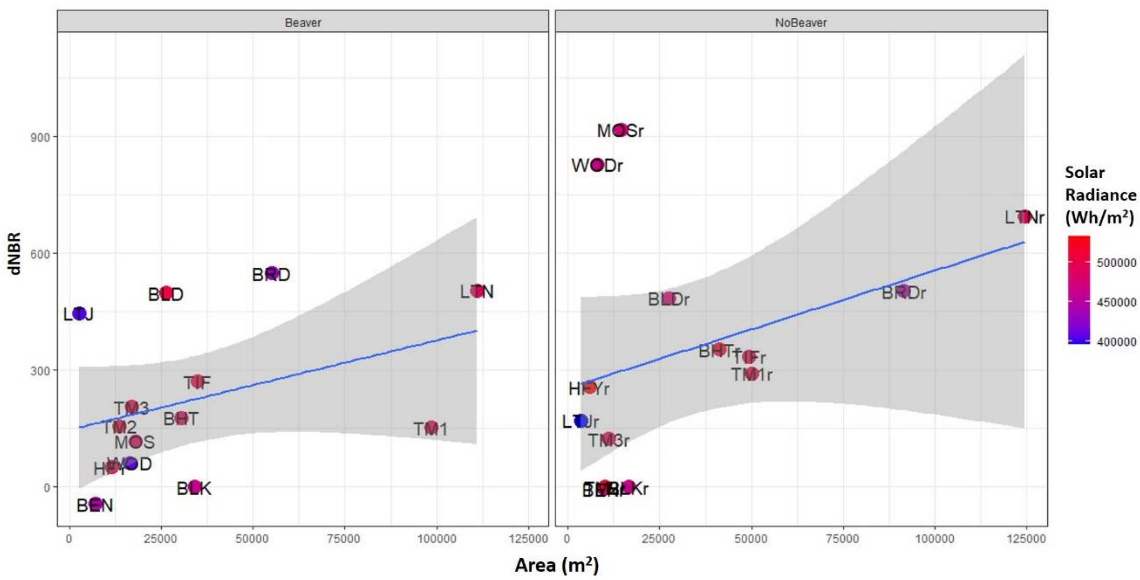

Figure 8a. Interacting effects of beaver dam presence, average slope, average solar radiance, on predicted values of dNBR in valley bottoms. 8b. Interacting effects of beaver dam presence, total area, and average solar radiance, on predicted values of dNBR in valley bottoms.

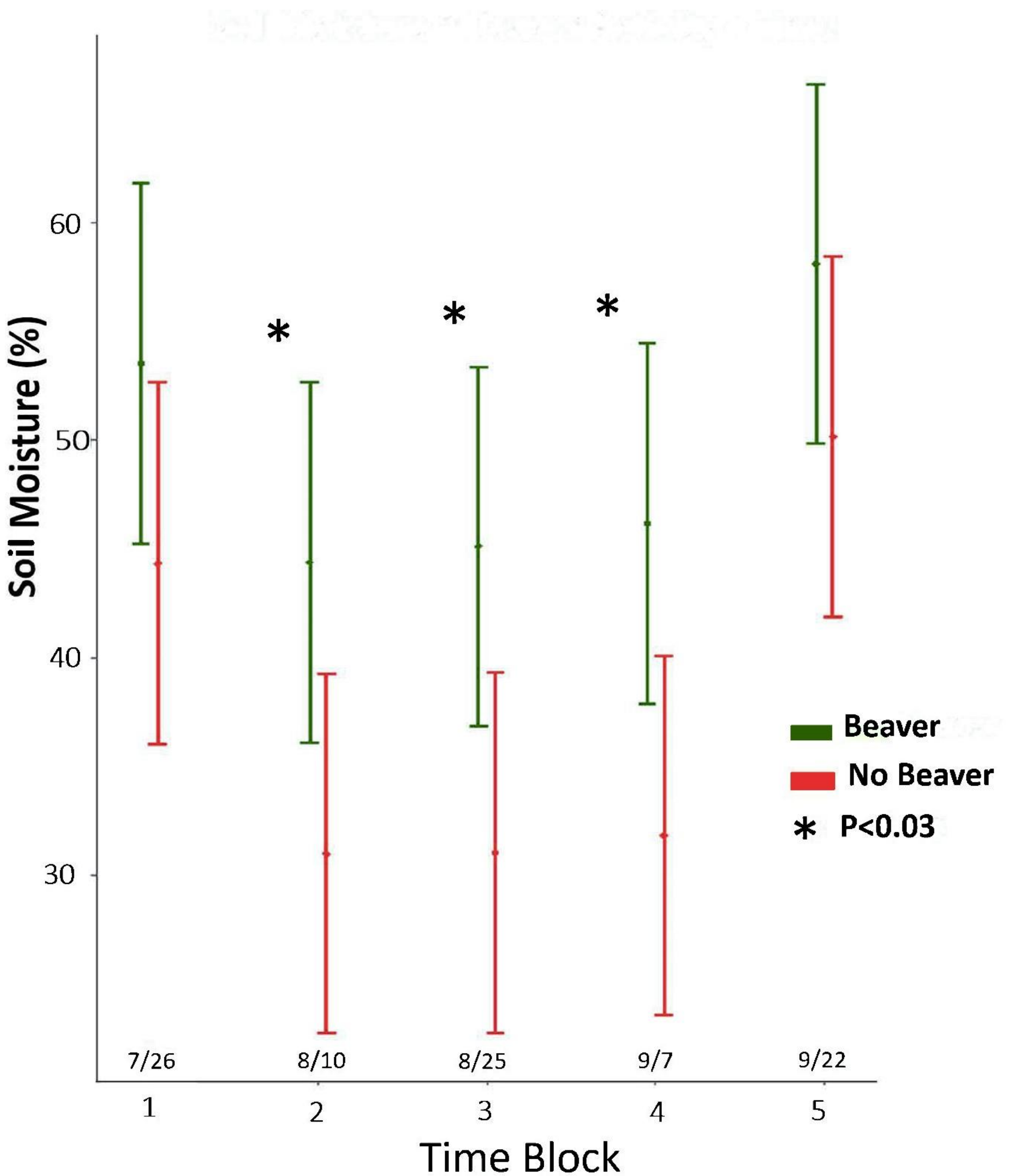

Figure 9. Average soil moisture between beaver impounded and non-impounded sites throughout the fire season. Each time block represents a 2-week sample period (date indicates median of sample period). Fire restrictions were implemented in the Methow Valley on 6/24 and removed on 9/12.

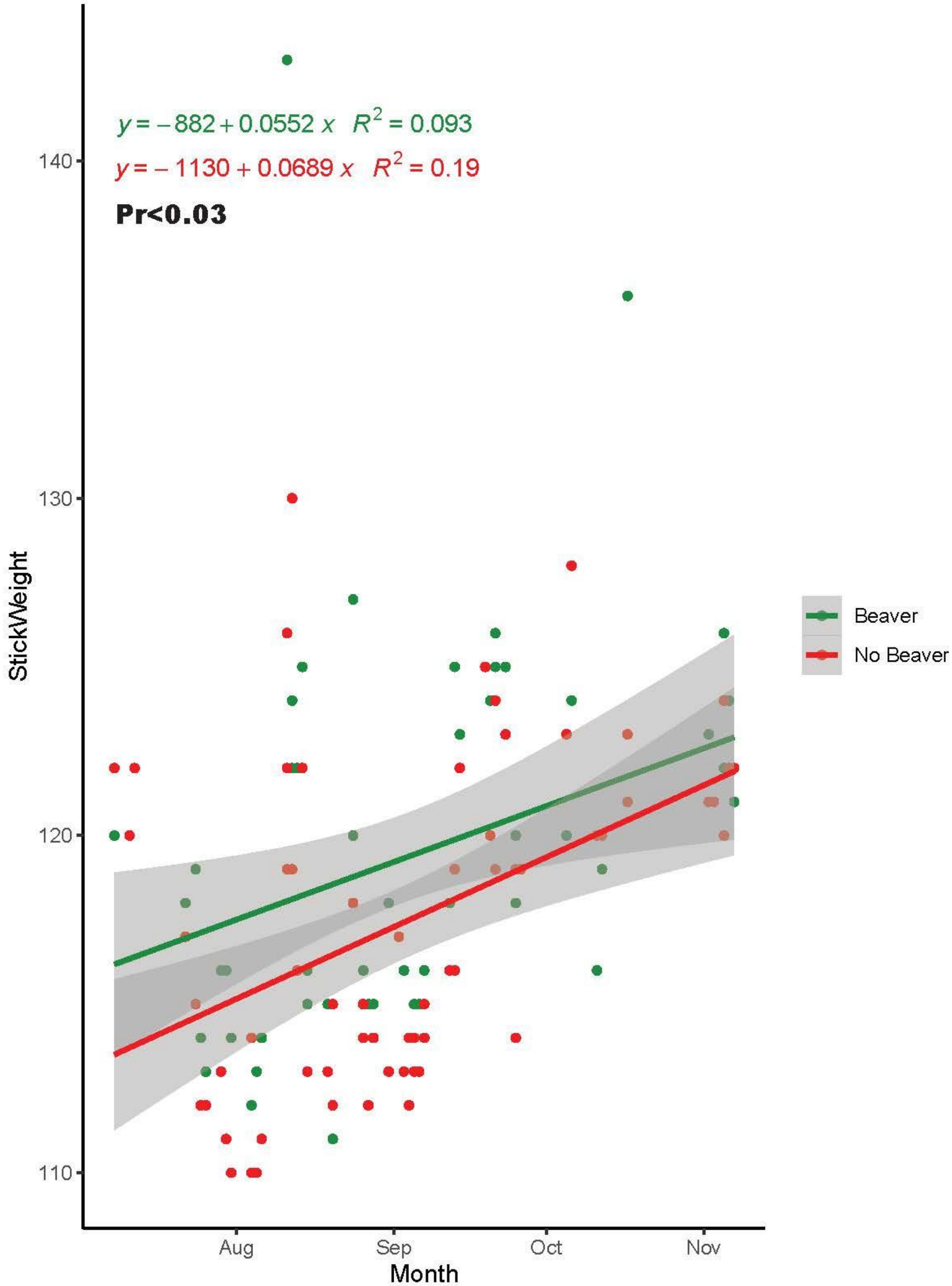

Figure 10. Linear model of 10 – hour fuel moisture stick weights in beaver impounded vs. non-beaver impounded riparian areas. Fuel sticks weigh 100 g when oven dry, thus every gram of water absorbed by the fuel stick corresponds to 1% of increased moisture. Large spikes of fuel moisture in August and September correspond with unseasonably high precipitation events (8/14 & 9/18).

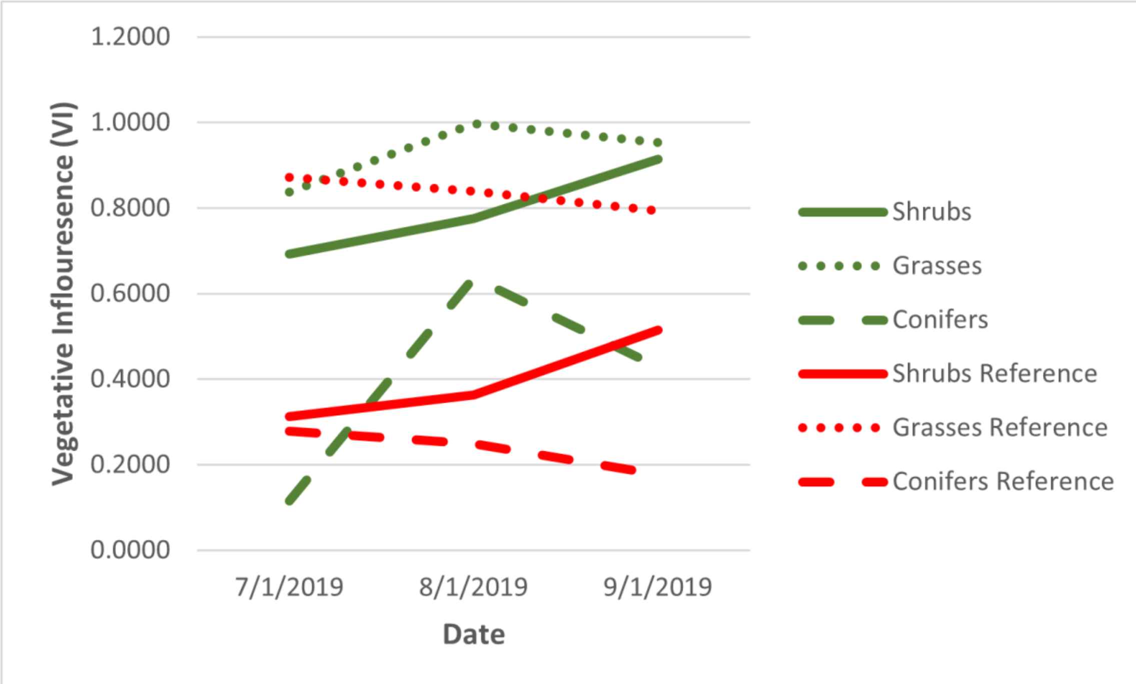

Figure 11. Comparison of vegetative inflorescence of varying vegetation types in beaver impounded and non-impounded riparian zones at Lightning Creek and reference site.

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VITA

Author: Joseph J. Weirich III
Place of Birth: Milwaukee, WI

Education

- Master of Science – Candidate, Biology: Ecology | Eastern Washington University (EWU) |
  Cheney, WA
- Graduate Certificate – Geographic Information Systems | Eastern Washington University (EWU) | Cheney, WA

- Bachelor of Science - Ecology and Environmental Biology -University of Wisconsin Eau Claire – Eau Claire, WI | May 2013

Work Experience

- Graduate Teaching Assistant | EWU – College of STEM – Biology Department, Cheney WA | Sept. 2018 – June 2020
  - Collaborated with professors weekly to implement lab exercises, develop assessment rubrics, evaluate, and grade student work .
  -
- Wildland Fire Fighter, Engine Crew - United States Bureau of Land Management, Vale, OR. 4/18-9/18.
  - Responded to wildland and prescribed fires throughout the Vale District.
  - Operated and maintained multiple power and hand tools (water pumps, chain saws, shovels, picks, etc.)

- Range Technician - Conservation & Land Management Program - Chicago Botanic Garden & Bureau of Land Management, Baker City, OR. 4/17 – 11/17.
  - Conducted long-term upland vegetation surveys of grasses, forbs, shrubs and utilization of upland grass communities following rotational livestock grazing.
  - Collected fuel moisture samples for the regional fire reports.
  - Implemented range improvement projects including cattle fence construction, bird ladders and endangered plant seeding.
  - Assisted regional wildlife biologists in sage grouse lek counts and PIT tagging Oregon spotted frogs.
- Hydrology/Riparian Survey Technician - Conservation & Land Management Program Chicago Botanic Garden & Bureau of Land Management, Baker City, OR. 4/16 - 4/17.
  - Conducted recurrent water quality sampling on over 25 streams across north east Oregon. Surveys included flow rate, temperature, pH, LDO%, conductivity, turbidity, alkalinity, bacteria count (fecal coliform /E. coli), and heavy metals.

  - Conducted long and short-term surveys of riparian condition using Multiple Indicator Monitoring protocol.
  - Drafted inter-agency report summarizing the current status of riparian habitat, risk factors and management recommendations for the Pritchard Creek grazing allotment, Durkee, OR.
  - Conducted fish salvage of threatened Lahontan trout (*Oncorhynchus clarkii henshawi*) on Little Whitehorse Creek, OR, during road construction.

Research Experience

Eastern Washington University

- Beaver Moderated Fire Resilience in the North Cascades and Potential for Climate Change Adaptation.
  - Studyied the potential interaction of beaver impounded wetlands and reduced burn severity by comparing soil and fuel moisture, infrared aerial imagery and GIS analysis of historic burn events in areas with and without beaver.
  - Led a field crew of undergraduate staff and public volunteers throughout the summer.

Chicago Botanic Garden & the Bureau of Land Management

- Dark Canyon Stream Response to the Windy-Ridge Complex Fire, 2015. (Spring 2016)
  - Explored the relationships between fire disturbance and riparian condition.
  - Compiled GIS, hydrologic, and historic land use data in order to predict how channel morphology will change post fire disturbance.
  - Recommended actions to restore stream sinuosity and bank stability to prevent future failure.
  - Presented findings at the Annual Water Quality Conference in Boise ID, hosted by Idaho DEQ.

University of Wisconsin – Milwaukee

- Wisconsin sport fish toxicology: algal toxin accumulation in Lake Winnebago. (Summer 2015)
  - Investigated the bioaccumulation of cyanotoxins within muscle, liver, intestine, and stomach of northern pike, walleye, crappie and perch.
  - Developed a protocol to prepare tissue samples for liquid chromatography-mass spectrometry analysis.

University of Wisconsin - Eau Claire

- Using nonfiction scientific literature for conservation biology education: The Tigerland Effect. (Summer 2015)

- Evaluated student responses (2009 – 2011) to reading *Tigerland and Other Unintended Destinations* by Eric Dinerstein.
- Study objective was to gain a better understanding of the conservation literacy of UWEC students and evaluate the effectiveness of *Tigerland* as a non-fiction teaching aid.
- We found that Tigerland reinforced conservation principles learned in class, increased vocabulary, and bolstered student engagement in class discussion.
- Findings published in the journal of *Applied Environmental Education & Communication.*

- The Monk's Community Forest: biodiversity and ethnobotany in a Cambodian REDD+ Project, Oddar Meanchey Province, Cambodia. (Summer 2013)
  - Collaborated with three UWEC students and faculty mentor in successful grant application to Asia Network and the Freeman Foundation for $26,000.
  - Funds supported 6-week expedition to northern Cambodia to catalogue rare and endangered mammals and birds.
  - Camped for 6 weeks in remote rainforest, conducting avian point counts, monitoring camera traps and canopy audio recordings.
  - Distributed a species manifest to community forest managers and organizations interested in preserving global forest resources (e.g. REDD+, PACT Cambodia).

- Floral Resource Availability on Native vs. Reconstructed Prairie for the Federally Endangered Karner Blue Butterfly (*Lycaeides melissa samuelis*). (Summer 2013)
  - Assessed the seasonal availability of forbs in native and reconstructed prairies in the Karner Blue State Acres for Wildlife Enhancement (SAFE) Conservation Program, Eau Claire County, WI.
  - Surveyed transects at sites searching for native/non-native forbs serving as possible nectar sources for the Karner Blue Butterfly.

- Datazone Biodiversity Project: Research Dissemination and Science Outreach in the Galapagos Islands. (Summer 2012)
  - Maintained herbarium specimens, photographed and catalogued additions to the Charles Darwin Research Station online collection, Santa Cruz Island, Galapagos.

- Recruitment, Retention, and Advancement of Female STEM Students at the University of Wisconsin-Eau Claire. (Spring 2012)
  - Surveyed the female STEM population at UWEC on available resources and their preparations graduate education.
  - Study identified lack of female mentorship and post baccalaureate prospects in fields engineering and chemistry.

- Stochastic vs. Niche-Based Processes: What Drives Lichen Community Assembly following Fire Disturbance? (Fall 2012)

  - Developed a proposal to study lichen community composition following forest fires in the Boundary Waters Canoe Area Wilderness, MN (BWCA).
  - Surveyed burned and unburned areas recording species composition as well as abiotic variables e.g. canopy cover, soil compaction, dominant vegetation.
  - Presented research at Ecological Society of America annual conference in Portland, OR. (2012)

- Stream-Riparian Linkages: Searching for Patterns in Invertebrate Community Structure. (Fall 2011)
  - Examined emergent and terrestrial invertebrates and establish trends in their abundance as well as predator concentrations throughout the riparian zone of Beaver Creek, a sandy-bottomed Wisconsin stream.
  - Sorted invertebrate samples and identify specific taxonomic groups.

- Assemblage of Lichen Communities on Rocky Shorelines of the North Woods. (Fall 2010)
  - Developed research project to study lichen community assembly on rocky shorelines in the Boundary Waters Canoe Area Wilderness.
  - Spent one week in the Boundary Waters, traveling solely by canoe, collecting lichen species and abiotic data.
  - Presented research poster at student research day and ESA Annual Conference in Austin, TX (2011).

Publications

Kleintjes Neff, P., Weiss, N.M., Middlesworth, L., Weirich, J., Beilke, E., Lee, J., Rohlinger, S. and Pletzer, J., 2017. Using nonfiction scientific literature for conservation biology education: The Tigerland effect. Applied Environmental Education & Communication, 16(2), pp.71-83.

Teaching/ Leadership Experience:

- Graduate Teaching Assistant – Eastern Washington University (Fall 2018-Spring 2020)
  - Instructed undergraduate labs for the introductory “core” biology courses as primary income during graduate school.

- Undergraduate Student Academic Apprentice – UW-Eau Claire (Spring 2013)
  - Assisted faculty mentor in instructing an upper level conservation field course.
  - Helped select course projects, designed and set up lab activities, drove students during off campus field trips, and assisted in instructing course topics.

- Undergraduate Student Academic Apprentice – UW-Eau Claire (Fall 2012)

- Assisted faculty mentor in leading 14 students of varying wilderness experience through the BWCA during a collaborative research course.
- Maintained expedition safety, survey, camping and canoe equipment, as well as clean campsite throughout the expedition.

Skills/Certifications/trainings:

- ArcGIS training
- First Aid and CPR
- 4-wheel drive vehicle training
- ATV & UTV certified