RIPARIAN RESILIENCE IN THE FACE OF INTERACTING DISTURBANCES:

UNDERSTANDING COMPLEX INTERACTIONS BETWEEN WILDFIRE, EROSION, AND BEAVER (*Castor canadensis*) IN GRAZED DRYLAND RIPARIAN SYSTEMS OF LOW ORDER STREAMS IN NORTH CENTRAL WASHINGTON STATE, USA

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Alexa Whipple

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THESIS OF ALEXA WHIPPLE APPROVED BY

_______________________________ Date:______________

Dr. Rebecca Brown PhD, Chair Graduate Study Committee

_______________________________ Date:______________

Dr. Margaret O’Connell, Graduate Study Committee

_______________________________ Date:______________

Dr. Lauren Stachowiak, Graduate Study Committee

_______________________________ Date:______________

Dr. Sue Niezgoda, Graduate Study Committee

ABSTRACT

Riparian systems of low order streams in the western United States (US) provide critical ecosystem functions and services such as diverse habitat for numerous species, flood attenuation and essential water storage in water limited environments. These systems have experienced long term disturbance from anthropogenic activities including mining, timber harvest, livestock grazing and near extirpation of a keystone riparian species, *Castor canadensis* (North American beaver). However, increasing frequency of large-scale wildfires and climate change driven weather is altering the severity and scale of riparian disturbance, often shifting highly impacted streams to a stable degraded state, unable to store water or provide other once inherent ecosystem functions. Beaver restoration has been gaining traction as a way to address long term riparian degradation, yet little has been documented regarding the impact of restored beaver activity on recently burned riparian systems, especially those in a stable degraded state. To address this, my study documented the interactions between largescale wildfire impact, subsequent erosion events and dam building beaver populations in riparian systems of the Methow River watershed, north central Washington (WA), US. I tested the hypothesis that beaver increase the resiliency of streams to wildfire using a fully factorial study comparing stream side riparian vegetation, stream channel morphology, and chemistry of stream reaches across burned vs. not burned sites with and without hydrologically significant beaver dams. My study was conducted June through November of 2018 in sub-basins of the Methow River watershed. I found reduced stream nutrient transport and pH, increased stream channel and floodplain connectivity, increased vegetation diversity in floodplain landforms, and reduced non-native species in burned riparian systems with beaver, which suggest that beaver can effectively increase wildfire resilience in streams.

By studying the interacting variables of fire, stream channel erosion, water chemistry, riparian vegetation and beaver activity in degraded stream systems, more effective and holistic approaches to adaptive ecological and economic management will emerge, particularly in the face of increasing riparian disturbance from large scale wildfire.

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PREFACE

This thesis has been written in two chapters: the first provides background for my research and reviews the published literature regarding the effects of interacting disturbances in riparian ecosystems. The second chapter is written as a manuscript to be submitted for peer review, which reports the results from my thesis research project assessing the interacting effects of wildfire, stream channel erosion, and beaver restoration on riparian ecosystem conditions.

I chose to pursue this research subject after witnessing the degradation of low order streams and their riparian systems after large scale, severe wildfires occurred in 2014 very near my home and in my beloved Methow River watershed. Upon pursuing more information from local land managers on broad scale restoration of severely incised channels after fire, the only answer given was time. Considering the anthropogenic impacts on our local and global landscape in addition to the increasing uncertainty of climate change, I did not feel that time was the best solution for recovery of ecological function, biodiversity, and resiliency in these highly impacted and highly critical riparian systems. Running through the burned landscape just months after the 2014 fires were quelled by cool Autumn temperatures and precipitation, I happened across a beaver pond in an area burned in a patchwork by the recent fires yet already supporting a new colony of beavers. I later learned that these were “nuisance” beavers relocated to public lands from private agricultural land by the Methow Beaver Project. Over the next two years, the burned but beaver occupied riparian landscape was transformed into a native plant and avian refugia, in better condition than prior to the fires. Witnessing this transformation inspired the following research.

CHAPTER ONE

RIPARIAN RESILIENCE IN THE FACE OF INTERACTING DISTURBANCES

INTRODUCTION

Riparian environments are under ever increasing pressure to deliver goods and services to an exponentially growing human population. However, anthropogenic disturbances have dramatically altered and simplified these interfaces between aquatic and terrestrial systems, drastically diminishing ecological function. Historic accounts document the physical challenge of exploring watersheds of western North America and their labyrinthian channels (Sadosky 2009) inferring significant complexity and likely resiliency to disturbance. In modern times, most river and stream channels are highly simplified and controlled for human advancement, leaving the majority of the world's freshwater streams and rivers highly impacted by humans (Knopf et al. 1988, Patten 1998, Wohl 2010, Poff et al. 2011). More than 80% of those impacted are considered to have degraded or destroyed ecological function, diversity and productivity (Naiman et al. 1995). If we are to restore ecological function and biodiversity to freshwater streams and their interdependent riparian systems, appropriate, affordable, and process-based tools must be rapidly developed and applied.

As dynamic areas of transition, riparian systems in the western United States (US) support disproportionately diverse biological communities while representing less than 2% of western US landmass (Svejcar 1997). In water-limited environments, riparia increase water storage, moderate flood and drought conditions, improve water quality, reduce erosion, and moderate water temperature (Naiman et al 1993, Poff et al. 2011). Functioning riparian systems are considered crucial for maintaining biodiversity and mitigating climate change impacts in the western US (Naiman et al. 1993, Capon et al. 2013). Predictive climate models describe generally warmer temperatures, reduced winter snowpack and longer dry seasons in regions dependent on extended snowmelt for recharging water systems (Figure 1.1; Littell et al. 2009, Polley et al. 2013). These conditions could potentially be mitigated by the restoration and conservation of high functioning riparian systems able to store water falling on the landscape as rain or snow (Poff et al. 2011).

Functioning riparian ecosystems are particularly important for salmonids, which like many native freshwater organisms, are threatened by loss of habitat and climate change in the western US as human priorities continue to reduce favorable stream habitat and tolerant conditions for cold water dependent species (Littell et al 2009). Climate models in Washington State (WA) predict striking decreases in cold stream habitat availability (Figure 1.2) and anthropogenic obstacles such as dams, culverts and warm, lentic reservoirs may prevent salmonids from reaching what favorable habitat remains (Littell et al. 2009).

One potential tool for landscape scale riparian restoration could be the reintroduction of North American beavers (*Castor canadensis*). As a keystone species in riparian systems, beavers create dynamic chains of water impoundments or ponding that alter many riparian characteristics key to biodiversity and ecosystem function (Naiman et al. 1988, Rosell et al. 2005, Gibson et al. 2014, Hood & Larson 2015, Law et al. 2016, Wegener et al. 2017, Wohl et al. 2017). These complexes increase water storage and habitat complexity, in turn, supporting high floral and faunal biodiversity, which increases response diversity and resiliency in an inherently changing ecosystem (Brown et al. 1996, Lake 2000, McKinstry et al. 2001, Pollock et al. 2004, Cunningham et al. 2006, Hood and Bayley 2008, Oliver et al.

2015, Law et al. 2016). Beaver dam complexes also provide habitat for endangered salmonids that have evolved with beavers, creating productive and protected smolt rearing environments as well as refugia in late season and/or low water conditions (Naiman et al. 1988, Pollock et al 2003, Pollock et al 2004, Rosell et al. 2005, Gibson et al. 2014, Bouwes et al. 2016).

Riparian habitat heterogeneity supports exceptional biodiversity and is dependent on periodic flooding disturbance driven by physical processes (Naiman et al. 1993, Poff et al. 1997, Montgomery and Buffington 1997, Wohl 2013, Wheaton et al. 2019). Geomorphology, climate and hydrology contribute to flood regimes causing alternating erosion and aggradation of sediment in stream channels (Junk et al. 1989, Montgomery and Buffington 1997, Wohl 2013). Riparian biota such as soil microorganisms, plants, macroinvertebrates and vertebrates then capitalize on the resulting dynamic physical environment with numerous niches and periodically replenished resources (Knopf et al. 1988, Naiman et al. 1997, Poff et al. 2011).

In the dry western US, diverse organisms evolved to occupy riparian zones, many of which are obligate riparian species for all or part of their life cycle. These species generally depend on periodic flood disturbance or are resilient to it (Gregory et al. 1991, Naiman et al. 1993, Kelsey and West 1998, Capon et al. 2013). However, long and sustained anthropogenic disturbance pressure may be more than riparian communities can continually function with or recover from (Poff et al. 2011, Oliver et al. 2015).

During the last 200 years, riparian systems have increasingly been impacted by human activities including mining, grazing, timber harvest, water withdrawal, damming for energy and flood control, beaver trapping, agriculture, recreation, and now climate change

(Naiman et al. 1995, Patten et al. 1998, Magilligan & Nislow 2005, Brown & Chenoweth 2008, Poff et al. 2011, Beschta et al. 2013, Goldfarb 2018). More recently, large scale "megafires" greater than 100,000 acres have been increasing disturbance to riparian systems of the western US (McKenzie et al. 2004, Hessburg et al. 2005, Dennison et al. 2014, Odion et al. 2014, Weber et al. 2017). Through widespread losses of vegetation, habitat, biodiversity and water storage, these large, high severity fires are causing accelerated stream bank destabilization and increasingly severe erosion resulting from post-fire precipitation induced debris flows (Moody & Martin 2009, Cannon et al. 2010, O'Connor et al. 2014, Bladon et al. 2014, Tippet et al. 2015, Leonard et al. 2017, Sherson et al. 2017). Despite the importance of riparian ecosystems, anthropogenic and natural disturbance interactions and their compounding impact on riparian system resilience is not well understood. Greater knowledge regarding multiple disturbance interactions in riparian systems is necessary for effective management and restoration of riparian ecosystems to maintain function, biodiversity and ecosystem resilience, particularly in water-limited environments (Naiman and DeCamps 1993, Poff et al 2011).

My study documents the interactions of historical beaver extirpation and current restoration, increased high severity wildfire, extreme erosion influenced by fire and climate change, and their combined impact on grazed riparian systems in the Methow River watershed, northcentral Washington State. This research is intended to be applicable on a macroscale to most of the arid western United States with similar geomorphology, climate, biodiversity and anthropogenic history throughout the dryland portion of the region. The following background provides context and greater detail for the research described in Chapter 2.

BACKGROUND

Disturbance in Riparian Systems

Disturbance can be defined as a rapid change in environmental conditions that alters an ecosystem's biomass, structure and potentially function (Odum 1971, Connell & Sousa 1983, Huston 2014). The physical and ecological role of disturbance in riparian systems is complex. The natural disturbance to which species are adapted is necessary for maintaining high biodiversity and function (Junk et al 1989, Naiman et al. 1993, Poff et al. 1997). However, determining whether disturbance is beneficial or degrading is often contextual, and for humans, value and priority based. Scientifically, disturbance can be gauged in terms of magnitude, response time, as well as the resilience threshold beyond which, a system can no longer return to its previous state (Connell & Sousa 1983, Beechie et al. 2008, Cluer & Thorne 2014, Oliver et al. 2015b). Disturbance has short-term ecological effects, but severe, large or prolonged disturbance can have evolutionary scale impacts, dismantling inherent riparian resilience and causing shifts to alternate functions and/or communities (Poff 1992, Beechie et al. 2008, Cluer & Thorne 2014, Oliver et al. 2015b).

Varying types of disturbance impact riparian systems including natural and anthropogenic. Typical natural disturbances that shape and define riparian systems include seasonal flooding, mass wasting, drought, herbivory and wildfire (Naiman et al. 1995, Wohl 2017). Anthropogenic disturbance typical of western riparian systems include the impact of dams for power generation, water abstraction and flood control, livestock grazing, beaver trapping and removal, timber harvest, invasive species, fire suppression, mineral mining, industrial, commercial and residential development, pollutants, recreation and climate change (Knopf et al. 1988, Jacobs et al. 1999, Dwire & Kauffman 2003, Brown & Chenoweth 2008, Pess et al. 2008, Suding 2011, Beechie et al. 2012, Gonzalez et al. 2015, Timpagne et al. 2017, Wohl 2017). Each of these disturbances has been individually studied or described in detail but there is comparatively little research on multiple interacting disturbances (Poff et al. 2011). To understand and better manage the complexity that exists in our diverse ecosystems, we need to understand these multifaceted ecosystem drivers.

Impacts of Fire

Fire is an essential part of western US landscapes and their ecosystems, which coevolved with periodic wildfire (Dwire & Kauffman 2003, O'Connor et al. 2014, Odion et al. 2014). Many plants depend on fire to complete their life cycle and many organisms benefit from the complex mosaic of diverse habitat left on the landscape typical of historic fire patterns. Historically, fire tended to be frequent and of low intensity (Dwire & Kauffman 2003, Noss et al. 2006, Steel et al. 2015). However, in the last several decades, wildfires burning >100,000 acres in the western US have been occurring more frequently (Figure 1.4; Newcomer et al. 2009, Dennison et al. 2014, Barbero et al. 2015, Scasta et al. 2016, NIFC 2018, Weber et al. 2018). These events are driven by more than a century of systematic fire suppression, widespread ecosystem disturbance from resource extraction and anthropogenic related changes in Earth's climate (McKenzie et al. 2004, O'Connor et al. 2014, Steel et al. 2015).

Since the late 1800's, fire suppression has been an institutional priority of the United States Forest Service (USFS) and other agencies tasked with managing natural resources (Calkin et al. 2005, Bladon et al. 2014, Odion et al. 2014, Steel et al. 2015). Long-term manipulation of wildfire events that western ecosystems evolved with has changed dominant forest conditions (Steel et al. 2015) in the western US and Canada. Now it is common to see mature trees, with a dense understory of saplings, competing for light (Figure 1.5; Noss et al. 2006, Bladon et al. 2014). In many systems, natural cycles of frequent ground fires historically maintained an open forest understory, killing sensitive young conifers but sparing mature conifers adapted to fire. Current crowded understory conditions create ladder fuels and increase forest vulnerability to stand replacing crown fires, but also to disease, insect damage and mortality compounding forest fuel loading (Noss et al. 2006, Steel et al. 2015). Biodiversity is impacted when young tree saplings crowd and shadow the forest floor and canopy openings, fruit and/or seed producing grasses, forbs and shrubs are less able to compete for resources (Dwire & Kauffman 2003, Noss et al. 2006). In fire evolved ecosystems, fire suppression can reduce biodiversity, ecological function, resistance to disease, pests, and catastrophic wildfire, and potentially resilience to climate changes (Dwire & Kauffman 2003, Steel et al. 2015).

Climate change has brought increasingly warmer temperatures across the west and often reduced precipitation, creating longer cycles of severe drought and more vulnerable fire conditions (Guyette et al. 2014, Scasta et al. 2016). Warmer temperatures increase evaporation from terrestrial and aquatic environments as well as increase evapotranspiration from vegetation, increasing vulnerability to fire (Barbero et al. 2015, Fairfax & Small 2018). Some destructive forest insect species also benefit from warmer temperatures increasing their range and reproductive opportunities, causing increased densities of standing dead trees that are vulnerable (O’Connor et al. 2014).

Warmer air masses, regionally and seasonally indicative of climate change, have also increased convective instability in the atmosphere (Prein et al 2016). This instability increases storm energy in arid regions, causing increased lightning strikes, erosive downbursts of rain and often extremely high winds, respectively increasing ignition events, eroding sensitive landscapes and fueling fires (Dale et al. 2001, Prein et al. 2016). The intense heat often generated by stand replacing fires greatly increases potential for soil sterilization, pyrolysis of organic matter and soil hydrophobicity leading to impermeable and highly erodible soils (Debano 1999). Broad removal of vegetation coupled with highly erodible soils and powerful convective storms has led to landscape scale erosion and severe stream channel incision in many fire impacted watersheds (Dale et al. 2001, Dwire & Kauffman 2003, Tuckett & Koetsier 2016, Leonard et al 2017). Such events can cause dramatic changes in biodiversity of aquatic and terrestrial organisms and recovery is often determined by the condition of the ecosystem prior to disturbance as well as management afterwards (Burton 2005, Dudgeon et al 2006, Johnson & Molesworth 2015, Perry et al. 2015, Tuckett & Koetsier 2016).

Coupled with climate induced fire conditions, suppression induced ladder fuels and degraded riparian conditions, high intensity, large scale crown fires are leading to dramatic changes in ecosystem functions and services (Tuckett & Koetsier 2016). Impacts of watershed altering fires and subsequent storm erosion events travel well beyond the stark fire boundaries into the communities that depend on functioning stream ecosystems (McKenzie et al. 2004, CWFR 2017).

Impacts of Grazing

Ranching and livestock grazing have a long and complex relationship with public land use, fire cycles and riparian impacts (Madany & West 1983, Beschta et al. 2013, Dalldorf et al. 2013, Hughes 2014, Swanson et al. 2015). Ranching is a cultural and economic driver in the western US, and more recently, intensely managed grazing has been promoted as a potentially beneficial tool for addressing invasive species control, grass fuel reduction, and resulting fire abatement (Svejcar 1997, Swanson et al. 2015). Many studies show that grazing impacts can be mitigated through management and even benefit the landscape as well as increase carbon sequestration (Swanson et al. 2015, Timpagne et al. 2017). However, grazing is better known for its negative effects on biodiversity than its benefits, particularly in critical riparian systems (Naiman et al. 1995, Patten 1998, Poff et al. 2011, Beschta et al. 2013, Hughes et al. 2014).

According to Naiman et al. (1993), greater than 80% of riparian systems in the US have disappeared or been degraded by development and overgrazing, yet their restoration is rarely prioritized (Naiman et al. 1995, Poff et al. 2011). Livestock grazing has been particularly disruptive in systems that did not evolve with large herbivore herd grazing pressure, like the shrub-steppe and mixed conifer forests of eastern Washington and Oregon (Mack & Thompson 1982). Riparian areas provide convenient water sources and late season forage for livestock in the arid to semi-arid western US, but often at unsustainable cost. Grazing has been the most studied disturbance impact on riparian areas over the last five decades, (Beschta et al. 2014) and research shows that grazing is the most pervasive disturbance in these essential ecosystems (Poff et al. 2011, Beschta et al. 2013). Nearly 200 years of continuous under-managed grazing by non-native herbivores in these late-season, dryland oases has dramatically altered the function, biodiversity and resilience of impacted riparian areas (Sayre 2005, Beschta et al. 2013, Hughes 2014, Small et al. 2016).

Under-management of grazing can result in stream channel incision from livestock accessing water and preferred riparian forage. Channel incision, coupled with consistent physical stress on riparian vegetation from herbivory and trampling, can dramatically reduce vegetation diversity, productivity and cover, wildlife diversity, water quality and riparian resilience (Beschta et al. 2014, Oliver et al. 2015, Middleton et al. 2017). Stream channel incision associated with long term livestock grazing across the dryland west is different in its evolution from wildfire and storm caused incision, but has generally been more widespread, causing greater disturbance and pervasive impacts (Beechie et al. 2012, Hughes 2014). Studies have repeatedly shown that free access livestock grazing in riparian systems diminishes species diversity, increases non-native species, increases sedimentation and erosion, compacts soil, and consistently has a greater impact on native ecosystems than fire (Madanay & West 1983, Jacobs et al. 1999, Dudgeon et al. 2006, Dwire et al. 2006, Dalldorf et al. 2013). Livestock grazing in riparian systems has also been shown to compete with and reduce beaver colonies (Small et al. 2016, Fesenmeyer et al. 2018). Herbivory competition for mutually preferred woody browse such as willow, degradation of water quality from livestock urine and feces, as well as livestock trampling of dam infrastructure and stream banks often drives beaver from the system (Small et al. 2016, Fesenmeyer et al. 2018).

In this new era of climate change and increased high severity/large scale fire, the impacts of livestock grazing on burned riparian systems is not well studied (Jones 2000, Beschta et al. 2004). Conservation focused land managers may prescribe extended rest periods absent of livestock for three to five years for burned grazing allotments on public lands (USFS 2018). This allows time for soil and vegetation to recover and potentially for beaver to colonize impacted riparian zones without competition from livestock herbivory. However, in many cases, there are no changes in grazing practices after fire on public lands, which can compound fire impacts. Trampling of burned, sterilized surface soil by livestock can limit vegetation regrowth and prevent subsurface post-fire fungal species from colonizing and knitting soils back together (Belsky & Blumenthal 1997, Davies et al. 2010). This fungal crust is critical for stabilizing highly erosive soils on severely burned landscapes. This suggests that post-wildfire grazing should be addressed conservatively for both recovery from and resistance to wildfire impacts.

Currently, post-fire livestock management varies tremendously, with many challenging ecological and economic factors. Alternative conservation strategies for managing livestock exist that can reduce grazing impacts to riparian systems before and after wildfire while bolstering the ranching economy and assuaging the social stigma of destructive cattle on public lands (CNW 2016, TMBA 2017). Strategies such as managing cattle with range riders using low stress livestock handling techniques, or grazing pastures using rest and rotation are not new, but can be effective (TMBA 2017). Combined with varying seasonal grazing, creating riparian exclosures or limiting access, and reducing riparian use with time and stocking rate, more sustainable management of rangelands is possible (Svejcar 1997, Swanson et al. 2015).

Conservation minded management with beaver is an approach that may even benefit livestock. Studies have shown that beaver elicit a positive feedback on vegetation productivity which improves their own food supply as well as that of other herbivores. Beaver also increase water availability in dryland landscapes (Donkor & Fryxell 1999, Wheaton et al. 2015).

Ecologically based livestock grazing management strategies must be increasingly evaluated and supported, both ecologically and economically, to address long-term ecosystem impacts and the need to adapt to a changing environment (WSE 2018). Degraded riparian ecosystems cannot regain full function or native communities without addressing widespread channel incision across grazed and burned watersheds that could take centuries or more to restore on their own (Cluer & Thorne 2014, Shakesby et al. 2016).

Impacts of Disturbance on Channel Morphology

Stream channel incision can be the result of river and riparian disturbances both natural and anthropogenic (Naiman et al. 1995, Wohl 2006, Beechie et al. 2008, Poff et al. 2011, Wohl 2013). Historical and modern anthropogenic resource use and extraction has reduced the complexity of stream channel through loss of vegetation, beaver and large woody debris removal, and often the physical straightening of channels to speed movement of water through the landscape (Naiman et al. 1995, Wohl 2006, Poff et al. 2017). Large scale disturbances like extreme wildfire, followed by heavy precipitation events, can cause rapid, watershed altering channel incision (Figure 1.6; Cannon et al 2010, Kendon et al. 2014, Johnson & Molesworth 2015, Leonard et al. 2016). These events can cause the widespread development of erosive small channels or soil runneling across burned uplands, coalescing into scouring of downstream channels (Leonard et al. 2017). Confined and incised trenches develop rapidly, replacing formerly more broad, elevated streams, and physically lower the stream channel and corresponding water table below the floodplain (Cluer & Thorne 2014). The newly lowered water table and confined stream ultimately reduce groundwater recharge and vegetation root zone wetting throughout impacted riparian zones (Cooke & Reeves 1976). This highly disturbed condition of deeply incised stream channels disconnected from adjacent floodplains reduces recovery and survivorship in terrestrial and aquatic biotic communities in burned areas (Bozek & Young 1994, Burton 2005, Beechie et al. 2008, Cluer & Thorne 2014, Polvi et al. 2014).

Once incised and disconnected from riparian floodplains, stream channels transport sediment and nutrients more rapidly and farther downstream, particularly when few natural impediments are present in the scoured channel to slow water sufficiently and allow deposition of suspended particles (Beechie et al. 2008, Leonard et al. 2017). The potential for nutrient transport increases significantly after wildfires due to the conversion of living organic matter into mineral rich ash. This ash is easily mobilized by precipitation along with sediment no longer held in place by rooted plants and layers of duff or organic matter litter once protecting sediment from transport before fire (Silins et al. 2014, Rust et al. 2018). Wherever stream flow does decrease enough to deposit suspended sediment particles, high nutrient concentrations from ash and sediment transport can influence primary production. Nitrogen and phosphorus are usually limiting nutrients in the environment and their reduced availability typically limits primary productivity. After wildfire, increased concentrations of these nutrients can lead to increased primary productivity in aquatic systems, or eutrophication (Figure 1.7). Eutrophication causes significant imbalances among organisms and communities within fire and often anthropogenic impacted systems, often leading to intolerable conditions for native aquatic organisms (Bladon et al. 2014). Increased temperature, altered stream chemistry, and reduced dissolved oxygen can create anoxic conditions, increasing the risk of mortality in oxygen sensitive organisms such as endangered salmonids (Bladon et al. 2014, Silins et al. 2014).

Incised channels can recover ecological function without human assistance, but depending on stream size and lithology, or disturbance severity and recurrence, recovery can take place on a logarithmic timescale over hundreds to thousands of years (Figure 1.8)

(Cluer & Thorne 2014, Pollock et al. 2014). Studies also describe some incised channels as being stuck in a stable degraded state. In this state, without elements of roughness added artificially to the channel, there is no large organic material available to start the channel widening process and degradation actually self-perpetuates (Beechie et al. 2008, Wohl 2013, Wohl et al. 2017). Under these circumstances, sediment starved watersheds may not erode or widen the stream, but may very slowly aggrade what little sediment is being transported in the channel in low gradient systems (Beechie et al. 2008, Wohl 2013).

According to Cluer and Thorne (2014), the first step in recovery from deep confining channel incision is the widening of the narrowly confined channel. Research has shown that incised stream channels benefit greatly from the presence of biogenic factors, such as woody debris, vegetation, and beaver activity or beaver dam analogues (BDA's), which hasten channel widening (Beechie et al. 2008, Pollock et al. 2012, Pollock et al. 2014, Wohl et al. 2017). Biogenic factors add complexity to incised channels and begin to reduce stream power with physical obstructions. The added roughness causes reduced stream power, stream flow deflection, bank erosion, and point bar deposition, synergistically driving the process of channel widening, aggradation and revegetation to rebuild anastomosing and ecologically resilient stream systems (Montgomery & Buffington 1997, Beechie et al. 2008, Wheaton et al. 2011, Levine & Mayer 2013, Cluer & Thorne 2014). Reintroducing several biogenic factors in series may be a feasible approach to repairing the severe channel scouring occurring after large wildfires followed by significant precipitation events. Process based restoration or PBR (Wheaton et al. 2019) combines the installation of wood-based structures of varying design in severely degraded streams with the intention that beaver will ultimately maintain the new structures and more importantly the improving stream condition. This low technology, easily scaled, ecosystem-based accelerated recovery method could apply to the restoration of acute channel scouring events as well as long term anthropogenic stream and riparian degradation.

Impacts of Beavers and their Dams

Beavers and their dams once provided important ecosystem services on a large scale, occupying a large majority of ponds, small streams, and side channels of larger rivers across the United States, Canada and northern Mexico (Naiman et al. 1988, Gibson & Olden 2014, Goldfarb 2018). However, beaver populations, estimated at 60-400 million prior to European and American exploitation, were largely extirpated from their expansive range by the late 1800's (Naiman et al. 1988, Fountain 2014). Harvesting beaver pelts was a highly profitable activity spurred by European fashion and geopolitical retaliation on a young American colony, but beavers were also extirpated as a nuisance species when their engineering interfered with anthropogenic priorities (Fountain 2014, Goldfarb 2018). Beaver denning and damming activities were rarely tolerated where they threatened human priorities on the western frontier and these conflicts remain today where beaver populations have rebounded (Fountain 2014, Pilliod et al. 2018, Goldfarb 2018). However, as beaver extirpation and development of the west progressed, their absence was occasionally noticed in the reduced ecosystem function and services in a beaver barren landscape (Poff et al. 2011, Fountain 2014, Goldfarb 2018).

Dam building beavers are considered ecosystem engineers because of their ability to alter their environment for food and shelter (Rosell et al. 2005, Goldfarb 2018). In building their dams across low order streams, channels or even lakes and ponds, beavers create or expand impoundments of water and add heterogeneity to the resident channel. These impoundments create an aquatic safe zone, allowing beavers to rear young in secure island or bank lodges. The submerged entrances of these lodges, allow beavers to safely swim to their preferred woody food sources and avoid predation by limiting travel on land (Gibson & Olden 2014, Goldfarb 2018). Dam building beavers moderate water flow seasonally and store water higher in the landscape resulting in longer residence time and steady release through dry seasons and particularly drought conditions (Fairfax & Small 2018, MBP 2019). Beaver dams reduce natural and anthropogenic sediment and nutrient flow by slowing their transport and increasing deposition and channel aggradation which reduces stream channel incision and restores lost area of riparian habitat while storing large volumes of water (Figure 1.3; Burchsted et al. 2010, Pollock et al. 2012, Hafen 2017, Goldfarb 2018, Brick & Woodruff 2019, MBP 2019). These unintended benefits of beaver impoundments to a large array of other species and the ecosystems that support them, including humans, is clear and well documented. In the face of climate change and ecosystem degradation, these benefits may outweigh the perceived negative side effects of beaver activity (Naiman et al. 1988, McKinstry et al. 2001, Pollock et al. 2003, Pollock et al. 2012, Gibson et al. 2014, Law et al. 2016, MBP 2018, Pilliod et al. 2018, Brick & Woodruff 2019).

Limited restoration efforts began in the early 1930's to reestablish beavers in disturbed riparian systems of the western US and has continually been pursued by some land managers as an effective tool to restore ecological processes in degraded riparian systems (USFS 1931, Heter 1950, Pollock et al. 2012, Fountain 2014, Gibson et al. 2014, Wheaton et al. 2015, Goldfarb 2018, MBP 2018, Brick & Woodruff 2019). Reintroducing beavers to their historic range can address long-term anthropogenic disturbance and degradation of riparian systems across the west including livestock impact, wildfire and storm erosion as well as current and predicted climate change impacts while increasing water storage, ecosystem function and biodiversity (Lawler et al. 2009, Wild 2011, Pollock et al. 2014, Brick & Woodruff 2019).

Where streams have become severely incised from disturbance, often eroded to bedrock, narrow and deep with high stream power, beaver are not likely to succeed as a restoration tool on their own (Pollock et al. 2003, Demmer & Beschta 2008, Pollock et al. 2012, Wheaton et al. 2019). However, their establishment in these conditions could be greatly improved with assistance from human engineers, BDA's beaver dam analogues), PAL's (post assisted log structures), and PBR (process-based restoration) as described earlier (Pollock et al. 2014, Pollock et al. 2015, Wheaton et al. 2019). BDA's are human built temporary dams of wooden posts and woven local vegetation intended to decrease and deflect stream power, or force of flowing water, by adding structure and roughness to simplified, incised channel (Pollock et al. 2012). PAL's work similarly to BDA's though don't usually take the form of a dam, more likened to large woody debris adding structure and complexity to a channel. This can change the incised channel flow enough to allow beavers to re-establish in the channel, potentially maintaining and strengthening the temporary BDA's as their own dams while increasing heterogeneity, sedimentation and therefore recovery of the channel (Pollock et al. 2014, Wheaton et al. 2019). Facilitated by these human activities, beavers can greatly improve riparian system diversity, variability and function with their natural behaviors even in areas of extreme degradation (Pollock et al. 2012, OHA 2014, Wheaton et al. 2015, Bouwes et al 2016, Wheaton et al. 2019).

Beaver restoration can have its challenges depending on management priorities. Critics point to threats of economic loss from dam failure and flooding, warmer stream temperatures with increased ponding of water and mature tree loss from felling, as well as limited monitoring post-restoration to assess effectiveness (Pilliod et al. 2018). However, the potential for accelerated recovery of critical ecological processes in highly impacted riparian systems and incised stream channels have spurred many communities to recognize beaver restoration benefits likely far outweigh the debated and often mitigatable risks (Goldfarb 2018, Worth A Dam 2019, MBP, 2019, OHA 2019, BRNW 2019, TLC 2019). Great strides in developing successful beaver activity mitigation techniques as well as coexistence education efforts are changing attitudes about living with beavers (Fountain 2014, Gibson et al 2014, Portugal et al 2015, MBP 2019, Beaver Institute 2019, Beavers Northwest 2019, Worth A Dam 2019). With extreme wildfire and climate challenges increasingly becoming an impact risk to remaining functional riparian ecosystems and biodiversity across the dryland west, managing for wildfire resistance and resilience with beavers could be the most effective and feasible element in mediating and adapting to future risks and impacts.

SUMMARY AND NEED FOR FURTHER RESEARCH

As disturbance in riparian systems continues to increase in complexity and intensity, we need more knowledge of adaptive management to interacting disturbances to ensure an efficient mitigation response. While many studies have examined individual disturbances in riparian systems, relatively few have documented multiple interacting impacts such as large-scale wildfire, subsequent soil and channel erosion, and beaver activity on the recovery of riparian system processes and functions after wildfire, particularly where long-term continuous impacts exist, such as livestock grazing. Considering livestock grazing is present across most of the western US, the impact of grazing on recovering burned and eroded streams is also important to understand. Understanding thresholds for coexistence between beaver and livestock grazing must also be more thoroughly understood to manage for potential benefits of both (Wheaton et al. 2015, Fesenmeyer et al 2018, MBP 2019).

There are so many competing uses and impacts as well benefits of riparian systems and they all potentially influence one another in different manners under different contexts. Additionally, most low order stream systems across the western United States are classified as degraded and are therefore suitable for an expansive study exploring multiple disturbance interactions in critical riparian systems (Naiman et al 1995). As the groundbreaking work of Nakano, Murakami, Power and Fausch elucidated, the terrestrial and aquatic environments of riparian systems are not only interacting but depend on one another to achieve and maintain a dynamic and resilient equilibrium (Simberloff 1994, Nakano & Murakami 2001, Fausch et al. 2002). This fluctuating state naturally offers great resiliency and resistance to disturbance if anthropogenic impacts can be managed appropriately (Suding 2011, Oliver et al. 2015).

LIST OF FIGURES

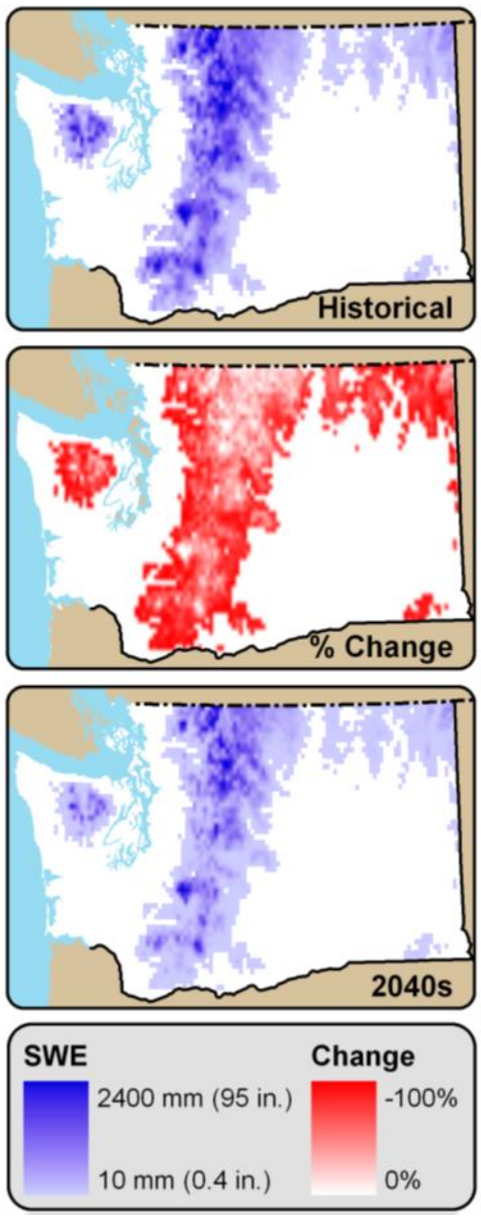


Figure 1.1 Climate models show historical vs future (2040) predicted changes in April snowpack, as well as percent change between the two time periods, showing an overall reduction in predicted Spring snowpack in WA State with snow water equivalent, SWE, being the quantity of water produced if snow were melted at once. Source: Littell et al 2009, Figure 5, reprinted with permission.

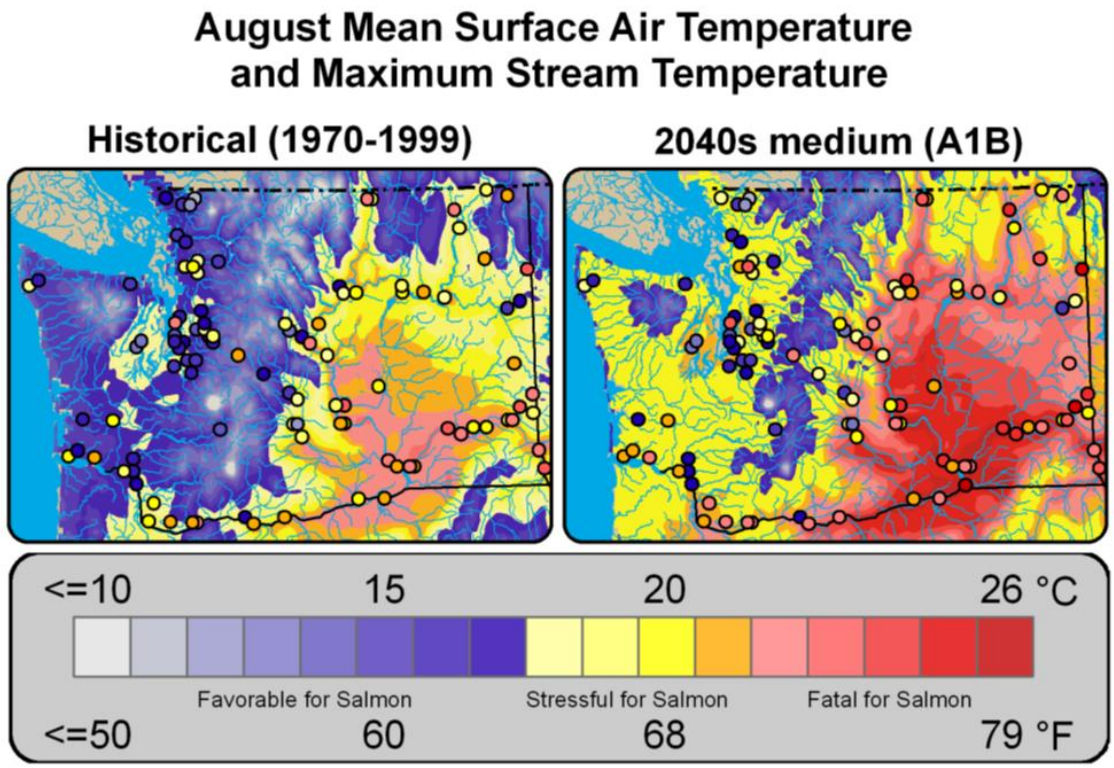


Figure 1.2 Climate models for WA State show stark reductions in favorable salmonid habitat statewide due to predicted and trending increasing air and stream temperatures. Source: Littell et al 2009, Figure 9, reprinted with permission.

Figure 1.3 Beaver complex holding millions of gallons of water year- round in the Methow River Watershed. Source: Methow Beaver Project, reprinted with permission.

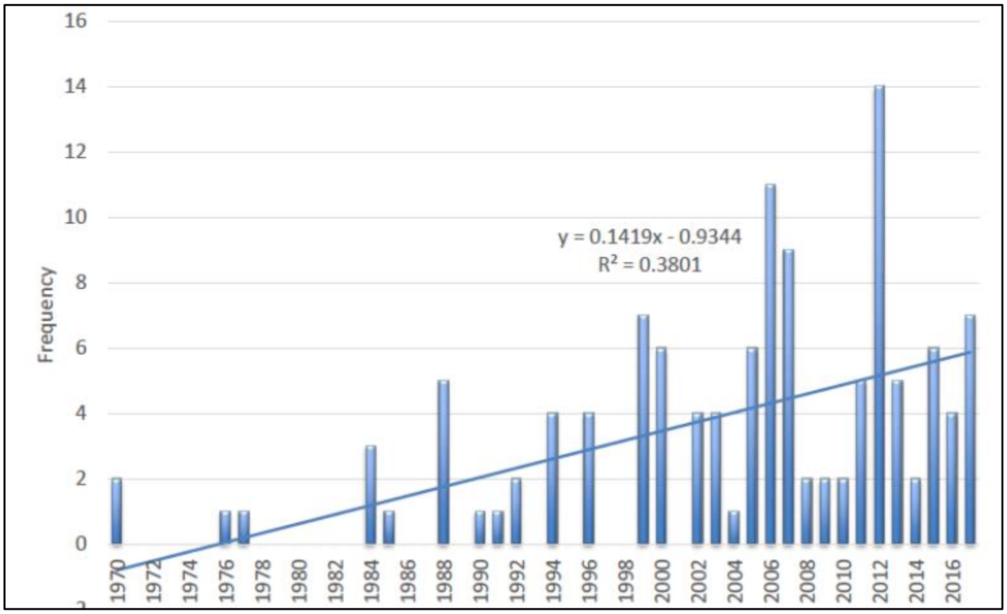


Figure 1.4 Frequency of individual fires burning >100,000 acres (megafires) per fire season in the western US between 1970 and 2016 with no documented megafires prior to 1970. Source: Weber et al 2018, reprinted with permission, Creative Commons CCO.

Figure 1.5 An example of increased tree density over time in a Montana Ponderosa Pine community where fire had been excluded since 1895. A. 1909. B. 1948, C. 1989. Reprinted with permission from Bladon et al 2014, Figure 2, reprinted with permission. Copyright 2014 American Chemical Society.

Figure 1.6 Lake Creek, a tributary of the Middle Fork Boise River in Idaho, burned in the Hot Creek Fire, July 2003. One month later, an hour-long convective storm induced an accumulating debris flow, scouring and deeply incising the stream channel. Cannon et al 2010, Figure 7, reprinted with permission. Copyright 2010 Geological Society of America.

Figure 1.7 Left - Stream in unburned western US watershed. Right - Stream in recently burned western US watershed. Bladon et al 2014, Figure 3, reprinted with permission. Copyright 2014 American Chemical Society.

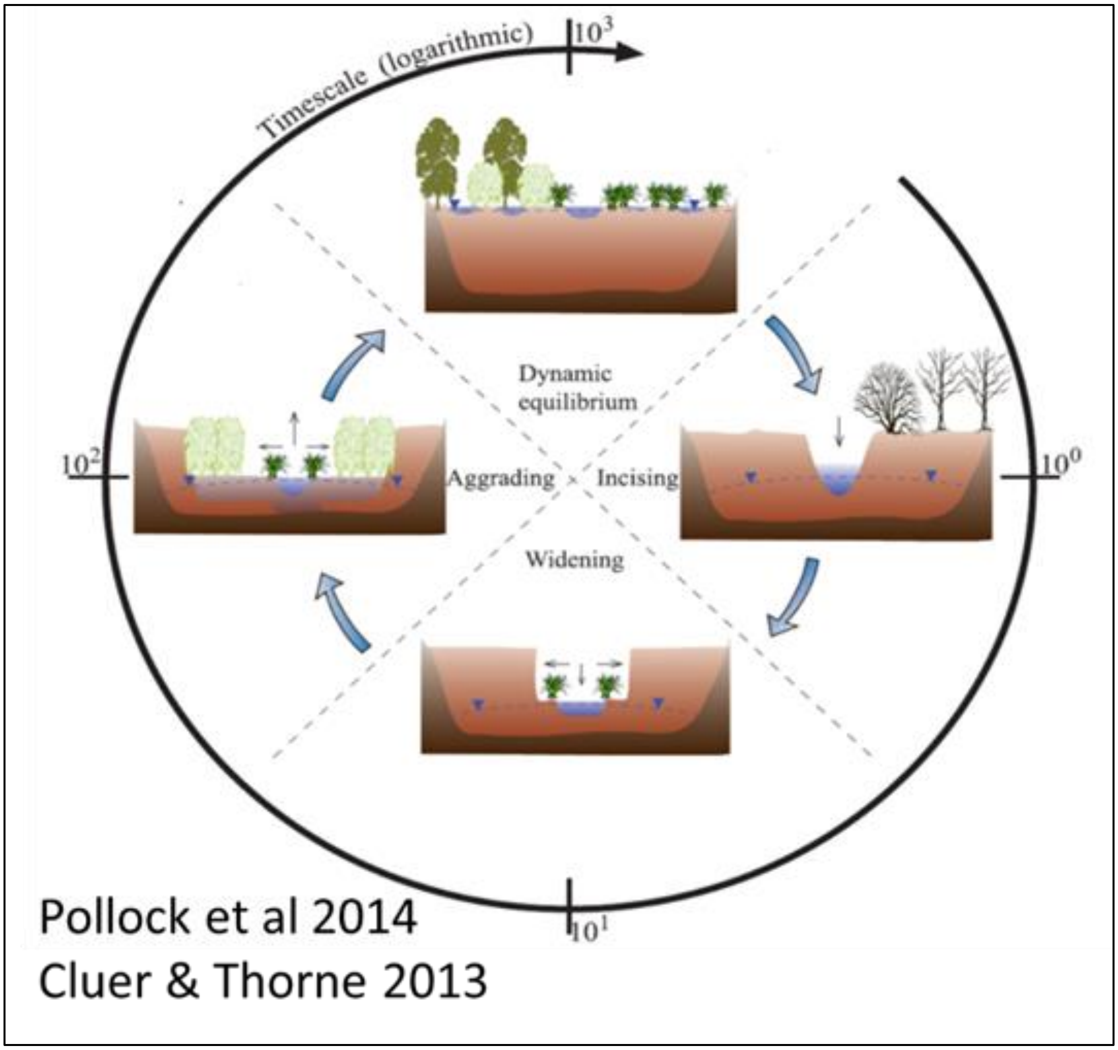


Figure 1.8 Stream evolution model as described by Pollock et al 2014 and adapted from Cluer and Thorne 2013. Note the logarithmic timescale. Pollock et al 2014, Figure 2, reprinted with permission. Copyright 2014 Oxford University Press.

CHAPTER TWO

WILDFIRE, EROSION AND BEAVER (CASTOR CANADENSIS): INTERACTIONS AND DISTURBANCE IMPACTS ON NUTRIENT TRANSPORT, WATER QUALITY, STREAM CHANNEL MORPHOLOGY, AND VEGETATION IN DRYLAND RIPARIAN SYSTEMS OF LOW ORDER STREAMS IN NORTH CENTRAL WASHINGTON STATE, USA.

INTRODUCTION

Riparian systems of the dryland western United States (US) comprise less than 2% of the landscape (Svejcar 1997) yet are essential for critical ecosystem functions, biodiversity and climate adaptation in water-limited environments (Knopf et al. 1988, Naiman & DeCamps 1997, Capon et al. 2013, Isaak et al. 2018). As the interface between terrestrial and aquatic systems, freshwater riparian systems depend on periodic connectivity with their associated water bodies to effectively store water, exchange subsidies and support complex habitat giving rise to diverse floral and faunal riparian communities (Naiman & DeCamps 1997, Poff et al. 1997, Kelsey & West 1998, Nakamura et al. 2000, Nakano & Murakami 2001, Wissmar 2004). Anthropogenic interests often center around riparian areas due to their high productivity and valuable resources. However, anthropogenic disturbance such as water abstraction/control infrastructure, overharvesting, and habitat loss from expanding human development has resulted in widespread degradation and loss exceeding 80% of historically documented riparian areas in the US (Naiman et al. 1995, Patten 1998, Dudgeon et al. 2006, Poff et al.

2011). More recently, increased scale and severity of wildfire (Westerling et al. 2006, O'Connor et al. 2014, Weber et al. 2018) has compounded riparian disturbance, further challenging the remaining systems' resilience and persistence (Dwire & Kauffman 2003, Bladon et al. 2014).

Resilience in ecological systems can be defined as the ability to respond to change or disturbance that enables recovery or return to approximate pre-disturbance conditions (Holling 1973). Biodiversity and complexity support greater resilience within an ecosystem (Thomas et al. 2015). These adaptive characteristics are critical to spawning a range of reactions stimulating community reorganization, renewal and a return to functional ecosystem processes and services after a myriad of disturbances (Thomas et al. 2003). However, decreasing biodiversity caused by accelerating anthropogenic impact threatens many ecosystem's ability to resist, respond and recover from disturbance (Thomas et al. 2015).

Dryland western landscapes and their associated floral and faunal communities evolved with periodic fire disturbance, yet fire has been suppressed to protect human priorities and values (Hessburg et al. 2005, Odion et al. 2014, Steel et al. 2015). Institutional forest management in the US has been unable to match fires' ability to efficiently manage landscape fuels and necessary disturbance to the benefit of broad ecosystem function and resilience (North et al. 2012, Steel et al. 2015). As a result, vulnerable fuel-loaded forest conditions are contributing to current trends in severe, large-scale fire events. Coupled with post-fire precipitation and erosion events, large fires are dramatically altering ecosystem function and species communities and threatening their ability to adapt or return to a pre-disturbance state (Bozek & Young

1994, Poff et al. 2011, O'Connor et al. 2014, Dennison et al. 2014, Thomas et al. 2015, Steel et al. 2015, Leonard et al. 2017, Weber et al. 2018).

Low-order streams in the mountainous western US may be at increased risk to severe wildfire and subsequent storm degradation due in part to perceived isolation of upper watersheds and the prioritization of limited fire suppression resources in urban/forest interfaces (Pierce et al. 2004, Wohl 2006, O'Connor et al. 2014, MTBS 2018). However, the functional condition of mountain watersheds has a significant influence on water storage and seasonal availability of water for downstream communities (Wohl 2006). Increased storage and extended release of water from mountain riparian systems benefit ecosystem function and services to human communities while increasing refugia for organisms highly sensitive to climate change impacts (Isaak et al 2018, Halofsky et al 2018).

Changes in climate are also increasing landscape vulnerability to extreme fire in western landscapes. Climate models predict increasing temperatures in the western US as well as shifting precipitation patterns from primarily winter snowfall to rain dominated precipitation (Barnett et al. 2005, Littell et al. 2009, Elsner et al. 2010, Hafen 2017). Reduction in snowpack and landscape water storage combined with warming air temperatures in dryland environments is expected to increase drought conditions, evapotranspiration, the frequency and energy of convective storms, and wildfire ignitions (Dale et al. 2001, Dwire & Kauffman 2003, Kendon et al. 2014, Tippett et al. 2015, Tuckett & Koetsier 2016, Prein et al. 2016, Leonard et al. 2017).

High energy, moisture laden convective storms associated with climate change in dryland western landscapes are often double-edged swords. Their brief but copious downbursts of precipitation do little to suppress wildfire ignited by previous storms in fuel loaded forests and instead contribute to severe debris flows of sediment, organic matter and nutrients from newly burned landscapes (Moody & Martin 2001a, Moody & Martin 2009, Tucket & Koetsier 2016, Leonard et al. 2017). Debris flows cause channel scouring, incision and simplification of stream habitat (Tuckett & Koetsier 2015) disconnecting streams from their floodplains, altering hydrology, water storage and flood disturbance regimes which often decrease late season water availability, riparian vegetation recruitment and terrestrial subsidy exchange (Tuckett & Koetsier 2015). Channel incision negatively effects local biotic communities, adjacent terrestrial communities, as well as downstream systems through increased flow velocity, severe flooding and import of excessive sediment and nutrients (Minshall et al. 2001, Dwire & Kauffman 2003, Johnson & Molesworth 2015, Scasta et al. 2016, Wohl 2006, Tuckett & Koetsier 2015).

High concentrations of limiting nutrients such as Phosphorus (P) may accumulate in low gradient, aggrading stream segments downstream of burning for several years following wildfire (Rust et al. 2018). This accumulation of P specifically may cause significant increases in primary productivity, leading to eutrophic stream conditions including decreased solar exposure for benthic organisms, increased stream temperature, decreased dissolved oxygen and increased pH (Silins et al. 2014). Many aquatic organisms, such as macroinvertebrates and salmonids, have a narrow tolerable condition range relating to stream temperature and water chemistry and are particularly vulnerable to extended changes in water chemistry and quality following large scale wildfire (Wohl 2006, Silins et al. 2014, Sherson et al. 2015, Rust el al 2018).

Channel incision of this magnitude may take hundreds to thousands of years to widen, aggrade, and recover its original complex form, according to stream evolution models (Figure 2.1; Cluer & Thorne 2014, Pollock et al. 2014). However, debris flow impact may be of such great magnitude as to change the stream evolution cycle within highly impacted areas reflecting a new stable degraded and incised state (Figure 2.1; Beechie et al. 2007, Cluer & Thorne 2014) that may not recover without restoration interventions. Prior to European influences, mountain streams and their associated riparian systems likely stored water and sediment at much greater capacity than they do currently owing partly to accumulation of channel spanning woody debris creating channel structure, logjam ponding and stream complexity (Abbe & Montgomery 2003, Wohl 2013, Livers & Wohl 2016). But likely even more influential in shaping North America's rivers and streams was the North American beaver (*Castor canadensis*) (Naiman et al. 1988, Cunningham et al. 2006, Wohl 2006, Pollock et al. 2003, Gibson & Olsen 2014, Hood & Larson 2015, Laurel & Wohl 2016, Goldfarb 2018) .

Beavers once occupied the North American landscape in very large numbers, estimated at 60-400 million, or 3-10 beavers per river km (Naiman et al. 1988). Prior to near extirpation by fur-trappers in the early 1900's, beavers played a critical ecological role in shaping and maintaining complex riparian systems supporting exceptional biodiversity (Naiman et al. 1988, Polvi & Wohl 2012). Some land managers recognized the folly in the mass removal of beavers from the landscape as their absence was reflected in loss of upland water storage, bank stabilizing vegetation, productivity of biotic communities and seasonal flood control (Naiman et al. 1998, Polvi et al. 2014, Fountain 2014). As early as the 1930's, beavers were being restored to riparian systems across the US (Heter 1950, USFS MRD 2018) but the population has only recovered to a fraction of historic levels, estimated at 15 million across the US (Naiman et al. 1988).

In 2008, the Methow Beaver Project (MBP) (Brick & Woodruff 2019), located in the Methow River watershed, a tributary of the Columbia River in north central Washington State (WA), renewed long dormant beaver restoration efforts as a response to climate change prediction models (Littell et al. 2009). In addition to warming, shifting precipitation and reduced snowpack, these models predict increasing carbon release, elevational and poleward species range shifting and overall biodiversity loss (Littell et al. 2009, Bartel et al. 2010, Elsner et al. 2010, Poff et al. 2011, Laurel & Wohl 2016). The MBP's pioneering collaborative mission with federal and state agencies initially focused on restoring dam-building beaver populations high in the watershed on public lands to increase water storage on the landscape (Burchsted et al. 2010, Baldwin 2015, Hafen 2017, Brick & Woodruff 2019). However, increased beaver activity has the potential to provide many more benefits including attenuation of seasonal flooding (Naiman et al. 1998, Rosell et al. 2005, Westbrook et al. 2013, Puttock et al. 2018), increasing habitat complexity and biodiversity (Brown et al. 1996, McKinstry et al. 2001, Wright et al. 2002, Nummi et al. 2011, Gibson & Olden 2014, McCaffery & Eby 2016, Law et al. 2016), reducing sediment and nutrient transport downstream (Polvi et al. 2014, Puttock et al. 2018, Laurel & Wohl 2018) to the Columbia River, improving endangered salmonid habitat (Pollock et al. 2004, Pollock et al. 2012, Pollock et al. 2014, Bouwes et al. 2015, Weber et al. 2015, Wheaton et al. 2015, Law et al. 2017) and repairing anthropogenic degradation from resource extraction and livestock grazing across the mountainous watershed (Naiman et al. 1995, Pierce et al. 2004, Wohl 2006, Beschta et al. 2013, Gonzalez et al. 2015, Small et al. 2016, Fesenmeyer et al. 2018). Beavers might also repair channel incision after wildfire as well as increase resistance to (Fairfax & Small 2018) and resilience after wildfire in watersheds of the dryland western US (Brick & Woodruff 2019). However, little research has focused on the potential benefits of beaver activity after wildfire which has inspired the deeper investigation of interacting disturbances among wildfire, erosion and beaver documented in this study.

In addition to the MBP's decade of beaver restoration, the Methow watershed has experienced an increase in frequency of large scale, high severity wildfires over the last 20 years (Table 2.1; NIFC 2018) and subsequent widespread stream channel incision after fire (USFS-BAER 2018). Since 2006, three successive "largest wildfire in WA's history" distinctions have been bestowed upon wildfires occurring primarily or partially within the Methow watershed's boundaries (Table 2.1; NIFC 2018). In the 2006 Tripod Complex Fire (including the Tatoosh Butte and Tripod Peak fires), approximately 90,000 hectares burned within the watershed followed eight years later by the 2014 Carlton Complex Fire (including Little Bridge Creek and Upper Falls Creek) burning more than 110,000 hectares, primarily within the watershed. In the following year, the current "largest in WA" wildfire, the 2015 Okanogan Complex Fires, burned a record 240,000 hectares shared across the Methow and Okanogan river watersheds (including the Twisp River and Black Canyon fires at ~20,000 hectares). Most recently, in 2017 and 2018, three more large fires (Diamond Peak Fire 2017, Crescent Mountain and McCloud Fires 2018) burned a combined 70,000 hectares in the Methow watershed.

Increasing wildfire and subsequent riparian degradation is becoming common across dryland western landscapes as it is in the Methow River watershed, however beaver restoration programs within western watersheds are still rare. To study the interactions between fire impacts and beaver activity, the knowledge of current active beaver locations and date of site establishment were essential. The availability of these data combined with known fire and channel incision history make the Methow watershed an ideal study area to investigate and document the interactions between three increasingly significant disturbance variables of wildfire, erosion and beaver activity and their resulting impact on riparian ecosystem functions and services.

To clarify research questions, a conceptual model (Figure 2.2) was developed to visualize the complex relationships between biotic (green) and abiotic (blue) disturbances in dryland western watersheds, particularly the Methow River. While many of the relationships in this conceptual figure have been studied (e.g., effect of beavers on riparian systems or effect of fire on water quality and channel morphology), to date there are almost no studies assessing the interacting effects of fire, subsequent channel erosion and beaver on low order streams and their riparian zones. However, the potential management implications are profound considering the need for critical riparian functions and services, their imperiled existence and their restoration regarding increasing impacts and disturbance of large scale, severe wildfire.

My overarching research objective was to determine how dam-building beavers affect the function and biodiversity in riparian systems disturbed by large scale wildfire and subsequent channel erosion compared to burned riparian systems without dam-building beavers. The following hypothesis that beaver dam-building activity increases riparian resilience to wildfire impacts by improving water quality, increasing channel complexity, and increasing diversity and density of vegetation in burned watersheds was tested by comparing sites on low order Methow watershed tributaries with and without dam building beavers that either burned in the 2014 Carlton Complex fires or had not burned in at least ten years. I predict: 1) burned riparian systems with beaver dams have reduced phosphorus concentrations, cooler temperatures and higher dissolved oxygen downstream of beaver dams, and lower pH compared to burned riparian systems without beaver dams 2) in both burned and not burned streams, beaver dams increase channel bankfull width/depth ratios, stream and floodplain connectivity, and structural complexity of ground cover within their impoundments, compared to downstream of dams and streams with no beaver activity and 3) burned riparian systems with beaver dams support greater native vegetation diversity and density and influence plant community composition, specifically increasing density of deciduous woody vegetation species, compared to burned riparian systems without beaver dams.

METHODS

Study Area Description

The Methow River is a free-flowing tributary of the Columbia River located in north central Washington State. Its watershed encompasses 4727 km2 from the eastern crest of the North Cascades Mountains to the Columbia River, 129 km to the southeast (Figure 2.3). The watershed has a dry continental climate with precipitation, primarily falling as snow November-March, ranging from ~200 cm/year in the headwaters to ~ 25 cm/year at its confluence with the Columbia (NCDC 2018). Spring snowmelt in the North Cascades Mountains and foothills brings seasonally high river discharge rates tapering into mid-summer and early autumn. Geomorphology, hydrologic regime, climate variation and anthropogenic disturbance in the watershed contribute to variations in vegetation patterns at different elevations and aspects.

The Methow River watershed is dominated by ponderosa pine (*Pinus ponderosa*)/shrub steppe plant communities at middle to lower elevations and by subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*) and endangered whitebark Pine (*Pinus albicaulis*) forest and meadow communities at high elevations (Mahalovich & Stritch 2013). Riparian communities along the Methow River and its tributaries consist of diverse forbs, sedges, rushes, and grasses as well as primarily deciduous shrubs and trees including aspen (*Populus tremuloides*), cottonwood (*Populus trichocarpa*), alder (*Alnus incana*), river birch (*Betula occidentalis*), red-osier dogwood (*Cornus sericea*), numerous species of willow (*Salix spp*.) and the frequent riparian conifer, Douglas Fir (*Pseudotsuga menziesii*).

Study Design and Site Selection

Changes in water quality, stream channel form, and riparian vegetation in low order stream ecosystems were documented in a fully factorial study design with 3 replicates each for a total of 12 study sites (Figure 2.5). I compared burned to unburned sub-basins with and without beaver activity as well as changes below and within beaver complexes. Each site had evidence of stream erosion to be quantified and described using channel cross-section analyses. Evidence of current or historic livestock grazing existed in each site and was considered a continuous disturbance impact across the Methow River watershed.

For the sake of consistency and clarity, the terms “beaver” and “no beaver” will be used when referring to sites that had beaver activity or not. Sites were considered to have beaver activity if there were one or more hydrologically significant beaver-built dams altering the stream flow, whether or not beaver were still present. Hydrological significance (HS) refers to the ability of a beaver dam to significantly slow water, capture sediment and cause surface pooling. Determination of a beaver dam versus a natural large woody debris jam was based on beaver tooth impressions in the ends of wood used in the structure of the dam. The terms "burned" and "unburned" are used to represent sites impacted by fire in 2014 (burned) or not impacted by fire for at least 10 years (unburned). Similarly, downstream transects are identified as "T1" and impoundment transects are identified as "T2".

Historic and current beaver location data were acquired from the Methow Beaver Project (MSRF 2017, 2018) and the USFS Methow Ranger District, then overlaid with wildfire boundary layers (Figure 2.4) (MTBS 2018). Known beaver locations from the MPB were used to select six study sites with beaver dams and inform selection of non-beaver sites to avoid choosing sites influenced by beavers higher in their watershed (Figure 2.4).

Suitable sites without beaver were determined by creating a beaver habitat suitability model (HSM) based on abiotic watershed conditions adapted from Dittbrenner et al. (2018). HSM modeling using ArcMAP permitted the prioritization, search and identification of suitable beaver sites across the Methow watershed based primarily on the delineation of stream gradient, watershed size, stream order delineation, elevation and aspect to locate approximately equivalent non-beaver sites for comparison to beaver occupied sites (Pollock et al. 2014, Small et al. 2016, Dittbrenner et al. 2018).

Data from the National Hydrography Dataset (NHD) website were used in conjunction with 10 m digital elevation maps (DEM's) in ArcMAP to delineate the Methow River watershed in fine detail (USGS NHD 2017, UW WA DEM's 2018). Multiple 10 m DEM's were mosaicked together in ArcMAP to create seamless stream data for the entire watershed, allowing the beaver habitat suitability model to delineate and reclassify stream segments that were stream order <= 4 and gradient <= 10% as well as classify watershed aspect and elevation. StreamStats, a web based integrated spatial analytics tool (USGS StreamStats 2018), was used to generate sub-basin boundaries and characteristics such as average gradient, elevational changes, average precipitation and watershed area for each study site to inform the accuracy of the HSM model.

Time since wildfire, wildfire boundary and burn severity data used in this study were acquired from the US Forest Service's Burned Area Emergency Response (USFS-BAER 2018) website and the collaborative web-based database, Monitoring Trends in Burn Severity (MTBS 2018). Burned study sites were located by overlaying fire boundary and burn severity maps over the known beaver locations and the BIP habitat suitability model to determine the extent of burning in beaver sites and similar non-beaver sites. Sites with greater than 50% of their watershed classified as moderate to high burn severity were considered burned. Six sites within 2014 wildfire boundaries were chosen that could accommodate beaver, three with known beaver presence and three chosen using the described habitat suitability model for the Methow River watershed (Figure 2.5).

On each study site, two transects were established perpendicular to stream flow that encompassed the entire width of smaller riparian systems, valley wall to valley wall, or, in broader riparian systems with large valley widths, the transect spanned 10 m of riparian zone on either side of the stream. In sites with beavers, transect locations were established based on the total stream length of the beaver dam complex, from the most downstream dam in the beaver complex to the upstream most extent of influence from one beaver colony (Figure 2.6). In these sites, the first transect (T1) was placed 20m downstream from the lowest intact or hydrologically significant (HS) dam in the complex (Figure 2.6). The second transect (T2) was placed upstream from the lowest dam, within the beaver complex, at the point equivalent to 2/3 of the total stream length of the complex. This standardized location ratio was selected to capture effects of beaver on representative riparian vegetation within a beaver dam complex; often riparian vegetation can be completely inundated closer to the downstream end of the complex. Total complex length was determined by measuring the distance from the downstream most dam to the upstream extent of obvious beaver influence. Transect locations from beaver sites were then overlaid on paired sites with no beavers, but that could accommodate beavers based on modeling described above. Paired sites were selected based on similar size watersheds, valley widths, gradient, and abiotic characteristics to prevent these variables from confounding the beaver/no beaver comparisons.

For each transect location, the left bank of the stream was always determined by orienting downstream and the left bank pin (LBP), or 0 on the meter tape, was placed 1 m into the upland landform on the left. The tape was then drawn across the valley width perpendicularly to the opposite valley wall and the right bank pin (RBP) was also placed 1m into upland. Distance from water edge to valley wall was recorded for all sites. If valley width was prohibitively wide and the landform was unchanged within 10 m of the water's edge, the LBP was placed10 m from surface water edge perpendicular to flow in stream channel. Changes in landform were defined as abrupt changes in elevation across the riparian zone (landform classifications are described in a later section). If the landform did change within 10 m of the water's edge, the LBP was placed 10 m into the next unchanging landform. Where stream channels were severely incised, a second meter tape was pinned within the stream channel, mirroring the transect length tape in order to accurately mark station location while identifying variables within the incised channel. LBP and RBP elevations were recorded with a handheld GPS unit (type) and all travel was conducted on the downstream side of the transect to avoid vegetation trampling.

At each transect, water quality sampling, channel cross section surveys, and line intercept vegetation surveys were conducted. Field sites were verified and sampled between July 9 and August 10, 2018, with the exception of eight out of 24 channel cross section surveys. These eight were sampled between September and November 2018 when there was less vegetation to block the line of site.

Water Quality Sampling

Water quality parameters were sampled following standard procedures as described in Finlay et al. (2011). Both transects in a site were sampled within 30 minutes of each other to ensure that temporal variation did not affect differences between samples. Water parameters were sampled only in the morning, between 9 - 11 am and between July 9 - Aug 11 to reduce diel and seasonal temperature variation between sampling. To measure total phosphorous (TP) and dissolved phosphate (DP), two water samples were collected in 30 ml bottles from each transect. To measure DP, one sample was filtered to remove particulate forms of P greater than 0.45 micron with a single use glass filter. The other sample was left unfiltered to measure TP. To avoid disturbing the water column and influencing turbidity, samples were collected without entering the stream, 10 cm below surface waters as close to the thalweg as possible. In lentic water within beaver complexes, water samples were collected 0.5 m from the shoreline and 10 cm below the surface water, with minimal water disturbance prior to collection.

For each sample, water was collected in a 100 ml syringe rinsed 3 times in the study stream, then attached to a filter housing containing a filter. Filtered water was then used to rinse one sample bottle and cap 3 times, before filling with 20 ml of filtered stream water. The same syringe was then used without the filter and housing to rinse the second sample bottle and cap 3 times before filling with 20 ml of unfiltered stream water. All water samples were then stored on ice in a cooler (less than 6 hours) until transfer to a chest freezer for longer term storage prior to lab processing.

Lab processing of stream water samples to measure TP and DP followed standard Environmental Protection Agency EPA approved lab techniques and procedures (EPA Method 365.3, Finlay et al. 2011). Standard acid persulfate digest was performed for TP (Patton & Kryskalla 2003) and Molybdenum blue colorimetric tests were performed on DP and digested TP samples as well as known Phosphorus concentration standards for analysis using WinFlow flow-injection spectrophotometer reflectance (OI Analytical 2009). Results were provided as TP and DP concentrations in ppm.

Temperature, pH and dissolved oxygen (%DO) were measured with a YSI 556 water meter at both benthic and surface levels in the stream thalweg beginning at downstream transect T1 to avoid disturbing the water column, then proceeding to T2 for sampling within 30 minutes of T1.

Surveying Channel Cross-Section, Landform and Ground Cover

Stream channel cross section elevations were measured along previously described transects T1 and T2 following standard USFS methods (Harrelson et al. 1994). Key channel characteristics measured included channel bankfull elevation on left and right bank (Harrelson et al. 1994), edge of water on both sides of channel, and channel depths measured approximately every 20 cm across the wetted area. Bankfull elevation is defined as the elevation at which seasonal high stream flows overflow onto adjacent channel floodplains (Harrelson et al. 1994). However, bankfull elevation can be difficult to determine in degraded and incised channels, as bankfull flows may be disconnected from the floodplain due to deepening of the channel. In these channels, bankfull indicators such as changes in peripheral channel substrate size, bank vegetation composition, evidence of organic debris or bank scarring from high flows, bank undercutting, and water staining on crustose lichens within the channel can be used to consistently determine bankfull elevation, as was done in this study (Harrelson et al. 1994).

Landform and ground cover classifications were identified (Table 2.3) and recorded as percent of total transect along the channel cross section (T1 and T2) using the line intercept method (LI) (Coulloudon et al. 1999). Landform classifications were defined as wetted channel (water), bar (within generally wetted channel area but not submerged), floodplain bank (typically high gradient transition between wetted channel and floodplain), floodplain (low gradient riparian area adjacent to stream channel that typically experiences seasonal high flow inundation and disturbance), floodplain terrace (former floodplain but currently isolated from seasonal high flow inundation, often by channel incising events) and upland (high gradient transition away from stream channel and riparian floodplain into dryland habitat) (Table 2.4). Ground cover classifications were based on the size and composition of organic material (large and small woody litter and herbaceous litter) and particle composition differences including rock (of any size), sand (less than 2 mm), and bare soil (mixed organic material). The channel substrate sediment particle size distribution in stream channels was measured using the pebble count method as described in Wolman (1954). Using a zigzag pattern covering 5 m upstream and downstream of transects within the normally wetted channel, sediment particle sizes were measured and recorded until a sample size of 100 was acquired.

Surveying Vegetation Species Composition and Strata

Plant species and their strata location were identified on T1 and T2 using the line intercept method (LI) (Coulloudon et al. 1999). Beginning at the LBP, all vegetation intercepting the transect, under and above, were identified to species, either in the field or later with an ethically collected voucher specimen or high-quality photo voucher for limited representation species. When a single species had extended continuous representation along the transect, only gaps greater than 10 cm were recorded. The dominant vertical stratification location for each species was documented with classification described in Table 2.3.

Data analysis

To determine whether phosphorous transport decreased in burned watersheds with beaver, the effects of disturbance interactions between beaver, wildfire and transect location on total phosphorous and total dissolved phosphate concentrations (mg/L) were analyzed using linear mixed-effects models with the lme4 package (Bates et al. 2015) and graphed using ggplot2 in RStudio version 3.4.4 (Wickham & Chang 2016, RStudio Team 2019). Temperature (C), percent dissolved oxygen (%DO), and pH were also analyzed with the same procedure as described for Phosphorus, using linear mixed-effects model to determine effects of interacting explanatory or independent variables including beaver/no beaver, burned/unburned watershed and transect location downstream/in pond on the various response variables within these systems.

To test my prediction that beaver dams in burned riparian systems increases channel complexity, raw channel cross section data were first processed using streaMMetricsTM (Gemmill 2000). Bankfull and surface water elevations in each site were standardized with a base elevation of 100m. Descriptive channel characteristics were then identified, such as bankfull width and bankfull width/depth ratios, as described previously. Channel response variables (Table 2.3), or their log transformations were then statistically analyzed with linear mixed-effects models using the lme4 package in RStudio 3.4.4 (Bates et al. 2015, RStudio Team 2019) for the interacting effects of beaver, burning, and transect location. These models were then visualized with the ggplot2 package in RStudio (Wickham & Chang 2016).

To determine effects of beaver, burning, and transect location on species richness, I used a linear mixed-effects model with the lme4 package in R Studio version 3.4.4 (RStudio Team 2019). Results were graphically represented using the ggplot2 package in RStudio (Wickham and Chang 2016), as previously described for analyses of water quality parameters and channel characteristics. For each transect, species richness was calculated as the number of unique species per linear meter and species density as percent cover of transect, both standardized by transect length. To further assess differences in plant community composition associated with beaver and burning, nonmetric multidimensional scaling (NMDS) and permutational multivariate analysis of variance (PERMANOVA), were performed using the Vegan package (Oksanen et al. 2018) in R version 3.4.4 (R Studio Team 2019) and PRIMER 7 and PERMANOVA+ (Clarke and Gorley 2015). To standardize vegetation species data, square root transformation followed by Bray Curtis Resemblance similarity index transformation was performed prior to ordination analyses. Environmental data were log transformed and compared to determine correlations, then these vectors were plotted onto the species composition NMDS ordination using Primer 7 (Clarkey & Gorley 2015).

RESULTS

Water Quality

Total phosphorus (TP) as well as total dissolved phosphate (DP) concentrations were highest in burned sites without beaver (df=1, df=1, Figure 2.7a, b; as in the methods, beavers refers to sites with beaver dams). Beaver reduced TP and DP concentrations in burned sites almost to the same low levels in sites not experiencing wildfire in at least 10 years (Figure 2.7). Beaver had no significant effect on stream temperature, whether in burned sites or not (df=1, Figure 2.8a). Beaver lowered % DO in all treatments with the greatest effect in burned sites within beaver impoundments (df=1, Figure 2.8b). Beaver lowered the high pH in burned sites to levels found in unburned riparian sites and increased pH in unburned sites (df=1, Figure 2.8c).

Channel Cross-Section, Landform and Ground Cover

Beaver increased bankfull widths and width/depth ratios within beaver ponds compared to downstream transects or no beaver sites, whether burned or not (df=1, Figures 2.9, Figure 2.10). In unburned sites, beaver increased surface water depth within ponds, however, beaver did not have a significant effect on bankfull depth, surface water width, floodprone width, entrenchment, nor channel substrate particle size.

Floodplain (FP) and floodplain terrace (FT) were the only landforms whose size varied with beaver activity or burning (df=1, Figure 2.11a). FP area increased in beaver sites, regardless of fire, but the effect was greater between burned systems with and without beaver. Alternately, burning and beaver each had a main effect on FT area with beavers decreasing FT area, regardless of burning, but with burning increasing FT area compared to unburned sites (df=1, Figure 2.11b). Beaver and burning interacted to affect the ground cover classes of sand and woody litter. Sand was most prevalent in burned sites with no beavers; beaver presence did not affect sand cover in unburned sites (df=1, Figure 2.12a). Beaver increased woody litter in sites that had burned in 2014 (df=1, Figure 2.12b). In unburned sites, beaver decreased woody litter within their ponds.

Riparian Vegetation Community Composition and Strata

Total vegetation species richness increased when unburned sites were occupied by beaver, however, the opposite was true of burned sites, which had decreasing plant diversity in response to beaver activity (df=1, Figure 2.13a). Introduced species richness decreased in burned sites with beaver but increased in unburned sites with beaver (df=1, Figure 2.13b). Though not statistically significant, beaver increased total vegetation density except in downstream transects of burned sites and decreased the density of introduced vegetation except in downstream transects of unburned sites (Figure 2.14a, b).

Plant community composition varied significantly among treatments (df=1, Figure 2.15) with woody species communities, including Cornus sericea, Salix spp., Populus spp., Rosa spp. and Alnus incana, more dense in the FP landform and the shrub strata of burned sites with beaver (df=5, Figure 2.16a, df=5, Figure 2.16b) This can be visualized with NMDS ordination (Figure 2.17). Area in each landform was compared and vectors plotted on the community composition NMDS ordination (Figure 2.15). The variation in plant community composition correlates with burning and beaver as well as landform (Figure 2.15).

DISCUSSION

This study provides evidence that dam building beavers have increased the resilience of burned watersheds and post-fire incised stream channels in the Methow River watershed. The reduction of P in burned riparian systems with beaver impoundments, compared to sites without impoundments, provides strong evidence that beaver activity improves nutrient and sediment sequestration after fire. P naturally adsorbs to sediment which facilitates both its transport in post-fire erosion events and its deposition in more lentic beaver ponds (Tuckett & Koetsier 2015). High concentrations of P in streams are not uncommon immediately following wildfire, but a recent study by Rust et al. (2018) documented long-term monitoring after severe wildfires showing P concentrations remaining high five years after fire, which was also seen in this study (Silins et al. 2014, Rust et al. 2018). Extended water quality impacts to aquatic organisms after wildfire can be detrimental to their survival (Bladon et al. 2014). P is generally a limiting nutrient in aquatic systems, but fire and other anthropogenic activities, such as agriculture, increase P availability through soil erosion and can cause increased primary productivity, potentially leading to eutrophic conditions including decreasing light, increasing pH, and hypoxic or anoxic stream conditions, lethal to many aquatic organisms (Chislock et al. 2013, Sherson et al. 2015, Dodds et al. 2016, Puttock et al. 2018). Arsenate presence in stream water can sometimes cause artificially high levels of P, however, considering the extremely low P concentration results in all sites except burned sites without beaver, arsenic interference is likely not a factor (EnvExp 2019).

In capturing sediment and nutrients released after fire, beaver dams also moderated the stream alkalinity compared to streams without beaver. Increased alkalinity likely resulted from suspended ash from burned organic matter. Extremes in pH can cause varying challenges for aquatic organisms including a blinding effect on organisms that use water chemistry to locate food or detect predators, weakening of calcium carbonate shells, increased drift response, and increased effect of heavy metal contaminants (Courtney & Clements 1998, Silins et al. 2014). The lower pH found in sites with beaver is more likely to support alkaline sensitive species in burned sub-basins, creating a water quality refuge in beaver ponds after wildfire.

The benefits of attenuating water and settling of particulates above beaver dams after fire are clear but effects on water temperature within and below beaver dams were inconclusive. With increased solar exposure and lentic conditions, larger beaver impoundments can be expected to have higher water temperatures than lotic downstream segments characterized by increased ground water recharge and release below beaver ponds. This was not observed. However, beaver sites overall were no warmer than their burned, no beaver counterparts. The lack of difference may be due to higher stream temperatures in burned and not burned sites with no beaver lacking adequate stream shading vegetation from either fire, large post-fire debris flows, grazing or other historic and current anthropogenic activities (Tuckett & Koetsier 2016).

Temperature and % DO are key water quality parameters for aquatic organisms, salmonids in particular (Carter 2005, Littell et al. 2009, Weber et al. 2017), that can potentially be negatively affected by beaver reintroduction. Though lentic beaver ponds can naturally have lower dissolved oxygen levels due to reduced hydraulic mixing and increased surface water temperatures, they can also buffer extremes in diel stream temperatures that occur in watersheds with limited shading vegetation and decreased stream channel complexity (Weber et al. 2017). Most beaver occupied sites in this study had only slightly lower % DO concentrations than sites without beaver; with the lowest % DO concentration of ~ 65 %, above low levels considered detrimental for salmonid productivity (Carter 2005). Downstream from beaver impoundments, % DO levels were similar to sites without beaver, and offer evidence that beaver effects on % DO likely do not project downstream from their dams. These results offer supporting evidence that the effects of beaver activity on water quality following wildfire is largely positive specifically pertaining to post-fire phosphorus capture and pH mitigation which may inform future watershed management priorities after large scale wildfire and subsequent channel incision.

In this study, beaver dams in burned study sites were built in the four years since the 2014 Carlton Complex Fires and have contributed to widening and aggrading fire impacted, incised channels. These changes in channel form are consistent with stream evolution processes (Cluer & Thorne 2014, Pollock et al. 2014) and were accelerated in burned sites with beaver compared to burned sites without beaver, likely due to sediment capture and deposition upstream of dams. The potential for channel widening depends on the context of erosion events, geomorphology and bank erosion potential, but in this study, and others not focused on wildfire related erosion, beaver activity has proven to accelerate channel widening, compared to channels without beaver (Beechie et al. 2007, Pollock et al. 2014, OHA 2018). This beaver accelerated channel widening leads to an inset floodplain and increasing channel complexity that simultaneously erodes incised channel walls while aggrading sediment, eventually reconnecting the incised stream with its original floodplain, while improving ecological processes in a much reduced timeframe compared to sites with no beaver (Pollock et al. 2014, OHA 2014, MBP 2018). In my study, beaver dams in burned sites increased floodplain landform area likely because beaver dam-building naturally aggrades stream channels and spills high flows onto adjacent landforms (Gibson et al. 2014). Burned sites without beaver dams had floodplain terrace landform areas likely due to severe channel incision having disconnected streams from their floodplains. Without beaver or other large woody debris accumulation within these degraded systems, former floodplains have been left isolated as floodplain terraces, demonstrated in channel cross sections as well as landform and corresponding vegetation results (Figures 2.10, 2.11, 2.16). With four years since fire and incision, these degraded channels without beaver have not begun to widen, consistent with the stream evolution model (Figure 2.10), have species more typical of floodplain terrace landforms, (Figure 2.16), have 50% more sand ground cover (Figure 2.12), and may be starved for structure such as woody debris and riparian vegetation that could potentially induce channel complexity and widening (Wohl 2013, Wheaton et al. 2019). Beaver dam-building activity in these systems can quickly create structure and complexity within the incised channel, redirecting water, reducing stream power, eroding banks and aggrading sediment and debris. Accelerated widening and increased complexity from beaver advances the stream evolution cycle toward a more quickly restored connection between stream and floodplain and therefor process based function (Wheaton et al. 2019).

Substrate particle size can also help determine stream morphology and channel evolution condition (Cluer & Thorne 2014). Though my substrate classifications did not differ dramatically between sites, they did provide distribution curves representing surficial channel bed sediment size within the below transect channel segment. These distribution curves inform sediment or bedload transport rates, grain roughness for the site, stream evolution, as well as habitat conditions for organisms utilizing surficial stream bed environments. The lack of difference between sites could be attributed to naturally varying stream conditions, debris flow events and previous dam failures, even where beaver dam building activity was present; consistent with research on small dams by Skalak & Pizzuto (2002). Future studies of these same sites will take a closer look at the differences between treatments regarding sediment transport and deposition as well as macroinvertebrate communities, offering greater insight to substrate differences in burned watersheds with and without beaver.

The vegetation present in riparian systems is highly correlated to each system's hydrogeomorphology, connection with high seasonal stream flows, disturbance regime, greatest landform representation and overall surface and ground water access (Hupp &

Bornette 2003, MacFarlane et al. 2017). Sites with beaver and no fire had the greatest species richness in vegetation communities with the greatest abundance of wetland obligate species and the highest percentage of floodplain landform. However, these sites also had the highest number of introduced species, possibly relating to anthropogenic activities such as livestock grazing. Though some riparian systems have been fenced to exclude livestock access and disturbance, fences fail regularly allowing access to high quality forage and surface water found in less degraded riparian systems, especially in late summer (Fesenmeyer et al. 2018). Livestock foraging can introduce non-native species into these riparian systems as well as reduce function of riparian processes and restoration through excessive trampling, loafing, herbivory, and nutrient input, especially after fire (Dwire et al. 2006, Beschta et al. 2013, Dalldorf et al. 2013, Small et al. 2016.)

Sites that had experienced fire and hydrologically significant beaver activity had the lowest total species richness. However, burned systems with beaver had the lowest richness of introduced plant species four years after fire. One explanation may be that native plant species, ex. *Cornus sericea, Balsamorhiza sagittata*, in pine/steppe ecosystems have evolved with and are often stimulated by fire, possibly outcompeting annual introduced species for at least a window of time post-fire (Smith & Fischer 1997). However, severe channel incision can leave native species without connection to necessary water sources, which may reduce their ability to respond to the stimulus of fire. The disconnected stream and floodplain, and lack of water in burned systems, may favor ruderal non-native species and enable an advantage in disturbed riparian systems isolated from stream flows (Keeley 2006). For all sites, total species density and introduced species density did not vary significantly from one another in main or interaction effects.

Further research regarding restoration of severely incised channels and the native versus introduced plant species competitive post-fire window would benefit the timing of restoration application and prescribed burning in order to better manage introduced species often prevalent in riparian systems.

Woody deciduous plant species are also an important indicator of riparian condition and channel evolution potential (Webb & Leake 2006, Polvi et al. 2014, MacFarlane et al. 2017). Woody species including Salix, Populus, Alnus, Cornus and Rosa species contribute immensely to riparian bank stability (Polvi et al. 2014) with fast growing, net-like root systems. They also aid in process-based functions like slowing and deflecting flow and capturing debris and sediment (Naiman & DeCamps 1997, Wissmar 2004, Gonzalez et al. 2015). These species provide diverse habitat for organisms in the form of food, shelter, and habitat, especially for the keystone riparian species, beaver (Pollock et al. 1997, Nakano & Murakami 2001, Capon et al. 2013). Burned riparian systems with beavers had the greatest woody species cover of any treatment, primarily in floodplain landforms and in shrub strata. These findings suggest that beaver dam building activity accelerated recovery of vegetation communities and diversified habitat structure between herb and strata layers after fire and erosion disturbance. Managing for native, fire and flood adapted, woody riparian species after fire may be the most critical vegetation to support to stabilize channel banks, provide food and shelter for beavers and facilitate restoration of fire impacted streams and riparian systems (Naiman & DeCamps 1997, Dwire & Kauffman 2003, Polvi et al. 2014, et al. 2017).

CONCLUSION

Freshwater ecosystems, including riparian systems, may be the most threatened ecosystems globally due to the broad biodiversity they host, their high obligate species dependency, increasing anthropogenic degradation and mounting pressures from climate extremes including severe wildfire threatening their resilience (Dudgeon et al. 2006, Thomas et al. 2015)). Evidence from my research suggests that beaver dam building activity in wildfire impacted watersheds hastens restoration of these degraded systems. By improving water quality, increasing nutrient sequestration, accelerating stream evolution and improving riparian plant communities, beavers are increasing riparian resiliency after fire compared to burned watersheds without beaver activity (Figure 2.18). Evidence also suggests that restoring beaver to degraded riparian systems may require human intervention, especially following severe wildfire impact in low order streams. Where habitat is too degraded for initial restoration with beaver, the installation of beaver dam analogs and post assisted log structures (Pollock et al. 2014, Wheaton et al. 2019) may help slow high seasonal flows and jump start the stream evolution model with accelerated channel widening and sediment aggradation. Improving stream conditions enough to enable successful beaver recolonization, may be a feasible approach to restoring the most degraded low order streams after fire. Overall, evidence in this study suggests that restoring beaver to the western dryland landscape is a practical, low technology, relatively low cost, self-maintaining and perpetuating, landscape scale approach to repairing current, as well as historical, riparian system degradation. This study will hopefully inform short term application and long-term adaptive management planning for increased beaver restoration, conservation and ecological research, especially in response to wildfire impacts on low order stream riparian systems of the intermountain western US.

LIST OF TABLES AND FIGURES

Table 2.1 Approximate area burned in the Methow River watershed between 2001-2018. (USFS 2018)

Methow River Watershed Wildfire History		**Area Burned**
Fire Year	**Fire Name**	**Hectares**
2001	Thirtymile Creek	3,773
2001	Libby Creek South	1,538
2003	Farewell Creek	33,140
2006	Tatoosh Butte	21,391
2006	Tripod Peak	70,012
2014	Carlton Complex	103,270
2014	Little Bridge Creek	1,997
2014	Upper Falls Creek	3,391
2015	Twisp River Fire	4,541
2015	Black Canyon	13,248
2017	Diamond Creek	39,310
2018	Crescent Mountain	21,291
2018	McLeod	9,879
Approximate hectares burned since 2001		**326,781**

Table 2.2 a. Table describing my fully factorial study design of four treatments with three replicates and a total of 12 study sites. b. Study site matched replicates describing beaver and wildfire presence/absence at site. “Yes” for beaver can mean actual presence or hydrologically significant “HS” damming created by beavers but not currently maintained by beavers.

a.

12 sites	Beaver	No Beaver
Fire	3	3
No Fire	3	3

b.

Site	**Site ID**	**Watershed Area sq km**	**Beaver Presence**	**Burned Status**
Replicate 1				
South Fork Beaver Creek	9	30.95	Yes	No
Middle Fork Beaver Creek	9_2	21.86	No	No
Bear Creek	45	29.63	Yes	Yes 2014
Benson Creek	45_2	31.91	No	Yes 2014
Replicate 2				
Upper Cub Creek	21	2.64	Yes	No
Third Creek	21_3	3.11	No	No
South Fork Benson Creek	13	4.06	Yes	Yes-2014
North Fork Benson Creek	13_2	10.38	No	Yes-2014
Replicate 3				
Mission Creek	49	23.93	Yes (HS)	No
Chicamun Creek	49_5	9.89	No	No
Swaram Creek/Hunter Mtn Rd	32	23.38	Yes (HS)	Yes-2014
Frazer Creek	49_3	21.93	No	Yes-2014

Table 2.3 Landform, ground cover and strata classification.

Landform Classification	Ground Cover Classification	Vegetation Strata Classification	
Upland	Woody > 10 cm	Herb	< 0.5 m
Floodplain Terrace	Woody litter < 10 cm	Shrub	0.5 - 1.5 m
Floodplain	Litter	Understory	1.5 - 15 m
Floodplain Bank	Bare soil	Canopy	15 - 30 m
Bar	Rock	Emergent	> 30 m
Water	Sand	Snag	Dead standing

Table 2.4 Primary physical characteristics of stream channel cross sections and sediment particle size distribution in study site transects.

Transect		**Presence**		**Channel Characteristics**						**Particle Size**		
Transect ID	**T1 T2**	**Beaver**	**Burned**	**Bankfull Width**	**Bankfull Depth-mean**	**W/D Ratio**	**Max depth**	**Surface Water Width**	**Surface Water Depth**	**D16**	**D50**	**D84**
Replicate 1												
91	T1	Yes	No	5.16	0.44	11.73	0.59	5.99	0.14	16	90	256
92	T2	Yes	No	6.07	0.16	37.8	0.38	6.43	0.21	4	4	6
921	T1	No	No	6.1	0.35	17.43	0.85	6.49	0.29	4	11	32
922	T2	No	No	5.75	0.46	12.5	0.71	3.66	0.13	4	22	90
451	T1	Yes	Yes	2.18	0.47	4.64	0.56	2.63	0.09	4	8	45
452	T2	Yes	Yes	67	0.22	304.6	0.56	26.3	0.39	4	4	4
4521	T1	No	Yes	6.21	0.29	21.41	0.58	2.25	0.06	4	32	128
4522	T2	No	Yes	2.26	0.44	5.14	0.60	1.87	0.29	4	32	128
Replicate 2												
211	T1	Yes	No	24.14	0.34	71	0.92	17.3	0.24	4	4	4
212	T2	Yes	No	33.2	0.21	160.9	0.85	1.5	0.44	4	4	4
2131	T1	No	No	2.25	0.19	11.84	0.24	1.62	0.03	4	8	22
2132	T2	No	No	1.82	0.16	11.38	0.28	0.59	0.07	4	32	90
131	T1	Yes	Yes	3.4	0.4	8.5	0.69	0.65	0.05	6	8	11
132	T2	Yes	Yes	6.82	0.19	35.89	0.53	4.15	0.20	4	4	4
1321	T1	No	Yes	4.56	0.46	9.91	0.62	1.15	0.05	4	6	8
1322	T2	No	Yes	3.12	0.38	8.21	0.58	1.50	0.11	4	6	8
Replicate 3												
491	T1	Yes	No	3.7	0.25	14.8	0.4	3.14	0.15	4	11	32
492	T2	Yes	No	83.7	0.62	135	1.43	76.9	0.79	4	4	4
4951	T1	No	No	1.89	0.09	20.02	0.14	1.63	0.05	22	45	90
4952	T2	No	No	1.47	0.12	11.8	0.21	0.95	0.03	16	64	128
321	T1	Yes	Yes	2.56	0.37	6.92	0.49	2.39	0.21	4	64	181
322	T2	Yes	Yes	3.35	0.4	8.38	0.59	3.10	0.03	4	16	90
4931	T1	No	Yes	3.35	0.55	6.09	0.74	2.08	0.13	4	45	128
4932	T2	No	Yes	3.5	0.42	8.33	0.63	2.42	0.13	4	64	181

Table 2.5 Percent cover of varying landforms and ground cover in each study transect.

Transect		**Presence**		**Landforms**						**Ground Cover**					
Transect ID	**Transect location**	**Beaver**	**Burned**	**% Upland**	**% Floodplain Terrace**	**% Floodplain**	**% Floodplain Bank**	**% Bar**	**% Water**	**% Litter**	**% Woody Litter**	**% Wood**	**% Rock**	**% Sand**	**% Bare Soil**
91	T1	Yes	No	16.9	0	45.1	38	0	10.1	72.4	17.3	23.4	1.5	9.4	2.6
92	T2	Yes	No	24.9	7.95	41.1	7.95	8	12.15	94.9	14.9	4.7	0.0	6.9	0.0
921	T1	No	No	0	0	36.8	19.3	8.9	34.9	16.4	27.5	6.0	0.0	8.8	0.8
922	T2	No	No	0	0	65.5	21	0	13.5	78.5	69.2	9.1	0.0	3.7	0.0
451	T1	Yes	Yes	20.1	0	60.8	13.7	0	4	92.7	65.4	4.9	0.0	0.0	1.3
452	T2	Yes	Yes	1.39	0	68.1	1.3	0	29.6	10.7	60.3	6.2	0.0	0.0	0.0
4521	T1	No	Yes	39.7	47.2	0	2	7.8	3.3	33.8	28.0	1.3	5.8	67.5	11.0
4522	T2	No	Yes	0	80.3	0	12.93	0	6.8	66.0	37.6	6.9	0.3	25.8	0.0
211	T1	Yes	No	3.8	0	48	37.6	5.8	4.8	90.4	42.5	4.9	0.0	4.8	0.0
212	T2	Yes	No	0	0	92.6	0	0	7.3	90.8	22.4	6.5	0.0	0.0	0.0
2131	T1	No	No	15.2	14.5	51.1	13.7	0	5.5	91.6	28.8	8.5	0.0	0.0	2.1
2132	T2	No	No	0	12.7	65.2	18	0	4.1	83.7	87.4	0.5	12.5	0.0	3.8
131	T1	Yes	Yes	22.7	0	63.7	8.7	2.2	2.7	83.5	74.3	8.0	1.1	2.2	2.4
132	T2	Yes	Yes	0	0	52.6	30.2	8.2	9	58.6	96.6	6.6	0.0	0.0	8.2
1321	T1	No	Yes	37.5	31.4	0	14.3	11.3	5.6	69.4	20.5	0.0	0.0	21.1	0.0
1322	T2	No	Yes	0	82.7	0	5	4.4	7.9	83.9	1.7	0.0	0.0	7.1	0.6
491	T1	Yes	No	40.7	0	34.72	0	6.6	17.8	82.2	59.9	4.6	3.8	0.0	1.2
492	T2	Yes	No	3.2	0	14.67	7.11	0	75	17.3	2.4	0.7	0.0	0.0	0.0
4951	T1	No	No	25.1	38.4	13.5	15.3	0	7.5	93.4	69.3	3.6	7.5	0.0	0.0
4952	T2	No	No	58.7	16.4	0	20.1	0	4.6	96.5	84.8	0.0	4.6	0.0	0.0
321	T1	Yes	Yes	0	73.2	0	15.4	2.2	9.2	89.2	48.6	3.9	1.0	0.0	0.0
322	T2	Yes	Yes	0	33	58	1.7	0.1	3.4	0.0	44.2	4.8	0.0	0.0	1.4
4931	T1	No	Yes	29.9	37.7	0	23.7	0	9.1	81.7	18.5	4.3	0.0	43.3	0.0
4932	T2	No	Yes	0	42.5	0	44.9	5.6	7.2	83.6	59.4	0.0	14.1	4.1	0.0

Table 2.6 Plant species that indicate deciduous woody habitat, representing and supporting increased bank stabilization, habitat complexity and biodiversity in riparian systems.

Woody Species	Burned Sites No Beaver	Burned sites Yes Beaver
Acer glabrum	22.8	43.7
Alnus incana	22.9	161.1
Cornus sericea	56.9	177
Populus tremuloides	36.3	9.4
Populus trichocarpa	35.4	0
Pseudotsuga menziesii	45.4	194.4
Rosa spp.	44.7	53.4
Salix spp.	28.6	42.2

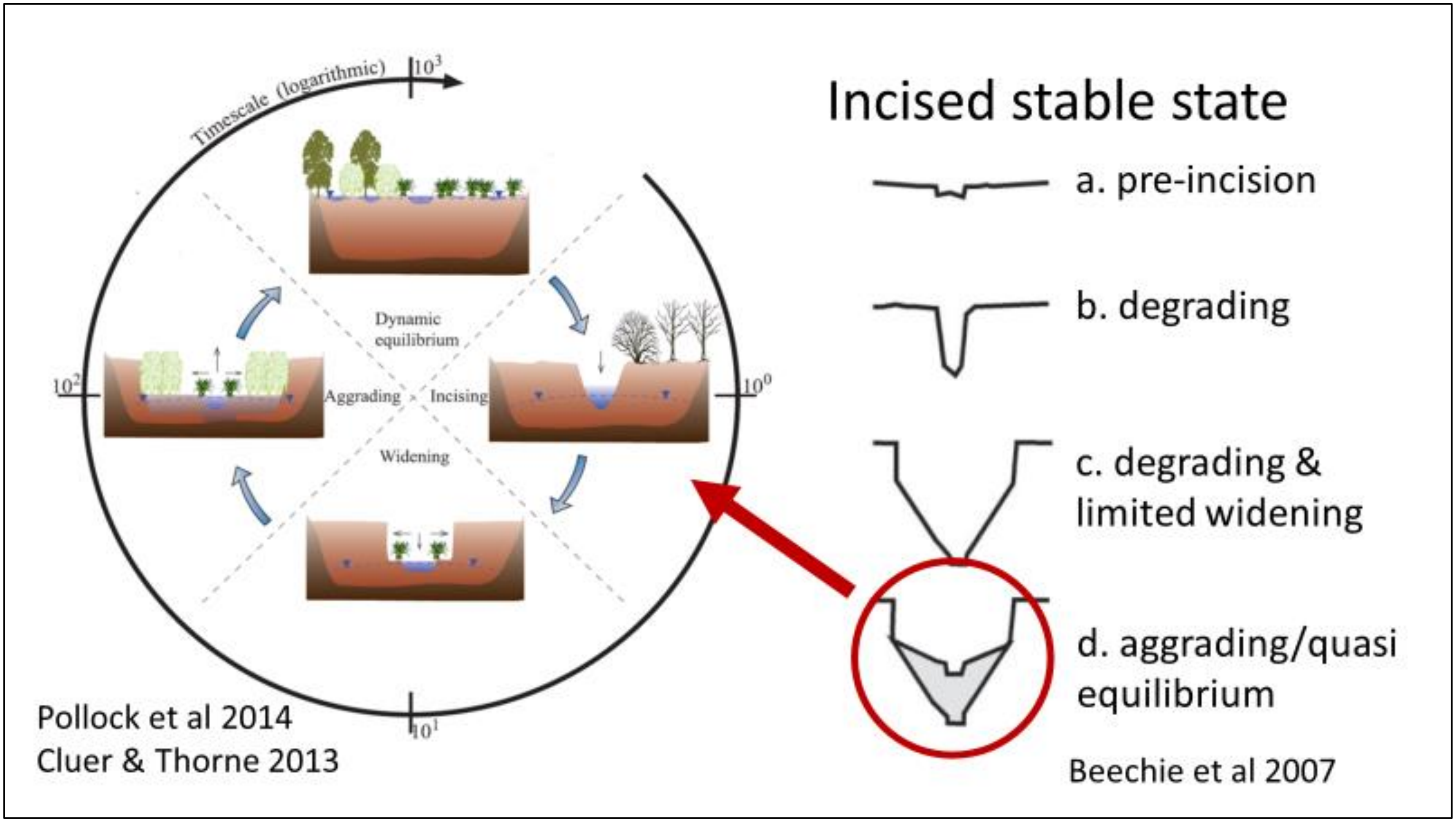


Figure 2.1 Stream evolution models and stable degraded state concepts are helping to explain the risk, vulnerability and reality that exists in burned watersheds across the western US. Reprinted with permission from Pollock et al 2014. Copyright 2014 Oxford University Press. Reprinted from Beechie et al 2007. Wiley Science public domain.

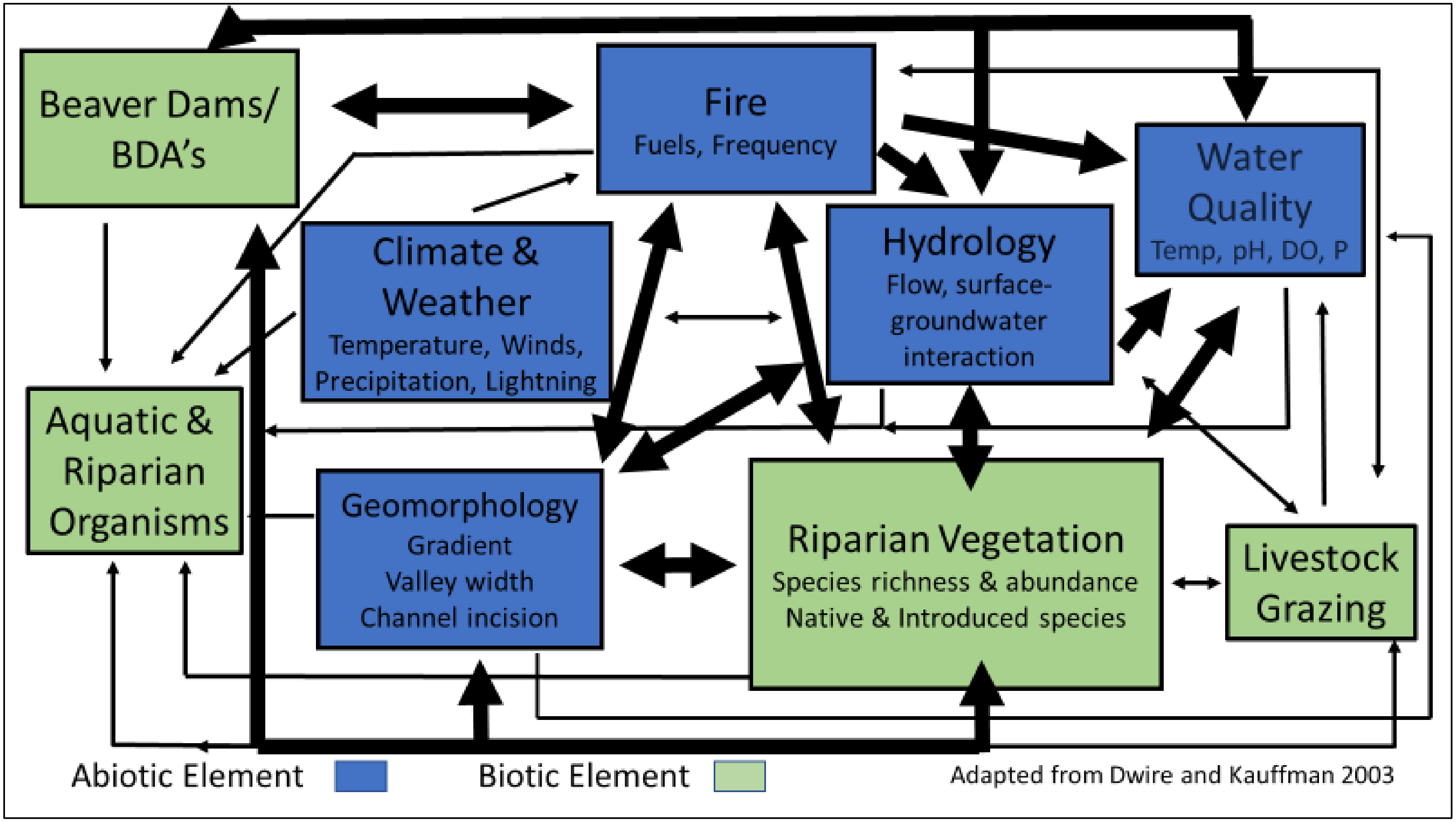


Figure 2.2 Conceptual model of physical and biotic disturbance interactions within Methow River sub-basins. Bold arrows indicate interactions investigated in this study. Adapted with permission from Dwire and Kauffman 2003. US Dept of Agriculture. Copyright 2003 Elsevier.

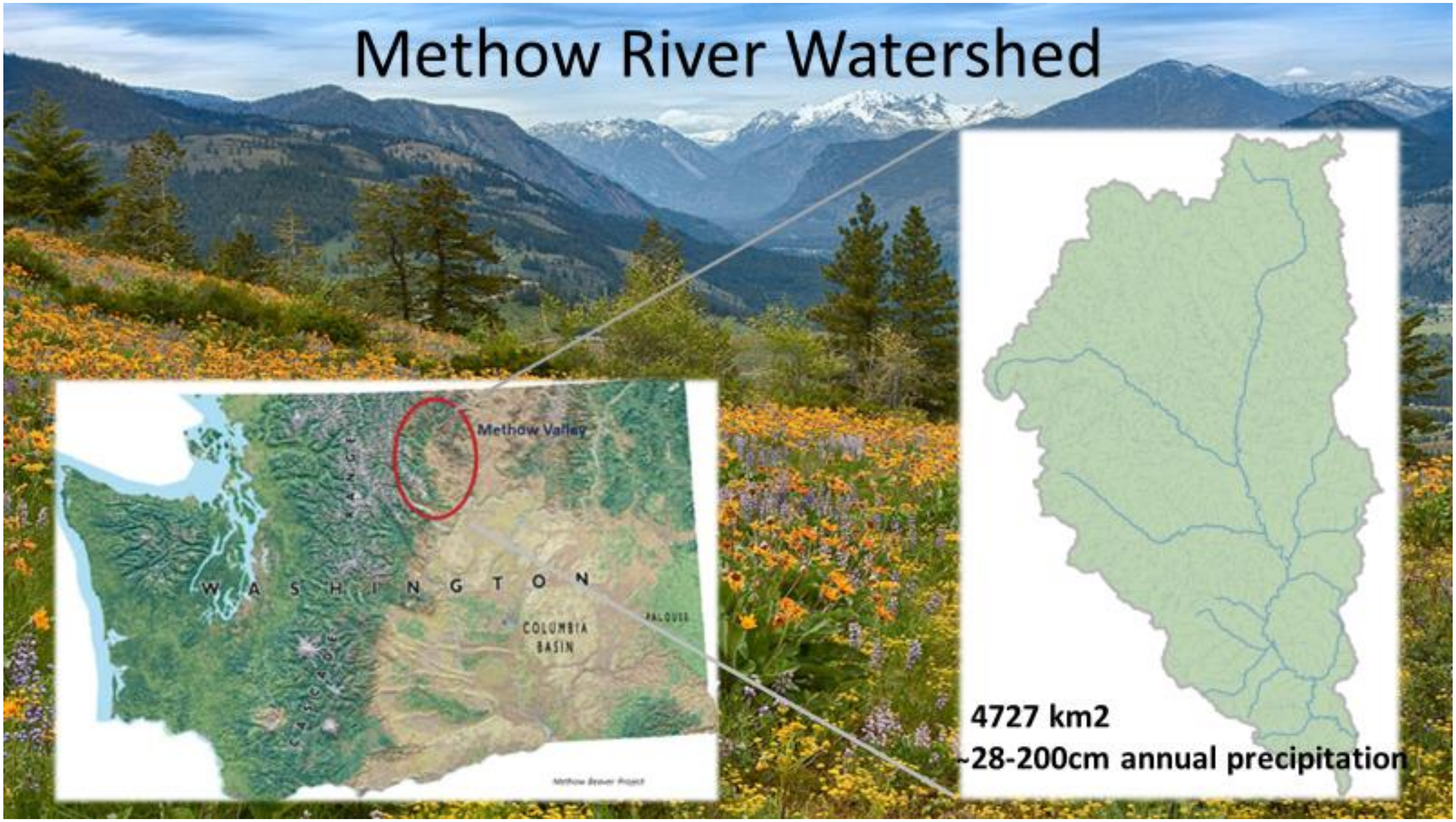


Figure 2.3 The Methow River watershed, a tributary of the Columbia River, comprised of 4727 km^2 of sagebrush steppe and Ponderosa Pine dominated plant communities and located in north central Washington State on the eastern crest of the North Cascades Mountains. (WA state map: Methow Beaver Project)

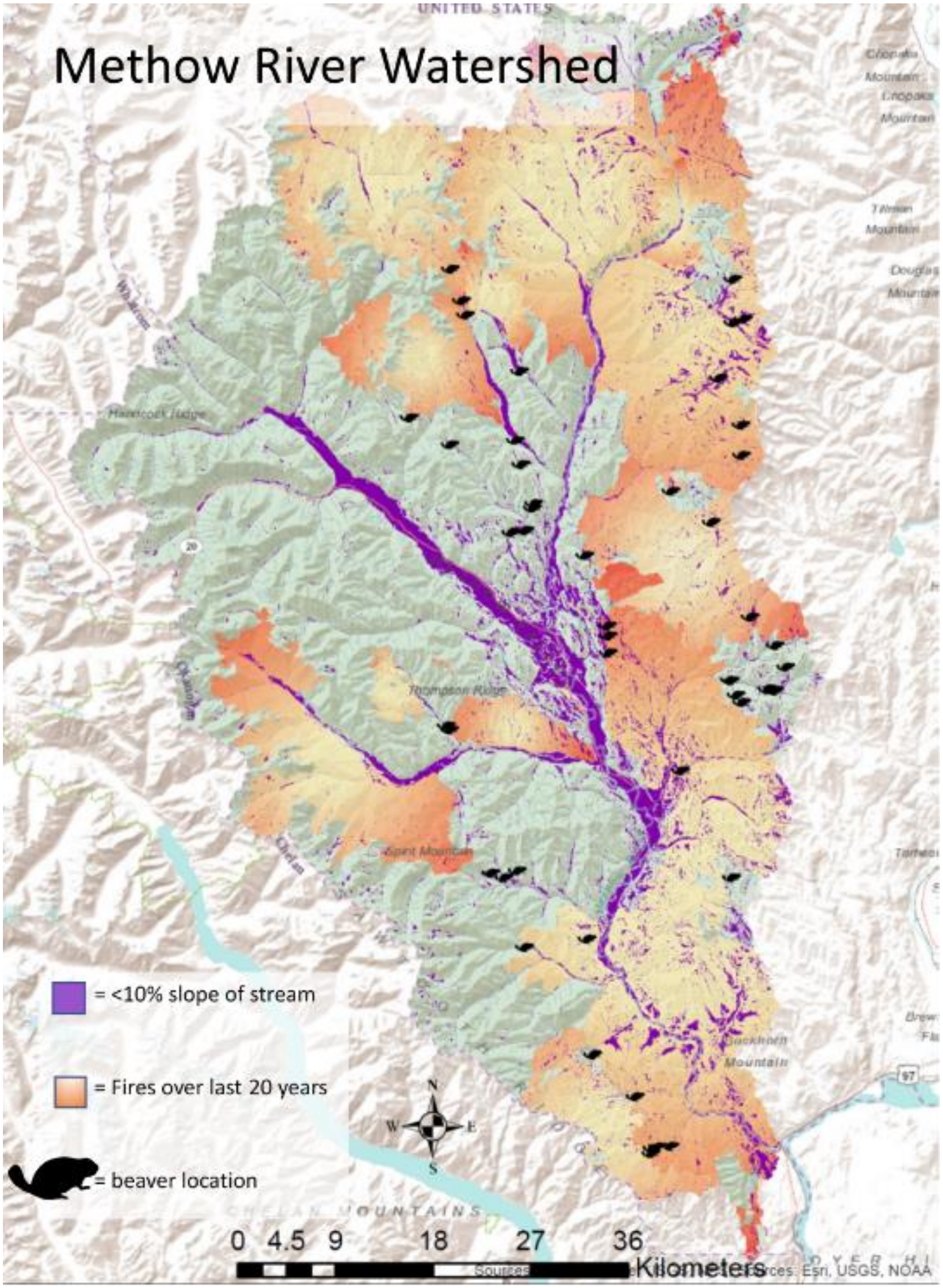


Figure 2.4 Known beaver locations, current and historic with wildfire boundaries in orange gradient from the last 20 years of fire and stream channels with gradients <10% in purple.

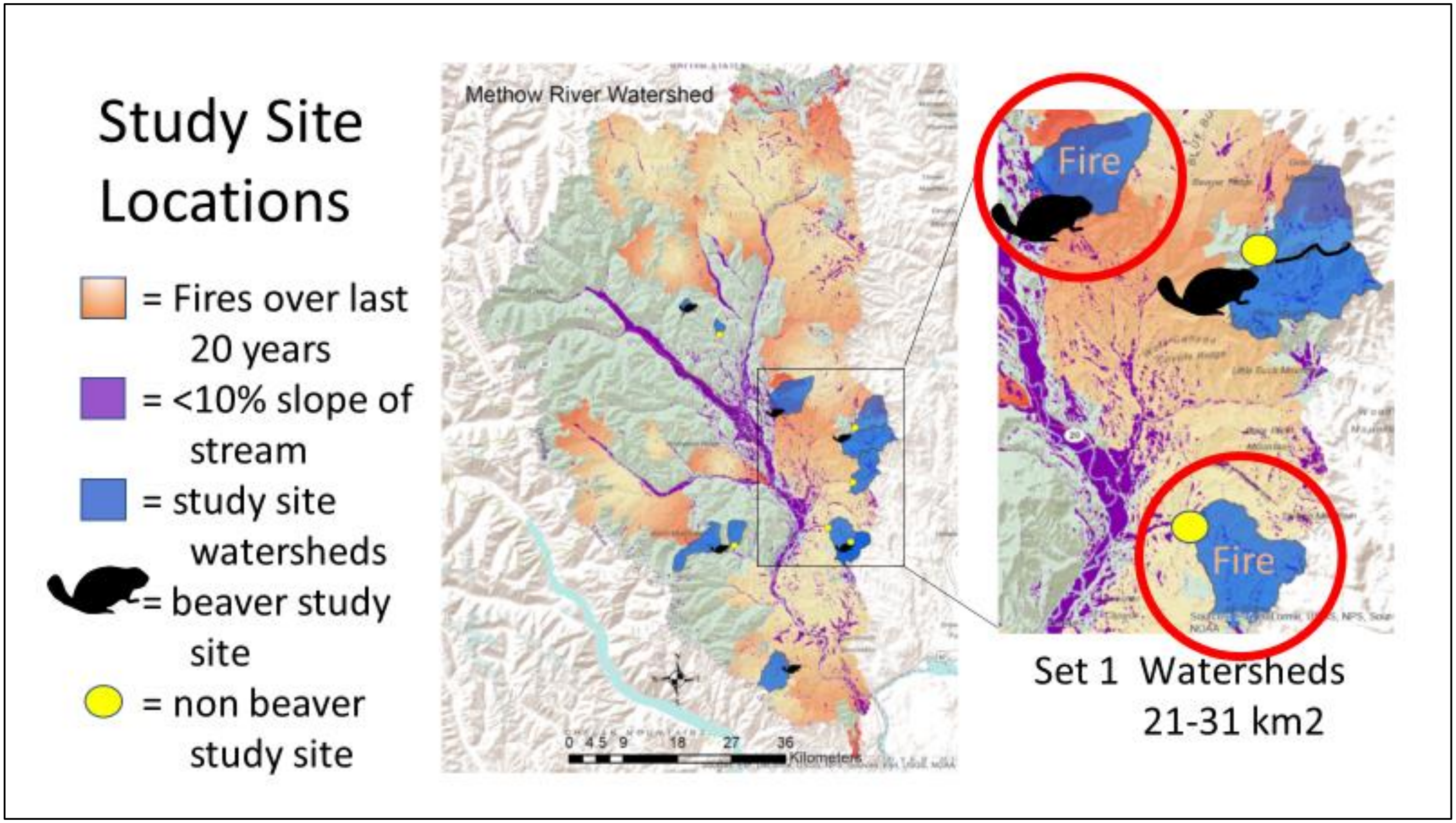


Figure 2.5 Twelve study site locations grouped as three replicates of four treatments, example of one replicate expanded.

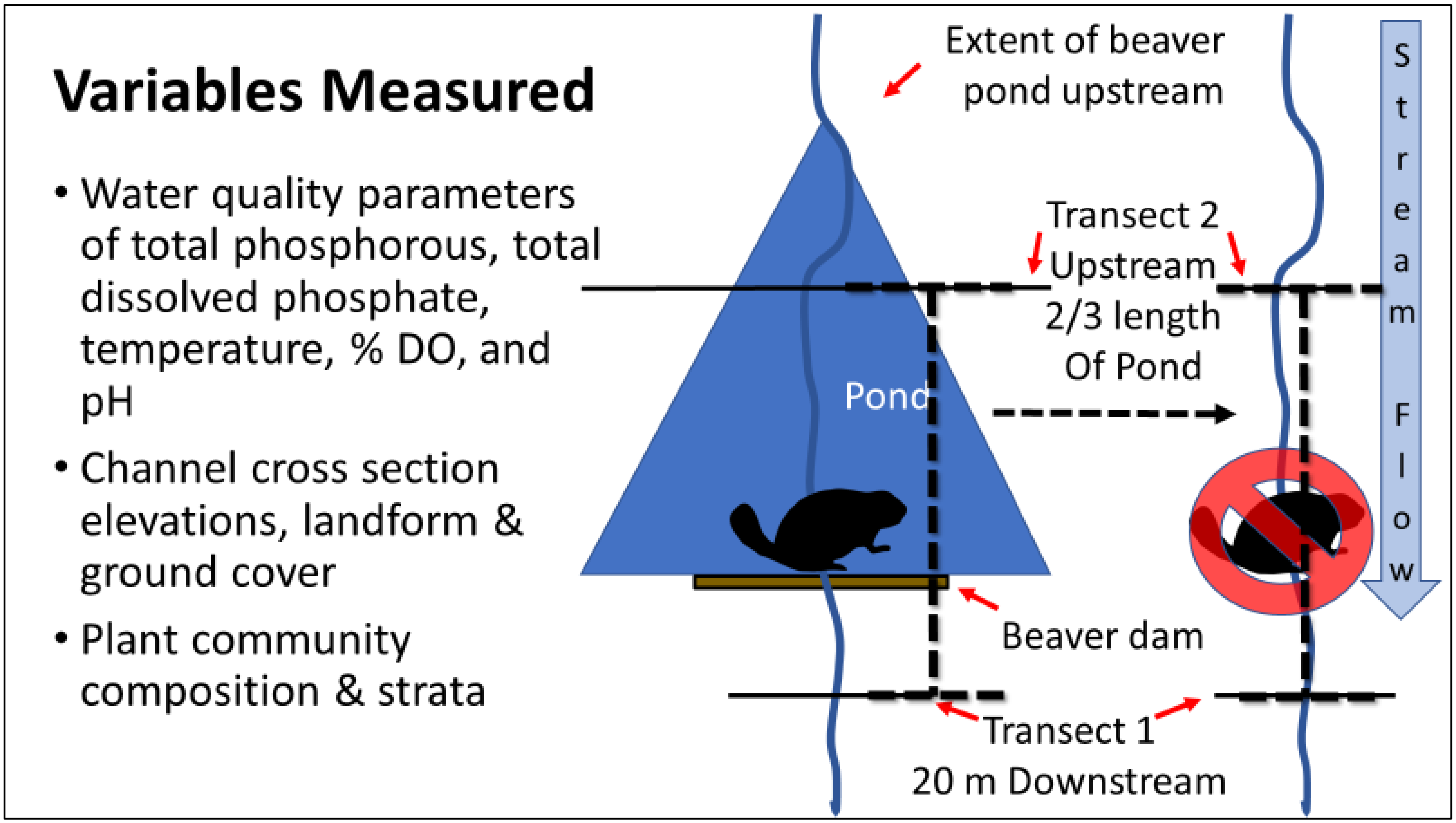


Figure 2.6 Transect locations determined by most downstream beaver dam and extent of obvious beaver ponding influence upstream. Transect one located 20 m downstream of lowest dam and Transect 2 located 2/3 the distance between lowest dam and upper extent of beaver complex in order to standardize variation between sites. Transect locations from beaver sites were overlaid on paired non-beaver sites with similar watershed size and abiotic conditions to standardize. Three categories of dependent variables were measured at each transect.

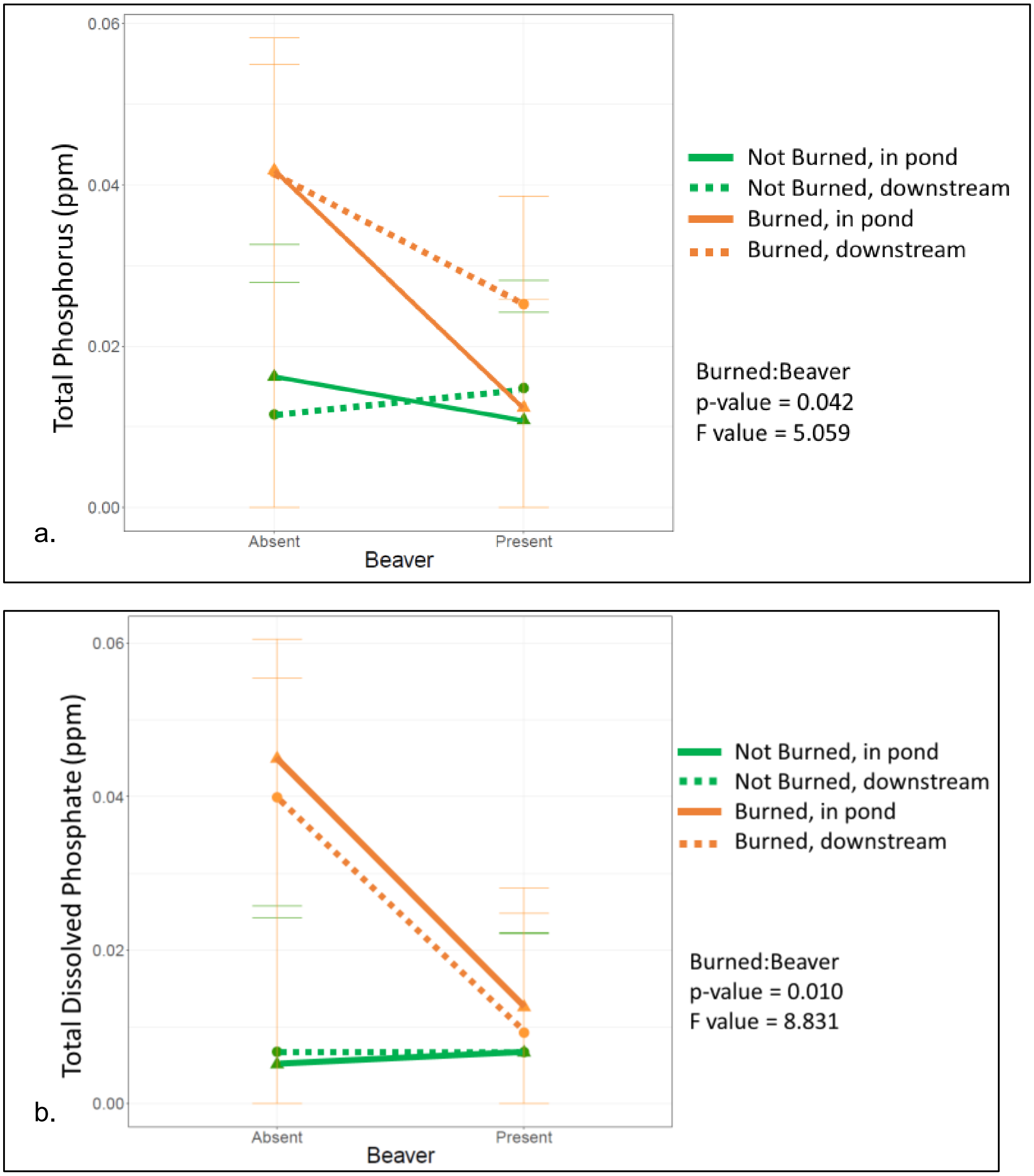


Figure 2.7 Effects of beaver, burning, and transect location on both a. Total Phosphorus (ppm) and b. Total Dissolved Phosphate (ppm) in riparian systems four years after wildfire. P values reported are from mixed model analyses (Appendix 2.2).

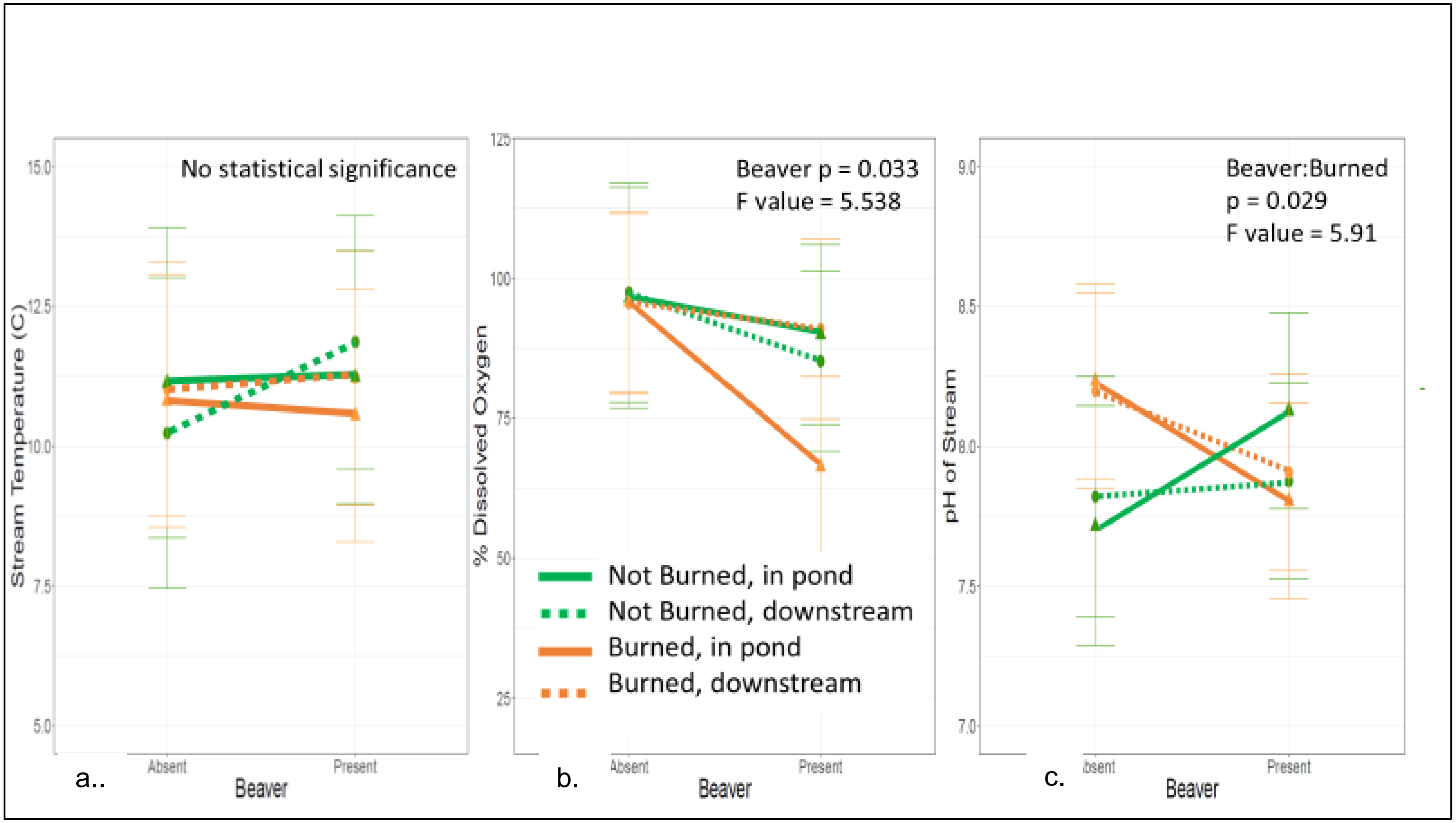


Figure 2.8 a. Effects of beaver, burning, and transect location on stream temperature, b. % dissolved oxygen, c. and stream pH with p values from mixed model analysis (Appendix 2.2).

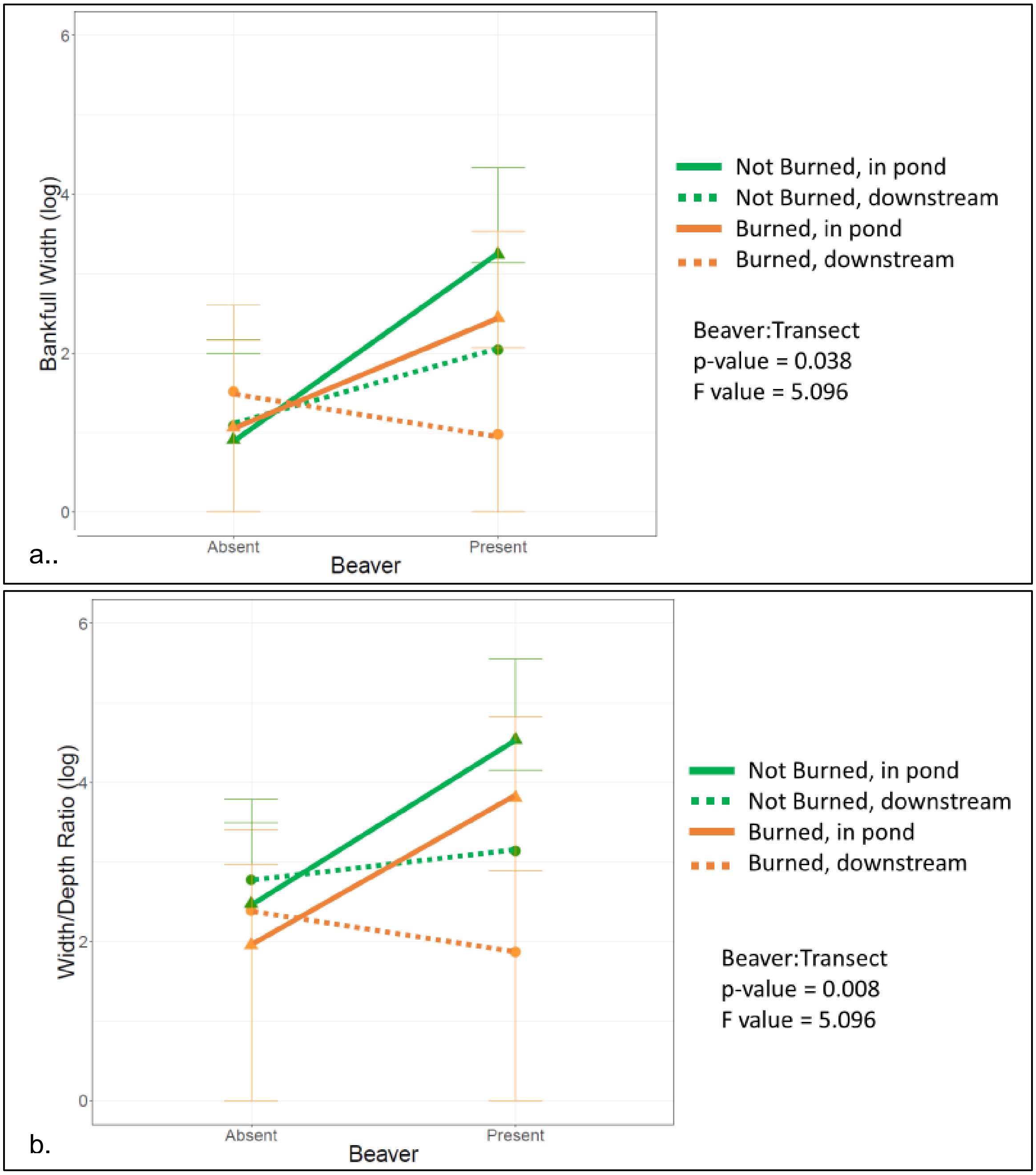
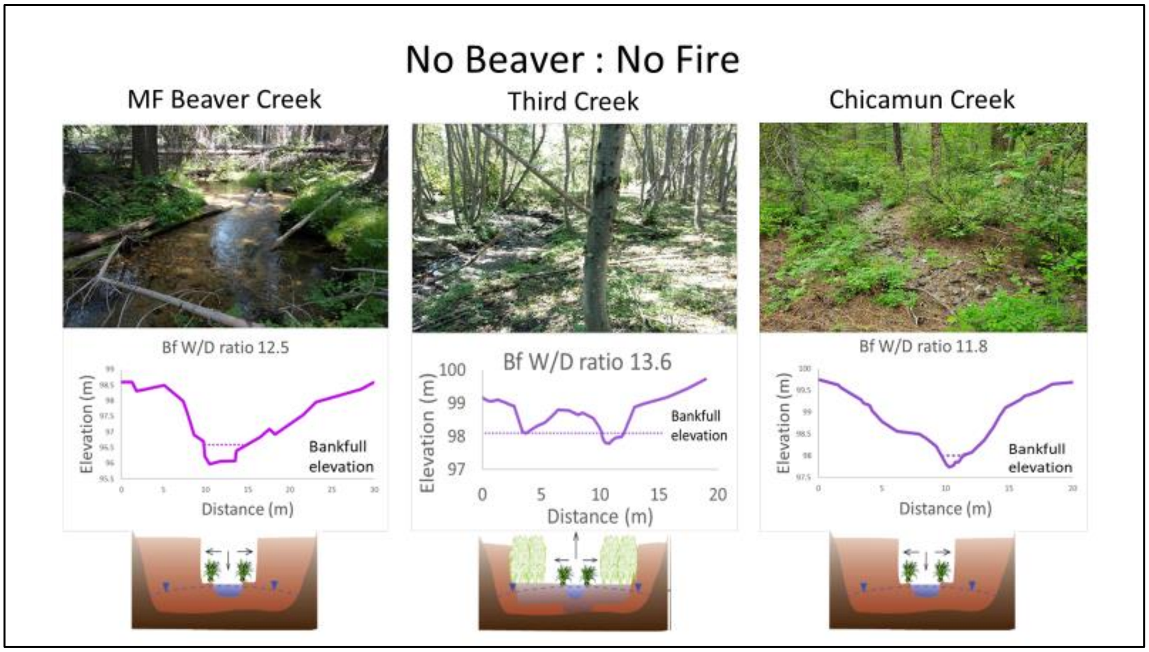
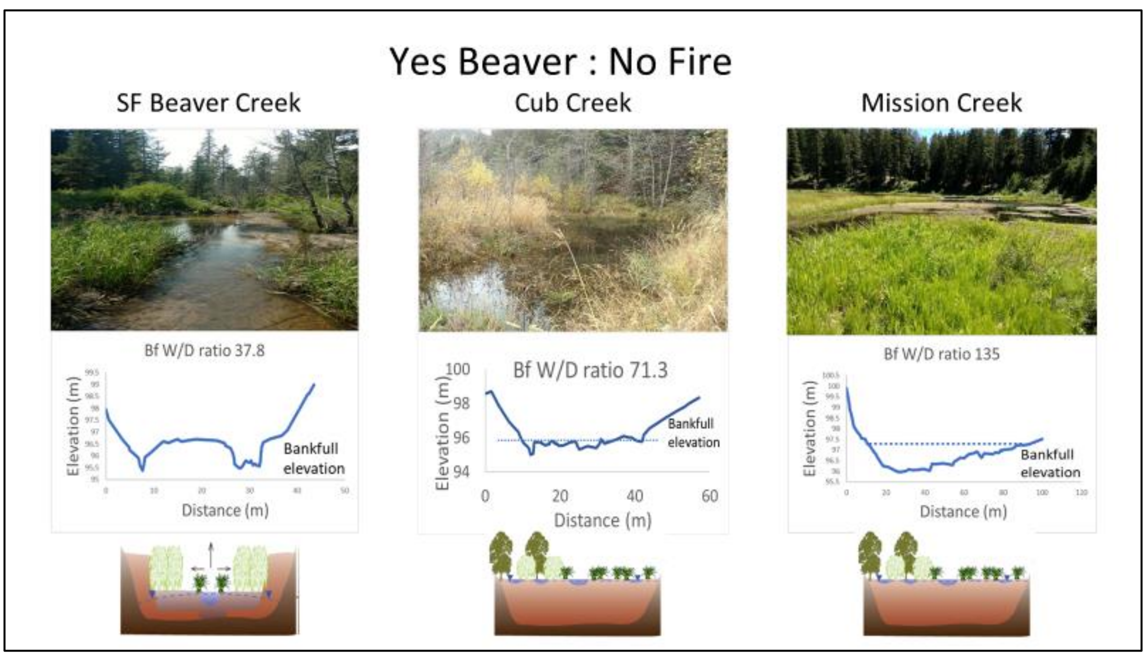


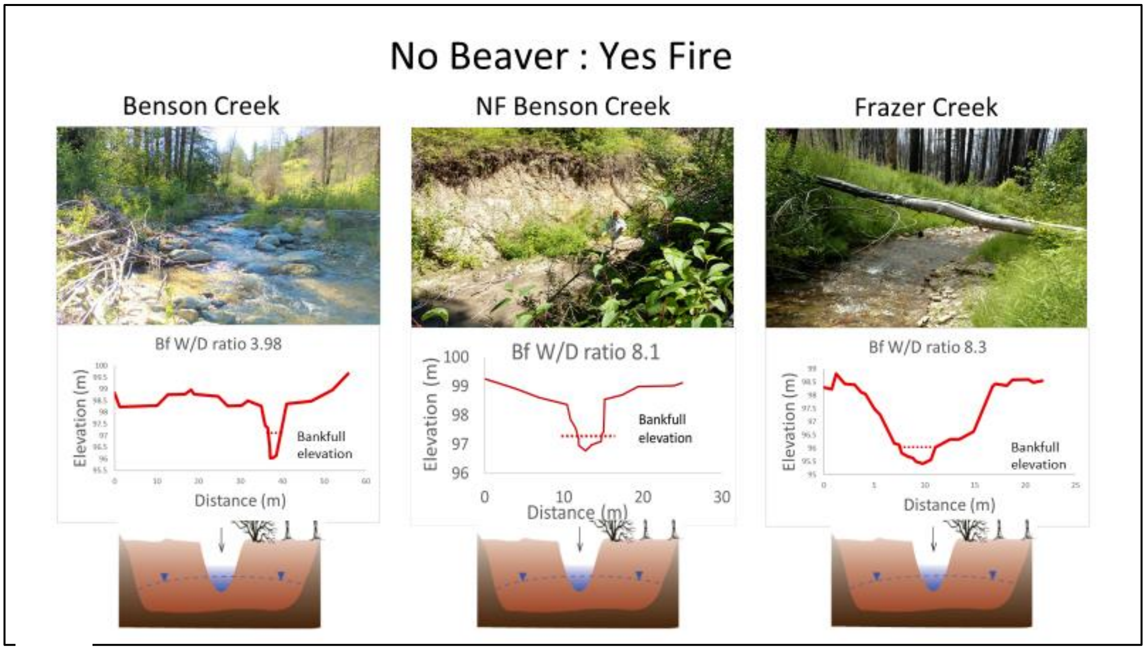
Figure 2.9 Effects of beaver, burning, and transect location on a. bankfull widths and b. width/depth ratios, with p values from mixed model analysis (Appendix 2.2).


No Beaver : No Fire
MF Beaver Creek
Third Creek
Chicamun Creek
Bf W/D ratio 12.5
Bf W/D ratio 13.6
Bf W/D ratio 11.8
Elevation (m)
Distance (m)
Bankfull elevation

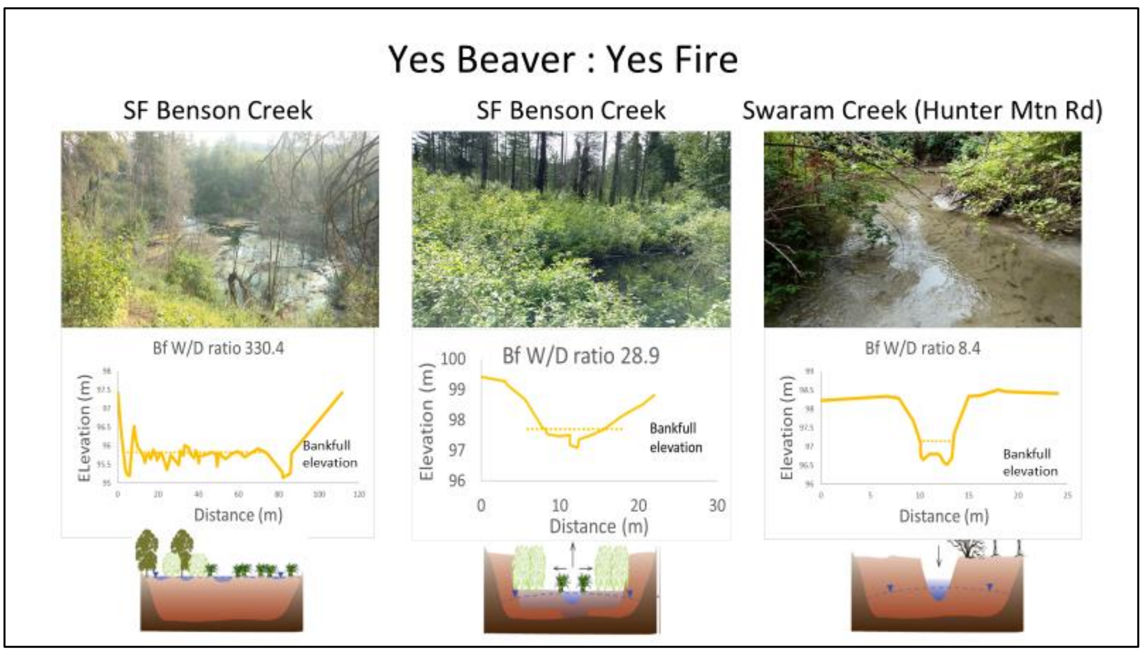
a..


Yes Beaver : No Fire
SF Beaver Creek
Cub Creek
Mission Creek
Bf W/D ratio 37.8
Bf W/D ratio 71.3
Bf W/D ratio 135
Elevation (m)
Distance (m)
Bankfull elevation

b..



c..



d..

Figure 2.10 Stream channel cross sections for each site, grouped by treatment, a. no beaver:no fire, b. yes beaver:no fire, c. no beaver:yes fire, d. yes beaver:yes fire, and channel condition compared to modeled stream channel evolution.

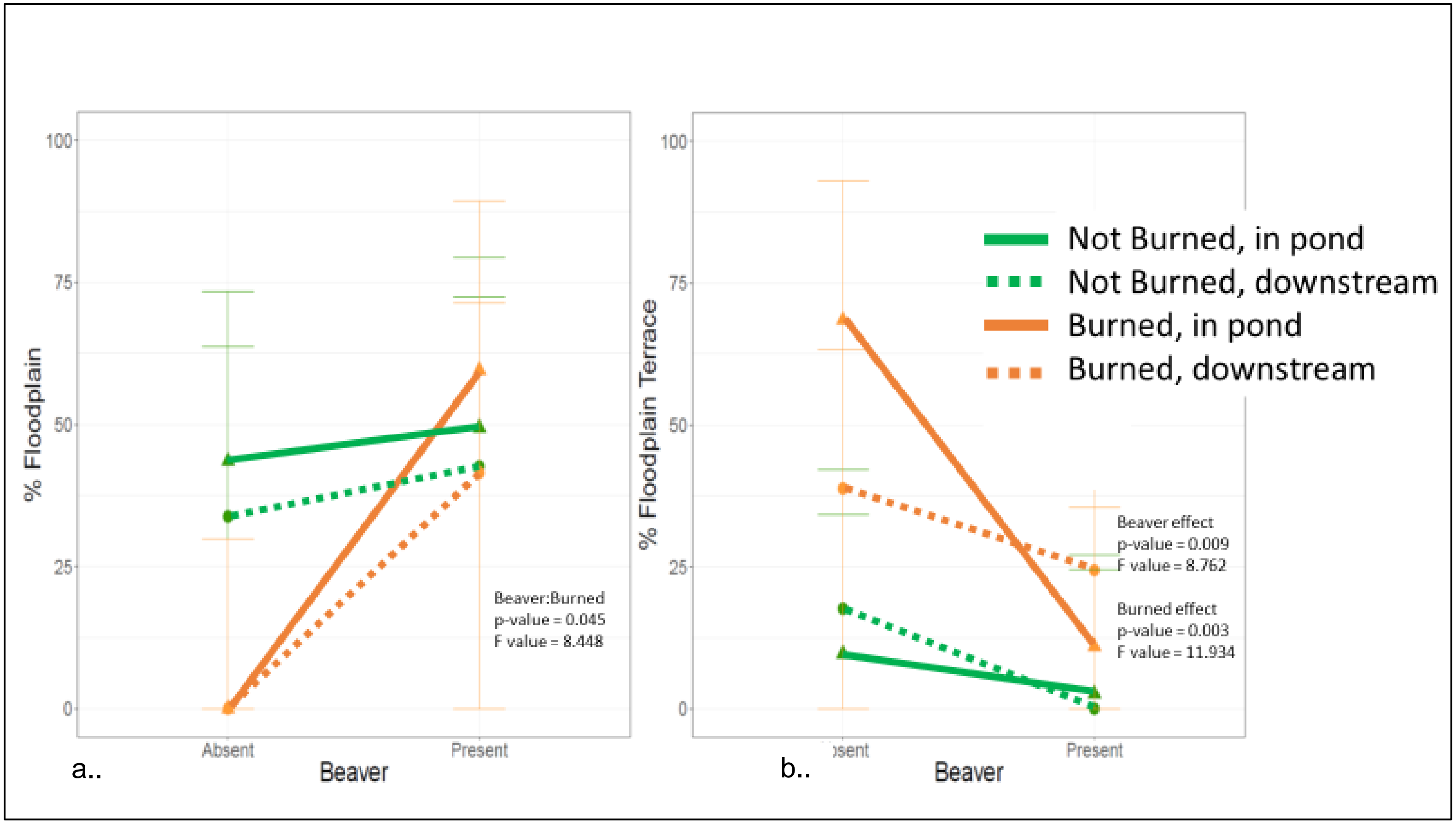


Figure 2.11 Effects of beaver, burning, and transect location on a. Floodplain and b. Floodplain Terrace landform representation across stream channel profiles with p values reported from mixed model analysis (Appendix 2.2).

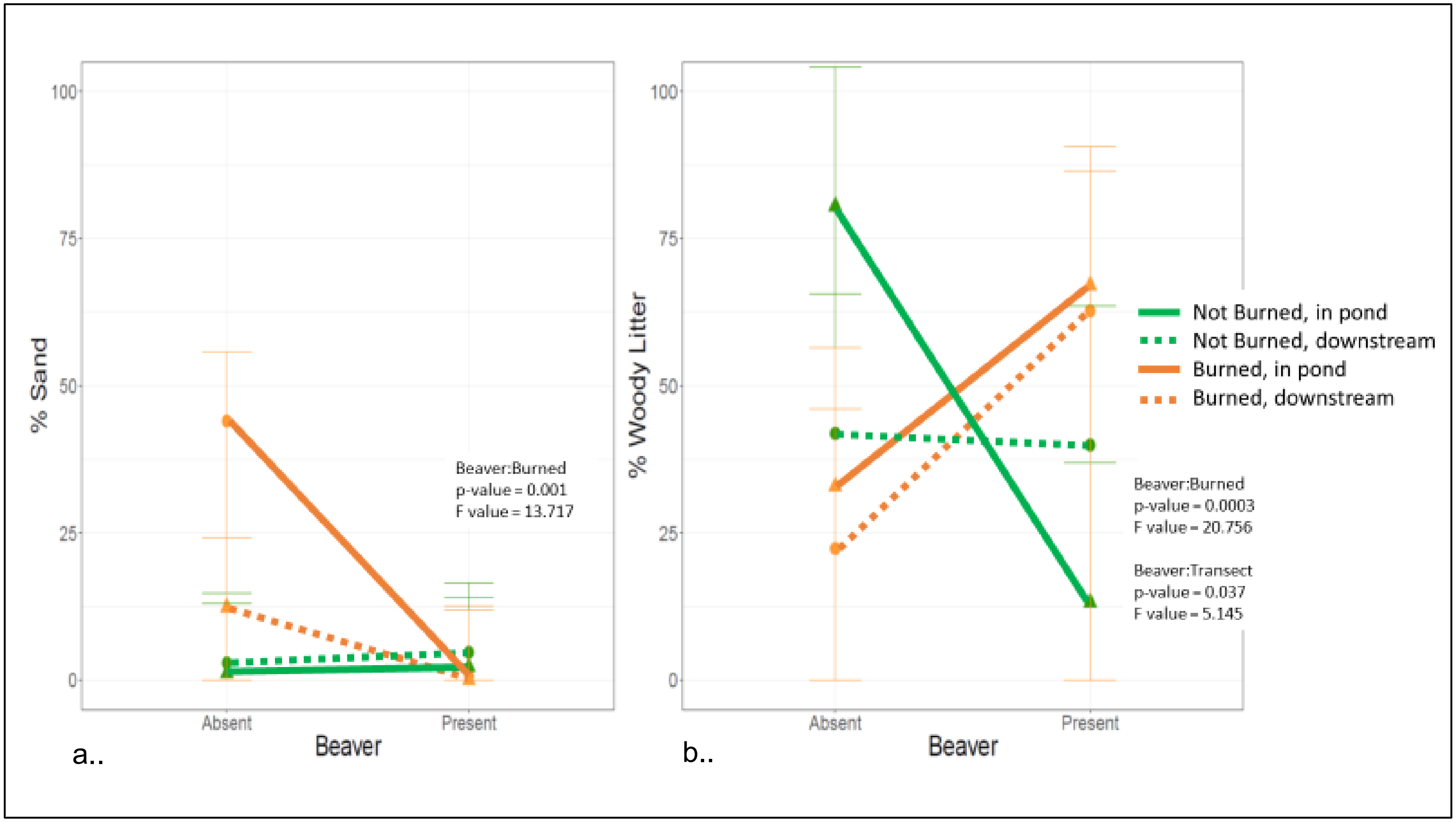


Figure 2.12 Effects of beaver, burning, and transect location on a. Sand and b. Woody Litter ground cover across channel profiles with p values reported from mixed model analysis (Appendix 2.2).

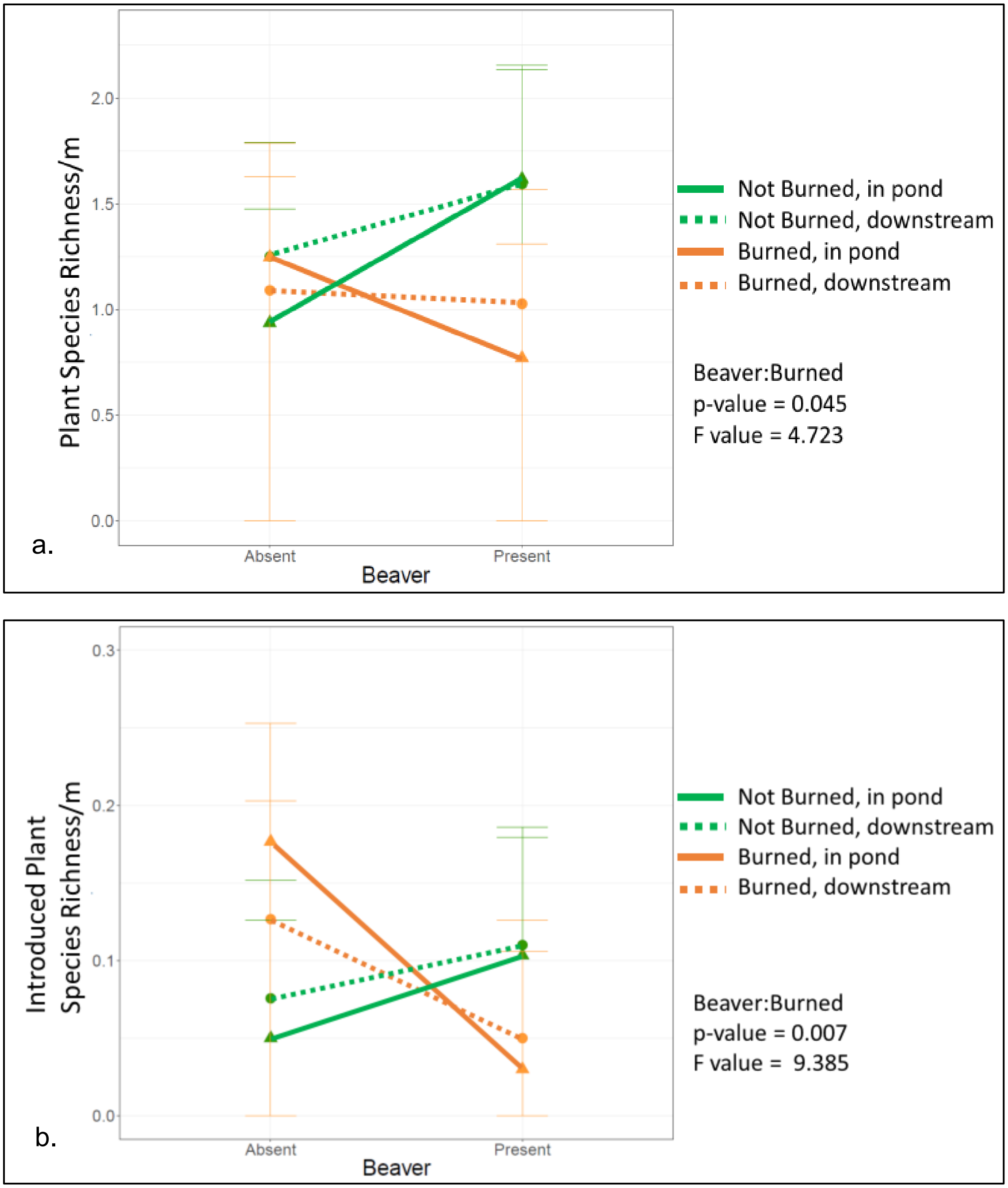
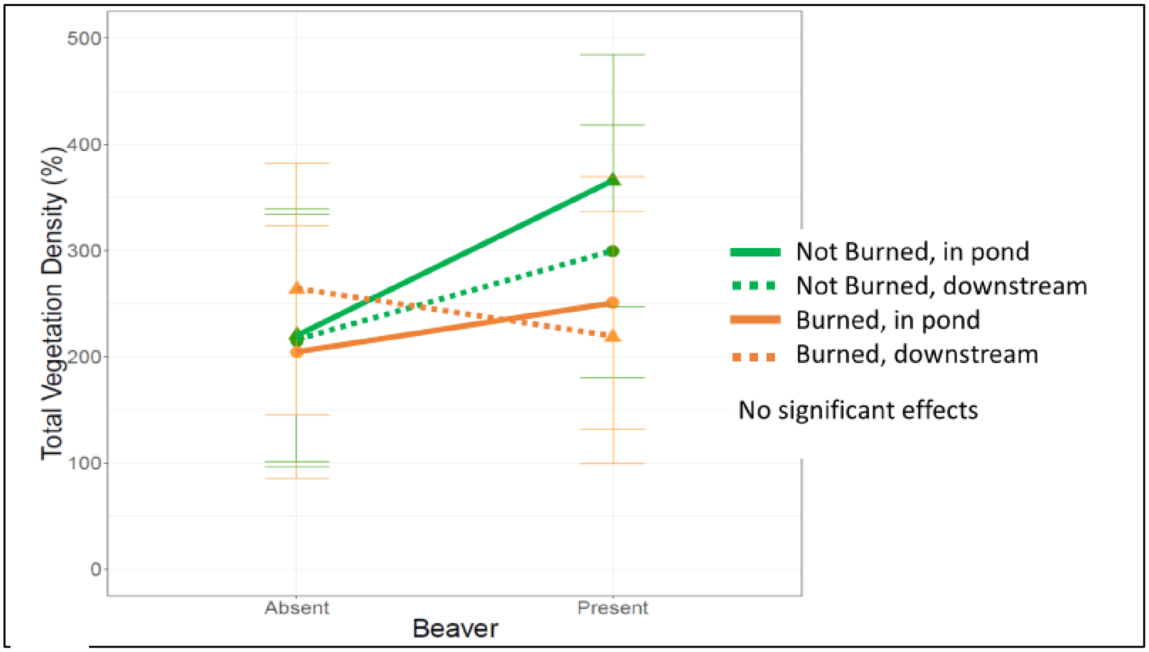
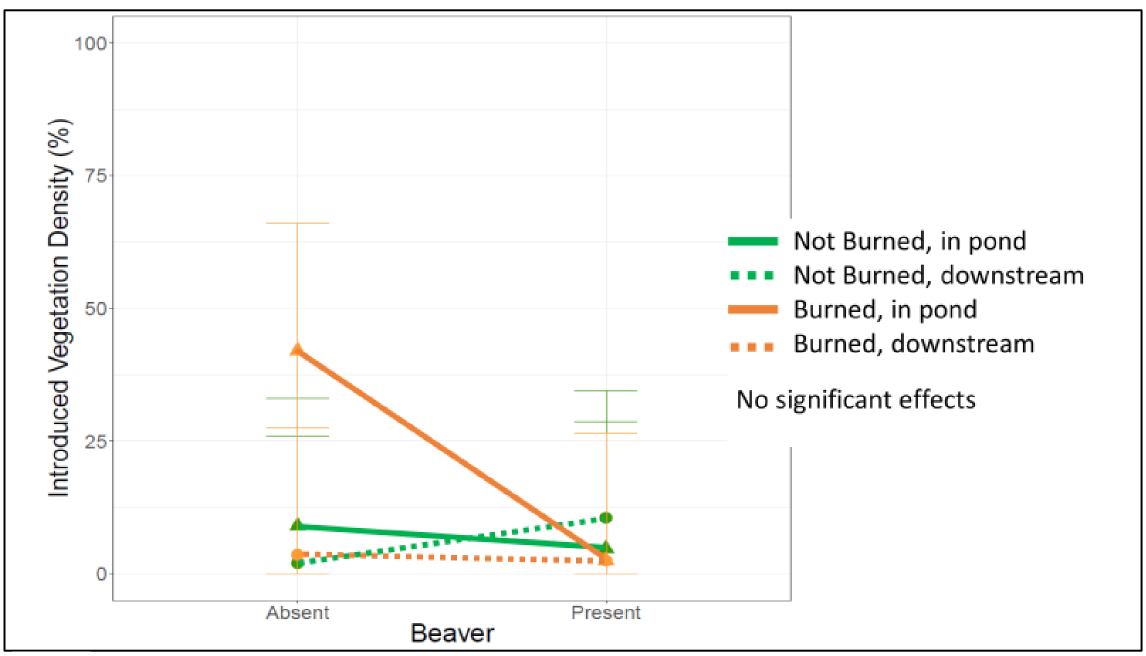


Figure 2.13 a. Effect of interactions between beaver, burning and transect location factors on a. total plant species richness/meter and b. introduced (non-native) plant species richness/meter with p values reported from mixed model analysis (Appendix 2.2).



a.



b.

Figure 2.14 Effects of beaver, burning, and transect location on a. total vegetation density (% of transect) and, b. introduced species density with p values reported from mixed model analyses (Appendix 2.2).

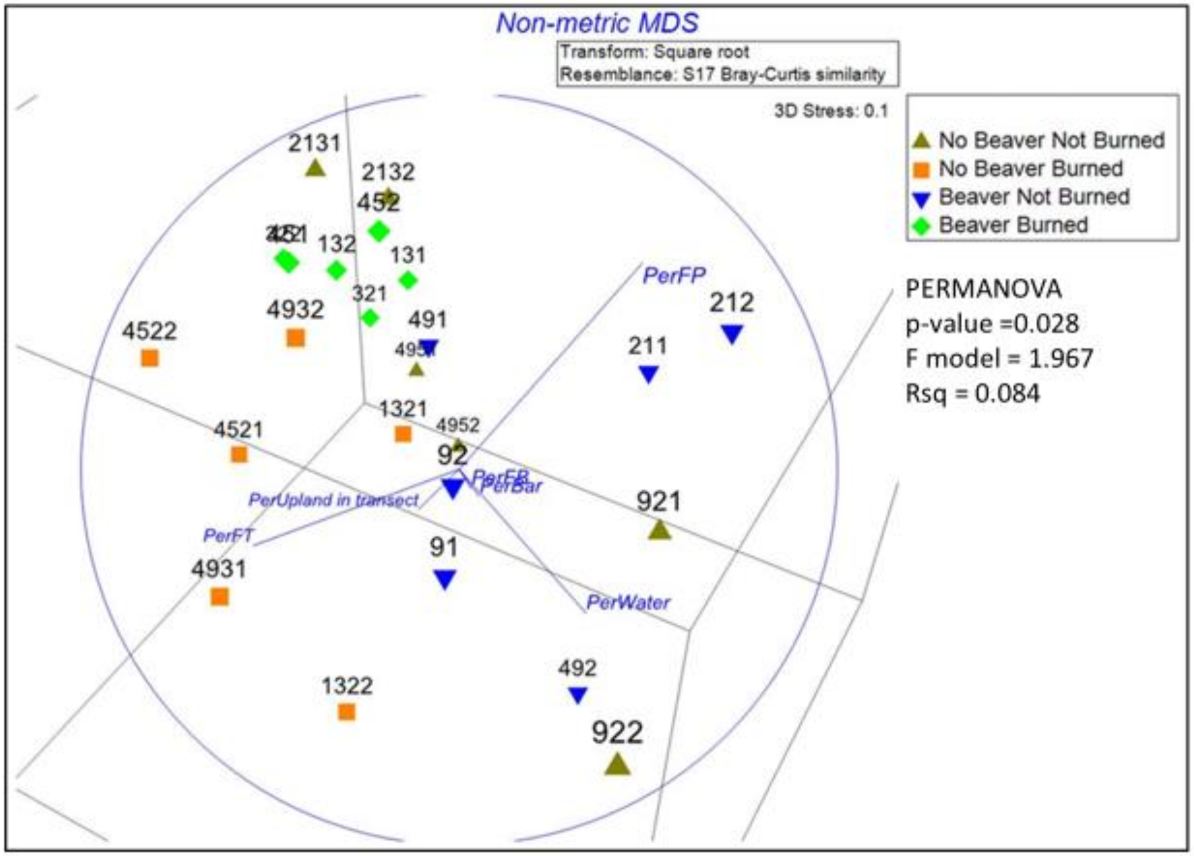
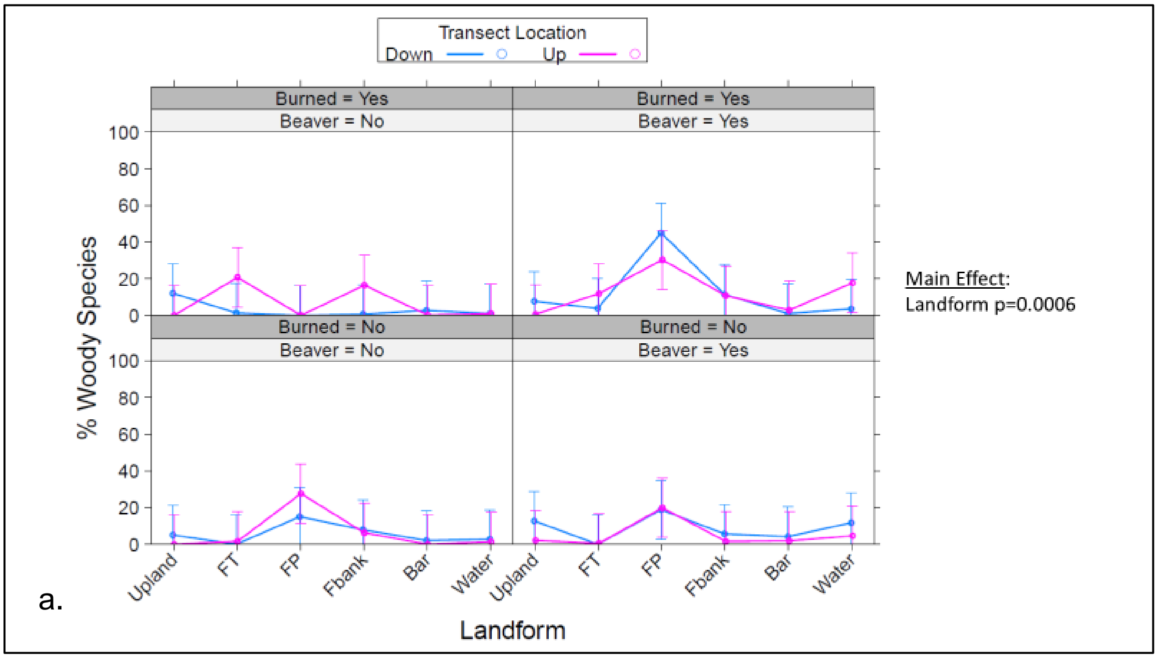


Figure 2.15 Vegetation species composition correlated with landform vectors using NMDS ordination (Appendix 2.3).



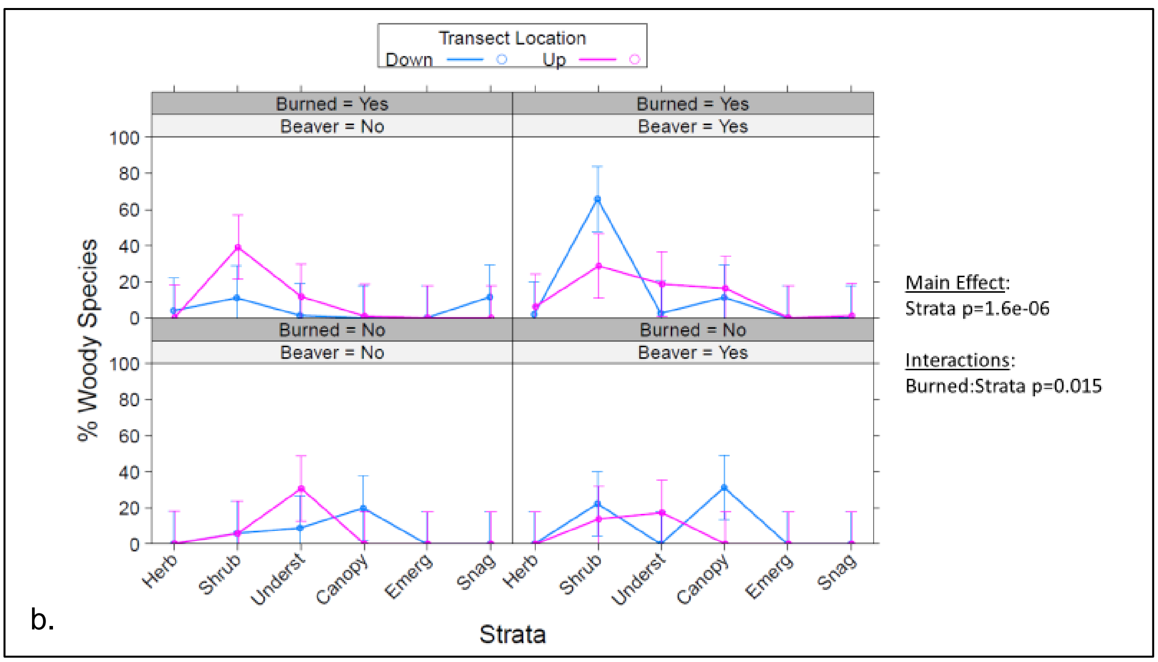


Figure 2.16 Effects of beaver, burning and transect location on woody "habitat" vegetation (Table 2.6) density in relation to a. landform (F value = 4.703, df = 5) and b. strata classification (F value = 8.261, df = 5). P values reported are from mixed model analyses (Appendix 2.2).

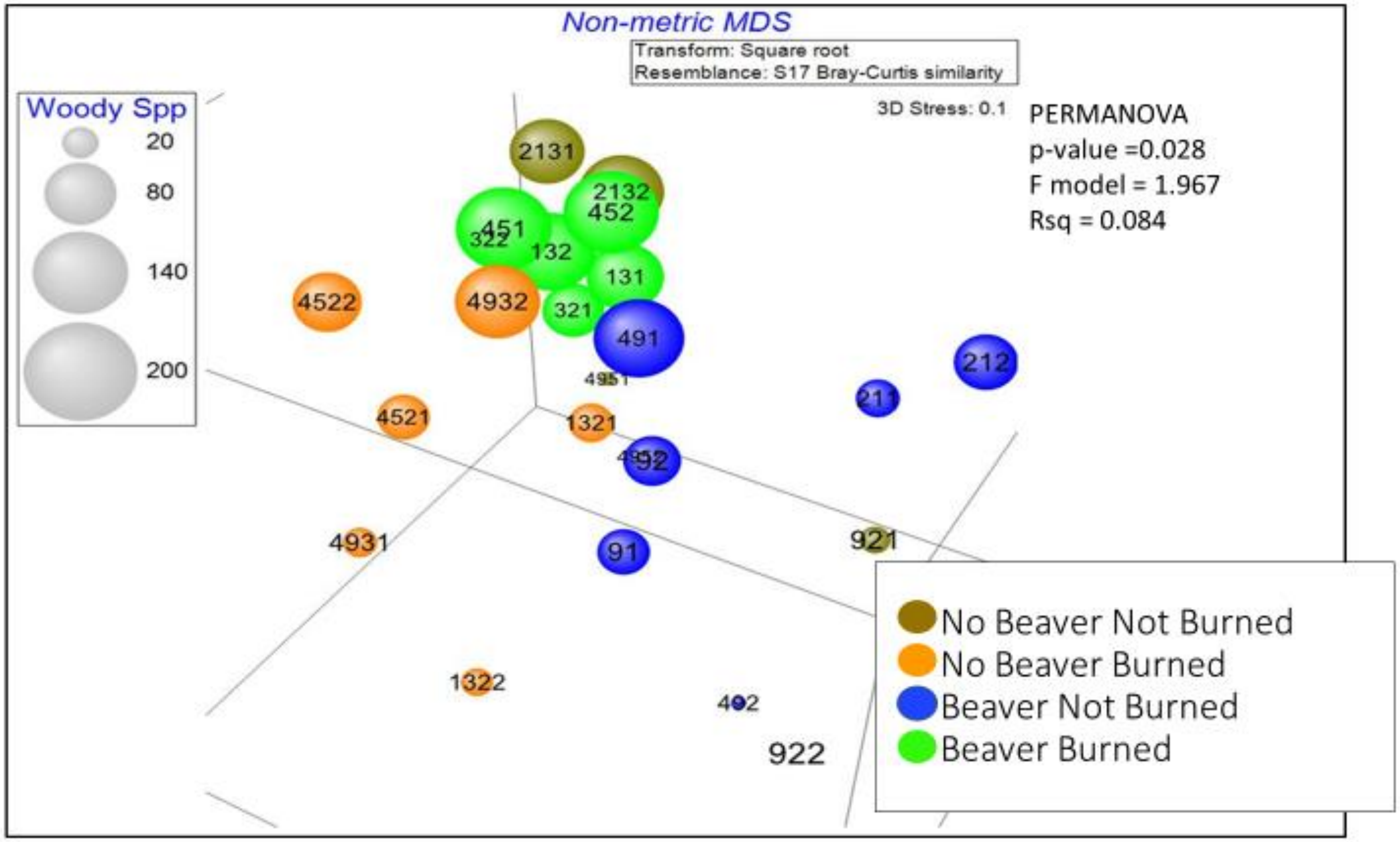


Figure 2.17 Woody species (Table 2.6) density in each transect visualized in a NMDS vegetation species community composition similarity matrix (Appendix 2.3).

Figure 2.18 Lightning Creek photographed in 2018 burned in the 2006 Tripod Complex Fire, the largest and highest severity fire in WA's history at the time. Shortly afterward, Lightning Creek was successfully colonized by relocated "nuisance" beavers courtesy of the Methow Beaver Project. Twelve years later, this nearly two km beaver complex is an oasis of riparian habitat supporting diverse flora and fauna in a sea of regenerating lodgepole pine (*Pinus contorta*) saplings.

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APPENDIX

Appendix 2.1 Plant species list for all study sites. Species names follow the USDA Plants National Database downloaded in spring 2019.

Species Name	Common Name
Abies lasiocarpa	subalpine fir
Acer glabrum	Douglas' maple
Achillea millefolium	yarrow
Aconitum columbianum	Columbian monkshood
Actaea rubra	baneberry
Agoseris glauca	pale agoseris
Agrostis exarata	spiked bent
Agrostis species	na
Agrostis stolonifera	spreading bentgrass
Alnus incana	mountain alder
Alopecurus aequalis	little foxtail
Amelanchier alnifolia	serviceberry
Angelica arguta	Lyall's angelica
Antennaria microphylla	rosy pussytoes
Arctium minus	common burdock
Arctostaphylos uva-ursi	red bearberry, kinnikinnik
Arnica chamissonis	narrowleaf arnica
Arnica cordifolia	heart leaf arnica
Asteraceae species	na
Astragalus miser	weedy milk vetch
Betula occidentalis	river birch
Botrychium pinnatum	northwestern moonwort
Bromus tectorum	cheat grass
Bromus vulgaris	Columbian brome
Calamagrostis canadensis	bluejoint reedgrass
Calamagrostis rubescens	pinegrass
Canadanthus modestus	few flowered aster
Cardamine pensylvanica	Pennsylvania bittercress
Carex species 1	na
Carex species 2	na
Carex athrostachya	slender-beak sedge
Carex deweyana	dewey's sedge
Carex disperma	short-leaf sedge
Carex douglasii	Douglas' sedge
Carex microptera	small-winged sedge
Carex praticola	northern meadow sedge
Carex praegracilis	silvery sedge
Carex stipata	awl-fruited sedge

Carex utriculata	beaked sedge
Ceanothus sanguineus	redstem ceanothus
Ceanothus velutinus	mountain balm
Cerastium arvense	field chickweed
Cerastium fontanum	mouse-ear chickweed
Chamaenerion angustifolium	fireweed
Chenopodium album	lambsquarters
Chimaphila umbellata	prince's pine
Circaea alpina	enchanter's nightshade
Cirsium species	na
Cirsium arvense	Canada thistle
Cirsium vulgare	bull thistle
Claytonia cordifolia	heart-leaf springbeauty
Clematis ligusticifolia	western clematis
Collomia grandiflora	large-flowered collomia
Conyza canadensis	horseweed
Cornus sericea	red osier dogwood
Cornus unalaschkensis	western bunchberry
Dactylis glomerata	orchard grass
Deschampsia elongata	slender hair grass
Dodecatheon dentatum	white shooting star
Drymocallis glandulosa	sticky cinquefoil
Dryopteris carthusiana	toothed wood fern
Elymus glaucus	blue wild-rye
Elymus repens	creeping wild rye
Epilobium species	na
Epilobium brachycarpum	autumn willowherb
Epilobium ciliatum	ciliate willowherb
Epilobium glaberrimum	smooth willowherb
Epilobium hallianum	glandular willowherb
Epilobium hornemannii	Hornemann's willow-herb
Epilobium lactiflorum	white-flower willowherb
Epilobium minutum	small willowherb
Equisetum arvense	common horsetail
Equisetum hyemale	scouringrush horsetail
Equisetum scirpoides	small scouring rush
Erigeron lonchophyllus	short rayed daisy
Erigeron nivalis	northern daisy
Erigeron philadelphicus	Philadelphia daisy
Erigeron subtrinervis	three-veined fleabane
Eriogonum heracleoides	Parsnip flowered buckwheat
Erythranthe guttata	seep monkey-flower
Erythranthe microphylla	small-leaved monkey-flower
Erythranthe moschata	musk flower

Eurybia conspicua	showy aster
Eurybia radulina	Rough leaved aster
Fabacaea species	na
Filago arvensis	field cotton rose, cudweed
Fragaria virginiana	mountain strawberry
Gaillardia aristata	blanketflower
Galium bifolium	twin-leaf bedstraw
Galium triflorum	fragrant bedstraw
Galium trifidum	small bedstraw
Geum macrophyllum	large leaf avens
Glyceria borealis	small floating manna grass
Glyceria elata	tall mannagrass
Glyceria grandis	American mannagrass
Gnaphalium palustre	western marsh cudweed
Heracleum maximum	American cow-parsnip
Heuchera glabra	alpine alumroot
Hieracium albiflorum	white flowered hawkweed
Holodiscus discolor	Ocean-spray
Hydrophyllum capitatum	ballhead waterleaf
Juncus acuminatus	knotty leaf rush
Juncus articulatus	jointed rush
Juncus balticus	Baltic rush
Juncus ensifolius	dagger rush
Juniperus communis	common juniper
Lactuca biennis	tall blue lettuce
Lactuca serriola	prickly lettuce
Lappula longespina	long-spined stickseed
Larix occidentalis	western larch
Lemna minor	common duckweed
Linnaea borealis	twinflower
Lithospermum ruderale	puccoon
Lonicera involucrata	twinberry
Lupinus species	na
Luzula parviflora	small flowered woodrush
Mahonia aquifolium	holly-leaf Oregon-grape
Mahonia nervosa	Cascade Oregon-grape
Maianthemum dilatatum	wild lily-of-the-valley
Maianthemum racemosum	large false Solomon's seal
Maianthemum stellatum	star-flowered Solomon's-seal
Marchantia polymorpha	thallose liverwort
Medicago lupulina L.	black medick
Mentzelia albicaulis	white stem blazingstar
Mentha arvensis L.	field mint
Mentha canadensis	wild mint

Micranthes odontoloma	brook saxifrage
Moneses uniflora	1 flowered wintergreen
Myosotis laxa	small forget-me-not
Nasturtium officinale	watercress
Neottia banksiana	northwestern twayblade
Orthilia secunda	one-sided pyrola
Osmorhiza berteroi	mountain sweet-cicely
Packera pauciflora	rayless alpine butterweed
Paxistima myrsinites	Oregon boxleaf
Penstemon confertus	lesser yellow beardtongue
Persicaria amphibia	water smartweed
Phalaris arundinacea	reed canary grass
Philadelphus lewisii	Lewis' mock orange
Phleum pratense	timothy grass
Picea engelmannii	Engelmann's spruce
Pinus contorta	lodgepole pine
Pinus ponderosa	ponderosa pine
Plantago major	common plantain
Platanthera dilatata	scentbottle, bog orchid
Podagrostis thurberiana	Thurber's bent grass
Polygonum douglasii	Douglas' knotweed
Polystichum munitum	common sword fern
Populus tremuloides	quaking aspen
Populus trichocarpa	cottonwood
Prunus virginiana	common chokecherry
Prunella vulgaris	Self-heal
Pseudotsuga menziesii	Douglas-fir
Pseudoroegneria spicata	bluebunch wheatgrass
Pteridium aquilinum	bracken fern
Pyrola asarifolia	common pink wintergreen
Ranunculus macounii	Macoun's buttercup
Ranunculus uncinatus	little buttercup
Ribes acerifolium	Maple leaf currant
Ribes aureum	Golden currant
Ribes bracteosum	stink currant
Ribes cereum	wax currant
Ribes hudsonianum	western black currant
Ribes inerme	whitestem gooseberry
Ribes lacustre	swamp currant
Ribes viscosissimum	mountain currant
Rosa gymnocarpa	baldhip rose, wood rose
Rosa nutkana	Nootka rose
Rosa woodsii	Wood's rose
Rubus species	na

Rubus idaeus	red raspberry
Rubus leucodermis	blackcap raspberry
Rubus nutkanus	Thimbleberry
Rubus pubescens	dwarf red blackberry
Rubus spectabilis	salmonberry
Salix species	na
Salix amygdaloides	peach-leaf willow
Salix drummondiana	Drummond's willow
Salix scouleriana	Scouler's willow
Sambucus cerulea	blue elderberry
Saxifraga mertensiana	Merten's saxifrage
Scirpus microcarpus	panicled bulrush
Senecio triangularis	arrowleaf groundsel
Shepherdia canadensis	soopolallie
Solanum dulcamara	bittersweet nightshade
Solidago lepida	western Canada goldenrod
Spiraea lucida	shiny-leaf spiraea
Spirodela polyrhiza	Greater duckweed
Spiraea xpyramidata	pyramid spiraea
Stellaria borealis	starwort
Stellaria obtusa	blunt-sepaled starwort
Streptopus amplexifolius	clasping twisted stalk
Symphoricarpos albus	common snowberry
Symphyotrichum ascendens	intermountain aster
Symphyotrichum foliaceum	alpine leafybract aster
Symphoricarpos mollis	creeping snowberry
Taraxacum officinale	common dandelion
Tellima grandiflora	fragrant fringecup
Thalictrum occidentale	western meadow rue
Thalictrum venulosum	veiny-leaf meadow-rue
Trifolium repens	Dutch clover, white clover
Urtica dioica L.	stinging nettle
Utricularia vulgaris	common bladderwort
Vaccinium myrtillus	dwarf blueberry
Vaccinium scoparium	grouseberry
Verbascum thapsis	mullein
Veronica americana	American brooklime
Veronica anagallis-aquatica	blue water speedwell
Veronica serpyllifolia	thyme-leaved speedwell
Viola canadensis	Canada violet
Viola glabella	pioneer violet
Viola nephrophylla	bog violet
Viola orbiculata	darkwoods violet
Viola palustris	marsh violet

Appendix 2.2 Results of mixed model statistical analyses. (* = statistically significant)

ANOVA	Factors and Factor Interactions	Df	F value	Pr(>F)	
Water Quality					
Total Phosphorus/Digested	Beaver	1	8.151	0.013	*
	Burned	1	10.562	0.006	*
	Transect	1	0.883	0.364	
	Beaver:Burned	1	5.059	0.042	*
	Beaver:Transect	1	1.259	0.282	
	Burned:Transect	1	0.553	0.47	
	Beaver:Burned:Transect	1	0.054	0.829	
	Residuals	13			
Dissolved Phosphate	Beaver	1	12.58	0.003	*
	Burned	1	11.84	0.003	*
	Transect	1	0.137	0.717	
	Beaver:Burned	1	8.831	0.01	*
	Beaver:Transect	1	0.005	0.946	
	Burned:Transect	1	0.202	0.66	
	Beaver:Burned:Transect	1	0.023	0.881	
	Residuals	14			
Temperature	Beaver	1	0.252	0.623	
	Burned	1	0.112	0.743	
	Transect	1	0.104	0.752	
	Beaver:Burned	1	0.315	0.583	
	Beaver:Transect	1	0.317	0.582	
	Burned:Transect	1	0.109	0.746	
	Beaver:Burned:Transect	1	0.112	0.743	
	Residuals	14			
Percent Dissolved Oxygen	Beaver	1	5.538	0.033	*
	Burned	1	0.982	0.338	
	Transect	1	0.983	0.338	
	Beaver:Burned	1	0.446	0.515	
	Beaver:Transect	1	0.758	0.398	
	Burned:Transect	1	1.982	0.181	
	Beaver:Burned:Transect	1	1.862	0.194	
	Residuals	14			
pH	Beaver	1	0.794	0.388	
	Burned	1	0.935	0.35	
	Transect	1	0.066	0.801	
	Beaver:Burned	1	5.91	0.029	*
	Beaver:Transect	1	0.149	0.705	
	Burned:Transect	1	0.301	0.591	
	Beaver:Burned:Transect	1	1.025	0.328	

	Residuals	14			
Channel Morphology					
Bankfull Width (log)	Beaver	1	8.055	0.011	*
	Burned	1	0.765	0.394	
	Transect	1	1.965	0.18	
	Beaver:Burned	1	2.839	0.111	
	Beaver:Transect	1	5.096	0.038	*
	Burned:Transect	1	0	0.994	
	Beaver:Burned:Transect	1	0.137	0.716	
	Residuals	16			
Width/Depth ratio (log)	Beaver	1	7.732	0.013	*
	Burned	1	4.619	0.047	*
	Transect	1	3.7	0.072	
	Beaver:Burned	1	0.651	0.431	
	Beaver:Transect	1	9.048	0.008	*
	Burned:Transect	1	0.09	0.768	
	Beaver:Burned:Transect	1	0.247	0.626	
	Residuals	16			
Mean Surface Water Depth (m)	Beaver	1	5.065	0.038	*
	Burned	1	1.425	0.249	
	Transect	1	3.64	0.074	
	Beaver:Burned	1	2.82	0.112	
	Beaver:Transect	1	2.189	0.158	
	Burned:Transect	1	0.078	0.783	
	Beaver:Burned:Transect	1	2.361	0.143	
	Residuals	16			
Landform					
Percent Floodplain	Beaver	1	8.448	0.01	
	Burned	1	2.946	0.105	
	Transect	1	0.758	0.396	
	Beaver:Burned	1	4.703	0.045	
	Beaver:Transect	1	0.145	0.708	
	Burned:Transect	1	0.001	0.971	
	Beaver:Burned:Transect	1	0.278	0.605	
	Residuals	16			
Percent Floodplain Terrace	Beaver	1	8.762	0.009	*
	Burned	1	11.934	0.003	*
	Transect	1	0.115	0.739	
	Beaver:Burned	1	2.092	0.167	
	Beaver:Transect	1	0.996	0.333	
	Burned:Transect	1	0.439	0.517	
	Beaver:Burned:Transect	1	2.71	0.119	

	Residuals	16			
Ground Cover					
Percent Sand	Beaver	1	11.155	0.004	*
	Burned	1	8.463	0.01	*
	Transect	1	5.358	0.034	*
	Beaver:Burned	1	13.717	0.001	*
	Beaver:Transect	1	3.653	0.074	
	Burned:Transect	1	3.209	0.092	
	Beaver:Burned:Transect	1	4.026	0.062	
	Residuals	16			
Percent Woody Litter	Beaver	1	0.028	0.868	
	Burned	1	0.091	0.767	
	Transect	1	0.717	0.409	
	Beaver:Burned	1	20.756	0.0003	*
	Beaver:Transect	1	5.145	0.0375	*
	Burned:Transect	1	0.008	0.928	
	Beaver:Burned:Transect	1	3.501	0.079	
	Residuals	16			
Vegetation					
Total Plant Species Richness	Beaver	1	0.451	0.511	
	Burned	1	3.084	0.098	
	Transect	1	0.294	0.595	
	Beaver:Burned	1	4.723	0.045	*
	Beaver:Transect	1	0.011	0.916	
	Burned:Transect	1	0.07	0.795	
	Beaver:Burned:Transect	1	1.087	0.312	
	Residuals	16			
Wetland Indicator Species Richness	Beaver	1	3.436	0.082	
	Burned	1	3.436	0.082	
	Transect	1	0.161	0.693	
	Beaver:Burned	1	7.467	0.014	*
	Beaver:Transect	1	0.106	0.749	
	Burned:Transect	1	0.03	0.865	
	Beaver:Burned:Transect	1	1.186	0.292	
	Residuals	14			
Introduced Species Richness	Beaver	1	1.786	0.2	
	Burned	1	0.191	0.668	
	Transect	1	0.001	0.981	
	Beaver:Burned	1	9.385	0.007	*
	Beaver:Transect	1	0.252	0.622	
	Burned:Transect	1	0.377	0.547	

	Beaver:Burned:Transect	1	0.769	0.393	
	Residuals	16			
Total Species Density	Beaver	1	2.122	0.165	
	Burned	1	1.058	0.319	
	Transect	1	0.384	0.544	
	Beaver:Burned	1	2.077	0.169	
	Beaver:Transect	1	0.039	0.846	
	Burned:Transect	1	0.081	0.78	
	Beaver:Burned:Transect	1	0.926	0.35	
	Residuals	16			
Introduced Species Density	Beaver	1	1.293	0.272	
	Burned	1	0.577	0.458	
	Transect	1	1.54	0.232	
	Beaver:Burned	1	1.97	0.18	
	Beaver:Transect	1	2.573	0.128	
	Burned:Transect	1	1.36	0.261	
	Beaver:Burned:Transect	1	0.644	0.434	
	Residuals	16			
Landform Woody Habitat Vegetation	Transect	1	0.004	0.947	
	Beaver	1	3.455	0.066	
	Burned	1	0.769	0.382	
	Landform	5	4.703	0.0006	*
	Transect:Beaver	1	0.651	0.421	
	Transect:Burned	1	0.528	0.469	
	Beaver:Burned	1	1.85	0.176	
	Transect:Landform	5	0.844	0.521	
	Beaver:Landform	5	1.657	0.152	
	Burned:Landform	5	0.467	0.799	
	Transect:Beaver:Burned	1	0.019	0.891	
	Transect:Beaver:Landform	5	0.357	0.876	
	Transect:Burned:Landform	5	0.81	0.545	
	Beaver:Burned:Landform	5	2.159	0.065	
	Transect:Beaver:Burned:Landform	5	0.316	0.902	
	Residuals	96			
Strata Woody Habitat Vegetation	Transect	1	0.011	0.915	
	Beaver	1	1.888	0.172	
	Burned	1	1.498	0.224	
	Landform	5	8.261	1.60E-06	*
	Transect:Beaver	1	0.89	0.347	
	Transect:Burned	1	0.296	0.587	
	Beaver:Burned	1	0.912	0.341	

	Transect:Landform	5	2.085	0.0739	
	Beaver:Landform	5	1.612	0.164	
	Burned:Landform	5	2.976	0.0153	
	Transect:Beaver:Burned	1	0.025	0.875	
	Transect:Beaver:Landform	5	1.568	0.176	
	Transect:Burned:Landform	5	1.023	0.408	
	Beaver:Burned:Landform	5	0.337	0.889	
	Transect:Beaver:Burned:Landform	5	1.157	0.336	
	Residuals	96			
Landform Wetland Obligate Species	Transect	1	0.873	0.352	
	Beaver	1	2.179	0.143	
	Burned	1	1.601	0.208	
	Landform	5	2.924	0.016	*
	Transect:Beaver	1	0.17	0.68	
	Transect:Burned	1	0.039	0.844	
	Beaver:Burned	1	4.674	0.033	*
	Transect:Landform	5	0.178	0.97	
	Beaver:Landform	5	3.308	0.008	
	Burned:Landform	5	2.707	0.024	*
	Transect:Beaver:Burned	1	1.248	0.266	
	Transect:Beaver:Landform	5	0.478	0.792	
	Transect:Burned:Landform	5	0.356	0.877	
	Beaver:Burned:Landform	5	1.562	0.178	
	Transect:Beaver:Burned:Landform	5	0.275	0.925	
	Residuals	96			
Strata Wetland Obligate Species	Transect	1	1.032	0.312	
	Beaver	1	4.959	0.028	*
	Burned	1	2.489	0.117	
	Landform	5	10.25	6.83E-08	
	Transect:Beaver	1	0.466	0.496	
	Transect:Burned	1	0.261	0.61	
	Beaver:Burned	1	5.765	0.018	*
	Transect:Landform	5	0.928	0.466	
	Beaver:Landform	5	4.584	0.0008	*
	Burned:Landform	5	2.326	0.048	
	Transect:Beaver:Burned	1	1.169	0.282	
	Transect:Beaver:Landform	5	0.398	0.849	
	Transect:Burned:Landform	5	0.184	0.968	
	Beaver:Burned:Landform	5	5.515	0.0001	*
	Transect:Beaver:Burned:Landform	5	0.993	0.426	
	Residuals	96			

Appendix 2.3 Results of PERMANOVA analysis comparing plant species composition across all treatments and transects.

PERMANOVA	**Factors and Factor Interactions**	**Df**	**Sum of Sqs**	**Mean Sqs**	**F Model**	**R Sq**	**Pr(>F)**	
Vegetation Diversity								
Total Species Diversity	Beaver	1	0.3382	0.33824	1.03268	0.04414	0.379	
	Burned	1	0.683	0.68303	2.08538	0.08913	0.019	*
	Transect	1	0.1864	0.1864	0.56909	0.02432	0.936	
	Beaver:Burned	1	0.6451	0.64514	1.96969	0.08419	0.028	*
	Beaver:Transect	1	0.2022	0.20221	0.61737	0.02639	0.898	
	Burned:Transect	1	0.1531	0.15314	0.46757	0.01998	0.984	
	Beaver:Burned:Transect	1	0.2143	0.21434	0.65441	0.02797	0.884	
	Residuals	16	5.2405	0.32753		0.68387		
	Total	23	7.663			1		

VITA

Author: Alexa S. Whipple
Place of Birth: Palo Alto, California

EDUCATION

Master of Science-Candidate, Biology: Ecology | Eastern Washington University (EWU), Cheney, WA | June 2019
Thesis: Riparian Resilience in the Face of Interacting Disturbances: Understanding Complex Interactions Between Wildfire, Erosion and Beaver (*Castor canadensis*) in Dryland Low Order Streams, Methow River Watershed, WA, US.

Certificate in Agroecology | University of California Santa Cruz (UCSC), Santa Cruz, CA | 2000

Bachelor of Science, Wildlife Science | Virginia Polytechnic Institute & State University (Virginia Tech),
Blacksburg, VA | 1995

EXPERIENCE

Graduate Researcher | EWU-College of STEM-Biology Department, Cheney, WA | Sep 2017-Present

- Correlated research on wildfire, stream channel erosion, and beaver interactions and their impact on riparian vegetation, channel morphology, nutrient transport and water quality in dryland streams of western US
- Managed field/lab team of 4, reviewed and synthesized literature, created ArcGIS based beaver habitat suitability model specific to thesis research objectives, designed fully factorial study, collected/ analyzed field and lab data, presented findings, co-authored two soon to be published manuscripts.
- Submitted and awarded multiple research/presentation related research grant proposals.
- Consulted and collaborated with local, state and federal agencies regarding research.
- Co-reviewed a technical manuscript for publication with mycology professor at EWU.
- Assisted faculty mycology research relating to lichen taxonomy using chemical analysis methods of spot testing, thin layer chromatography and next generation DNA sequencing.

Graduate Teaching Assistant | EWU-College of STEM-Biology Department, Cheney, WA | Sep 2017-Present

- Collaborated with professors weekly to implement lab exercises, develop assessment rubrics, evaluate and grade student work.
- Assisted and advised undergraduate/graduate students in Independent Research, Restoration Ecology, Botany, Field Botany and Genetics.

Consultant in Sustainable Agriculture | Okanogan Conservation District**,** Okanogan, WA | Sep2016-Oct2017

- Proposed and implemented an economic development and sustainable food systems feasibility study to the United States Department of Agriculture's (USDA) Rural Business Development Grant program for a local USDA Inspected meat processing facility. Grant awarded June 2017.
- Contributed rangeland health monitoring aspect to a regional collaborative federal grant proposal, including 5 WA county conservation districts and EWU, for USDA's Natural Resources Conservation Service Conservation Innovation Grant program specifically for improving rangeland health. Not awarded.

Co-Owner/Operator | Beaver Creek Well Services, Winthrop, WA | 2007-2018

- Administrative duties including customer relations, bookkeeping, state compliance, insurance and bonding.

Owner/Operator | Twelve Moons Farm, Winthrop, WA | 2002-16

- Developed and managed a commercial diversified produce and livestock farm focused on sustainable food production, conservation, and community education while employing 2 field assistants seasonally.
- Presented sustainable agriculture curriculum to youth and adults through school districts and non-profit organizations.

Educator | Conservation Northwest, Okanogan, WA | March-June 2015

- Contracted to perform short term education and outreach regarding the Grizzly Bear Recovery Plan for the North Cascades Region.

Consultant in Sustainable Agriculture/Board Member | Methow Conservancy, Winthrop, WA 2014-2016

- Contracted to develop and perform an Agricultural Community Needs Assessment for Methow Valley, WA.
- Board member advocating for development of a local conservation corp and sustainable grazing focus group, 1.5 years

Educator/Coordinator/Board Member | Classroom In Bloom, Winthrop, WA | 2011-2017

- Managed 3 staff and 350 students, faculty and volunteers on a 1-acre educational garden and orchard on the Methow Valley School District campus.
- Created and co-taught garden based science curriculum for K-10 students as well as an annual adult education series.
- Sourced and applied for grants and co-managed fundraising campaigns, familiar with donor databases.
- Treasurer of board for 2 years, member at large for 1 year

Field Coordinator for Okanogan County | Grizzly Bear Outreach Project, Bellingham, WA | 2004-05

- Conducted one-on-one and small group meetings with students and community members to share information regarding coexistence with Black Bears and Grizzly Bears.

Field Manager | Persephone Farm, Indianola, WA | 2001-02

- Assisted owner in all aspects of operation of 14-acre organic farm.
- Managed 2 apprentices and 4-10 volunteers weekly.
- Managed restaurant and grocer wholesale accounts.
- Managed farmer's market stands weekly.

Biological Science Technician | U.S. Fish and Wildlife Service, Klamath Falls, OR | 1999

- Monitored impacts of agricultural chemical use on fish and wildlife populations in Klamath Basin National Wildlife Refuges.
- Performed research on small rodent population impacts in response to agricultural chemical use.

Botany Instructor | National Audubon Society-Rocky Mountain Ecology Camp, Dubois, WY | 1998

- Introduced basic botanical and ecological concepts to adults during week-long ecology immersion seminars

Biological Field Assistant | Wisconsin Department of Natural Resources (WDNR), Gordon, WI | 1996

- Assisted graduate student in collection of field data to assess habitat and behavioral patterns of gray wolf selection of highway crossings in NW Wisconsin in an effort to reduce vehicular deaths in wolf populations.
- Assisted WDNR Biologist with trapping, collaring, and monitoring of gray wolf population.

Biological Field Assistant | University of Wisconsin-Stevens Point, Stevens Point, WI | 1995

- Collected Gap Analysis data with a focus on avian and vegetation diversity in the Bighorn Mountains of north central Wyoming.

Biological Field Assistant | Virginia Tech, Blacksburg, VA | 1995

- Gathered field data to assess effects of group selection timber harvesting on nesting and reproductive success of the Blue-headed Vireos (formerly solitary vireo) in southern Virginia.

Undergraduate Teaching Assistant | Virginia Tech, Blacksburg, VA | 1994-95

- Assisted undergraduate students in *Techniques in Wildlife Management* lab

GRANTS AWARDED

EWU Graduate Service Appointment/Teaching Assistantship | September 2017-June2019
EWU College of STEM Graduate Student Travel Grant | November 2018 and March 2019
EWU University and Provost's Graduate Student Travel Grant | November 2018 and March 2019
EWU College of STEM Graduate Research Grant | February 2018
John Joy Science Scholarship, EWU | September 2018-19
Swartz & Werschler Graduate Fellowship, EWU | September 2018-19
USDA Rural Business Development Grant | June 2017

USDA Natural Resources Conservation Service High Tunnel Grant | March 2016

PRESENTATIONS

United States Regional Association of the International Association for Landscape Ecology, US-IALE Invited Oral presentation, Fort Collins, CO | April 2019
River Restoration Northwest Annual Conference, Oral presentation, Stevenson, WA | Feb 2019
Society for Ecological Restoration, PNW Regional Conference, Poster presentation, Spokane, WA | Oct 2018

PROFESSIONAL MEMBERSHIPS

Society for Ecological Restoration
River Restoration Northwest
US-International Association of Landscape Ecologists