Influence of the Mountain Pine Beetle disturbance on large wood dynamics and channel morphology in mountain streams

by

Bryce Kendrick Marston

B.S., University of Wyoming, 2008
M.S., University of Nebraska at Omaha, 2011

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography
College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2017

Abstract

Disturbance regimes are important determinants of both terrestrial and aquatic ecosystem structure and function. Disturbances may linger in the landscape and lag temporally, influencing stream ecosystem form and function for decades, if not centuries. The recent enhanced Mountain Pine Beetle (MPB) infestation in pine forests of the Rocky Mountain region has resulted in extensive tree mortality, producing the potential for significant increases in carbon supply to stream channels. To better understand MPB impacts on in-stream large wood (LW), a census was conducted in 30 headwater streams within the Medicine Bow National Forest in south-central Wyoming, across the temporal spectrum from early- to late-stage MPB-infestation. A subset of those streams exhibiting mean conditions at each level of infestation was surveyed to determine any significant differences in channel morphology or aquatic ecosystem function. Results indicate that wood loads related to the MPB-infestation significantly increase with time since initial infestation. However, even in late-stage infestation streams, many of the fallen MPB-killed trees are bridging across the channels and have yet to break and ramp down sufficiently enough to enter between the channel margins. Wood loads will continue to increase as more trees fall and bridging pieces decompose, break and then enter the channel. Measurable increases in the amount of LW with time since initial beetle infestation have both positive and negative effects on channel form and function. Although forest MPB-infestation has peaked in the study area, streams are still early on a curve of rapidly increasing wood loads that are beginning to affect streams and have the potential to dramatically increase the carbon base of regional stream ecosystems.

Influence of the Mountain Pine Beetle disturbance on large wood dynamics and channel morphology in mountain streams

by

Bryce Kendrick Marston

B.S., University of Wyoming, 2008
M.S., University of Nebraska at Omaha, 2011

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography
College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2017

Approved by:

Major Professor
Dr. Charles Martin

Copyright

Abstract

Disturbance regimes are important determinants of both terrestrial and aquatic ecosystem structure and function. Disturbances may linger in the landscape and lag temporally, influencing stream ecosystem form and function for decades, if not centuries. The recent enhanced Mountain Pine Beetle (MPB) infestation in pine forests of the Rocky Mountain region has resulted in extensive tree mortality, producing the potential for significant increases in carbon supply to stream channels. To better understand MPB impacts on in-stream large wood (LW), a census was conducted in 30 headwater streams within the Medicine Bow National Forest in south-central Wyoming, across the temporal spectrum from early- to late-stage MPB-infestation. A subset of those streams exhibiting mean conditions at each level of infestation was surveyed to determine any significant differences in channel morphology or aquatic ecosystem function. Results indicate that wood loads related to the MPB-infestation significantly increase with time since initial infestation. However, even in late-stage infestation streams, many of the fallen MPB-killed trees are bridging across the channels and have yet to break and ramp down sufficiently enough to enter between the channel margins. Wood loads will continue to increase as more trees fall and bridging pieces decompose, break and then enter the channel. Measurable increases in the amount of LW with time since initial beetle infestation have both positive and negative effects on channel form and function. Although forest MPB-infestation has peaked in the study area, streams are still early on a curve of rapidly increasing wood loads that are beginning to affect streams and have the potential to dramatically increase the carbon base of regional stream ecosystems.

Table of Contents

List of Figures

List of Tables

Acknowledgements

There are many people, agencies and organizations who have contributed to the completion of this research. The Department of Geography at Kansas State University and the United States Forest Service financially supported this research. The Brush Creek/Hayden Ranger district office provided invaluable assistance during the entire project. Specifically, I would like to thank Dave Gloss, who has always been a supportive friend and mentor, and Carol Purchase who initially hired me and introduced me to water resource management. Benjamin Kessler assisted with morphological surveys in occasionally unfavorable conditions. Ellen Terry, Stephanie Bartlett, Mike Rawitch, and Katie Buchan also assisted with data collection. My office and lab mates, departmental colleagues and family members were all very supportive throughout my time at Kansas State. My mother and father were responsible for introducing me to Geography at a young age by traveling the world and walking over glaciers and lava fields. Finally, I would like to thank Dr. Melinda Daniels, Dr. Charles Martin, Dr. Sandra Ryan-Burkett, Dr. Jack Oviatt and Dr. Abigail Langston for their mentorship and enthusiasm as members of my supervisory committee.

Dedication

This dissertation is dedicated to my mother. She remained supportive and positive while successfully battling cancer, and I would not have made it to this point without her.

Preface

This dissertation is original, unpublished, independent work by the author, B. Marston, in partial fulfillment of the requirements for the degree Doctor of Philosophy from the Department of Geography. In keeping with traditional peer-reviewed format, the research in this dissertation is presented in third person.

Chapter 1 - Introduction

Disturbance regimes are important determinants of both terrestrial and aquatic ecosystem structure and function (Dillon et al., 2003; Sibold et al., 2007; Magilligan et al., 2008). Natural disturbances, such as fire and disease outbreaks, affect streams via riparian-forest influence pathways, including the supply of wood to stream channels (Dillon et al., 2003). Human-mediated disturbances can disrupt this natural disturbance regime through logging and other watershed land-use modifications (Magilligan et al., 2008; Ruffing et al., 2015). Anthropogenic climate change may also magnify natural disturbances (Dillon et al., 2003). The influence of both natural and anthropogenic disturbances may linger in the landscape, affecting streams for many subsequent decades, if not longer (James, 1989, 1991, 1999; Ruffing et al., 2015).

There have been numerous anthropogenic disturbances in forested mountain ecosystems throughout history. Within the Rocky Mountain region, modern and legacy disturbances include watershed logging, tie-driving, mining and watershed diversions (Young et al., 1994; Ruffing et al., 2015). There are also natural disturbances, which include forest fires (Zelt and Wohl, 2004), beetle infestations and disease (Dillon et al., 2003). Small-scale natural disturbances can include mass movement, large flood events, and microburst blowdowns (Massey, 2000; Sibold et al., 2007; Feinstein, 2012; Wohl, 2013a). Lodgepole pines require stand-replacing fires at an interval of 100 years in order to fully develop (Sibold et al., 2007). In the interim between stand-replacing fires, secondary disturbances such as a Mountain Pine Beetle (MPB) outbreak can occur (Schmid and Mata, 1996). MPB outbreaks have been observed to occur on the order of 20-30 year intervals (Schmid and Amman, 1992). The last MPB outbreak in the Rocky Mountain region occurred during the 1970s and caused extensive tree mortality across numerous watersheds (Sibold et al., 2007).

Anthropogenic disturbances currently present in the Rocky Mountain region include logging, mining, flow regulation and urbanization (Wohl, 2006). These human activities simultaneously interact with natural disturbances, such as blowdowns, floods, forest fires, mass movement and insect infestation, to modify landscapes over large spatial and temporal scales. The recent MPB infestation has produced extensive tree mortality throughout pine forests in the Rocky Mountains. MPB infestations have occurred in the past (Logan and Powell, 2001), however they were limited by lower winter temperatures, which increases beetle mortality (Carroll et al., 2003). Changing global climate has resulted in elevated winter temperatures in the Rockies and allowed an unprecedented MPB infestation in recent years (Klutsch et al., 2009), extending throughout the entire United States Rocky Mountain region (Ehle and Baker, 2003). Some National Forest lands along the Colorado Front Range and in southern Wyoming have 100 percent mature tree mortality (Dillion et al., 2003), producing a potentially significant change in wood supply to stream channels.

A combination of historical land uses and stream-altering legacy disturbances, working simultaneously with tree mortality associated with the current MPB outbreak, has the potential to radically alter wood loading and channel morphology of Rocky Mountain headwater streams. The nature of wood loading from MPB mortality may vary substantially from conventional understandings of stream wood budgets. For example, there may be a twenty to thirty year time-lapse from initial MPB disturbance until there is a measurable increase to wood load in stream (Figure 1.1).

Typically, MPB-killed trees remain standing for approximately ten years, after which their risk for toppling increases dramatically (Mitchell and Preisler, 1998). However, as time since infestation increases, the source for wood loading may decline as most trees have already fallen, producing a sharp and sustained decline in wood loading to channels. Furthermore, the nature of MPB infestation and subsequent fungal rot (Ehle and Baker, 2003) of the trees may cause them to shatter into smaller pieces more readily when they do fall, in contrast to non-MPB-killed trees.

Large wood (LW) is defined as a wood piece at least 1 meter in length and 10 centimeters in diameter (Jackson and Sturm, 2002). LW in headwater mountain streams has a significant impact on geomorphological and ecological systems (Gurnell et al., 2002; Mongomery et al., 2003; Hassan et al., 2005). LW loads vary between watersheds and are dependent upon the location in the watershed, adjacent forest stand composition, natural and anthropogenic disturbance histories, and by the mobility of individual pieces of LW (Wohl, 2011; Wohl and Cadol, 2011). Flow hydraulics, sediment storage and transport, and channel form can all be influenced by pieces of LW within a stream channel (Bilby and Ward, 1991; Montgomery et al., 1995; Abbe and Montgomery, 1996).

Gurnell and Sweet (1998) and Ralph et al. (1994) studied the secondary morphological effects of LW on stream channel morphology including channel planform alterations (pool depth and area), changes in channel geometry, and the occurrences of in-stream bed forms. Depending on how stable the LW is within the stream channel, a channel avulsion may occur (Gurnell et al., 1995). Channel avulsions are more common in streams with a large number of debris jams (Montgomery and Abbe, 2006). Avulsions ultimately increase overbank inundation, which creates spatially-localized erosional and depositional features in the valley bottoms (Kochel et al., 1987; Jeffries et al., 2003). Faustini and Jones (2003) found that mean channel width is greater for stream channels located in old-growth forests compared to narrower channels in clear-cut sites.

Geomorphic-ecological associations in mountain stream channels have not been extensively studied (Urban and Daniels, 2006; Sullivan, 2012; Ruffing et al., 2015). LW is known to add nutrients and enhance nutrient spiraling within stream channels (Bilby and Likens, 1980; Cummins et al., 1983; Lienkaemper and Swanson, 1987). Large wood has also been associated with increased organic matter storage in stream substrates (Daniels, 2006b). Large amounts of carbon can be stored throughout stream ecosystem compartments, including in floodplain sediments, as coarse dead wood, fine organic matter or as riparian vegetation (Wohl et al., 2012; Beckman and Wohl, 2014). Stream channels act as pathways for the removal of carbon from a watershed (Hall et al., 2002). Drifting pieces of LW are important for food webs in downstream ecosystems (Wipfli and Gregovich, 2002), as they can accumulate into debris jams. Anthropogenic disturbances, such as removing wood from a stream channel or logging a watershed, can have major impacts on stream ecosystem function (Lisle, 1995; Buffington et al., 2002; Broadmeadow and Nisbet, 2004), and have been understudied (Hassan et al., 2005). Logging can reduce the amount of LW being supplied into the system for extensive time periods (Magilligan et al., 2008). LW inputs lag behind riparian zone regrowth, thereby reducing the total amount of LW within the stream channel (Magilligan et al., 2008). Natural disturbances, such as a Mountain Pine Beetle (MPB) infestation or fire, can also severely alter carbon dynamics and stream ecosystem function.

The potential MPB wood supply will enter stream channels that, in many National Forests, also now support substantial inter-basin water diversions that may alter a stream’s ability to mobilize, sort and transport wood. Any change to a stream’s discharge regime is important to consider, as wood is transported and sorted by stream flows (Nakamura and Swanson, 1994; Abbe and Montgomery, 1996; Braudrick and Grant, 2001; Wohl and Jaeger, 2009; Cadol and

Wohl, 2010; Morris et al., 2010; Jones et al., 2011; Wohl et al., 2011). The addition of water to one segment may increase wood transport and decrease retention, whereas the removal of water from another segment may increase retention and decrease transport.

The combination of a MPB infestation and water-diversion alterations on LW supply and transport regimes has important implications for the ecogeomorphology of Rocky Mountain headwater networks. Previous research on MPB-scale inputs of LW in mountain stream channels have been limited to large blow-downs, fires and volcanic activity (Lisle, 1995; Dwire and Kauffman, 2003; Zelt and Wohl, 2004; Meyer et al., 2005; Elder et al., 2006); none of these studies have addressed systems where water diversions are also an important disturbance.

This dissertation studies the impacts of the MPB infestation and water diversions on LW dynamics and channel morphology throughout the Medicine Bow National Forest in south-central Wyoming. MPB infestation and water diversion are the most spatially widespread disturbances affecting regional headwater streams, and both will have legacy effects on the physiometric characteristics of forested mountain watersheds. Chapter 1 presents a comprehensive literature review pertaining to our current understandings of LW dynamics, channel morphology and MPB infestations. Study systems selected for this dissertation are also described in detail. In Chapter 2, alterations to LW dynamics in headwater streams were documented across watersheds experiencing varying degrees of MPB infestation. The technique of substituting space for time allows for measurements of MPB infestation at varying temporal scales. Chapter 3 documents alterations to channel form by newly-input pieces of LW in watersheds infested by the MPB. Morphological surveys were conducted to find significant differences in channel morphology from early to late-stage infestation. In Chapter 4, stream channels regulated by water diversions were measured to determine any significant differences in channel form upstream and downstream from diversion structures. Chapter 5 summarizes results from the previous chapters. These data will provide baseline information for studying the impacts of the MPB on wood supply in forested headwater mountain streams.

Literature Review

Over the last decade, numerous studies have analyzed the importance of LW in fluvial systems. LW has been recognized as an important structural component to stream habitat as it increases habitat complexity and provides cover for fish and aquatic invertebrates (Dolloff and Warren, 2003). The geomorphological structure of stream channels is also influenced by LW. Pool formation, frequency and type (Keller and Swanson, 1979; Andrus et al., 1988; Bilby and Ward, 1991; Montgomery et al., 1995; Abbe and Montgomery, 1996; Gurnell and Sweet, 1998; Rosenfeld and Huato, 2003; Kreutzweiser et al., 2005) can influence sediment storage and transportation through a stream system (Thompson, 1995; May and Gresswell, 2003; Daniels, 2006b). LW also augments flow resistance (Assani and Petit, 1995; Shields and Gippel, 1995; Gippel et al., 1996; Manga and Kirchner, 2000; Curran and Wohl, 2003; Hygelund and Manga, 2003; Bocchiola et al., 2006; Manners et al., 2007) and reduces sediment transport (Bilby and Ward, 1989; Nakamura and Swanson, 1994). LW also has been shown to increase longitudinal variation for both channel depth and width (Montgomery et al., 2003).

Characterizing the Spacing, Storage, Loading and Transportation of LW

Due to the lack of a standardized methodology to characterize LW in stream channels, numerous unrelated classification schemes have been developed. Some methods are more qualitative in nature, relying on visual interpretations of size and estimations on species, decay class and total volume (Robinson and Beschta, 1990; Hyatt and Naiman, 2001; Marcus et al., 2002; Kraft and Warren, 2003; Faustini and Jones, 2003; Comiti et al., 2007). Other methods are more rigorous, measuring diameters and lengths of LW samples to estimate volume of LW within a stream channel study reach (Wallace and Benke, 1984). A methodology to classify the spatial location and structural patterns of LW and debris jams within stream channels was developed by Abbe and Montgomery (1996). Three examples of LW jam classifications used by Abbe and Montgomery (1996) on the Queets River in northwest Washington are bar-top jams (BTJ), bar-apex jams (BAJ), and meander jams (MJ). Active, complete and partial dam taxonomies were used by Gregory et al. (1985) to collect data on log-jam structures. Active dams span the entire stream channel, creating a step-pool environment. Complete dams also span the stream channel, but do not create step pools. Partial dams simply do not span the width of a stream channel (Gregory et al., 1985; Gurnell and Sweet, 1998). Shields and Smith (1992) used the South Fork Obion River in Tennessee to develop a methodology that quantifies LW density based on visual surveys. Nine size classes were based on visual estimates of the maximum length of each LW formation below the plane of the water surface in directions perpendicular and parallel to the primary flow direction (Shields and Smith, 1992: pg.150). LW size taxonomy developed in this study was based on the study reach's mean water surface width (Shields and Smith, 1992).

Wood loading has been shown to decrease downstream (Wohl and Jaeger, 2009). However, it was noted that wood loading can be affected not only by downstream positioning, but also by drainage area, elevation, channel width, gradient and total stream power (Wohl and Jaeger, 2009). It has been shown that LW tends to move farther in higher-order stream channels with more flow, and shorter pieces of LW are usually transported farther than longer pieces (Nakamura and Swanson, 1994). Wohl and Jaeger (2009) conducted one of the first studies examining the longitudinal distribution of wood within channel networks and the potential controls on its distribution.

Due to the logistics of mapping the spacing and movement of LW, there is limited research on the transport of LW after it has entered the stream channel (Curran, 2010). Warren and Kraft (2008) tagged 112 pieces of LW along a 400-meter reach of a high-gradient stream channel, then relocated each piece in 2001, 2003 and 2004. Results from the subsequent surveys showed that LW length strongly influenced the ability of that piece to move, and that increasing the number of LW jams reduced the total travel distance for individual LW pieces (Warren and Kraft, 2008). Daniels (2006a) showed that storage of benthic organic matter occurred in pulses and can be correlated with the mobility of LW. Fisher et al. (2010) used cosmogenic beryllium-7 isotope dating taken from sediments trapped behind LW to estimate the storage time of those sediments. Higher amounts of LW were shown to increase sediment sequestration and storage time (Fisher et al., 2010). Lienkaemper and Swanson (1987) identified this as an issue, stating that the delivery of LW into the stream system and the movement of that LW once it enters the channel needs to be addressed. Most LW transport in headwater channels occurs during high-flow events such as spring runoff or floods (Braudrick and Grant, 2001; Haga et al., 2002). Abbe et al. (1993) stated that a log will reside in a certain location within the stream channel when the water depth is less than half the log diameter.

Riparian zones and forest stands surrounding mountain stream channels are the contributing source for LW being input into the system (Hyatt and Naiman, 2001). LW inputs into mountain stream channels are controlled by complex bank and hillslope processes, for instance, falling trees, debris flows and landslides (Comiti et al., 2007). According to Ralph et al. (1994), timber harvesting decreases the average size of LW being input into the stream channel, a finding similar to that of Faustini and Jones (2003). Wood loading and log-jam frequencies have been found to be lower in forest stands that have a history of timber harvesting (Costigan and Daniels, 2011). Less LW in these harvested forest stands has an effect on the morphology of the stream channel, and LW becomes more mobile within the channel (Ralph et al., 1994; Costigan and Daniels, 2011). Gurnell and Sweet (1998) also concluded that LW in these harvested systems is more mobile, decreasing the number of step-pools and amount of bedload/organic matter stored within the stream channel. Ehrman and Lamberti (1992) quantitatively demonstrated the Gurnell and Sweet (1998) idea by relating the density of LW to movement and storage of LW, bedload and organic matter. Larger debris-jam structures with multiple pieces of LW are more stable than a single piece of LW (Lienkaemper and Swanson, 1987; Marcus et al., 2002). Bilby and Likens (1980) removed all LW jams from Hubbard Brook Valley in New Hampshire and studied the effects. The streams' ability to retain coarse particulate organic matter (CPOM) decreased dramatically (Bilby and Likens, 1980). Lienkaemper and Swanson (1987) quantitatively demonstrated a relationship between the movement of LW and channel morphology by relating the length of a LW piece to channel width. Recruitment and residence times were calculated by Hyatt and Naiman (2001) by collecting cores from pieces of LW. Ages ranged from one year to 1400 years, and results showed that larger pieces of LW were recruited within the last decade whereas smaller LW pieces were older (Hyatt and Naiman, 2001). Marcus et al. (2002) found that the percent of pools increased as age class of LW accumulations decreased.

High-gradient mountain stream channels were shown to have less LW within the channel lower down in the watershed, which is a reverse trend from low-gradient stream channels (Gurnell and Sweet, 1998; Robinson and Beschta, 1990). Relating this to Bilby and Likens

(1980), a stream channels' ability to transport LW increases lower in the watershed, which then decreases the streams' ability to store CPOM. A theory has also developed that increased sinuosity causes more LW accumulations and debris jams located along the outside of a meander or near erosional features (Wallace and Benke, 1984; Gippel et al., 1996). Kraft and Warren (2003) developed a conceptual model for the development of spatial patterns of LW in stream channels. Two taxonomies of LW jams, aggregation (multiple pieces of LW) and segregation (single pieces of LW) were used to classify LW within the study reach (Kraft and Warren, 2003). More recently, Warren et al. (2009) developed a model using space-for-time analyses to quantify LW loading from young to old-age forest stands into stream channels with varying sizes and gradients. The volume and frequency of LW increased linearly with the age of the dominant tree canopy (Warren et al., 2009).

LW provides habitat and food for invertebrate species upon which different fish species feed (Angermeier and Karr, 1984; Benke et al., 1985). LW also contributes habitat complexity, which is important for fish species that overwinter in stream channels (Keller and Swanson, 1979). According to Moulin et al. (2011), LW is important in contributing to stream foodwebs, habitat-specific abundance, biomass and productivity. Therefore, it is obvious that LW increases biodiversity (Piégay et al., 1999). Fish movement throughout an ecosystem decreases as the amount of LW increases (Winker et al., 1995), suggesting the LW creates a hospitable habitat. Retaining CPOM long enough within a stream ecosystem increases processing time without being transported out of the system (Bilby and Likens, 1980). Scour pools behind boulders and debris jams/step-pools provide low-energy resting spots and spawning areas for fish species (Fausch and Northcote, 1992). LW may also provide protection from predators, cold water temperatures or refuge from high-flow events (Angermeier and Karr, 1984; McMahon and Hartman, 1989).

Floodplain Dynamics

Wohl (2013b) identified two interactions between LW in streams and the adjacent floodplain. The amount of LW in the stream channel can affect floodplain dynamics or respond to floodplain dynamics (Wohl, 2013b). Vegetation-limiting topography surrounding a mountainous stream channel, such as vertical bedrock cliffs, can create longitudinally dissimilar amounts of LW inputs into a stream system (Wohl, 2013b). Therefore, it is necessary to understand how valley geometry affects LW inputs, especially throughout watersheds experiencing the mountain pine beetle infestation.

Instream wood can affect floodplain dynamics in numerous ways. Erosional and depositional processes associated with channel-spanning debris jams can increase bank instability by directing flow into the banks. Bank stability influences the distribution, structure and age of riparian vegetation (Wohl, 2013b). Clusters of debris jams, such as step-pool channels, can create longitudinally discontinuous floodplains adjacent to the channel margins. Overbank flow can facilitate the transport and deposition of LW atop the floodplain in two ways (Wohl, 2013b). First, limited flow depths atop the floodplain can reduce LW transport and second, the diffusion of flow throughout the floodplain reduces stream power between the channel margins, possibly allowing for LW to settle within the natural channel (Wohl, 2013b). Overbank flow limits increases in stage and hydraulic forces during a flood; the floodplain acts as a ‘safety valve’ diffusing energy across a much larger cross-sectional area (Wohl, 2011: pg. 198).

Instream wood can be affected by floodplain dynamics, hillslope processes and the flow regime (Wohl, 2013b). Standing or buried pieces of LW can be conveyed into the natural stream channel through various methods. Most notably is the lateral migration or avulsion of a channel across and throughout the floodplain. Channel migration is affected by overbank flows and by the resistance of floodplain sediments to erosion (Wohl, 2013b). Floodplain resistance to erosion may increase as the number of dead falling MPB-killed trees resting on the floodplain increase.

Carbon Storage

Watershed-scale carbon dynamics is a somewhat understudied concept developed by Wohl et al. (2012). The rate of input and transportation of LW and organic matter can influence the amount of carbon stored within the stream system (Wohl et al., 2012). Carbon can be stored as floodplain sediment, coarse dead wood, fine organic matter or as riparian vegetation (Wohl et al., 2012). Greater channel complexity caused by channel-spanning debris jams can increase the amount of carbon stored within the stream system. Roughly a quarter of carbon measured within a watershed was located within the channel margins, which is less than one percent of the total surface area of a watershed (Wohl et al., 2012).

Wohl et al. (2012) identified four processes associated with carbon storage in valley bottoms. First, dissolved and particulate carbon can be stored throughout a floodplain. Overbank flow is necessary to deposit carbon on the floodplain, which typically happens due to a debris jam forcing flow out away from the channel margins. Second, saturated sediments due to an elevated water table limit microbial decomposition of carbon. Third, coarse wood decaying within the channel margins can create carbon pools. Wohl et al. (2012) noted that in the Colorado Rocky Mountains, it can take large-diameter conifer trees 300-900 years to completely decay. Finally, high flow events that do not create enough energy to erode the floodplain, such as spring runoff, can inundate the floodplain depositing carbon.

Nutrient Spiraling

Stream systems act as transport pathways for carbon to be removed from a watershed (Hall et al., 2002). This is especially important in headwater stream channels as they are directly linked with their surrounding hillslope processes, which input carbon into the stream system. Connectivity between the atmosphere, terrestrial, aquatic and subsurface can vary in both time and space, and can directly influence carbon inputs into headwater streams (Eggert et al., 2012). Carbon can be transported either as dissolved loads or as particulates. Nutrient uptake length is defined as the downstream distance a carbon atom must travel before being removed from stream flow (Hall et al., 2002). Uptake length can vary depending on hydrologic, geomorphic and other biological processes (Hall et al., 2002). During transport, carbon atoms may become trapped in hyporheic or surface areas, which is known as transient storage (Hall et al., 2002). These are areas where flow has less velocity than flow between the channel margins.

Ecology of the Mountain Pine Beetle

Research from previous studies has shown that MPB epidemics have existed throughout history and continue to be an integral part of forest ecology. Currently, the spread of the MPB is more extensive than previous infestations, possibly due to warming global temperatures. The Mountain Pine Beetle (MPB), *Dendroctonous ponderosae*, occurs in mountain pine forests throughout the Rocky Mountains (Campbell et al., 2007) and is native to the Rocky Mountain region (Leatherman, 2002). Lodgepole pine, ponderosa pine, western white pine and limber pine are all suitable hosts for MPB (Campbell et al., 2007). Klutsch et al. (2009) stated that the MPB is an integral part of forest ecology in lodgepole pine stands. In early stages of infestation, MPB target larger trees under stress from drought, fire damage, overcrowding, site conditions, root disease and old age (Leatherman, 2002). Three to five years after initial MPB attack, infested trees die and begin to fall (Mitchell and Preisler, 1998). Accumulations of coarse woody debris (CWD) and LW on the forest floor from beetle kill alters watershed hydrology and increases the potential for fire. LW accumulations within mountain stream channels also increases dramatically with MPB epidemics.

Adult beetles are black in color, stout and cylindrical in form, and roughly 6mm in length (Mattson, 1992). In lodgepole pine forests, they usually survive one calendar year (Mattson, 1992). Females burrow into suitable host trees, deep enough to reach the phloem layer of the tree, and produce roughly 75 eggs (Leatherman, 2002). New adult beetles emerge from the burrows between late June and early September (Mattson, 1992), after over-wintering within the phloem layer. Phloem is the living tissue layer beneath the bark that carries organic nutrients and sugars to any part of the living tree. The phloem layer of the tree is what the MPB larvae feed on once the eggs hatch; this reduces the ability of the infested tree to transport nutrients and eventually causes the tree to die. Trees are usually attacked within the lower third of the stump (Mattson, 1992).

Klutsch et al. (2009) noted three factors that contribute to the spread of MPB in the Rocky Mountains. 1) recent periods of drought increase stress on living forest stands, 2) cold temperatures, which are a major mortality agent for MPB, are less frequent due to increasing global temperatures, and 3) large forest stands of lodgepole pine are very susceptible to MPB epidemics (Klutsch et al., 2009). Dense lodgepole-pine stands have been shown to be the preference for MPB range expansion (Klutsch et al., 2009). Optimum temperatures for the MPB to thrive are between 23 and 25 degrees Celsius (Bentz et al., 1991). The MPB is cold blooded, so temperature acts as a control on the MPB’s life cycle (Carroll et al., 2003). Topographic elevation has been suggested as a control on MPB’s range, as higher elevations have a less optimum climate (Amman, 1969; Mattson, 1992). However, elevation has also been disproven as a control on MPB range by Klutsch et al. (2009). High moisture contents within the host tree have also been shown to increase beetle productivity and range expansion (Mattson, 1992).

Forests stands which are infested by the MPB are usually composed of trees at varying degrees of infestation (Eisenhart and Veblen, 2000; Klutsch et al., 2009; Pugh and Small, 2011). Previous research has determined that MPBs prefer trees with larger tree diameters and a thicker phloem layer (Amman and Baker, 1972; Berryman, 1976; Raffa and Berryman, 1982; Mitchell et al., 1983; Mattson, 1992; Pugh and Small, 2011). Smaller trees have a thin phloem layer and therefore are less likely to be selected by the MPB as a suitable host for the larvae (Amman and Baker, 1972; Berryman, 1976; Mitchell et al., 1983; Pugh and Small, 2011). Within an attacked forest stand, stress on trees adjacent to infested trees increases no matter the size (Mitchell et al., 1983), increasing the chance to become infested. Forest stands that have undergone tree thinning seem to be more resistant to MPB attack compared to old growth forest stands (Mitchell et al., 1983), a positive result due to current USFS logging practices. Campbell et al. (2007) note numerous reasons why the MPB epidemic is occurring, mostly due to “mismanagement” of the forests by the USFS and continuing warming global temperatures. Either way, historic and current MPB outbreaks have lasting effects on forest ecology, including altering stand structure and tree species distributions (Dordel et al., 2008).

Some research has been done studying CWD loading beneath MPB-infested lodgepole pine forest stands. Klutsch et al (2009) found no differences in CWD loads on the forest floor in infested lodgepole plots compared to live, un-infested forest stands over a two year study period.

However, Mitchell and Preisler (1998) found that over time, CWD loading increases in infested forest stands, which in turn increases fuel loads and fire potential. In infested forest stands that have been thinned, trees start falling three years after initial infestation compared to unthinned stands, within which trees do not start falling until five years after initial infestation (Mitchell and Preisler, 1998). In thinned stands, 50 percent of trees with at least a 40 centimeter diameter fell within eight years from initial infestation compared to six years for trees with diameters less than 40 centimeters. These fall times are shorter in relation to unthinned stands, possibly because thinning a tree stand increases the wind forces acting on each individual tree. It is apparent that fall rates of lodgepole pine trees are dependent on time after initial infestation (Mitchell and Preisler, 1998). Eleven years after initial infestation, 80-90 percent of infested trees had fallen to the forest floor in the thinned forest stand. These results were supported by Dordel et al. (2008), who also found that CWD mass increased in study plots located within infested forest stands.

Dating back to the late 1950s, the USFS and other managing agencies have sprayed chemicals onto trees within a forest stand in an attempt to control the MPB epidemic (Amman and Baker, 1972). Since lodgepole pine trees were thought to only be attacked in the lower 15 feet of the truck (Leatherman, 2002), trees were individually sprayed up to 30 feet. According to Amman and Baker (1972), seven operational factors control the effectiveness of chemical control of the MPB: 1) steepness of terrain, 2) ease of access, 3) training of control personnel, 4) experience of control personnel, 5) radius of treatment application around the stand of protected trees, 6) acreage infested and 7) initiation of control efforts while infestation is small. Since 1960, chemical control has proven unsuccessful at controlling the MPB epidemic, so another possible technique to control the MPB has been suggested. Solar treatments that raise underbark temperatures of trees to lethal levels for the MPB (110 degrees F) could be used to reduce MPB populations (Leatherman, 2002).

Study Systems

Research questions will be addressed in stream networks draining the Medicine Bow National Forest (MBNF) lands located in the Snowy and Sierra Madre mountain ranges in Wyoming (Figure 1.2). These systems are characterized by dramatic modern and legacy disturbances including wildfires, watershed logging, stream tie-driving, and water diversions. Tie-driving occurred in these watersheds from 1860 to 1970 (Young, 1991). Channel obstructions, such as boulders and LW, were removed by loggers to ready stream channels for tie-driving. Effects of tie-driving can still be seen today in many of the stream channels, noted by a lack of channel flow obstructions and low channel sinuosity. More recent land use disturbances include ditches and impoundments. Ditches act as water conveyance systems to transport water over a drainage divide from one watershed to another. Impoundments, stock ponds and reservoirs are also commonplace along streams of all sizes, reducing connectivity. MPBs are a native disturbance agent to forests in the region, and MPB population surges, or epidemics, have occurred frequently in the past. The last outbreak was during the 1970s and 1980s in the Laramie Mountains (Logan and Powell, 2001).

The Medicine Bow and Sierra Madre mountain ranges are located in a transitional zone between the 2.5 billion year old Superior Geochronologic Province in north-central Wyoming and 1.3 to 1.7 billion year old Central U.S. Geochronologic Province to the south in Colorado (Hills et al., 1968). Lithology is dominated by metamorphic and metasedimentary rocks including granite, proterozoic quartzite, gneiss, metagabbro and pegmatite (Hills et al., 1968). The highest point of the Snowy Range is Medicine Bow Peak (12,013 ft.). There are records of glaciation through remnant glacial deposits near the summit of Medicine Bow Peak (Oviatt, 1977) at an area named Libby Flats. These were thought to be deposited during the Pinedale Glaciation (Oviatt, 1977). The vegetation of MBNF is dominated by lodgepole pine and blue spruce. The Sierra Madre mountain range's geology and vegetation is similar to the Medicine Bow Mountains. The highest point is Bridger Peak (11,007 ft.), which lies along the Continental Divide. There are no records of glaciation in the Sierra Madre Range.

The climate of the MBNF varies with elevation (Dillon et al., 2003). Annual precipitation generally ranges between 38 centimeters at lower elevations to 100 centimeters in the subalpine zone (Martner, 1986). Roughly two-thirds of the precipitation above 2600 meters falls as snow. Temperatures range from -40 degrees Celsius to 43 degrees Celsius depending on season and elevation. The mean annual temperature ranges from 2 to 7 degrees Celsius (Dillon et al., 2003). The flow regime is characterized by high runoff periods in spring and early summer as snowmelt. Some of the smaller watershed headwater streams become intermittent during late summer through winter. Flash floods from rain-on-snow events occur on average every 50 years. During the 2011 flow season, flash floods from rain-on-snow in the French Creek and Brush Creek watersheds damaged road crossings and flushed fish and LW out of the headwater streams.

Historically, vegetation in the Medicine Bow Mountains was dominated by alpine tundra following glacial retreat during the late Pleistocene (15,330-11,500 yBP) (Mensing et al., 2012). These data were collected from pollen cores from East Glacier Lake near Libby Flats in the Snowy Range. The early to mid-Holocene (11,500-5200 yBP) was dominated by the growth of subalpine forests, including lodgepole pine forest stands (Mensing et al., 2012). Since 4200 yBP, treeline elevations began to decrease down to modern-day elevations. The timings of these post-glacial trends in vegetation are similarly related to records collected throughout the Rocky Mountains (Mensing et al., 2012).

According to data from Dillon et al. (2003) and annual aerial reconnaissance of dead forest stands provided by the US Forest Service, the MPB transitioned throughout the MBNF from the border with Colorado in the south to the northern tip of the Medicine Bow Mountains. Forest stands composed of high percentages of lodgepole pine are more susceptible to MPB infestation. Lodgepole pines tend to grow between the elevations of 2400 to 3000 meters above sea level in southeast Wyoming (Dillon et al., 2003), therefore it is expected that the majority of tree mortality related to MPB infestation will occur between those elevations. Concurrently, it can be expected that forest stands near the southern border with Colorado have been infested by MPB for a longer amount of time compared to stands in the northern Medicine Bow Mountains. Management agencies must account for variability in the degree of hillslope coupling along a stream network that passes through this elevational zone (Sullivan, 2012).

References

Abbe, T.B., Montgomery, D.R., Fetherston, K., McClure, E.M., 1993. A process-based classification of woody debris in a fluvial network: preliminary analysis of the Queets River, WA. EOS. *Transactions of the American Geophysical Union* 73, 296.

Abbe, T.B., Montgomery, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research & Management* 12, 201-221.

Amman, G.D, 1969. Mountain pine beetle emergence in relation to depth of lodgepole pine bark. USDA Forest Service Research Note INT-96, 1-8.

Amman, G.D., Baker, B.H., 1972. Mountain pine beetle influence on lodgepole pine stand structure. *Journal of Forestry* 70, No.4.

Andrus, C.W., Long, B.A., Froehlich, H.A., 1988. Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. *Canadian Journal of Fisheries and Aquatic Sciences* 45, 2080–2086.

Angermeier, P.L., Karr, J.R., 1984. Relationship between woody debris and fish habitat in a small warm water stream. *Transactions of the American Fisheries Society* 113, 716-726.

Assani, A.A., Petit, F., 1995. Log-jam effects on bed-load mobility from experiments conducted in a small gravel-bed forest ditch. *Catena* 25, 117–126.

Beckman, N.D. and Wohl, E., 2014. Carbon storage in mountainous headwater streams: The role of old-growth forest and logjams. *Water Resources Research* 50.3, 2376-2393.

Benke, A.C., Henry, R.L. III, Gillespie, D.M., Hunter, R.J., 1985. Importance of snag habitat for animal production in southeastern streams. *Fisheries* 10, 8-13.

Bentz, B.J., Logan, J.A., Amman, G.D., 1991. Temperature-dependent development of the mountain pine beetle (Coleoptera:Scolytidae) and simulation of its phenology. *Canadian Entomologist* 123, 1083-1094.

Berryman, A.A., 1976. Theoretical explanation of mountain pine beetle dynamics in lodgepole pine forests. *Environmental Entomology* 5, 1225-1233.

Bocchiola, D., Rulli, M.C., Rosso, R., 2006. Transport of large woody debris in the presence of obstacles. *Geomorphology* 76, 166-178.

Bilby, R.E., Likens, G.E., 1980. Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology* 61, 1107-1113.

Bilby, R.E., Ward, J.W., 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* 118, 368–378.

Bilby, R.E., Ward, J.W., 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and 2ndgrowth forests in southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 48, 2499–2508.

Braudrick, C.A., Grant, G.E., 2001. Transport and deposition of large woody debris in streams: a flume experiment. *Geomorphology* 41, 263-283.

Broadmeadow, S., Nisbet, T.R., 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. *Hydrology and Earth System Sciences* 8, 286-305.

Buffington, J.M., Lisle, T.E., Woodsmith, R.D., Hilton, S., 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. *River Research and Applications* 18, 507-531.

Cadol, D., Wohl, E., 2010. Wood retention and transport in tropical, headwater streams, La Selva Biological Station, Costa Rica. *Geomorphology* 123, 61-73.

Campbell, E.M., Alfaro, R.I., Hawkes, B., 2007. Spatial distribution of mountain pine beetle outbreaks in relation to climate and stand characteristics: a dendroecological analysis. *Journal of Integrative Plant Biology* 49, 168-178.

Carroll, A.L., Taylor, S.W., Regniere, J., Safranyik, L., 2003. Effect of climate change on range expansion by the mountain pine beetle in British Columbia. The Bark Beetles, Fuels, and Fire Bibliography, Paper 195.

Comiti, F., Andreoli, A., Mao, L., Lenzi, M.A., 2007. Wood storage in three mountain streams of the southern Andes and its hydro-morphological effects. *Earth Surface Processes and Landforms* 33, 244-262.

Costigan, K.H., Daniels, M.D., 2011. Spatial pattern, density and characteristics of large wood in Connecticut streams: Implications for stream restoration priorities in southern New England. *River Research and Applications* 29, 161-171.

Cummins, K.W., Sedell, J.R., Swanson, F.J., Minshall, G.W., Fisher, S.G., Cushing, C.E., Petersen, R.C., Vannote, R.L., 1983. Organic matter budgets for stream ecosystems: problems in their evaluation. Stream ecology. Springer US, 299-353.

Curran, J.H., Wohl, E., 2003. Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology* 51, 141-157.

Curran, J.C., 2010. Mobility of large woody debris (LWD) jams in a low gradient channel. *Geomorphology* 116, 320-329.

Daniels, M.D. 2006a. Distribution and dynamics of large woody debris and organic matter in a low-energy meandering stream. *Geomorphology* 77, 286-298.

Daniels, M.D., 2006b. Grain-size sorting in meander bends containing large woody debris. *Physical Geography* 27, 348-362.

Dillon, G.K., Knight, H., Meyer, C.B., 2003. Historic Variability for Upland Vegetation in the Medicine Bow National Forest, Wyoming. Medicine Bow National Forest, USFS Agreement No. 1102-0003-98-043.

Dollof, C.A., Warren, M.L., 2003. Fish relationships with large wood in small streams. *American Fisheries Society Symposium* 37, 179-193.

Dordel, J., Feller, M.C., Simard, S.W., 2008. Effects of mountain pine beetle (Dendroctonus ponderosae Hopkins) infestations on forest stand structure in the southern Canadian Rocky Mountains. *Forest Ecology and Management* 255, 3563-3570.

Dwire, K.A., Kauffman, J.B., 2003. Fire and riparian ecosystems in landscapes of the western USA. *Forest Ecology and Management* 178, 61-74.

Eggert, S.L., Wallace, J.B., Meyer, J.L., Webster, J.R., 2012. Storage and export of organic matter in a headwater stream: responses, to long-term detrital manipulations. *Ecosphere* 3, DOI: 10.1890/ES12-00061.1.

Ehle, D.S., Baker, W.L., 2003. Disturbance and stand dynamics in ponderosa pine forests in Rocky Mountain National Park, USA. *Ecological Monographs* 73, 543-566.

Ehrman, T.P., Lamerti, G.A., 1992. Hydraulic and particulate matter retention in a 3rd-order Indiana stream. *Journal of the North American Benthological Society* 11, 341-349.

Eisenhart, K., Veblen, T., 2000. Dendroecological detection of spruce bark beetle outbreaks in northwestern Colorado. *Canadian Journal of Forestry Research* 114: G01012.

Elder, K., Dwire, K.A., Hubbard, R., Rhodes, C., Ryan, S.E., Young, M., Porth, L., Dixon, M., Goodbody, A., 2006. Disturbance and water related research in the western United States. *Interagency Conference on Research in the Watersheds* 2, 3-21.

Faush, K.D., Northcote, T.G., 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. *Canadian Journal of Fisheries and Aquatic Sciences* 49, 682-693.

Faustini, J.M., Jones, J.A., 2003. Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology* 51, 187-205.

Feinstein, R.A. Effects of Catastrophic Blowdown on Headwater Streams in the Routt National Forest, Colorado. Doctoral Dissertation, Department of Earth and Atmospheric Sciences. University of Houston, 2012.

Fisher, G.B., Magilligan, F.J., Kaste, J.M., Nislow, K.H., 2010. Constraining the timescale of sediment sequestration associated with large woody debris using cosmogenic 7Be. *Journal of Geophysical Research* 115, F01013, doi:10.1029/2009JF001352.

Gippel, C.J., O’Neill, I.C., Finlayson, B.L., Schnatz, I., 1996. Hydraulic guidelines for the reintroduction and management of large woody debris in lowland rivers. *Regulated Rivers: Research & Management* 12, 223-236.

Gregory, K.J., Gurnell, A.M., Hill, C.T., 1985. The permanence of debris dams related to river channel process. *Hydrological Science Journal* 30, 371-381.

Gurnell, A.M., Gregory, K.J., Petts, G.E., 1995. The role of course woody debris in forest aquatic habitats: implications for management. *Aquatic Conservation: Marine and Freshwater Ecosystems* 5, 143-166.

Gurnell, A.M., Sweet, R., 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. *Earth Surface Processes and Landforms* 23, 1101-1121.

Gurnell, A.M., Piegay, H., Swanson, F.J., Gregory, S.V., 2002. Large wood and fluvial processes. *Freshwater Biology* 47, 601-619.

Haga, H., Kumagai, T., Otsuki, K., Ogawa, S., 2002. Transport and retention of coarse woody debris in mountain streams: an in situ field experiment of log transport and a field survey of coarse woody debris distribution. *Water Resources Research* 38, 1029-1044.

Hall Jr., R.O., Bernhardt, E.S., Likens, G.E., 2002. Relating nutrient uptake with transient storage in forested mountain streams. *Limnology and Ocenography* 47, 255-265.

Hassan, M.A., Hogan, D.L., Bird, S.A., May, C.L., Gorni, T., Campbell, D., 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. *Journal of American Water Resources Association* 41, 899-919.

Hills, F.A., Gast, P.W., Houston, R.S., Swainbank, I.G., 1968. Precambrian Geochronology of the Medicine Bow Mountains, Southeastern Wyoming. *Geological Society of America* 79, 1757-1784

Hyatt, T.L., Naiman, R.J., 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* 11, 191-202.

Hygelund, B., Manga, M., 2003. Field measurements of drag coefficients for model large woody debris. *Geomorphology* 51, 175–185.

Jackson, C.R., Sturm, C.A., 2002. Woody debris and channel morphology in first- and second-order forested channels in Washington’s coast ranges. *Water Resources Research* 38, 16-1 to 16.14.

James, L.A., 1989. Sustained storage and transport of hydraulic gold mining sediment in the Bear River, California. *Annals of the Association of American Geographers* 79, 570-592.

James, L.A., 1991. Incision and morphologic evolution of an alluvial channel recovering from hydraulic mining sediment. *Geological Society of America Bulletin* 103, 723-736.

James, L.A., 1999. Time and the persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California. *Geomorphology* 31, 265-290.

Jeffries, R., Darby, S.E., Sear, D.A., 2003. The influence of vegetation and organic debris on floodplain sediment dynamics: case study of a low-order stream in the New Forest, England. *Geomorphology* 51, 61-80.

Jones, T.A., Daniels, L.D., Powell, S.R., 2011. Abundance and function of large woody debris in small, headwater streams in the Rocky Mountain foothills of Alberta, Canada. *River Research and Applications* 27, 297-311.

Keller, E.A., Swanson, F.J., 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms* 4, 361–380.

Klutsch, J.G., Negron, J.F., Costello, S.L., Rhoades, C.C., West, D.R., Popp, J., Caissie, R., 2009. Stand characteristics and downed woody debris accumulations associated with a mountain pine beetle (Dendroctonus ponderosae Hopkins) outbreak in Colorado. *Forest Ecology and Management* 258, 641-649.

Kochel R.C., Ritter D.F., Miller J., 1987. Role of tree dams in the construction of pseudo-terraces and variable geomorphic response to floods in Little River valley, Virginia. *Geology* 15, 718–721.

Kraft, C.E., Warren, D.R., 2003. Development of spatial pattern in large woody debris and debris dams in streams. *Geomorphology* 51, 127-139.

Kreutzweiser, D.P., Good, K.P., Sutton, T.M., 2005. Large woody debris characteristics and contributions to pool formation in forest streams of the Boreal Shield. *Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere* 35, 1213–1223.

Leatherman, D.A., 2002. Mountain Pine Beetle. FROM: http://www.ext.colostate.edu/PUBS/INSECT/05528.html. Updated June 27, 2002.

Lienkaemper, G.W., Swanson, F.J., 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. *Canadian Journal of Forest Research* 17, 150-156.

Lisle, T.E., 1995. Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. *Water Resources Research* 31, 1797-1808.

Logan, J.A., Powell, J.A., 2001. Ghost forests, global warming, and the Mountain Pine Beetle (Coleoptera:Scolytidae). *American Entomologist* 47, 160-173.

Magilligan, F.J., Nislow, K.H., Fisher, G.B., Wright, J., Mackey, G., Laser, M., 2008. The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. *Geomorphology* 97, 467-482.

Manga, M., Kirchner, J.W., 2000. Stress partitioning in streams by large woody debris. *Water Resources Research* 36, 2373–2379.

Manners, R.B., Doyle, M.W., Small, M.J., 2007. Structure and hydraulics of natural woody debris jams. *Water Resources Research* 43, 17.

Marcus, W.A., Marston, R.A., Clovard Jr., C.R., Gray, R.D., 2002. Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone ecosystem, USA. *Geomorphology* 44, 323-335.

Martner, B.E., 1986. Wyoming climate atlas. University of Nebraska Press, Lincoln.

Massey, A.J. Large woody debris loading in forest streams due to 1997 Routt Divide blowdown, Routt National Forest, Colorado. 2000.

Mattson, M.J., 1992. The Role of Anthropods in Forest Ecosystem, pp. 3-18. Springer-Verlag, New York.

May, C.L., Gresswell, R.E., 2003. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, USA. *Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere* 33, 1352–1362.

McMahon, T.E., Hartman, G.F., 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (Oncorhynchus kisutch). *Canadian Journal of Fisheries and Aquatic Sciences* 46, 1551-1557.

Mensing, S., Korfmacher, J., Minckley, T., Musselman, R., 2012. A 15,000 year record of vegetation and climate change from a treeline lake in the Rocky Mountains, Wyoming, USA. *The Holocene* 22, 739-748.

Meyer, C.B., Knight, D.H., Dillon, G.K., 2005. Historic range of variability for upland vegetation in the Bighorn National Forest, Wyoming. USDA Forest Service General Technical Report RMRS-GTR-140.

Mitchell, R.G., Waring, R.H., Pitman, G.B., 1983. Thinning lodgepole pine increases tree vigor and resistance to mountain pine beetle. *Forest Science* 29, 204-211.

Mitchell, R.G., Priesler, H.K., 1998. Fall rage of lodgepole pine killed by the mountain pine beetle in central Oregon. *Western Journal of Applied Forestry* 13, 23-26.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., Pess, G., 1995. Pool spacing in forest channels. *Water Resources Research* 31, 1097-1105.

Montgomery, D.R., Collins, B.D., Buffington, J.M., Abbe, T.B., 2003. Geomorphic effects of wood in rivers. *American Fisheries Society Symposium* 37, 21–48.

Montgomery, D.R., Abbe, T.B., 2006. Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA. *Quaternary Research* 65, 147-155.

Morris, A.E.L., Goebel, P.C., Palik, B.J., 2010. Spatial distribution of large wood jams in streams related to stream-valley geomorphology and forest age in northern Michigan. *River Research and Applications* 26, 835-847.

Moulin, B., Schenk, E.R., Cliff, R.H., 2011. Distribution and characterization of in-channel large wood in relation to geomorphic patterns on a low-gradient river. *Earth Surface Processes and Landforms* 36, 1137-1151.

Nakamura, F., Swanson, F.J., 1994. Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon. *Canadian Journal of Forest Research* 24, 2395-2403.

Oviatt, C.G., 1977. Glacial geology of the Lake Marie area, Medicine Bow Mountains, Wyoming. *Rocky Mountain Geology* 16, 27-38.

Piégay, H., Thevenet, A., Citterio, A., 1999. Input, storage and distribution of large woody debris along a mountain river continuum, the Drome River, France. *Catena* 35, 19-39.

Pugh, E., Small, E., 2011. The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the Colorado River. *Ecohydrology* DOI:10.1002/eco.239.

Raffa, K.F., Berryman, A.A., 1982. Physiological differences between lodgepole pines resistance and susceptible to the mountain pine beetle and associated microorganisms. *Environmental Entomology* 11, 486-492.

Ralph, S.C., Poole, G.C., Conquest, L.L., Naiman, R.J., 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 51, 37-51.

Robinson, E.G., Beschta, R.L., 1990. Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, U.S.A. *Earth Surface Processes and Landforms* 15, 149-156.

Rosenfeld, J.S., Huato, L., 2003. Relationship between large woody debris characteristics and pool formation in small coastal British Columbia streams. *North American Journal of Fisheries Management* 23, 928–938.

Ruffing, C.M., Daniels, M.D., Dwire, K.A., 2015. Disturbance legacies of historic tie-drivers persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming. *Geomorphology* 231, 1-14.

Schmid, J.M., Amman, G.D., 1992. Dendroctonus beetles and old-growth forests in the Rockies. In: MR Kaufmann, WH Moir and WH Bassett (tech.eds) Old-growth forests in the southwest and Rock Mountain Regions, Preceedings of a Workshop, pg. 51-59. USDA Forest Service Rocky Mountain Research Station, *General Technical Report* RM-GTR-213.

Schmid, J.M., Mata, S.A., 1996. Natural variability of specific forest insect populations and their associated effects in Colorado. *General Technical Report* RM-275. USDA Forest Service, Fort Collins, Colorado, USA.

Shields, F.D., Smith, R.H., 1992. Effects of large woody debris removal on physical characteristics of a sand-bed river. *Aquatic Conservation: Marine and Freshwater Ecosystems* 2, 145-163.

Shields, F.D., Gippel, C.J., 1995. Prediction of effects of woody debris removal on flow resistance. *Journal of Hydraulic Engineering-ASCE* 121, 341–354.

Sibold, J.S., Veblen, T.T., Chipko, K., Lawson, L., Mathis, E., Scott, J., 2007. Influences of secondary disturbances on lodgepole pine stand development in Rocky Mountain National Park. *Ecological Application* 17, 1638-1655.

Sullivan, S.M.P., 2012. Geomorphic-ecological relationships highly variable between headwater and network mountain streams of northern Idaho, United States. *Journal of the American Water Resources Association (JAWRA)* 48.6, 1221-1232.

Thompson, D.M., 1995. The effects of large organic debris on sediment processes and stream morphology in Vermont. *Geomorphology* 11, 235–244.

Urban, M.A., Daniels, M.A., 2006. Introduction: exploring the links between geomorphology and ecology. *Geomorphology* 77.3, 203-206.

Wallace, J.B., Benke, A.C., 1984. Quantification of wood habitat in subtropical coastal plain streams. *Canadian Journal of Fisheries and Aquatic Sciences* 41, 1643-1652.

Warren, D.R., Kraft, C.E., 2008. Dynamics of large wood in an eastern U.S. mountain stream. *Forest Ecology and Management* 256, 808-814.

Warren, D.R., Kraft, C.E., Keeton, W.S., Nunery, J.S., Likens, G.E., 2009. Dynamics of wood recruitment in streams of the northeastern US. *Forest Ecology and Management* 258, 804-813.

Winker, K., Rappole, J.H., Ramos, M.A., 1995. The use of movement data as an assay of habitat quality. *Oecologia* 101, 211-216.

Wipfli, M.S. and Gregovich, D.P., 2002. Export of invertebrates and detritus from fishless headwater streams in southeastern Alaska: implications for downstream salmonid production. *Freshwater Biology* 47.5, 957-969.

Wohl, E., 2006. Human impacts to mountain streams. *Geomorphology* 79, 217-248.

Wohl, E., Jaeger, K., 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. *Earth Surface Processes and Landforms* 34, 329-344.

Wohl, E., Cenderelli, D.A., Dwire, K.A., Ryan-Burkett, S.E., Young, M.K., Fausch, K.D., 2010. Large in-stream wood studies: a call for common metrics. *Earth Surface Processes and Landforms* 35, 618-625.

Wohl, E., 2011. Threshold-induced complex behavior of wood in mountain streams. *Geology* 39, 587-590.

Wohl, E., and Cadol, D., 2011. Neighborhood matters: patterns and controls on wood distribution in old-growth forest streams of the Colorado Front Range, USA. *Geomorphology* 125, 132-146.

Wohl, E., Polvi, L.E., Cadol, D., 2011. Wood distribution along streams draining old-growth floodplain forests in Congaree National Park, South Carolina, USA. *Geomorphology* 126, 108-120.

Wohl, E., Dwire, K., Sutfin, N., Polvi, L., Bazan, R., 2012. Mechanisms of carbon storage in mountainous headwater rivers. *Nature Communications* 3, 1263.

Wohl, E., 2013a. Redistribution of forest carbon caused by patch blowdowns in subalpine forests of the Southern Rocky Mountains, USA. *Global Biogeochemical Cycles* 27.4, 1205-1213.

Wohl, E., 2013b. Floodplains and wood. *Earth-Science Reviews* 123, 194-212.

Wohl, E., 2014. A legacy of absence: Wood removal in US rivers. *Progress in Physical Geography* 38, 637-663.

Young, W.J., 1991. Flume study of the hydraulic effects of large woody debris in lowland rivers. Regulated Rivers: *Research & Management* 6, 203-211.

Young, W.J., Haire, D., Bozek, M.A., 1994. The effect and extent of railroad tie drives in streams of southeastern Wyoming. *Journal of Applied Forestry* 9, 125-130.

Zelt, R.B., Wohl, E., 2004. Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after a wildfire, Park County, Wyoming. *Geomorphology* 57, 217-233.

Figure 1.1 Conceptual models for (A) rate of wood recruitment, and (B) wood load related to MPB and diversion disturbances assuming no other subsequent large-scale disturbance. MPB infestation begins at zero years.

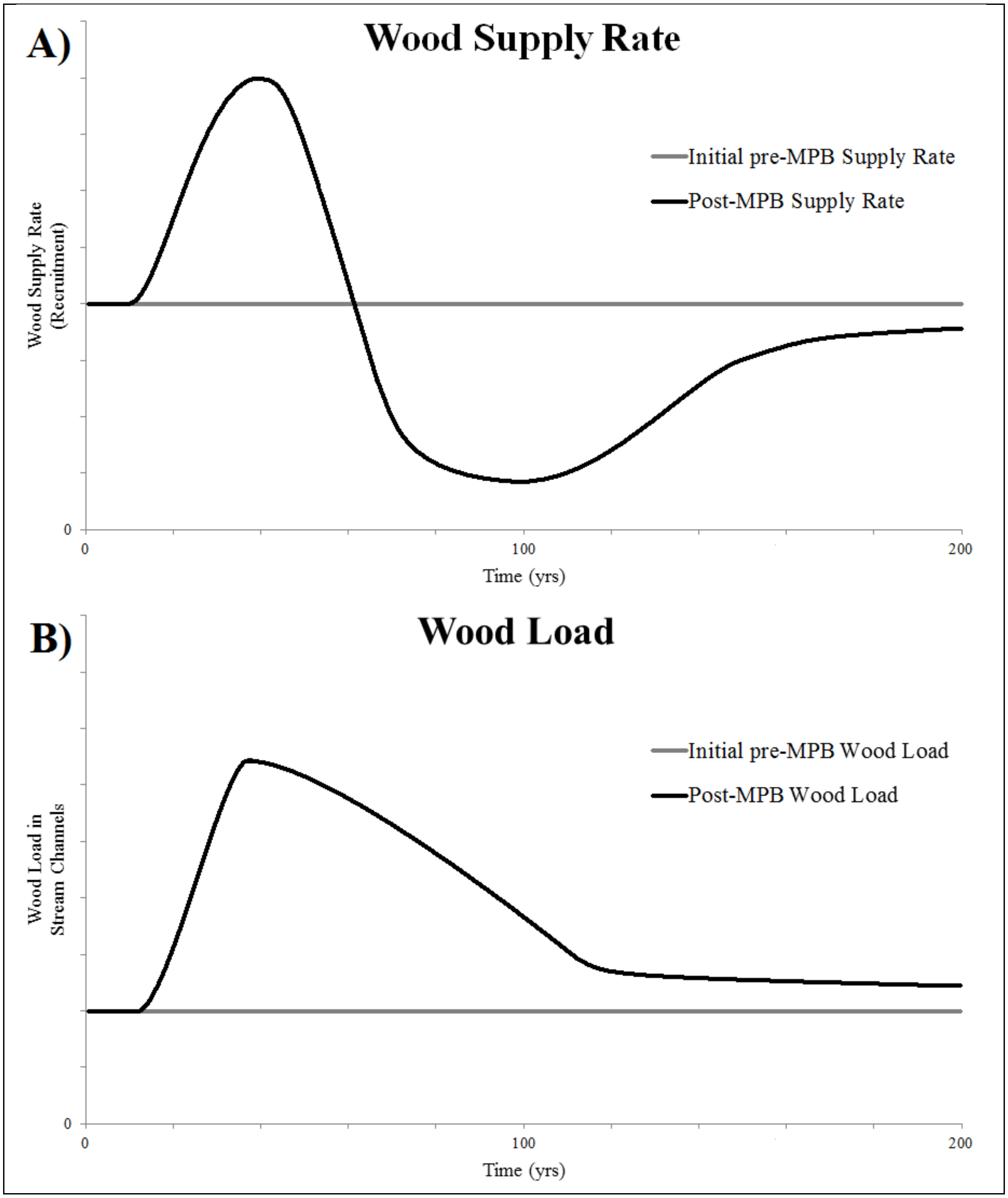
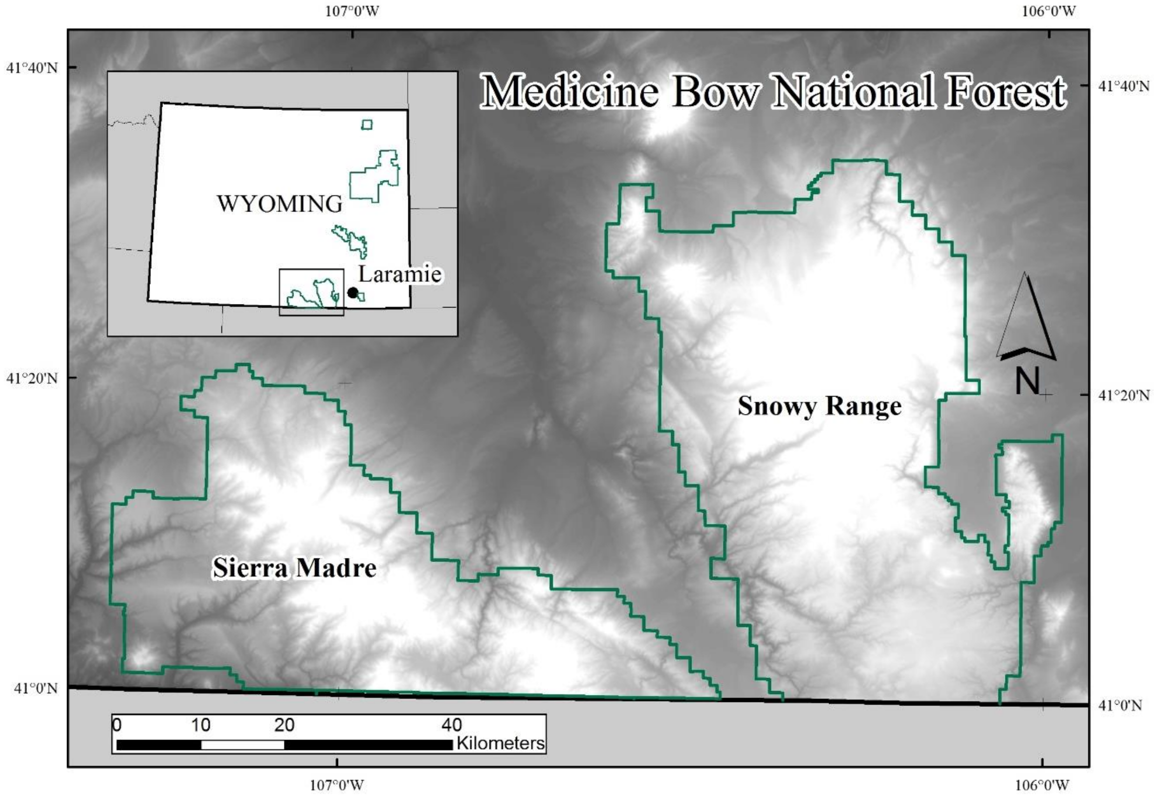


Figure 1.2 Medicine Bow National Forest, Wyoming. Study area includes the Sierra Madre and Snowy Mountain Ranges.



Chapter 2 - Large Wood Loadings in Rocky Mountain Headwater Streams across an Age Spectrum of Mountain Pine Beetle Infestation, Medicine Bow National Forest, Wyoming.

Abstract

Stream channels and their associated riparian corridors are influential components of the carbon cycle. Scientific knowledge is lacking pertaining to large wood (LW) loading into streams located within forested watersheds that are experiencing large-scale tree mortality due to beetle infestations. This dissertation chapter measures the amount and key characteristics of large wood being input into headwater mountain streams throughout watersheds experiencing varying stages of Mountain Pine Beetle (MPB) infestation. Large wood inventories were conducted along thirty-one stream segments across the stages of infestation. Total volume of MPB LW significantly increased with time since initial infestation. The number of MPB and non-MPB LW pieces increased with time since initial infestation, though not significantly. Decay classifications are significantly younger for MPB LW pieces compared to non-MPB pieces. Considering function and structure, a significant number of MPB LW pieces are bridging across channels until they are decayed enough to break and ramp down between the channel margins. Results from this chapter indicate that wood loads will continue to increase with time since initial MPB infestation, inducing both positive and negative effects to channel morphology and habitat complexity.

Introduction

Large wood (LW) is recognized as an important influence on fluvial geomorphic forms and processes. Pool formation, frequency and type (Keller and Swanson, 1979; Andrus et al., 1988; Bilby and Ward, 1991; Montgomery et al., 1995; Abbe and Montgomery, 1996; Gurnell and Sweet, 1998; Rosenfeld and Huato, 2003; Kreutzweiser et al., 2005) can influence sediment storage and transportation through a stream system (Thompson, 1995; May and Gresswell, 2003; Daniels, 2006b). LW also augments flow resistance (Assani and Petit, 1995; Shields and Gippel, 1995; Gippel et al., 1996; Manga and Kirchner, 2000; Curran and Wohl, 2003; Hygelund and Manga, 2003; Bocchiola et al., 2006; Manners et al., 2007) and reduces sediment transport (Bilby and Ward, 1989; Nakamura and Swanson, 1994). LW has been shown to increase longitudinal variation for both channel depth and width (Montgomery et al., 2003). LW is recognized as having an important influence on biological ecosystem processes in streams, such as nutrient and carbon cycling (Webster et al., 1999; Tank et al., 2010; Ruffing et al., 2015) and species distributions for both fish and aquatic invertebrates (Angermeier and Karr, 1984; Benke et al., 1985; Dolloff and Warren, 2003).

LW is an important morphological feature when studying both high- and low-gradient stream channels (Lisle, 1987; Wohl et al., 1997, 2004, 2009; Comiti et al., 2007; Wohl and Jaeger, 2009). Stream channels adjust to the presence or absence of LW (Curran, 2010). Mountain streams typically exhibit cascade, step-pool or plane bed channel characteristics (Grant et al., 1990; Montgomery and Buffington, 1997). Hydraulic steps contribute to channel stability and morphology (Ralph et al., 1994; Fetherston et al., 1995; Wood-Smith and Buffington, 1996; Buffington et al., 2002; Goode and Wohl, 2007). A strong presence of wood stabilizes channel planform, most commonly in forested headwater mountain stream channels (Keller and Swanson, 1979; Curran, 2010). Step-pool channels have been identified as an important class of mountain channels that are characterized by steep gradients (0.02–0.20m/m) and repeating sequences of boulder, log, or bedrock steps and intervening pools (Chin and Wohl, 2005).

Distribution and number of step-pools can be affected by sediment load, LW and other flow obstructions, and channel geometry and bed material size (Buffington et al., 2002).

LW loading can be influenced by drainage area, elevation, channel width, gradient and total stream power (Wohl and Jaeger, 2009). Headwater streams in forested mountain ecosystems are shown to have inherently high wood loads due to inputs from adjacent forest stands (Hyatt and Naiman, 2001; Ruffing et al., 2015). Old-growth forests input more LW into the stream channel, increasing bank erosion, which adds sediment into the system (Montgomery et al., 1995; Faustini and Jones, 2003). Steep surrounding hillslopes and a limited transport capacity amplify the amount of LW within a channel (Ruffing et al., 2015). Residence times for pieces of LW can range upwards of 250 years (Swanson et al., 1976; Murphy and Koski, 1989). Individual pieces of LW can remain in a stationary position upwards of 100 years (Swanson et al., 1976; Murphy and Koski, 1989). Longer, thicker pieces of LW are more likely to remain unmoved compared to shorter pieces (Nakamura and Swanson, 1994). Low-order headwater streams are inherently closely coupled to their surrounding hillslopes (Ruffing et al., 2015). Therefore, any alterations made to hillslope processes will likely have an effect on wood loading and channel morphology.

Mass wasting (Montgomery et al., 2003; Wohl et al., 2009), timber harvesting (Gurnell et al., 2000), fires (Zelt and Wohl, 2004), blowdowns (Massey, 2000; Sibold et al., 2007; Feinstein, 2012; Wohl, 2013), tie-driving (Young et al., 1994; Ruffing et al., 2015), diversion ditches (Ryan, 1994), road crossings (Jones et al., 2000; Wemple et al., 2001), insect infestations and climate change (Dillon et al., 2003) can all can affect LW loads in headwater mountain streams. This is especially true for LW dynamics related to the recent MPB infestation. Magilligan et al. (2008) found that logging forested mountain hillslopes decreased channel complexity.

Management activities, such as removing wood from a stream channel or logging a watershed, can have major impacts on stream channel function (Lisle, 1995; Buffington et al., 2002; Broadmeadow and Nisbet, 2004; Daniels and Rhodes, 2007), and have rarely been studied (Hassan et al., 2005). Volume of LW has been shown to increase with adjacent forest stand age (Warren et al., 2009). In the absence of anthropogenic activities, instream LW loads will reflect a balance among input rates, decay rates and export rates (Benda et al., 2003).

The number of pieces of LW per unit of stream channel can vary depending on the physiometric characteristics of the contributing watershed. Ryan (1994) found values ranging from 0.02 to 2.06 pieces of LW per meter in Colorado Rocky Mountain streams. Richmond and Fausch (1995) found values ranging from 0.02 to 0.22 pieces per meter in watersheds that have experienced previous management activities, such as logging. Ryan and others (2014) found a mean value of 0.69 pieces per meter in watersheds experiencing MPB infestation in Fraser Experimental Forest.

Tie-driving, or timber floating, was a common and expansive anthropogenic practice throughout the Rocky Mountain region that has rarely been studied (Ruffing et al., 2015). Timber was harvested and cut into railroad ties, then stored along streams until peak flows in spring could float the ties down out of the mountains to mills located down lower in the drainage (Young et al., 1994; Ruffing et al., 2015). Barriers within stream channels, such as boulders, LW, and debris jams were removed to allow ties to float downstream unobstructed (Young et al., 1994). Pulses of streamflow were stored behind check dams and released through feeder flumes to increase transport capabilities. Measureable legacy effects from tie-driving are still evident 100 years later in streams that have fewer pools and a lack of old, entrained LW, surrounded by low-density forest stands with almost no streamside riparian vegetation and similarly-aged trees indicating logging (Young et al., 1994; Ruffing et al., 2015). Tie-driven streams allow for the unique opportunity to study new inputs of LW from MPB-killed trees into carbon-starved plane-bedded channels.

In order to understand how the modern MPB outbreak may be altering LW loads in Rocky Mountain headwater streams, results are presented from extensive field surveys of streams across the temporal spectrum of MPB infestation. Instream LW census surveys are used to evaluate differences in wood loading from early to late-stage MPB infestation in headwater mountain streams within the Medicine Bow National Forest (MBNF), south-central Wyoming. It is hypothesized that wood loads in headwater stream channels will significantly increase non-linearly with time since initial MPB infestation of the contributing watershed. It is also hypothesized that MPB-killed pieces of LW will be significantly longer and thicker compared to non-MPB pieces.

Methodology

Study Site Selection

Utilizing annual aerial reconnaissance GIS data layers provided by the US Forest Service (Figure 2.1), local knowledge of lodgepole-dominant forest stands and known elevational control on lodgepole pine, at least 10 first- and second-order stream segments were identified in early-, middle- and late-stage MPB infestation watersheds. Each stream segment was located within a watershed that was predominantly north-oriented with equal contributing areas. Watersheds that experienced the first signs of beetle-kill between 2010 and 2011 were identified as early-stage infestation. If beetle-kill trees were present between the years 2005 to 2010, those watersheds were identified as middle-stage infestation. Any watersheds with the first signs of beetle-kill prior to 2005 were identified as late-stage infestation.

In total, 31 study reaches were selected and surveyed during the summer of 2012, consisting of 11 early-, 10 middle- and 10 late-stage infestation reaches. Reach length varied and included the entire length of a given stream order. For example, a second-order stream segment was surveyed from its beginning, where two first-order streams meet, downstream to the confluence with another stream of equal or greater order. Of the 11 early-stage reaches, eight were first-order ephemeral streams and three were second-order streams. Seven first-order ephemeral streams and three second-order stream segments were surveyed within middle-stage and late-stage watersheds. To account for the effects of water diversions on LW loads, stream segments impaired by diversion ditches were included in the original site selection for each level of infestation.

Wood Loading Data Collection

Following Wohl et al. (2010; Table 2.1), each singular piece of LW was measured within all survey reaches to evaluate the differences between MPB stages. Stream reach lengths were measured in line-of-sight segments using a laser range finder. Any individual piece of wood that was at least 1 meter in length and at least 10 centimeters in diameter was classified as LW, measured and recorded. Total length was measured from end to end for each piece of LW, along with total length in channel. Roughly every 20th piece was measured with a ruler and measuring tape to check for measurement accuracy. LW pieces bridging across the channel were included in the survey. Decay class, stability, the presence or absence of a root wad, function, channel type and structure of each piece of LW was categorized using taxonomy derived from Wohl et al. (2010; Table 2.1). MPB killed trees were identified by the presence of beetle burrow holes in the wood. Orientation was measured as the angle of LW related to the downstream flow direction. Riparian vegetation composition was estimated as a percentage of live green lodgepole pine, MPB-infested lodgepole pine, or other dominant vegetation category (spruce, aspen, willow, etc.). Bedload composition and any impairment along the stream segments were qualitatively noted, including any water diversion systems or other irregularities.

Data Analysis

Descriptive statistics were developed to characterize stream segments throughout the 31 identified watersheds. Comparisons between MPB and non-MPB LW were derived for all 31 study sites. MPB and non-MPB LW statistics were compared within each stage of infestation to understand how characteristics vary with time since initial infestation. Internal variability within MPB-killed LW is also demonstrated throughout the stages of infestation, as is non-MPB LW.

Analysis of Variance (ANOVA) was used to test for differences between the physical measurements of MPB and non-MPB LW throughout the stages of infestation. *P*-values are reported for these statistical tests for descriptive comparisons. *P*-values less than 0.05 indicate when data is heterogeneous.

Volume of LW per study site was calculated using the equation developed by Lienkaemper and Swanson (1987):

$$(1) \qquad \text{Volume} = (\pi(D_1 + D_2)L) / 8$$

where D1 and D2 are the end diameters for each individual piece and L is the length of each piece located within the channel margins.

Contingency analysis using the Chi Squared test was run on the categorical data collected during the LW survey. This tests whether or not categorical values are independent of one-another by identifying the presence or absence of an association. The strength of that association is determined by the Pearson's Chi Squared *p*-value, with low *p*-values representing strong inter-dependencies between variables. Due to the dependent nature of this categorical data, ANOVA is not appropriate for analysis. *P*-values associated with the Pearson's Chi Squared are reported for these statistical tests since all assumptions are met. Logistic regression was utilized to determine relationships between the dependent variables of infestation level and source (MPB or non-MPB) to the independent categorical variables collected during the LW survey.

Results

In total, 1951 pieces of LW were individually measured and categorized throughout 31 study sites encompassing 12,160 meters of stream channel. Of those 1951 pieces, 350 (18 percent) were identified as MPB-killed, 1601 were non-MPB killed pieces. Along 11 stream segments located within early-stage watersheds, 99 pieces out of a total of 725 (13.6 percent) were MPB pieces. There was a higher percent of MPB-killed pieces along 10 stream segments located in middle-stage watersheds with 118 out of 583 pieces (20.2 percent). Only a slightly higher percent was observed for late-stage watersheds, with 133 out of 643 pieces (20.6 percent) showing signs of MPB attack along 10 stream segments. There is therefore a positive trend in the number of MPB-killed pieces of LW compared to non-MPB LW with time since initial infestation.

LW Pieces

In total, 5760 meters of stream channel segments were surveyed within early-stage watersheds, 4010 meters within middle-stage watersheds, and 2391 meters within late-stage watersheds. Early-stage watersheds have the lowest numbers of pieces of LW per meter of stream channel, including both MPB and non-MPB sources (Figure 2.2). There is a 40 percent rise in MPB pieces of LW per meter transitioning from early- to middle-stage infestation, associated with only a 13 percent rise in the total number of pieces per meter. The transition from middle- to late-stage infestation returns the greatest variation, with a 48.2 percent increase in MPB pieces per meter and a 46.1 percent increase in the total number of pieces per meter. There is also an increase in the number of non-MPB pieces per meter between middle- and late-stage watersheds by 45.5 percent. Though there is no significant difference across the stages of infestation, there is an increase in the number of LW pieces per meter as time since initial infestation increases.

Physical Characteristics of LW

Total lengths (Figure 2.3), in-channel lengths (Figure 2.4) and diameters (Figure 2.5) for MPB and non-MPB pieces of LW were significantly different across the stages of infestation (Tables 2.2 & 2.3). For stream segments in early-, middle- and late-stage infestation watersheds, MPB pieces were significantly longer in total length and length within the channel margins ($p < 0.001$) than non-MPB LW (Table 2.4). Total lengths for MPB pieces range from 7.5 to 8.3 meters longer on average compared to non-MPB pieces across the stages of infestation. Lengths for MPB pieces were homogenous across the stages of infestation ($p = 0.21$). However, lengths for non-MPB pieces did differ significantly across the stages of infestation ($p = 0.039$).

MPB pieces were also significantly thicker compared to non-MPB pieces of LW throughout the entire stages of infestation ($p < 0.0001$) (Table 2.3). Diameters for MPB pieces range from 3.96 to 9.95 centimeters thicker on average compared to non-MPB pieces across the stages of infestation. Diameters for MPB pieces were not significantly different across the spectrum (Figure 2.4). However, the diameters for non-MPB pieces did differ significantly from early- to late-stage infestation ($p = 0.0013$) (Table 2.4).

Lengths of MPB and non-MPB pieces of LW within the channel margins were statistically different ($p < .0001$) across the stages of infestation (Tables 2.4 & 2.5). MPB pieces of LW tended to have longer in-channel lengths than non-MPB pieces. The proportions of each piece of LW located within the channel ranged from 23 to 28 percent for MPB-killed pieces. On average, 60 to 72 percent of each non-MPB piece will be located within the channel. In-channel proportions of MPB and non-MPB pieces were statistically different across the stages of infestation ($p < .001$) (Table 2.3). On average, less of each piece of MPB LW will be located within the channel compared to non-MPB pieces.

Proportions of MPB pieces of LW located within the channel were not statistically different from each other across the stages of infestation ($p = 0.134$) (Table 2.4). However, the proportion of non-MPB pieces located within the channel was significantly different across the stages of infestation ($p < .001$), with less of each piece of LW being exposed to the channel as time since initial infestation increases.

Volume of LW

Total volume of LW increased while transitioning from early- to middle-stage infestation and again from middle- to late-stage infestation (Table 2.3). Average volumes of MPB LW increased from 0.13-0.43m^3/100m from early- to middle-stage infestation, and then increased again to 0.97m^3/100m while transitioning to late-stage infestation (Figure 2.6). Average MPB LW volume significantly differs across the stages of infestation ($p = 0.0074$) (Table 2.4). Similarly, total volume of LW varies significantly across the spectrum ($p = 0.0092$), increasing with time since initial infestation. Volume of non-MPB pieces did not vary significantly across the spectrum ($p = 0.057$). However, volumes of non-MPB LW increased across the spectrum, increasing from 0.67-0.88m^3/100m from early- to middle-stage infestation and again to 1.44m^3/100m for late-stage infestation (Figure 2.7).

An examination of the variances of volume shows that MPB-killed LW volumes are highly variable throughout watersheds identified as late-stage infestation, with a variance of 0.91

m^3/100m. This is higher than variances for early- (0.008m^3/100m) and middle-stage (0.079m^3/100m) infestation MPB LW volumes. It therefore appears not only is there a greater volume of MPB-killed LW in late-stage infestation watersheds, but those individual pieces are highly variable in size. Variances of volumes for non-MPB killed pieces of LW were homogenous across the stages of infestation. Pieces ranged in volume by 0.41 and 0.40m^3/100m in early- and middle-stage infested watersheds. Late-stage watersheds returned the highest variance in non-MPB killed LW volume of 0.75m^3/100m.

Attributes of LW

Throughout stream segments in early-stage infestation watersheds, 725 pieces of LW were categorized by decay class, along with 583 pieces in middle-stage and 643 in late-stage watersheds. The percent of pieces of LW with protective layers of bark, indicating more recently killed pieces, increased from 25 to 33 percent from early- to middle-stage infestation, while the percent of bare pieces decreased by three percent and rotten pieces also decreased by eight percent. Transitioning from middle- to late-stage infestation, bare pieces of LW increase by six percent while pieces with a protective bark layer decrease by five percent.

Decay Classification

Within each stage of infestation, decay age classes were summarized for both MPB and non-MPB killed pieces of LW (Figure 2.8). Within early-stage infested watersheds, 83 percent of MPB-killed pieces were classified as having bark and needles. Only 19 percent of non-MPB killed pieces of LW were classified similarly. Eighty-one percent of non-MPB killed pieces of LW were classified as being decayed, rotten, retaining limbs or bare.

Functional Forms

The functional forms of LW varied throughout the stages of infestation (Figure 2.9). Bridges were the most common LW form, accounting for 39 percent of all surveyed pieces of LW. In early-stage infested watersheds, 32 percent of the pieces of LW bridged across the channel, compared to 46 and 39 percent in middle- and late-stage watersheds. Ramps were the next most common form, accounting for roughly 21 percent of the pieces of LW for each level of infestation. Incorporated pieces of LW were most commonly found in early-stage watersheds. Collapsed bridges and driftwood were the two least common functional forms, and were both most commonly found in early-stage watersheds. Sixty-two to 77 percent of the pieces of MPB-killed LW bridged across the channel in early- and late-stage study sites. In contrast, only 28 to 38 percent of non-MPB killed LW bridged across the channel in early- and late-stage stream segments.

Structure and Stability

The structural association of LW varied throughout the stages of infestation (Figure 2.10). The None/Other category was used as a classification for bridging pieces of LW. Examination of the data indicates a greater number of log steps in early-stage watersheds, accounting for 28 percent of the pieces of LW. Only nine percent of pieces in middle-stage and 16 percent in late-stage were classified as log steps.

Contingency Analysis

Results from the contingency analysis were all significant except for the stability of each individual piece of LW ($p = 0.2749$). Significant contingency means that the tested variables are related and dependent upon the stage of infestation. It is therefore necessary to interpret contingency tables for all significant tests to determine the strength of each association. Categorical variables may not be distributed evenly throughout the varying stages of infestation.

Sources of LW pieces were significant throughout the stages of infestation ($p = 0.0007$). A greater proportion of MPB to non-MPB pieces were located in late-stage watersheds. Therefore, as time since initial infestation increases, there are a greater number of MPB-killed pieces of LW within the channel margins throughout the stages of infestation.

Decay classifications were significantly related to stage of infestation ($p = 0.0001$). Across the stages of infestation, bark and rotten decay classes were the most common age class. Bark and rotten classes are on opposite ends of the classification spectrum. Results here indicate a bimodal distribution of age classes, which is indicative of an unnatural increase in new, young MPB-killed LW being added to the system.

The functional forms of LW throughout the stages of infestation were significant ($p < 0.0001$). Bridging pieces of LW were consistently the most common function throughout the stages of infestation. A greater number of LW pieces in early-stage watersheds were incorporated into the banks.

The structure of LW was significant across the stages of infestation ($p < 0.0001$). The none/other category relates to bridging pieces of LW that are elevated above the channel. This is by far the most commonly-occurring structure for LW across the stages of infestation. The number of bridging pieces of LW increases with time since initial infestation. A higher proportion of log steps exist throughout early-stage watersheds compared to middle- and late-stage.

Channel units were significant throughout the stages of infestation ($p < 0.0001$). Riffle and step-pool channel forms were the most common found throughout all stages of infestation.

The proportion of step-pools was highest in early-stage watersheds, possibly associated with the higher number of log steps found from the structure contingency analysis. Riffles were the most common channel unit type no matter the stage of infestation.

Results from the contingency analysis indicate that all descriptive categorical variables except stability are dependent upon the stage on infestation. In every case, this was a strong relationship represented by extremely low *p*-values. Therefore it appears that time since initial infestation has a significant effect on LW characteristics both for MPB and non-MPB sources.

Logistic Regression

Logistic regression analysis was run on the categorical data collected during LW surveys. Decay class, specifically younger pieces classified as having limbs ($p < 0.001$), bark ($p < 0.001$) or needles ($p < 0.001$), and the presence of a rootwad ($p < 0.001$) were significantly related to MPB pieces of LW (Table 2.6). Incorporated pieces of LW ($p = 0.023$) were also significant. Overall, decay class ($p < 0.001$), stability ($p = 0.00083$), the presence or absence of a rootwad ($p < 0.001$) and channel type ($p = 0.013$) were significant predictors as to whether or not a piece of LW was MPB-killed.

Logistic regression was also run on categorical variables to determine statistically significant predictors for time since initial infestation. MPB-killed pieces of LW were significantly related to stage of infestation ($p < 0.001$). The presence of a rootwad ($p = 0.005$), ramping pieces of LW ($p = 0.011$), log steps ($p = 0.025$) and bridging pieces of LW ($p = 0.007$) were all significantly related to time since initial infestation (Table 2.8). MPB pieces of LW ($p < 0.001$), decay classification ($p = 0.034$), the presence of a rootwad ($p = 0.0011$), function ($p < 0.001$), channel unit type ($p < 0.001$) and structure ($p < 0.001$) were all significant predictors for time since initial infestation (Table 2.9).

Discussion

Results show a significant increase in the number of pieces of both MPB and non-MPB LW per meter from early- to middle-stage and again from middle- to late-stage infestation. As time since initial infestation increases, the probability of a MPB-killed tree collapsing increases (Mitchell and Preisler, 1998). Non-MPB killed pieces of LW also increase from early- to middle-stage and again from middle- to late-stage infestation.

The number of LW pieces varied with time since initial infestation, ranging from 0.14 pieces/m in early-stage stream segments to 0.29 pieces/m in late-stage stream segments. These values fall within ranges identified during earlier LW surveys throughout the Colorado Rocky Mountains. Ryan (1994) found values ranging from 0.02 to 2.06 pieces/m. Richmond and Fausch (1995) measured 0.18 to 0.64 pieces/m and 0.02 to 0.22 pieces/m in historically logged watersheds. Wohl and Goode (2008) measured 0.13 to 1.40 pieces/m and Ryan et al. (2014) found values ranging from 0.4 to 1.0 pieces/m.

An increase in the number of pieces of LW in a channel has been shown to increase sediment sequestration (Fisher et al., 2010). However, a majority of the MPB-killed pieces in this study were bridging across the channel, above the in-channel flow. Eventually those pieces will decay to the point of collapse, at which point individual pieces could ramp down from the banks into the channel flow. Channel type for each piece of LW did not vary significantly across the stages of infestation. This could represent a lag time between the initial LW input and any morphological effects that piece may have on channel form. Future research could include measuring decay rates of MPB and non-MPB-killed LW in order to understand this temporal lag time, which extends beyond the scope of this study.

MPB pieces of LW were significantly longer compared to non-MPB LW across the stages of infestation. This was similarly the case for both in-channel and total lengths. Therefore, it is expected that individual pieces of MPB-killed LW will be longer on average, generating a greater number of stationary pieces of wood. LW transport has been shown to decrease as the length of a piece of wood increases (Nakamura and Swanson, 1994; Warren and Kraft, 2008). The low potential for transport of MPB LW suggests why the accumulation of wood into debris jams was uncommon across the stages of infestation. Ryan et al. (2014) found similar results for MPB-infested watersheds located in north-central Colorado. Pieces of MPB-killed LW tend to become entrained and incorporated into the banks and channels at the site of their initial input (Ryan et al., 2014).

MPB pieces of LW were significantly thicker compared to non-MPB LW across the stages of infestation. Thicker, longer pieces of MPB LW require more stream power to mobilize and transport (Nakamura and Swanson, 1994). Peak flows at these headwater survey reaches lack the necessary power to annually mobilize these pieces of LW. Therefore, these longer and thicker MPB-killed LW pieces are more likely to remain stationary as time since initial infestation increases. Less mobile pieces of LW could lead to the re-establishment of a step-pool channel form in plane-bed streams that were historically tie-driven.

Volume of MPB LW significantly increases with time since initial infestation, as does total LW volume. The volume of non-MPB LW did increase from early- to late-stage infestation, however not significantly. This suggests that new MPB LW almost singularly accounts for the increase in total volume.

Lengths and diameters for individual pieces of non-MPB LW significantly increased with time since initial infestation. Volume of non-MPB LW did increase from early- to late-stage infestation, however not significantly. This increase in non-MPB LW is the result of a greater number of falling MPB-killed trees collapsing nearby, adjacent to non-MPB trees. Falling, MPB-killed trees can become tangled with surrounding non-MPB tree branches causing an unequal distribution of weight on the trunk. The added weight increases the probability that non-MPB trees will fall along a similar trajectory as the initial MPB treefall. This domino-effect accounts for the additional pieces of non-MPB LW from early- to late-stage infestation. Smaller non-MPB trees are more likely to fall after being impacted by a falling MPB-killed tree. Even though the number of non-MPB LW pieces increases significantly from early- to late-stage infestation, the volume won't necessarily increase significantly if those pieces are smaller in size. As the number of falling MPB-killed trees increases with time since initial infestation, it can be expected that more non-MPB trees will fall.

All volume measurements throughout the study sites are comparable to earlier LW surveying throughout the Colorado Rocky Mountains. Wohl and Jaeger (2008) found wood volumes ranging from 0.01 to 10 m^3/100m in Colorado mountain streams. Wohl and Goode (2008) also found values ranging from 1.2 to 15.2 m^3/100m during subsequent surveys. Ryan et al. (2014) measured volumes averaging 4.7 m^3/100m.

Decay classifications were younger for pieces of MPB-killed LW across the stages of infestation compared to non-MPB pieces. Protective layers of bark on recently added MPB LW aid in protecting that piece from weathering. Non-MPB pieces were older on average, indicating longer residence times and exposure to weathering prior to the MPB infestation. Non-MPB pieces also spanned the entire range of decay classifications, suggesting a more natural wood-loading scheme that produces variable ages of in-stream LW pieces. Average age of in-channel LW for both MPB and non-MPB pieces increases with time since initial infestation. The proportion of each piece of LW located within the channel margins is directly related to age, where older pieces of LW have a greater proportion located within the channel. Lower proportions associated with the younger MPB-killed LW could assist in prolonging the integrity of those pieces since a higher proportion of those pieces is located outside the channel margins. This will be another factor that increases the lag time between initial LW input and any morphological effects on the channel.

The function of LW was shown to be significantly related to the stage of MPB infestation. Forty percent of total LW pieces were bridging across the channel (up to 77 percent for MPB pieces). For comparison, Ryan et al. (2014) found 25 percent of pieces were bridging across channels in Fraser Experimental Forest, Colorado. A greater proportion of bridging pieces will be a factor that contributes to the lag time between initial input of LW and any associated morphological effects on the channel.

Structure of LW pieces is strongly related to time since initial infestation. Results indicate that younger pieces of LW tend to bridge across the channel at a much higher rate compared to non-MPB pieces. By far the most common structural occurrences were bridging pieces and log steps. Log steps can trap sediment and organic matter upstream forming sediment wedges (Thompson, 1995; May and Gresswell, 2003), however bridging pieces are unable to do this. Even though the number of pieces of LW is increasing with time since initial infestation, those pieces may not be currently affecting channel morphology and hydrology.

Since pieces of MPB-killed LW have greater volumes, those pieces will be less likely to become drift wood (Nakamura and Swanson, 1994). These results show that LW is not relatively mobile, with only 11 to 14 percent of pieces of LW being classified as drift throughout the stages of infestation. Results also suggest that pieces of LW tend to become incorporated into the channel at their site of initial contact. Ryan et al. (2014) found similar results showing less mobile pieces of LW in Fraser Experimental Forest, Colorado.

Together, the function and structure of LW is especially important when discussing carbon storage and nutrient cycling throughout the varying stages of infestation. Channel complexity directly influences the amount of carbon stored between the channel margins (Wohl et al., 2012). Bridging pieces of LW are not contributing to channel complexity as they are elevated up out of the in-stream flow. Once those pieces collapse into the channel, then they can increase flow resistance and channel complexity. A detailed morphological survey of channels throughout the stages of infestation is required to understand this temporal lag.

Future wood loading rates are expected to increase with time since initial infestation as more dead trees fall across and into stream channels. Once regrowth begins to dominate attacked MPB forest stands in roughly 40-60 years, there will be a lack of sufficient forest cover to provide natural LW inputs before the stand recovers (Figure 2.11). Long-term monitoring to capture impending adjustments by the stream channels and alterations in the composition of surrounding forest stands are necessary in order to fully understand the spatial and temporal aspects of this disturbance.

Conclusion

The current MPB disturbance influences wood loads in forested headwater mountain streams throughout the MBNF. There are significant increases in the number of LW pieces and LW volumes from early- to late-stage infestation. MPB-killed pieces of LW are significantly longer and thicker compared to non-MPB LW. The age, functional form and structure of LW are dependent upon stage of infestation. Despite previous research that examines the effects of natural and anthropogenic disturbances on LW loads, this study uniquely addresses the influence of the current MPB infestation on wood loads across varying stages of infestation.

References

Abbe, T.B., Montgomery, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research & Management* 12, 201-221.

Andrus, C.W., Long, B.A., Froehlich, H.A., 1988. Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. *Canadian Journal of Fisheries and Aquatic Sciences* 45, 2080–2086.

Angermeier, P.L., Karr, J.R., 1984. Relationship between woody debris and fish habitat in a small warmwater stream. *Transactions of the American Fisheries Society* 113, 716-726.

Assani, A.A., Petit, F., 1995. Log-jam effects on bed-load mobility from experiments conducted in a small gravel-bed forest ditch. *Catena* 25, 117–126.

Benda, L., Miller, D., Sias, J., Martin, D., Bilby, R., Veldhuisen, C., Dunne, T., 2003. Wood recruitment processes and wood budgeting. Pages 49-73 in Gregory, S.V., Boyer, K.L., Gurnell, A.M., editors. The ecology and management of wood in world rivers. *American Fisheries Society Symposium* 37, Bethesda, Maryland.

Benke, A.C., Henry, R.L. III, Gillespie, D.M., Hunter, R.J., 1985. Importance of snag habitat for animal production in southeastern streams. *Fisheries* 10, 8-13.

Bilby, R.E., Ward, J.W., 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* 118, 368–378.

Bilby, R.E., Ward, J.W., 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and 2ndgrowth forests in southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 48, 2499–2508.

Bocchiola, D., Rulli, M.C., Rosso, R., 2006. Transport of large woody debris in the presence of obstacles. *Geomorphology* 76, 166-178.

Broadmeadow, S., Nisbet, T.R., 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. *Hydrology and Earth System Sciences* 8, 286-305.

Buffington, J.M., Lisle, T.E., Woodsmith, R.D., Hilton, S., 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. *River Research and Applications* 18, 507-531.

Chin, A., and Wohl, E., 2005. Toward a theory for step pools in stream channels. *Progress in Physical Geography* 29, 275-296.

Comiti, F., Andreoli, A., Mao, L., Lenzi, M.A., 2007. Wood storage in three mountain streams of the southern Andes and its hydro-morphological effects. *Earth Surface Processes and Landforms* 33, 244-262.

Curran, J.H., Wohl, E., 2003. Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology* 51, 141-157.

Curran, J.C., 2010. Mobility of large woody debris (LWD) jams in a low gradient channel. *Geomorphology* 116, 320-329.

Daniels, M.D., 2006b. Grain-size sorting in meander bends containing large woody debris. *Physical Geography* 27, 348-362.

Daniels, M.D., Rhodes, B.L., 2007. Influence of experimental removal of large woody debris on spatial patterns of three-dimensional flow in a meander bend. *Earth Surface Processes and Landforms* 32, 460-474.

Dillon, G.K., Knight, D.H., Meyer, C.B., 2003. Historic Variability for Upland Vegetation in the Medicine Bow National Forest, Wyoming. Medicine Bow National Forest, USFS Agreement No. 1102-0003-98-043.

Dollof, C.A., Warren, M.L., 2003. Fish relationships with large wood in small streams. *American Fisheries Society Symposium* 37, 179-193.

Faustini, J.M., Jones, J.A., 2003. Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology* 51, 187-205.

Feinstein, R.A. Effects of Catastrophic Blowdown on Headwater Streams in the Routt National Forest, Colorado. Doctoral Dissertation. University of Houston, 2012.

Fetherston, K.L., Naiman, R.J., Bilby, R.E., 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology* 13, 133-144.

Fisher, G.B., Magilligan, F.J., Kaste, J.M., Nislow, K.H., 2010. Constraining the timescale of sediment sequestration associated with large woody debris using cosmogenic 7Be. *Journal of Geophysical Research* 115, F01013, doi:10.1029/2009JF001352.

Gippel, C.J., O’Neill, I.C., Finlayson, B.L., Schnatz, I., 1996. Hydraulic guidelines for the reintroduction and management of large woody debris in lowland rivers. *Regulated Rivers: Research & Management* 12, 223-236.

Goode, J.R., Wohl, E., 2007. Relationships between land-use and forced-pool characteristics in the Colorado Front Range. *Geomorphology* 83, 249-265.

Grant, G.E., Swanson, F.J., Wolman, M.G., 1990. Pattern and origin of stepped bed morphology in high gradient streams, Western Cascades, Oregon. *Geological Society of America Bulletin* 102, 340-352.

Gurnell, A.M., Sweet, R., 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. *Earth Surface Processes and Landforms* 23, 1101-1121.

Gurnell, A.M, Petts, G.E., Harris, N., Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., 2000. Large wood retention in river channels: The case of the Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms* 25, 255-275.

Hassan, M.A., Hogan, D.L., Bird, S.A., May, C.L., Gorni, T., Campbell, D., 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. *Journal of American Water Resources Association* 41, 899-919.

Hyatt, T.L., Naiman, R.J., 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* 11, 191-202.

Hygelund, B., Manga, M., 2003. Field measurements of drag coefficients for model large woody debris. *Geomorphology* 51, 175–185.

Jones, J.A., Swanson, F.J., Wemple, B.C., Snyder, K.U., 2000. Effects of roads on hydrology, geomorphology and disturbance patches in stream networks. *Conservation Biology* 14, 76-85.

Keller, E.A., Swanson, F.J., 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms* 4, 361–380.

Kreutzweiser, D.P., Good, K.P., Sutton, T.M., 2005. Large woody debris characteristics and contributions to pool formation in forest streams of the Boreal Shield. *Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere* 35, 1213–1223.

Lienkaemper, G.W., Swanson, F.J., 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. *Canadian Journal of Forest Research* 17, 150-156.

Lisle, T.E., 1987. Overview: Channel morphology and sediment transport in steepland streams. Erosion and Sedimentation in the Pacific Rim, IAHS Publ. no. 165.

Lisle, T.E., 1995. Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. *Water Resources Research* 31, 1797-1808.

Magilligan, F.J., Nislow, K.H., Fisher, G.B., Wright, J., Mackey, G., Laser, M., 2008. The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. *Geomorphology* 97, 467-482.

Manga, M., Kirchner, J.W., 2000. Stress partitioning in streams by large woody debris. *Water Resources Research* 36, 2373–2379.

Manners, R.B., Doyle, M.W., Small, M.J., 2007. Structure and hydraulics of natural woody debris jams. *Water Resources Research* 43, 17.

Massey, A.J. Large woody debris loading in forest streams due to 1997 Routt Divide blowdown, Routt National Forest, Colorado. 2000.

May, C.L., Gresswell, R.E., 2003. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, USA. *Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere* 33, 1352–1362

Mitchell, R.G., Priesler, H.K., 1998. Fall rage of lodgepole pine killed by the mountain pine beetle in central Oregon. *Western Journal of Applied Forestry* 13, 23-26.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., Pess, G., 1995. Pool spacing in forest channels. *Water Resources Research* 31, 1097-1105.

Montgomery, D.R., Buffington, J.M., 1997. Channel reach morphology in mountain drainage basins. *Geological Society of America Bulletin* 109, 596-611.

Montgomery, D.R., Collins, B.D., Buffington, J.M., Abbe, T.B., 2003. Geomorphic effects of wood in rivers. *American Fisheries Society Symposium* 37, 21–48.

Murphy, M.L., Koski, K.V., 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. *North American Journal of Fisheries Management* 9, 427–436.

Nakamura, F., Swanson, F.J., 1994. Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon. *Canadian Journal of Forest Research* 24, 2395-2403.

Ralph, S.C., Poole, G.C., Conquest, L.L., Naiman, R.J., 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 51, 37-51.

Richmond, A.D., Fausch, K.D., 1995. Characteristics and function of large woody debris in mountain streams of northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* 52, 1789-1802.

Rosenfeld, J.S., Huato, L., 2003. Relationship between large woody debris characteristics and pool formation in small coastal British Columbia streams. *North American Journal of Fisheries Management* 23, 928–938.

Ruffing, C.M., Daniels, M.D., Dwire, K.A., 2015. Disturbance legacies of historic tie-drivers persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming. *Geomorphology* 231, 1-14.

Ryan, S.E., 1994. Effects of transbasin diversion on flow regime, bedload transport, and channel morphology in Colorado mountain streams. Dissertation, Department of Geography, University of Colorado.

Ryan, S.E., Bishop, E.L., Daniels, J.M., 2014. Influence of large wood on channel morphology and sediment storage in headwater mountain streams, Fraser Experimental Forest, Colorado. *Geomorphology* 217, 73-88.

Shields, F.D., Gippel, C.J., 1995. Prediction of effects of woody debris removal on flow resistance. *Journal of Hydraulic Engineering-ASCE* 121, 341–354.

Sibold, J.S., Veblen, T.T., Chipko, K., Lawson, L., Mathis, E., Scott, J., 2007. Influences of secondary disturbances on lodgepole pine stand development in Rocky Mountain National Park. *Ecological Application* 17, 1638-1655.

Swanson, F.J., Lienkaemper, G.W., Sedell, J.R., 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. *U.S. For. Serv. Gen. Tech. Rep.* PNW-56.

Tank, J.L., Rosi-Marshall, E.J., Griffiths, N.A., Entrekin, S.A., Stephen, M.L., 2010. A review of allochthonous organic matter dynamics and metabolism in streams. *Journal of the North American Benthological Society* 29, 118-146.

Thompson, D.M., 1995. The effects of large organic debris on sediment processes and stream morphology in Vermont. *Geomorphology* 11, 235–244.

Warren, D.R., Kraft, C.E., 2008. Dynamics of large wood in an eastern U.S. mountain stream. *Forest Ecology and Management* 256, 808-814.

Warren, D.R., Kraft, C.E., Keeton, W.S., Nunery, J.S., Likens, G.E., 2009. Dynamics of wood recruitment in streams of the northeastern US. *Forest Ecology and Management* 258, 804-813.

Webster, J.R., Benfield, E.F., Ehrman, T.P., Shaeffer, M.A., Tank, J.L., Hutchens, J.J., D'Angelo, D.J., 1999. What happens to allochthonous material that falls into streams? A synthesis of new and published information from Coweeta. *Freshwater Biology* 41, 687-705.

Wemple, B.C., Swanson, F.J., Jones, J.A., 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. *Earth Surface Processes and Landforms* 26, 191-204.

Wohl, E., Madsen, S., MacDonald, L., 1997. Characteristics of log and clast bed-steps in step-pool streams of northwestern Montana, USA. *Geomorphology* 20, 1-10.

Wohl, E., Kuzma, J.N., Brown, N.E., 2004. Reach-scale channel geometry of a mountain river. *Earth Surface Processes and Landforms* 29, 969-981.

Wohl, E., Goode, J.R., 2008. Wood dynamics in headwater stream of the Colorado Rocky Mountains. *Water Resources Research* 44, 1-14.

Wohl, E., Jaeger, K., 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. *Earth Surface Processes and Landforms* 34, 329-344.

Wohl, E., Ogden, F.L., Goode, J., 2009. Episodic wood loading in a mountainous neotropical watershed. *Geomorphology* 111, 149-159.

Wohl, E., Cenderelli, D.A., Dwire, K.A., Ryan-Burkett, S.E., Young, M.K., Fausch, K.D., 2010. Large in-stream wood studies: a call for common metrics. *Earth Surface Processes and Landforms* 35, 618-625.

Wohl, E., Dwire, K., Sutfin, N., Polvi, L., Bazan, R., 2012. Mechanisms of carbon storage in mountainous headwater rivers. *Nature Communications* 3, 1263.

Wohl, E., 2013. Redistribution of forest carbon caused by patch blowdowns in subalpine forests of the Southern Rocky Mountains, USA. *Global Biogeochemical Cycles* 27.4, 1205-1213.

Wood-Smith, R.D., Buffington, J.M., 1996. Multivariate geomorphic analysis of forest streams: implications for assessment of land use impacts on channel condition. *Earth Surface Processes and Landforms* 21, 377-393.

Young, W.J., Haire, D., Bozek, M.A., 1994. The effect and extent of railroad tie drives in streams of southeastern Wyoming. *Journal of Applied Forestry* 9, 125-130.

Zelt, R.B., Wohl, E., 2004. Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after a wildfire, Park County, Wyoming. *Geomorphology* 57, 217-233.

Figure 2.1 Aerial reconnaissance of MPB lodgepole pine tree mortality and large wood inventory sites. Data provided by the US Forest Service, Brush Creek/Hayden District.

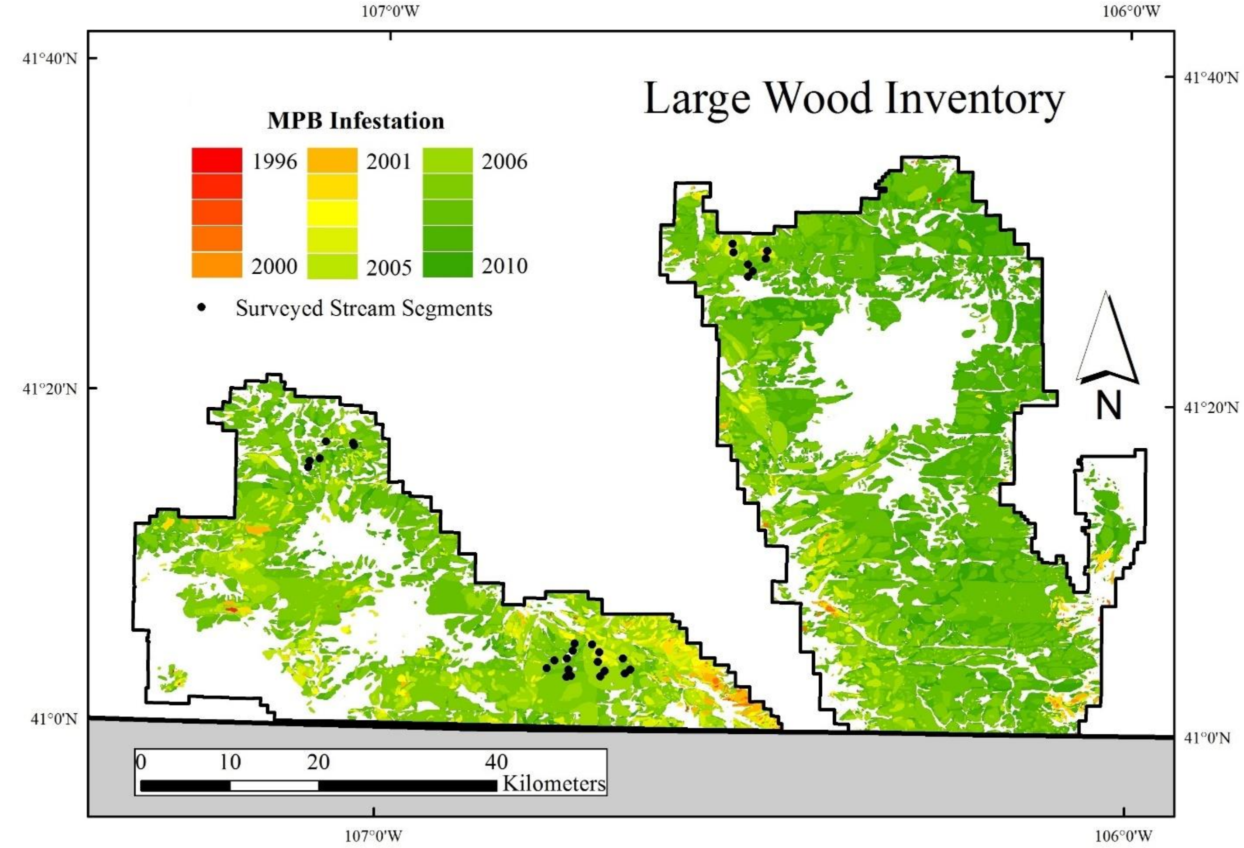


Figure 2.2 Frequency of MPB and Non-MPB pieces of LW per 100-meters of stream channel across the stages of infestation.

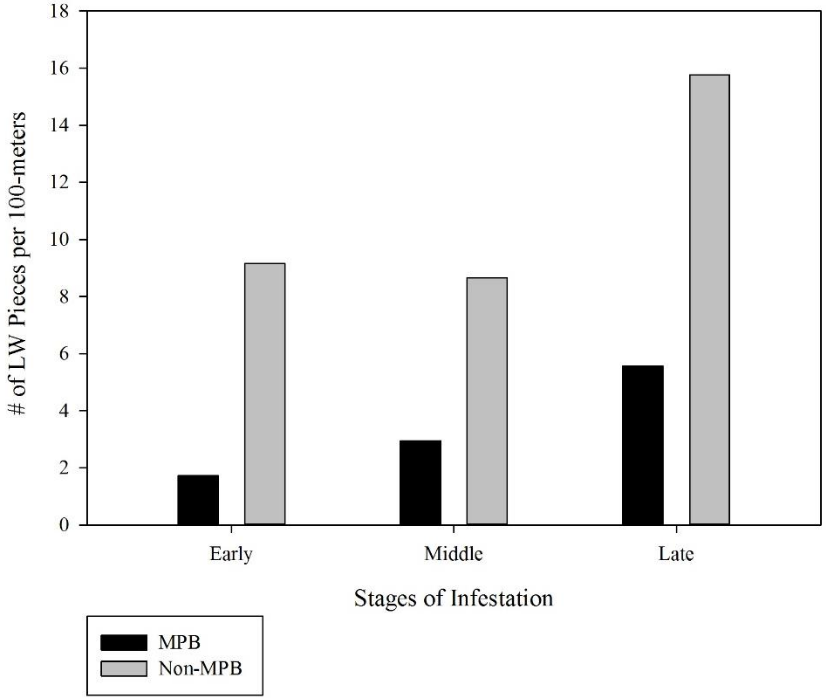


Figure 2.3 Average lengths of MPB and Non-MPB pieces of LW across the stages of infestation.

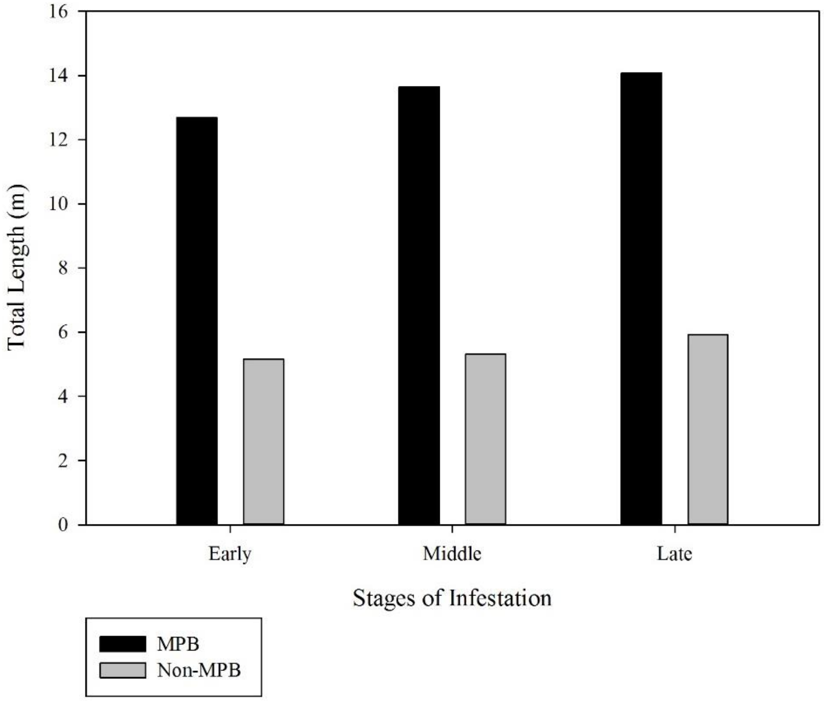


Figure 2.4 Average lengths of MPB and non-MPB pieces of LW within the channel margins across the stages of infestation.

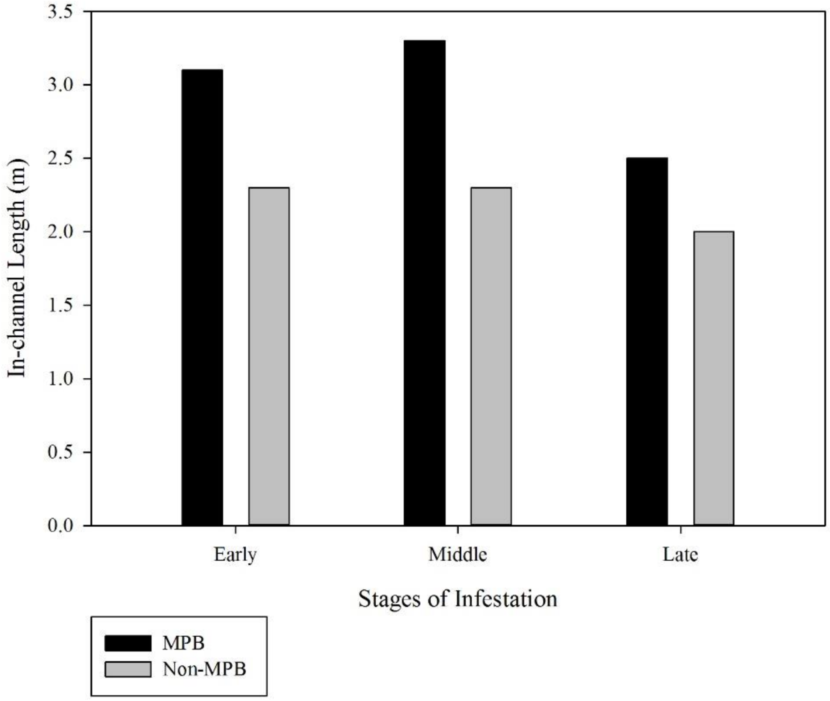


Figure 2.5 Average diameters of MPB and Non-MPB pieces of LW across the stages of infestation.

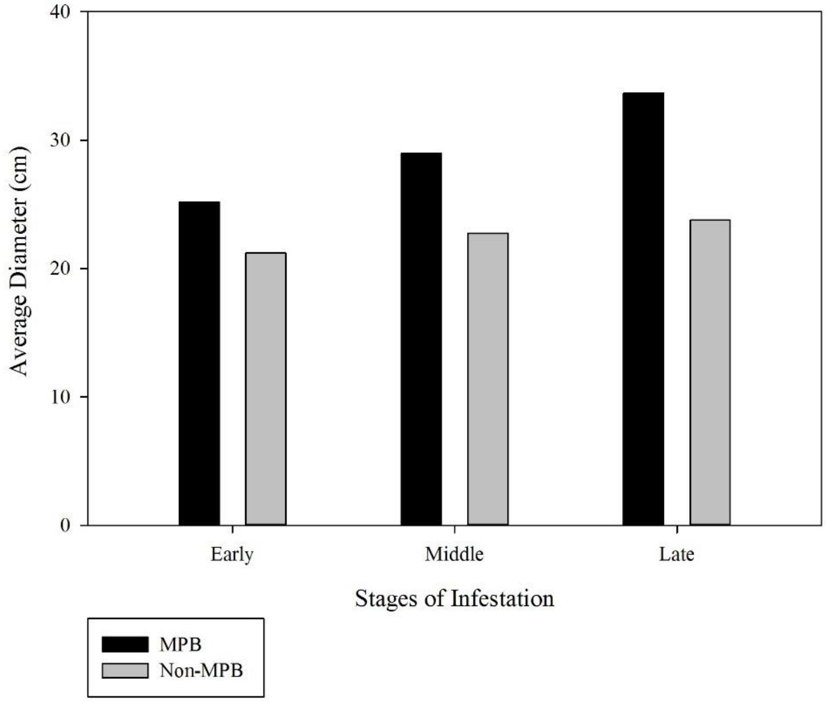


Figure 2.6 Volume of MPB pieces of LW per 100 meters of channel length across the stages of infestation.

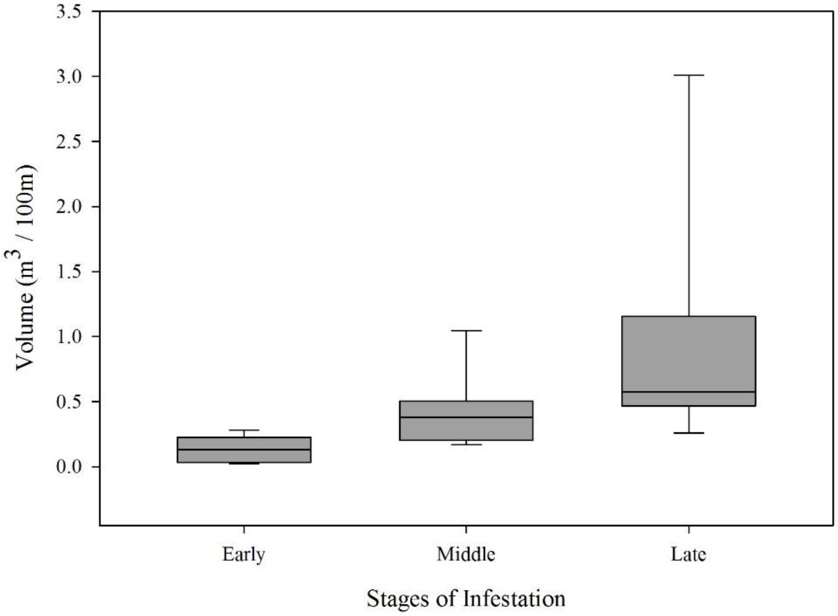


Figure 2.7 Volume of Non-MPB pieces of LW per 100 meters of channel length across the stages of infestation.

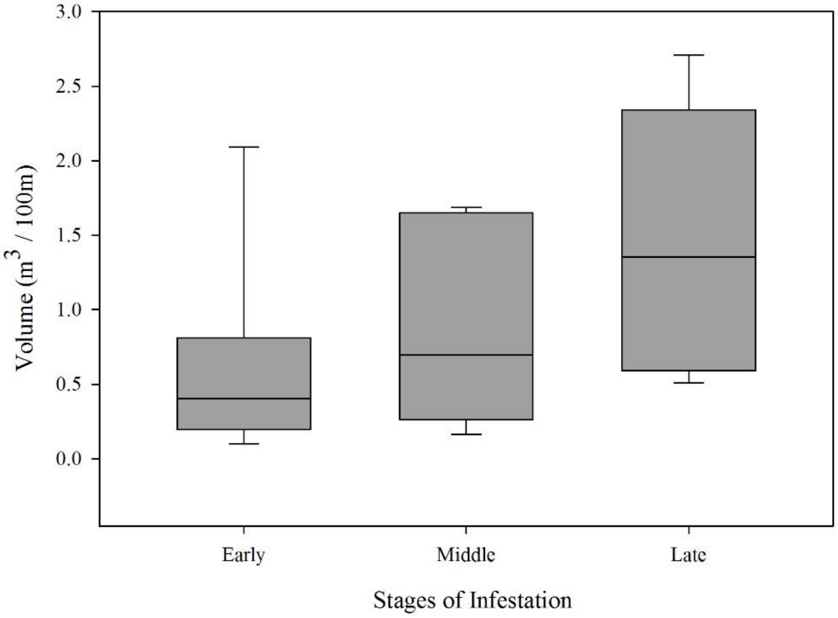


Figure 2.8 Decay classifications (age) of MPB and Non-MPB pieces of LW across the stages of infestation.

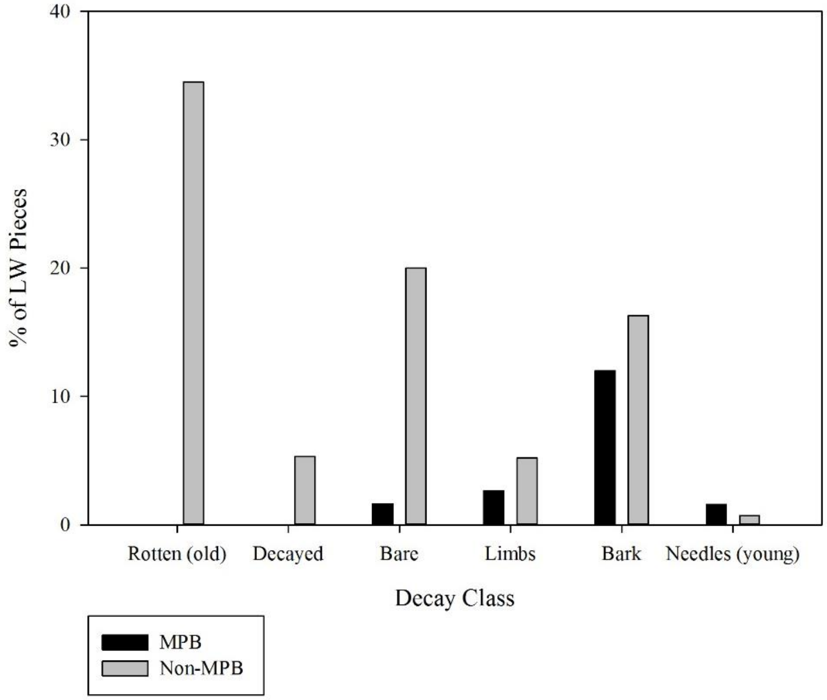


Figure 2.9 Functional forms of MPB and Non-MPB LW across the stages of infestation.

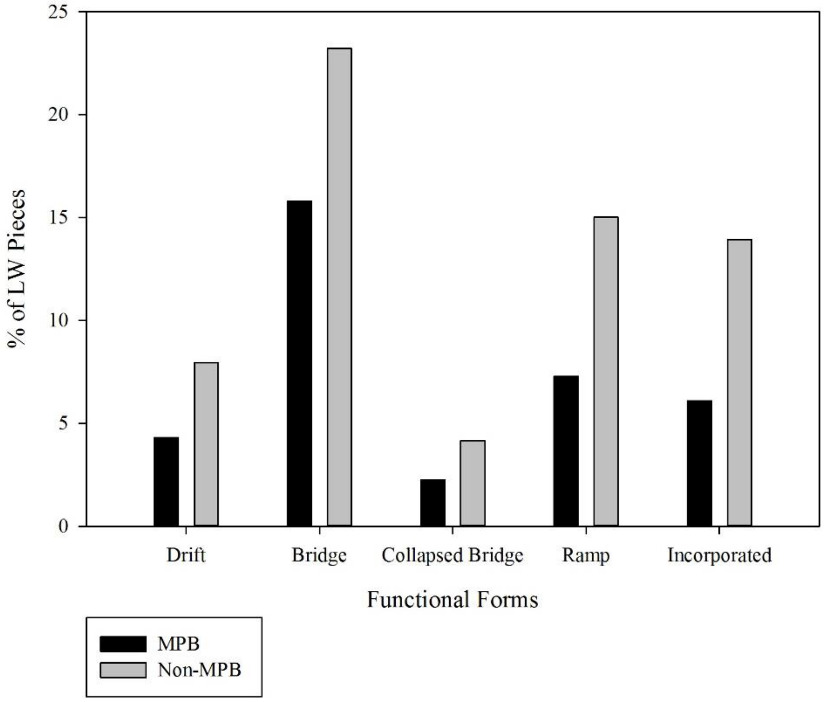


Figure 2.10 Structure of MPB and Non-MPB pieces of LW across the stages of infestation.

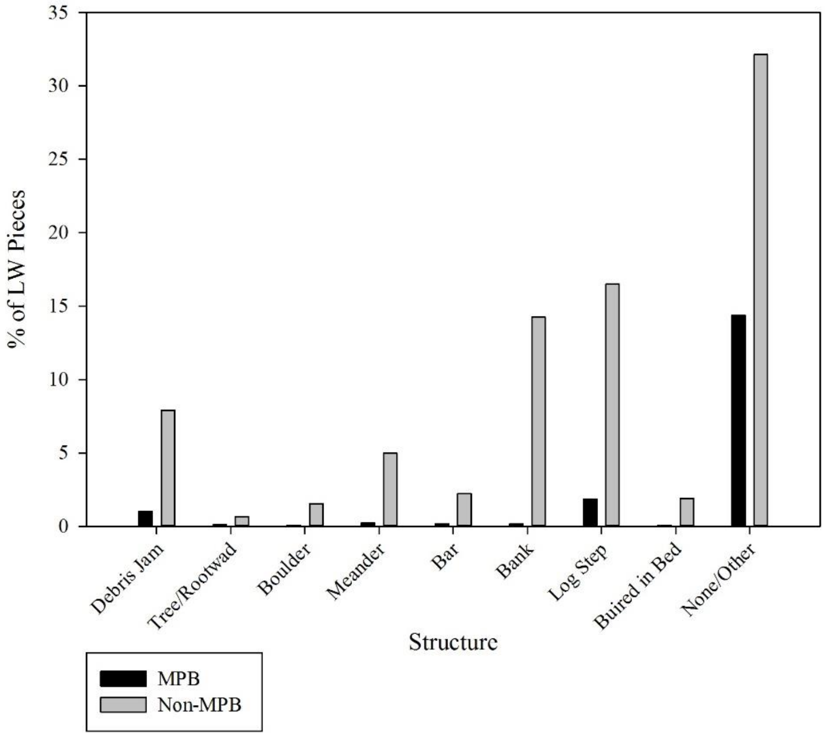


Figure 2.11 Conceptual models for (A) rate of wood recruitment, and (B) wood load related to MPB and diversion disturbances assuming no other subsequent large-scale disturbance. MPB infestation begins at zero years, red arrows conceptually mark current stage of wood dynamics.

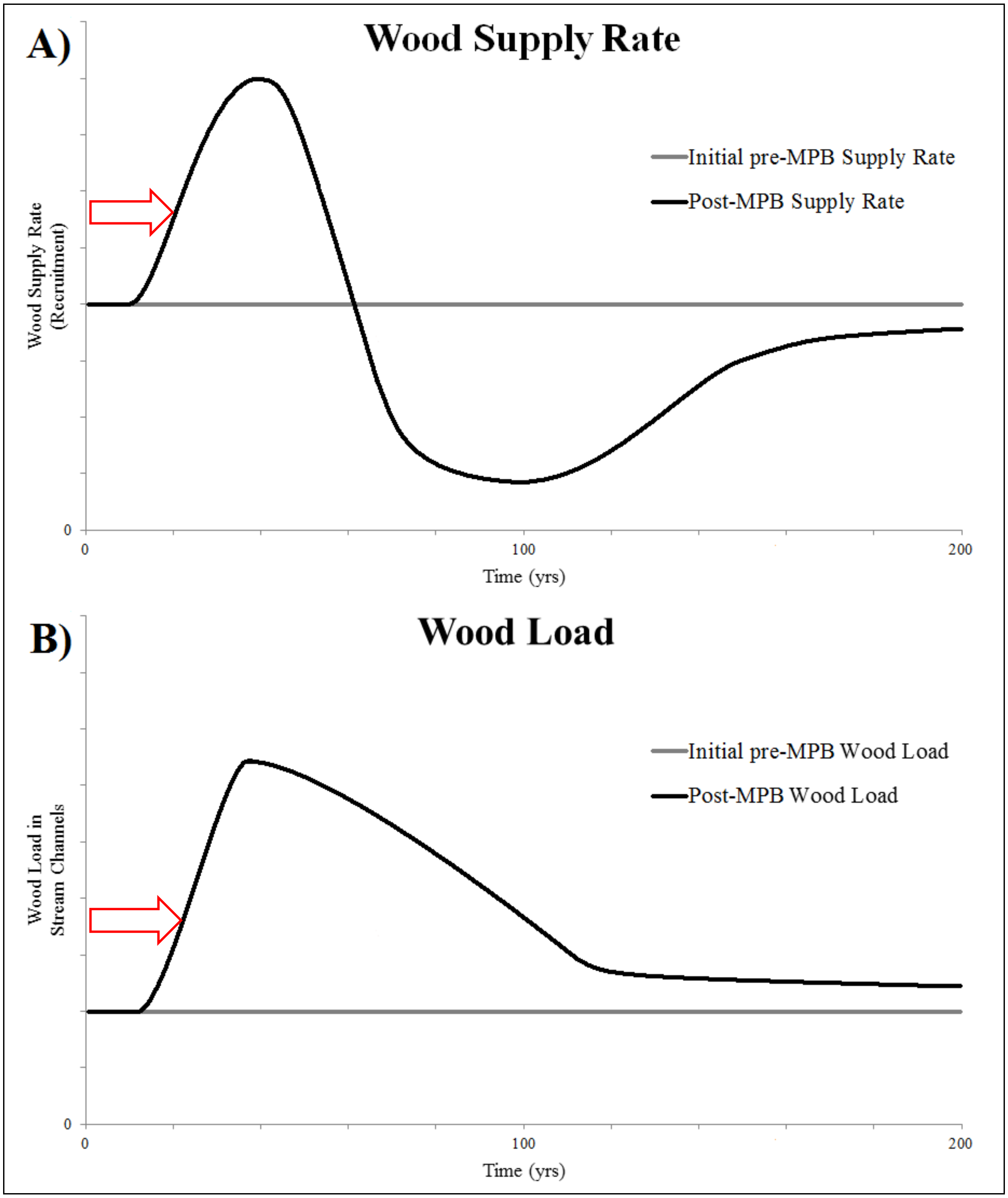


Table 2.1 Metrics selected for in-stream wood inventory (from Wohl et al., 2010).

Variable	Categories	Description
Decay Class: qualitative assessment of age based on decay	0 – Rotten	Soft wood broken apart easily
	1 – Decayed	Soft wood not easily pulled apart
	2 – Bare	No bark present
	3 – Limbs	Limbs intact with bark present
	4 – Bark	Bark is intact
	5 – Needles	Needles present or leaves attached
Stability: potential mobility/anchor points	0 – No Ends	Neither end anchored to bank
	1 – One End	One end anchored to bank or other structure
	2 – Both Ends	Both ends anchored to bank or other structure
Rootwad: self-explanatory	0 – Absence	Rootwad present
	1 – Presence	Rootwad absent
Function: process-based descriptor of function related to the channel	0 – Drift	Sitting on a bar with both ends within active channel
	1 – Bridge	Suspended above active channel
	2 – Collapsed Bridge	Both ends on banks, broken in the middle
	3 – Ramp	One end in channel, other suspended above channel
	4 - Incorporated	Portion buried in channel (could be a step)
Channel Type: Morphological channel unit where piece is located	1 – Pool	Flat surface, deep with downstream control
	2 – Riffle	Shallow, finer grained substrate, 1-2% slope
	3 – Glide	Between pool and riffle, no downstream control
	4 – Rapid	2.5-4% slope, plane bed, poorly defined steps, steep
	5 – Step/Pool	Well defined step/pool structure
	6 – Cascade	Very steep, fall, irregular step/pool morphology
	7 – Other	Explain in comments
Structure: channel feature that retains each piece of wood	1 – Debris Jam	Composed of 3 or more pieces
	2 – Tree/Rootwad	Associated with a living tree or rootwad
	3 – Boulder	Associated with
	4 – Meander	Anchored to the outside of a meander
	5 – Bar	Sitting atop a point or mid-stream bar
	6 – Bedrock	Anchored to bedrock

	7 – Beaver Dam	Associated with beaver dam
	8 – Bank	Imbedded in bank, buried by soil or bank materials
	9 – Log Step	Forms a step in the stream
	10 – Buried in Bed	Portion buried in channel, NOT functioning as a step
	0 – None/Other	Explain in comments

Table 2.2 Physical characteristics and volumes of MPB (top values) and Non-MPB (bottom values) LW across the stages of infestation.

Early-stage Infestation					
Survey Reach	**Avg. L (m)**	**Avg. L in-ch. (m)**	**Proportion in-ch. (%)**	**Avg. D (cm)**	**Volume (m^3/100m)**
Billie Creek - Lower	11.8 5.72	2.075 1.944	0.217 0.637	13.0 15.11	0.086 0.378
Billie Creek - Upper	11.057 4.109	2.474 2.160	0.220 0.742	21.478 25.851	0.067 0.797
East Fork Soap Creek	22.40 7.795	1.50 1.613	0.066 0.366	45.0 27.725	0.228 2.316
Mid NFSR 404 1st Order	11.292 4.366	2.833 2.269	0.313 0.750	27.250 19.231	0.135 0.402
NFSR 404 2nd Order - Unnamed	11.280 4.182	3.150 2.262	0.290 0.816	17.30 17.927	0.035 0.197
NFSR 452 - Unnamed	14.70 4.355	3.70 1.673	0.264 0.590	28.5 25.0	0.228 0.723
Soap Creek 2nd Order	7.70 2.392	1.50 1.692	0.247 0.887	29.0 17.385	0.157 0.371
West Branch Billie Creek Lower	17.89 6.860	4.914 2.680	0.279 0.575	23.71 21.88	0.132 1.184
West Branch Billie Creek Upper	11.95 6.274	3.375 2.513	0.380 0.642	38.19 20.05	0.298 0.812
West Fork Billie Creek Lower	10.067 4.446	3.533 3.273	0.35 0.87	16.33 16.0	0.032 0.124
West Fork Billie Creek Upper	15.031 4.417	3.781 2.540	0.25 0.78	22.44 19.42	0.126 0.349
Middle-stage Infestation					
Billie Creek 2nd Order	12.338 4.205	4.285 2.985	0.381 0.894	21.308 18.049	0.209 0.509

Beaver Creek Lower	16.575 9.231	5.725 3.596	0.336 0.511	38.0 25.0	1.083 1.685
Beaver Creek Upper	12.479 4.786	4.807 2.665	0.455 0.770	33.286 26.261	0.429 1.259
Highline - Lower	17.233 2.573	6.133 2.0	0.330 0.857	19.667 17.818	0.409 0.238
Lee Creek	14.720 6.767	2.460 2.088	0.187 0.637	24.667 22.080	0.369 1.687
NFSR 261 Lower - Unnamed	17.929 6.019	3.286 2.066	0.199 0.615	34.286 25.0	0.505 2.394
West Fork NFSR 404 - Unnamed	14.653 3.148	2.08 2.08	0.154 0.848	23.533 17.72	0.181 0.156
NFSR 414.1A Lower - Unnamed	11.827 3.809	3.16 2.15	0.331 0.768	22.0 16.54	0.313 0.270
NFSR 452 Lower - Unnamed	17.233 4.169	1.917 2.10	0.1202 0.788	35.50 25.551	0.389 1.638
Rankin Creek 2nd Order	16.133 6.84	2.33 2.022	0.173 0.595	37.444 18.10	0.730 0.870
Late-stage Infestation					
North Fork Big Creek	12.68 7.464	2.10 1.893	0.186 0.577	27.20 26.43	0.671 1.780
NFSR 136 1st Order	11.781 7.111	1.438 1.471	0.152 0.511	23.25 18.0	0.483 0.594
NFSR 136 2nd Order	14.563 6.942	2.594 2.087	0.192 0.474	32.56 17.42	0.737 0.502
NFSR 261 Upper - Unnamed	16.28 5.812	1.825 1.772	0.144 0.564	45.40 29.64	2.406 2.744
NFSR 414.1A Upper - Unnamed	14.722 3.557	3.333 1.891	0.230 0.824	24.111 19.286	0.244 0.573
NFSR 457.1B	15.929 3.033	4.229 2.035	0.293 0.832	25.857 22.041	0.554 0.714
Rankin Creek 1st Order	11.864 6.476	2.636 1.882	0.378 0.568	36.909 29.760	0.718 1.870
West Branch Billie Creek - Lower	13.773 9.037	1.633 1.877	0.196 0.401	37.20 23.298	0.60 0.970
West Fork Soap Creek	14.483 4.577	3.075 1.933	0.297 0.734	42.33 24.67	3.076 2.325

Table 2.3 ANOVA results testing differences in the physical characteristics and volume of MPB and Non-MPB LW across the stages of infestation.

Variable	F	Pr(>F)
Total Length	666.34	<0.0001***
In-Channel Length	61.18	<0.0001***
% in channel	422.87	<0.0001***
Diameter	91.94	<0.0001***
Volume (m^3/100m)	7.26	0.009**

'***' indicates significance at the p<0.001 level, '*' at the p<0.01 level.

Table 2.4 ANOVA results testing differences in the physical characteristics and volume of MPB and Non-MPB LW across the stages of infestation.

	MPB LW		Non-MPB LW		Total LW	
Variable	F	Pr(>F)	F	Pr(>F)	F	Pr(>F)
Total Length	1.572	0.209	3.241	0.0394*	9.204	0.00011**
In-channel Length	4.341	0.0137*	9.721	<0.0001**	11.958	<0.0001**
% in channel	2.016	0.135	14.123	<0.0001**	17.599	<0.0001**
Diameter	8.442	0.0002**	6.708	0.0012**	16.949	<0.0001**
Volume (m^3/100m)	5.882	0.0074**	3.177	0.0571	5.571	0.0092**

'**' indicates significance at the p<0.01 level, and '*' at the p<0.05 level.

Table 2.5 Contingency analysis testing categorical variables across the stages of infestation.

Variable	Df	Value	Prob.
Infestation	2	14.43	0.0007***
Decay Class	10	34.94	0.0001***
Stability	4	5.12	0.2749
Rootwad	2	7.22	0.0270*
Function	8	60.16	<0.0001***
Channel Type	12	123.14	<0.0001***
Structure	16	135.66	<0.0001***

'***' indicates significance at the p<0.001 level, '**' at the p<0.01 level, and '*' at the p<0.05 level.

Table 2.6 Logistic regression testing categorical variables for MPB and Non-MPB LW.

Coefficients	**Estimate**	**Standard Error**	**Z-Value**	**Pr(>Z)**
Intercept	-2.406	1.605	-1.499	0.1338
Decay Class **Bare used as reference*				
Rotten	-1.667e+01	4.039e+02	-0.041	0.9671
Decayed	-1.704e+01	1.012e+03	-0.017	0.9866
Limbs	1.719e+00	2.600e-01	6.613	<0.0001***
Bark	1.936e+00	2.118e-01	9.140	<0.0001***
Needles	2.751e+00	4.003e-01	6.870	<0.0001***
Stability ** No Ends used as reference*				
One End	3.544e-01	1.101e+00	0.322	0.7476
Two Ends	1.092e-01	1.091e+00	0.100	0.9203
Rootwad **No used as reference*				
Yes	1.249e+00	2.622e-01	4.764	<0.0001***
Function **Bridge used as reference*				
Drift	-1.149e+00	1.018e+00	-1.129	0.2590
Collapsed Bridge	-1.865e-03	3.047e-01	-0.006	0.9951
Ramp	-5.156e-01	3.567e-01	-1.445	0.1483
Incorporated	-1.077e+00	4.728e-01	-2.277	0.0228*
Channel **Cascade used as reference*				
Pool	-3.177e+00	1.359e+00	-2.337	0.0194*
Riffle	-4.435e-01	8.387e-01	-0.529	0.5970
Glide	-1.354e-01	4.370e+03	0.000	1.0000
Rapid	-1.591e-01	1.076e+04	0.000	1.0000
Step/Pool	-5.026e-02	9.563e-01	-0.053	0.9581
Other	1.940e+01	1.075e+04	0.002	0.9986
Structure **Bank used as reference*				
Debris Jam	-2.279e-02	8.335e-01	-0.027	0.9782
Tree/Rootwad	-9.927e-01	1.215e+00	-0.817	0.4140
Boulder	-5.018e-01	1.545e+00	-0.325	0.7453
Meander	3.958e-01	9.588e-01	0.413	0.6797

Bar	6.358e-01	1.020e+00	0.623	0.5332
Log Step	6.417e-01	8.755e-01	0.733	0.4636
Buried in Bed	-1.021e+00	1.289e+00	-0.792	0.4282
None/Other	5.312e-01	7.479e-01	0.710	0.4775

‘***’ indicates significance at the $p<0.001$ level, ‘**’ at the $p<0.01$ level, and ‘*’ at the $p<0.05$ level.

Table 2.7 Table of deviance testing categorical variables for MPB and Non-MPB LW.

	Df	**Deviance**	**Residual Df**	**Residual Deviance**	**Pr(>Chi)**
NULL			1950	1835.8	
Decay Class	5	602.76	1945	1233.0	<0.0001***
Stability	2	14.19	1943	1218.8	0.00083***
Rootwad	1	22.38	1942	1196.5	<0.0001***
Function	4	8.57	1938	1187.9	0.07289
Channel	6	16.14	1932	1171.8	0.01303*
Structure	8	10.06	1924	1161.7	0.26098

‘***’ indicates significance at the $p<0.001$ level, ‘**’ at the $p<0.01$ level, and ‘*’ at the $p<0.05$ level.

Table 2.8 Logistic regression output testing categorical variables across the stages of infestation.

Coefficients	**Estimate**	**Standard Error**	**Z-Value**	**Pr(>Z)**
Intercept	-2.406	1.605	-1.499	0.1338
MPB ** No used as reference*				
MPB	0.530	0.161	3.292	0.000994***
Decay Class **Bare used as reference*				
Rotten	-0.035	0.148	-0.236	0.814
Decayed	0.299	0.242	1.237	0.216
Limbs	0.140	0.216	0.649	0.517
Bark	-0.041	0.155	-0.263	0.793
Needles	-0.234	0.360	-0.650	0.516
Stability ** No Ends used as reference*				
One End	-0.255	0.510	-0.503	0.615

Two Ends	0.089	0.500	0.177	0.859
Rootwad _*No used as reference_				
Yes	-0.610	0.219	-2.791	0.005**
Function _*Bridge used as reference_				
Drift	0.402	0.512	0.785	0.432
Collapsed Bridge	0.031	0.232	0.132	0.895
Ramp	0.602	0.237	2.542	0.011*
Incorporated	0.436	0.235	1.857	0.063
Channel _*Cascade used as reference_				
Pool	16.887	308.134	0.055	0.956
Riffle	15.912	308.134	0.052	0.959
Glide	30.890	663.179	0.047	0.963
Rapid	31.501	1487.659	0.021	0.983
Step/Pool	15.661	308.134	0.051	0.959
Other	30.220	1487.659	0.020	0.984
Structure _*Bank used as reference_				
Debris Jam	0.307	0.278	1.106	0.269
Tree/Rootwad	-0.172	0.582	-0.296	0.767
Boulder	-0.814	0.477	-1.707	0.088
Meander	0.441	0.322	1.369	0.171
Bar	-0.207	0.376	-0.550	0.582
Log Step	-0.621	0.278	-2.238	0.025
Buried in Bed	0.727	0.414	1.756	0.079
None/Other	0.572	0.212	2.692	0.007

‘***’ indicates significance at the $p<0.001$ level, ‘**’ at the $p<0.01$ level, and ‘*’ at the $p<0.05$ level.

Table 2.9 Table of deviance testing categorical variables across the stages of infestation.

	Df	Deviance	Residual Df	Residual Deviance	Pr(>Chi)
NULL			1950	2574.6	
Infestation	1	14.848	1949	2559.7	0.00012**
Decay Class	5	12.052	1944	2547.7	0.0341*
Stability	2	2.540	1942	2545.1	0.2809
Rootwad	1	10.628	1941	2534.5	0.0011**
Function	4	29.303	1937	2505.2	<0.001***
Channel	6	78.097	1931	2427.1	<0.001***
Structure	8	32.450	1923	2394.6	<0.0001***

‘***’ indicates significance at the $p<0.001$ level, ‘**’ at the $p<0.01$ level, and ‘*’ at the $p<0.05$ level.

Chapter 3 - Influence of Large Wood on the Geomorphology of Rocky Mountain Headwater Streams across an Age Spectrum of Mountain Pine Beetle Infestation, Medicine Bow National Forest, Wyoming.

Abstract

Within forested watersheds, instream wood is an influential component of stream channel morphology and habitat complexity. However, the effects of increasing wood loads on channel form and function resulting from large-scale tree mortality have been understudied. This dissertation chapter investigates the effects of Mountain Pine Beetle (MPB) tree mortality and associated wood loads on forested mountain streams throughout watersheds experiencing varying stages of MPB infestation. Twelve reaches were selected for detailed morphological surveying across the stages of infestation, four in each stage of infestation that exhibit closest to average LW loads. Measured dimensions were scaled by watershed area and log-transformed for normalization. First-order channel widths, width-to-depth ratios and cross-sectional areas have all decreased with time since initial infestation, which was unexpected. All second-order channel dimensions have similarly decreased with time since initial infestation. However, spatially localized effects of MPB-killed LW include channel widening and deepening with the formation of pools. Regression analysis shows that the total number of LW pieces is a significant predictor for observed changes in channel dimensions with time since initial infestation. Due to the large number of bridging pieces of LW that have not yet decayed enough to break and ramp down between the channel margins, streams will continue to adjust beyond the

temporal scope of this study. Legacy effects on streams must be monitored to better understand the temporal lag between initial MPB infestation and recovery.

Introduction

Large wood (LW) controls the structure and function of headwater mountain streams throughout forested ecosystems (Bilby and Likens, 1980; Bilby and Ward, 1991). There tends to be a greater number of LW pieces in small, low-order streams throughout forested watersheds, and those pieces tend to be larger in size (Wohl, 2006; Wohl and Jaeger, 2009; Wohl, 2011). Flow patterns, sediment and organic matter storage, channel morphology and ecological function can all be influenced by LW between the channel margins (Bilby and Likens, 1980; Gippel, 1995; Gurnell et al., 1995; Montgomery et al., 1995; Thompson et al., 2005; Daniels and Rhodes, 2003; Daniels, 2006a, 2006b).

Flow patterns can be altered by increasing hydraulic resistance and flow deflection through the addition of LW (Gippel, 1995; Daniels and Rhodes, 2003). Similarly, obstructions such as bedrock outcrops, boulders, LW and debris jams entrained between the channel margins can influence flow velocities (Montgomery et al., 1995). This forcing mechanism causes flows to converge, creating fluctuation in velocity (Lisle, 1986). The interaction between flow and sediment can create freely-formed pools (Montgomery et al., 1995). LW redirects flow of water, creating backwater eddies, local scours and various types of pools (Manga and Kirchner, 2000). The orientation, size, distribution, amount, age and mobility of LW has been shown to drastically affect flow resistance within a stream channel (Gippel, 1995; Montgomery et al., 1995; Abbe and Montgomery, 1996; Gurnell and Sweet, 1998; Daniels and Rhodes, 2003; Daniels, 2006a; Wilcox et al., 2006; Wilcox and Wohl, 2006; Nowakowski and Wohl, 2008; David et al., 2010; Costigan and Daniels, 2011). Water alternates between supercritical and subcritical flow when moving over log steps and pools, causing energy dissipation (Curran and Wohl, 2003; David et al., 2010). Flow upstream of the obstruction is subcritical, trapping sediment and organic matter in wedge-shaped depositional features (Marston, 1982; Lisle, 1986; Bilby and Ward, 1989, 1991). Downstream of the obstruction, flow alternates to supercritical, which causes local bank scouring and incision of the channel bed (Marston, 1982; Lisle, 1986; Bilby and Ward, 1989, 1991). This hydraulic boundary roughness increases as LW is added to the system (Curran and Wohl, 2003). These step-pools contribute to the hydraulic complexity seen throughout forested, high-gradient mountain stream channels (Buffington et al., 2002). Any change to a stream's flow regime is important to consider as both sediment and LW pieces are transported and sorted by stream flows (Nakamura and Swanson, 1994; Abbe and Montgomery, 1996; Braudrick and Grant, 2001; Wohl and Jaeger, 2009; Cadol and Wohl, 2010; Morris et al., 2010; Jones et al., 2011; Wohl et al., 2011).

Channel form adjusts to the presence or absence of LW (Curran, 2010). In step-pool channels, the initial development of pools can either be forced or freely formed (Montgomery et al., 1995). LW loading, along with channel width, directly influence the frequency of pool spacing (Montgomery et al., 1995). Increasing channel stability and energy dissipation due to the addition of LW increases sediment sequestration (Bilby and Ward, 1989; Nakamura and Swanson, 1994; Ralph et al., 1994; Fetherston et al., 1995; Thompson et al., 1995; Wood-Smith and Buffington, 1996; Buffington et al., 2002; May and Gresswell, 2003; Daniels, 2006b; Goode and Wohl, 2007; Fisher et al., 2010). Sediments can be trapped behind log steps, altering bedload composition and sediment yields (Gurnell and Sweet, 1998; Faustini and Jones, 2003). Typically, these wedges of sediment represent an overall fining of bedload material, as smaller particles are more likely to be transported to and deposited upstream of the channel obstruction by stream flows (Faustini and Jones, 2003). Three stages of sediment transport in step-pool channels related to discharge have been identified: the perennial low-discharge transport of fine grained particles, frequent high-discharge transport of gravel particulates and infrequent high-discharge transportation of step-forming obstructions (Warburton, 1992). The orientation of the LW piece can affect the amount of sediment trapped upstream (Bilby and Ward, 1989). Greater amounts of sediment are likely to accumulate behind LW pieces oriented perpendicular to the channel. Perpendicular pieces can dissipate more stream energy by causing flow to transition from supercritical to subcritical (Gippel, 1995). Storage of organic matter can also increase with greater channel stability and energy dissipation (Thompson et al., 1995; May and Gresswell, 2003; Daniels, 2006b). LW is known to add nutrients and enhance nutrient spiraling within stream channels (Bilby and Likens, 1980; Cummins et al., 1983; Lienkaemper and Swanson, 1987). Habitat complexity increases with additions of LW, which is especially important for fish species that overwinter in headwater stream channels (Keller and Swanson, 1979). LW has also been associated with increases in biodiversity within a stream ecosystem (Piégay et al., 1999).

With overall warming of average yearly temperatures in the Rocky Mountain region, the MPB has been able to expand farther northward throughout the United States (Dillon et al., 2003; Klutsch et al., 2009). Previously, colder winter temperatures limited the expansion of the MPB (Klutsch et al., 2009). Tree mortality and toppling rates increase dramatically with time since initial infestation (Mitchell and Preisler, 1998), which sequentially increases the amount of LW being input into a stream system. There is the potential for a geomorphological resetting of previously disturbed stream channels through the large-scale introduction of numerous pieces of LW from falling MPB-killed trees. Greater amounts of LW will increase hydraulic resistance, which will then increase channel stability and energy dissipation. Sediment transport and storage patterns will be modified by these system alterations, inducing morphological channel adjustments.

Stream channels exhibiting legacy effects of tie-driving, such as a lack of channel-flow obstructions, low channel sinuosity and a lack of channel complexity (Young, 1991; Ruffing et al., 2015), will readjust to the additions of large, thick pieces of LW by redeveloping step-pool sequences throughout plane-bed channels. Young et al. (1994) compiled a list of known tie-driven streams throughout the Medicine Bow Mountains. In the late 1800s, channel obstructions were removed with dynamite to allow for pre-cut railroad ties up in the forest to float down out of the mountains with spring runoff. Tie-driven streams have been shown to be narrower, shallower and exhibit low cross-sectional roughness values and higher width-to-depth ratios compared to non-tie-driven streams (Ruffing et al., 2015). LW has been shown to increase the longitudinal variation for both channel depth and width (Montgomery et al., 2003). It is expected that additional pieces of MPB-killed LW will increase the longitudinal variability of channel widths and depths.

Forest infrastructure located near headwater mountain streams will be at greater risk, such as road crossings washing out due to plugged culverts or channel avulsions. What were considered reference systems and processes in national forest lands no longer apply in their post-MPB state. It is therefore important to understand how the geomorphic function of MPB wood is altering and ultimately forming a new reference state.

The primary research objective of this chapter is to evaluate the effects of increased LW supply from the current MPB infestation on the geomorphology of forested, headwater mountain streams. Study sites are representative of early-, middle- and late-stage MPB infestation in order to identify any significant differences pertaining to channel morphology and/or ecosystem function. It is hypothesized that the greater amounts of LW measured throughout late-stage study sites will alter longitudinal bedform patterns towards a step-pool sequence. It is also hypothesized that greater amounts of LW will increase sediment retention initiating an overall coarsening of substrate. These data will provide baseline information for studying the impacts of the current MPB infestation on channel morphology and ecosystem function in forested headwater mountain streams.

Methodology

Study Site Selection

Numerous studies have shown the benefits of paired watershed designs by increasing statistical power during analysis (Udawatta et al., 2002; Bishop et al., 2005; Veum et al., 2009), thereby increasing the probability of determining statistical differences between the stages of environmental conditions associated with the MPB infestation. Twelve survey sites were selected out of the 31 stream segments and surveyed during the summer of 2013 (Figure 3.1). Survey reaches throughout each of the three stages of infestation were selected because they exhibit mean LW conditions within the varying levels of infestation, as determined from analyses in Chapter 2 (Table 3.1). Multiple early-infestation survey reaches were selected throughout the Billie Creek drainage to account for any possible longitudinal variations in MPB tree mortality and LW loading throughout the watershed. In total, four reaches were located within watersheds experiencing early-stage MPB infestation. Three of these reaches were first-order channels. Four reaches, two first and second-order channels, were surveyed in middle-infestation watersheds. Four sites were surveyed in late-stage drainages, two first and two second-order channels.

Selected watersheds all have a north-facing aspect. Stream survey reaches are unhindered by water diversion ditches upstream, therefore they exhibit natural flow regimes. Watershed conditions were evaluated for anthropogenic and/or natural disturbances that could impact channel geometry. This was done through the use of field reconnaissance, aerial photography, satellite imagery and historical records provided by local museums and the US Forest Service. Forest stands with homogenous tree heights, diameters and ages, along with decay stumps cut at shoulder-height, indicate previous logging activity. Numerous charred decay stumps were indicative of previous fire-disturbance.

No survey reaches in this study were located in forest stands that would be considered old-growth. All survey reaches were conducted in primarily (+70%) lodgepole pine forest stands with 80 to 100+ year old trees, and at varying stages of infestation. These tree ages coincide with a peak in historic logging activities throughout the region, indicating widespread harvesting activities affected all survey reaches at about the same time. This creates a unique opportunity to observe the effects from the varying stages of MPB infestation on a somewhat uniform physical and biological setting. All survey reaches excluding one (Beaver Creek) were historically tie-driven. Channel adjustments to newly input pieces of MPB-killed LW could be easy to detect in these plane-bedded tie-driven streams.

Physiometric Characteristics

Watersheds for first-order survey reaches averaged 1.05 km^2 in size, while second-order watersheds averaged 2.86 km^2 (Table 3.2). First-order survey reaches were all located between 2660 and 2830 meters in elevation, while second-order reaches were located between 2580 and 2900 meters. Lodgepole pine forest stands tend to grow between the elevations of 2400 to 3000 meters above sea level in southeast Wyoming (Dillon et al., 2005). Valley widths for first-order drainages averaged 57.2 meters and had a smaller variance (135.95) compared to second-order valleys, which averaged 77.4 meters in width with a variance of 584.5. Valley slopes were steeper on average for first-order drainages (0.19m/m) compared with second-order drainages (0.10m/m).

Data Collection

Each survey reach extended 30 channel widths in stream length. Survey reach lengths were scaled to bankfull width to account for varying stream sizes. Eleven evenly-spaced cross-sections and one longitudinal profile following the thalweg were surveyed at each study reach with a stadia rod and level. Stream reaches were surveyed June through August, 2013 following peak spring runoff. Reaches were classified as either pool–riffle, plane–bed, step–pool, or cascade channel sequences following Montgomery and Buffington (1997). Meso-habitat was mapped for all individual survey reaches by measuring the channel lengths of each unit with a laser-range finder. Substrate sizes were measured within each survey reach following Wolman (1954) to determine any differences in particle size distributions across the varying levels of MPB infestation. One hundred particles were measured and classified with a gravelometer (Stream Systems Technology Center, 2012) during each count. Numerous zig-zag pebble counts (Bevenger and King, 1995) were made throughout varying channel unit types within each survey reach. Adjacent forest stand composition and stage of MPB infestation were noted for each survey reach. This included species, age and evidence of MPB burrow holes. Finally, LW surveys were conducted within each survey reach following the methodology from Wohl et al. (2010) and Chapter 2.

Data Analysis

Watershed area, valley width, slope and elevation were determined using ArcGIS. Channel dimensions including width, average depth, width-to-depth ratio, cross-sectional area and roughness were calculated for each cross-section. Cross-sectional area and longitudinal roughness values were calculated by taking the standard deviation of depths between the tops of the banks for each cross-section and along the longitudinal survey. Total LW volume and number of pieces per 100 meters of stream channel were calculated for MPB and non-MPB killed pieces within each survey reach. These values were then scaled to watershed area and log-transformed to meet with assumptions of normality. Percent cover of observed channel units, along with D50 and D84 values for substrate within those specified channel units, were calculated for each survey reach.

Analysis of Variance (ANOVA) was used to test for significant differences in channel morphology, LW dynamics, and mesohabitat across the stages of infestation. First and second-order sites were also tested separately to determine any specific adjustments that could be associated with scale at varying levels of infestation. *P*-values were calculated at $\alpha = 0.05$ and $\alpha = 0.01$ to determine significance. Simple linear regression was used to determine relationships between LW dynamics, physiometric watershed characteristics and scaled/log-transformed channel dimensions across the stages of infestation. Regression was run at $\alpha = 0.05$ and $\alpha = 0.01$ to determine model significance.

Results

Channel Morphology

Channel dimensions across the stages of infestation are summarized in Table 3.3 and were tested for significance. First-order channel widths ($p = 0.002$), width-to-depth ratios ($p =$

0.013), and cross-sectional area (*p* = 0.042) are all decreasing with time since initial infestation (Table 3.4). Similarly, second-order channel widths (*p* = 0.011) are decreasing from early- to late-stage infestation, however not enough to impact width-to-depth ratios.

There is internal heterogeneity within first-order and second-order sites at varying levels of infestation. Spatially localized effects of wood inputs, especially the larger, thicker MPB-killed pieces, creates this heterogeneity. In West Fork Billie Creek, two large, newly-input MPB-killed pieces of wood spanned the channel at 60 and 320 degrees to flow, and subsequently formed a wide, elongated sediment wedge directly within the survey reach (Figure 3.2). Five out of ten cross-sections show channel widening and shallowing across the sediment wedge. Depths were not affected because flow had already incised into the sediment wedge, which normalized measurements. These two, localized MPB-killed piece of wood increased channel widths enough to create internal heterogeneity amongst first-order, early-stage survey reaches. Second-order channel widths associated with middle- and late-stage infestation also show internal heterogeneity, but not enough to cause significant alterations to their associated width-to-depth ratios. Because the classes of infestation were deduced from localized watershed conditions, as described in Chapter 2, further statistical tests are required.

Channel dimensions were scaled by watershed area and log-transformed to meet with assumptions of normality. When tested within each level of infestation, widths and average depths were shown to be significantly different between all sites. Only width-to-depth ratios throughout middle-infestation sites demonstrate homogeneity (*p* = 0.998). This exhibits the heterogeneity between sites located within similar levels of infestation. Nevertheless, widths, average depths and width-to-depth ratios for all sites are shown to decrease with time since initial infestation.

Testing first and second-order channels separate from each other and within the varying levels of infestation yielded significant results. In early-infested watersheds, widths ($p < 0.001$) and width-to-depth ratios ($p = 0.004$) were significantly different between first-order channels. First-order average depths ($p = 0.006$), along with second-order channel widths ($p = 0.002$) and cross-sectional area ($p = 0.036$) were also significantly different throughout middle-stage infestation watersheds. All channel dimensions were heterogeneous for late-stage survey reaches.

When testing all survey reaches across the varying levels of infestation, results demonstrate significant differences in width (p-value < 0.001), average depth ($p < 0.001$), width-to-depth ratios ($p < 0.001$) and cross-sectional area ($p < 0.001$) (Table 3.5). First-order channels specifically exhibit significant differences in channel width ($p = 0.0012$), subsequent width-to-depth ratios ($p = 0.029$) and cross-sectional area ($p = 0.023$) across the stages of infestation (Table 3.4). Channel dimensions for second-order stream are all significant across the varying levels of infestation. Overall, channel dimensions are shown to decrease with time since initial infestation, indicating a narrowing and shallowing of stream channels.

Longitudinal roughness values were calculated for each survey reach by taking the standard deviation of depths along the thalweg. First-order roughness values were statistically significant across the varying levels of infestation ($p = 0.029$). However, longitudinal roughness coefficients for second-order channels were homogenous across the stages of infestation. Both first and second-order channels exhibit decreasing trends in longitudinal roughness values with time since initial infestation.

D50 and D84 values were calculated from zig-zag pebble count surveys. Average D84 for pools is 174mm, compared to 155mm for riffles and 89mm for sediment wedges. These D84 values were found to be significantly different between channel units ($p = 0.004$) across the stages of infestation. Results also indicate that both D50 ($p = 0.022$) and D84 ($p = 0.004$) values for pool channel units decrease with time since initial infestation.

Channel units observed throughout the survey reaches were dominantly plane-bed. No significant differences in channel units exists across the stages of infestation. However, results indicate that the percent of riffles decreases from 90 to 82 from early- to late-stage infestation for both first and second-order channels. Combined with the pebble count data, this indicates a slight overall coarsening of substrate with time since initial infestation.

Large Wood

Overall, the total volume of LW per 100 meters of stream channel increases with time since initial infestation ($p = 0.008$) within the survey reaches. However, neither the volumes for MPB ($p = 0.060$) nor non-MPB ($p = 0.165$) LW individually demonstrate significant differences for all combined survey reaches across the stages of infestation. The numbers of MPB ($p = 0.014$) and non-MPB ($p = 0.050$) killed pieces of LW per 100 meters of stream channel both significantly increase with time since initial infestation. Total number of LW pieces in second-order channels significantly increases with time since initial infestation ($p = 0.001$).

Regression analysis was used to determine any relationships between LW volume and number of pieces to channel width, average depth, width-to-depth ratios and cross-sectional area for all survey reaches. The total number of pieces of LW is a very good predictor for average depth ($p = 0.0015$) and cross-sectional roughness ($p = 0.047$) ($R^2 = 0.88$). Volume of LW was less accurate at predicting average depth ($p = 0.015$) and cross-sectional roughness ($p = 0.048$) ($R^2 = 0.66$).

LW volume ($R^2 = 0.962$) and number of pieces of LW ($R^2 = 0.977$) in first-order channels were both very accurate predictors for all channel dimensions across the stages of infestation. In second-order channels, LW volume ($R^2 = 0.927$) and number of pieces of LW ($R^2 = 0.921$) were accurate predictors for average depth, width-to-depth ratios and cross-sectional roughness.

Discussion

Physiometric characteristics of the watershed did not significantly account for LW volume or number of pieces in steep first-order drainages. Since all of the survey reaches fell directly in the optimal elevational zone for lodgepole pine, MPB-killed LW inputs must account for this discrepancy. Steep slopes and narrow valley widths characteristic of first-order channels both logically increase the probability that a MPB-killed tree will fall within the channel margins. First-order channel form is well-known to be highly correlated with hillslope processes. LW volume and number of pieces were highly correlated for second-order drainages, characterized by wider valley bottoms and low valley slopes.

Many first and second-order survey reaches at similar stages of infestation were heterogeneous from each other. This was likely a result of classifying survey reaches based on the composition and stage of MPB-infestation of surrounding forest stands from Chapter 2 analysis. The random pattern of tree mortality from the MPB creates spatially localized channel adjustments. It is possible that the total and MPB-killed LW loads of a watershed experiencing late-stage infestation, along with associated channel adjustments, could be less when compared to an early-stage infested watershed within a randomly-located survey reach.

Another possible forcing mechanism creating heterogeneity within the infestation classes could be wind-throw. All survey watersheds are north facing; however, dominant wind direction can vary depending on the surrounding topography. Winds may more freely flow down one drainage, which could increase the number of trees falling within the channel margins along the valley bottom. This could create heterogeneity between first-order drainage sites in both total and MPB-killed wood loads.

All survey reaches, except for Beaver Creek, were tie-driven and are inherently narrower, plane-bed channels when compared with a more natural step-pool form (Ruffing et al., 2015). Non-scaled and scaled channel dimensions show first and second-order stream channels are adjusting to greater amounts of total and MPB-killed LW across the stages of infestation. Overall, channels were narrowing and shallowing from early- to late-stage infestation, which is opposite what would be expected. The spatial scale of detailed morphological surveys was insufficient at capturing the entire context of MPB infestation on channel morphology. Spatial patterns of LW throughout an entire stream network can be difficult to account for (Kraft and Warren, 2003). LW can influence or be influenced by the physical characteristics of streams at varying spatial scales (Nakamura and Swanson, 1994; Abbe and Montgomery, 1996; Piégay et al., 1999). The highly-localized effects of LW being input into a small headwater stream are sometimes difficult to detect within a single, randomly-located survey reach. For example, the sediment wedge that developed behind two large MPB-killed LW pieces on West Fork Billie Creek (Figure 3.2) caused that tie-driven channel to significantly widen and shallow directly upstream until an avulsion occurred. The narrow widths of these historically tie-driven channels allow for a higher percentage of falling MPB and non-MPB-killed trees to bridge across the channel above the channel margins. These pieces of LW span the channel but do not affect channel morphology, unless flows reach bankfull stage. More detailed surveys conducted over longer longitudinal distances are recommended to fully capture the effect of MPB infestation on wood dynamics and channel morphology. For example, detailed morphological survey reaches can be supplemented with spot measurements of width and depth along entire stream segments at equal intervals or at specific locations where MPB-killed LW has entered into the channel.

There are strong relationships between channel dimensions and the volume and total number of pieces of LW across the stages of infestation for both first- and second-order channels. LW directly influences channel form (Marston, 1982; Montgomery et al., 1995; Curran, 2010). As more MPB and non-MPB-killed LW is added to the system over time, channels should adjust. Channel complexity in tie-driven streams is still limited 100+ years since the practice of tie-driving (Ruffing et al., 2015). One positive effect of the MPB-infestation is that more LW will be added to these tie-driven streams. If the pieces are large enough to become entrained, then streams could adjust towards a more natural step-pool channel form.

Longitudinally, first-order channels show a reduction of roughness values from early- to late-stage infestation. It was expected that roughness values would increase with time since initial infestation, as more LW enters between the channel margins and stabilizes steep-gradient channels (Chin and Wohl, 2005; Curran, 2010). Similar to measured channel dimensions, this is likely the result of randomly-located survey reaches failing to capture the highly-localized effects of LW on channel morphology in first-order channels, which inherently have shorter survey reach lengths.

LW loading has been shown in increase the frequency of pools (Montgomery et al., 1995; Manga and Kirchner, 2000; Buffington et al., 2002). First and second-order channel units show a slight transition from riffles to pools with time since initial infestation due to the additions of MPB-killed LW. Substrate measured in pools was significantly larger compared to riffles and sediment wedges, which indicates an overall coarsening of substrate with time since initial infestation. This could be further evidence for tie-driven streams, composed of almost entirely riffles, transitioning towards a more natural step-pool channel form.

It does appear that the MPB infestation may have varying effects on channel morphology depending on stream order and surrounding physiometric characteristics of the watershed. Smaller headwater streams are likely to be more affected by MPB infestation as they are highly coupled with their surrounding hillslope processes (Ruffing et al., 2015). Measuring residence times and sediment/carbon sequestration using 7Be isotopes following Fisher et al. (2010) could allow for more detailed mapping of sediment dynamics with time since initial infestation.

The temporal scale of this study was not sufficient enough to capture the entire context of MPB infestation on channel morphology. The majority (90%+) of MPB-killed lodgepole pine trees experiencing late-stage infestation are still standing. Numerous trees in these watersheds have fallen but are currently bridging across the channel. It is therefore logical to assume that the temporal lag for the collapse of a bridging piece of LW is greater than the time since initial infestation. This presents an opportunity for management agencies to cut and collapse bridging trees down between the channel margins, essentially accelerating wood loading rates. Channel adjustments associated with these added LW pieces could be indicative of future changes that extend beyond the temporal scope of this study.

Results indicate that streams are transitioning from plane-bed to step-pool channel forms, and substrate overall is coarsening, however these findings are not significant. As time increases past the scope of this study, it can be expected that a greater number of MPB and non-MPB killed trees will fall and eventually collapse down into the channel margins. The number of step-pools will increase with time since initial infestation as a greater number of MPB-killed trees fall between the channel margins and influence flow. Substrate in plunge pools has been shown to be significantly coarser throughout the study area. Therefore, as the number of step-pools increase, it is expected that substrate will coarsen. Follow-up surveys over the next 10-20 years would be ideal to capture this temporal lag.

Conclusion

The MPB disturbance increases LW loads in forested headwater mountain streams, which initiates channels adjustments. Overall trends indicate channels are narrowing and shallowing from early- to late-stage infestation, which is unexpected. Spatially localized effects of non-bridging pieces of MPB-killed LW include channel widening and deepening with the formation of pools. A high percentage of MPB-killed trees are still standing and have yet to fall. As time since initial infestation increases, it is expected that a greater number of MPB-killed trees will eventually fall causing channels to significantly widen and deepen with the formation of step-pools. Results presented here are unique because few studies have addressed channel response following extensive disturbance related to the MPB infestation.

References

Abbe, T.B., Montgomery, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research & Management* 12, 201-221.

Angermeier, P.L., Karr, J.R., 1984. Relationship between woody debris and fish habitat in a small warmwater stream. *Transactions of the American Fisheries Society* 113, 716-726.

Beckman, N.D. and Wohl, E., 2014. Carbon storage in mountainous headwater streams: The role of old-growth forest and logjams. *Water Resources Research* 50.3, 2376-2393.

Bevenger, G.S., King, R.M., 1995. A pebble count procedure for assessing watershed cumulative effects. *U.S. Department of Agricultue Forest Service Res. Pap.*, RM-RP-319.

Bilby, R.E., Likens, G.E., 1980. Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology* 61, 1107-1113.

Bilby, R.E., Ward, J.W., 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* 118, 368–378.

Bilby, R.E., Ward, J.W., 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and 2ndgrowth forests in southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 48, 2499–2508.

Bishop, P.L., Hively, W.D., Stedinger, J.R., Rafferty, M.R., Lojpersberger, J.L., and Bloomfield, J.A., 2005. Multivariate analysis of paired watershed data to evaluate agricultural best management practice effects on stream water phosphorus. *Journal of Environmental Quality* 34.3, 1087-1101.

Braudrick, C.A., Grant, G.E., 2001. Transport and deposition of large woody debris in streams: a flume experiment. *Geomorphology* 41, 263-283.

Broadmeadow, S., Nisbet, T.R., 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. *Hydrology and Earth System Sciences* 8, 286-305.

Buffington, J.M., Lisle, T.E., Woodsmith, R.D., Hilton, S., 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. *River Research and Applications* 18, 507-531.

Cadol, D., Wohl, E., 2010. Wood retention and transport in tropical, headwater streams, La Selva Biological Station, Costa Rica. *Geomorphology* 123, 61-73.

Costigan, K.H., Daniels, M.D., 2011. Spatial pattern, density and characteristics of large wood in Connecticut streams: Implications for stream restoration priorities in southern New England. *River Research and Applications*, In Press.

Cummins, K.W., Sedell, J.R., Swanson, F.J., Minshall, G.W., Fisher, S.G., Cushing, C.E., Petersen, R.C., Vannote, R.L., 1983. Organic matter budgets for stream ecosystems: problems in their evaluation. Stream ecology. Springer US, 299-353.

Curran, J.H., Wohl, E., 2003. Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology* 51, 141-157.

Curran, J.C., 2010. Mobility of large woody debris (LWD) jams in a low gradient channel. *Geomorphology* 116, 320-329.

Daniels, M.D. 2006a. Distribution and dynamics of large woody debris and organic matter in a low-energy meandering stream. *Geomorphology* 77, 286-298.

Daniels, M.D., 2006b. Grain-size sorting in meander bends containing large woody debris. *Physical Geography* 27, 348-362.

Daniels, M.D., Rhodes, B.L., 2007. Influence of experimental removal of large woody debris on spatial patterns of three-dimensional flow in a meander bend. *Earth Surface Processes and Landforms* 32, 460-474.

Daniels, M.D. and Rhoads, B.L., 2003. Influence of a large woody debris obstruction on three-dimensional flow structure in a meander bend. *Geomorphology* 51.1, 159-173.

Dillon, G.K., Knight, D.H., Meyer, C.B., 2003. Historic Variability for Upland Vegetation in the Medicine Bow National Forest, Wyoming. Medicine Bow National Forest, USFS Agreement No. 1102-0003-98-043.

Dillon, G.K., Knight, D.H., Meyer, C.B., 2005. Historic range of variability for upland vegetation in the Medicine Bow National Forest, Wyoming. *USDA Forest Service General Technical Report* RMRS-GTR 139.

Faush, K.D., Northcote, T.G., 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. *Canadian Journal of Fisheries and Aquatic Sciences* 49, 682-693.

Faustini, J.M., Jones, J.A., 2003. Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology* 51, 187-205.

Fetherston, K.L., Naiman, R.J., Bilby, R.E., 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology* 13, 133-144.

Fisher, G.B., Magilligan, F.J., Kaste, J.M., Nislow, K.H., 2010. Constraining the timescale of sediment sequestration associated with large woody debris using cosmogenic 7Be. *Journal of Geophysical Research* 115, F01013, doi:10.1029/2009JF001352.

Gippel, C.J., 1995. Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering* 121.5, 388-395.

Goode, J.R., Wohl, E., 2007. Relationships between land-use and forced-pool characteristics in the Colorado Front Range. *Geomorphology* 83, 249-265.

Grant, G.E., Swanson, F.J., Wolman, M.G., 1990. Pattern and origin of stepped bed morphology in high gradient streams, Western Cascades, Oregon. *Geological Society of America Bulletin* 102, 340-352.

Gurnell, A.M., Gregory, K.J., Petts, G.E., 1995. The role of course woody debris in forest aquatic habitats: implications for management. *Aquatic Conservation: Marine and Freshwater Ecosystems* 5, 143-166.

Gurnell, A.M., Sweet, R., 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. *Earth Surface Processes and Landforms* 23, 1101-1121.

Hall Jr., R.O., Bernhardt, E.S., Likens, G.E., 2002. Relating nutrient uptake with transient storage in forested mountain streams. *Limnology and Oceanography* 47, 255-265.

Hassan, M.A., Hogan, D.L., Bird, S.A., May, C.L., Gorni, T., Campbell, D., 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. *Journal of American Water Resources Association* 41, 899-919.

Jones, T.A., Daniels, L.D., Powell, S.R., 2011. Abundance and function of large woody debris in small, headwater streams in the Rocky Mountain foothills of Alberta, Canada. *River Research and Applications* 27, 297-311.

Keller, E.A., Swanson, F.J., 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms* 4, 361–380.

Klutsch, J.G., Negron, J.F., Costello, S.L., Rhoades, C.C., West, D.R., Popp, J., Caissie, R., 2009. Stand characteristics and downed woody debris accumulations associated with a mountain pine beetle (Dendroctonus ponderosae Hopkins) outbreak in Colorado. *Forest Ecology and Management* 258, 641-649.

Kraft, C.E., Warren, D.R., 2003. Development of spatial pattern in large woody debris and debris dams in streams. *Geomorphology* 51, 127-139.

Lienkaemper, G.W., Swanson, F.J., 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. *Canadian Journal of Forest Research* 17, 150-156.

Lisle, T.E., 1986. Effects of woody debris on anadromous salmonid habitat, Prince of Wales Island, southeast Alaska. *North American Journal of Fisheries Management* 6.4, 538-550.

Lisle, T.E., 1995. Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. *Water Resources Research* 31, 1797-1808.

Manga, M., Kirchner, J.W., 2000. Stress partitioning in streams by large woody debris. *Water Resources Research* 36, 2373–2379.

Marston, R.A., 1982. The Geomorphic Significance of Log Steps in Forest Streams. *Annals of the Association of American Geographers* 72.1, 99-108.

Magilligan, F.J., Nislow, K.H., Fisher, G.B., Wright, J., Mackey, G., Laser, M., 2008. The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. *Geomorphology* 97, 467-482.

May, C.L., Gresswell, R.E., 2003. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, USA. *Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere* 33, 1352–1362.

McMahon, T.E., Hartman, G.F., 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (Oncorhynchus kisutch). *Canadian Journal of Fisheries and Aquatic Sciences* 46, 1551-1557.

Mitchell, R.G., Priesler, H.K., 1998. Fall rage of lodgepole pine killed by the mountain pine beetle in central Oregon. *Western Journal of Applied Forestry* 13, 23-26.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., Pess, G., 1995. Pool spacing in forest channels. *Water Resources Research* 31, 1097-1105.

Montgomery, D.R., Buffington, J.M., 1997. Channel reach morphology in mountain draiage basins. *Geological Society of America Bulletin* 109, 596-611.

Morris, Arthur E.L., Goebel, P.C., Palik, B.J., 2010. Spatial distribution of large wood jams in streams related to stream-valley geomorphology and forest age in northern Michigan. *River Research and Applications* 26, 835-847.

Moulin, B., Schenk, E.R., Cliff, R.H., 2011. Distribution and characterization of in-channel large wood in relation to geomorphic patterns on a low-gradient river. *Earth Surface Processes and Landforms* 36, 1137-1151.

Nakamura, F., Swanson, F.J., 1994. Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon. *Canadian Journal of Forest Research* 24, 2395-2403.

Nowakowski, A.L., Wohl, E., 2008. Influences on wood load in mountain streams of the Bighorn National Forest, Wyoming, USA. *Environmental Management* 42, 557-571.

Piégay, H., Thevenet, A., Citterio, A., 1999. Input, storage and distribution of large wood along a mountain river continuum, the Drome River, France. *Catena* 35, 19-39.

Ralph, S.C., Poole, G.C., Conquest, L.L., Naiman, R.J., 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* 51, 37-51.

Ruffing, C.M., Daniels, M.D., Dwire, K.A., 2015. Disturbance legacies of historic tie-drivers persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming. *Geomorphology* 231, 1-14.

Sullivan, S.M.P., 2012. Geomorphic-ecological relationships highly variable between headwater and network mountain streams of northern Idaho, United States. *Journal of the American Water Resources Association (JAWRA)* 48.6, 1221-1232.

Thompson, R.M. and Townsend, C.R., 2005. Energy availability, spatial heterogeneity and ecosystem size predict food-web structure in streams. *Oikos* 108.1, 137-148.

Udawatta, R.P., Krstansky, J.J., Henderson, G.S., and Garrett, H.E., 2002. Agroforestry practices, runoff, and nutrient loss. *Journal of Environmental Quality* 31.4, 1214-1225.

Urban, M.A., Daniels, M.A., 2006. Introduction: exploring the links between geomorphology and ecology. *Geomorphology* 77.3, 203-206.

Veum, K.S., Goyne, K.W., Motavalli, P.P., and Udawatta, R.P., 2009. Runoff and dissolved organic carbon loss from a paired-watershed study of three adjacent agricultural watersheds. *Agriculture, ecosystems & environment* 130.3, 115-122.

Warburton, J., 1992. Observations of bed load transport and channel bed changes in a proglacial mountain stream. *Arctic and Alpine Research*, 195-203.

Wilcox, A.C., Nelson, J.M., and Wohl, E., 2006. Flow resistance dynamics in step-pool channels: 2. Partitioning between grain, spill, and woody debris resistance. *Water Resources Research* 42.5.

Wilcox, A.C. and Wohl, E., 2006. Flow resistance dynamics in step-pool stream channels: 1. Large woody debris and controls on total resistance. *Water Resources Research* 42.5.

Winker, K., Rappole, J.H., Ramos, M.A., 1995. The use of movement data as an assay of habitat quality. *Oecologia* 101, 211-216.

Wipfli, M.S. and Gregovich, D.P., 2002. Export of invertebrates and detritus from fishless headwater streams in southeastern Alaska: implications for downstream salmonid production. *Freshwater Biology* 47.5, 957-969.

Wohl, E., 2006. Human impacts to mountain streams. *Geomorphology* 79.3, 217-248.

Wohl, E., Jaeger, K., 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. *Earth Surface Processes and Landforms* 34, 329-344.

Wohl, E., Cenderelli, D.A., Dwire, K.A., Ryan-Burkett, S.E., Young, M.K., Fausch, K.D., 2010. Large in-stream wood studies: a call for common metrics. *Earth Surface Processes and Landforms* 35.5, 618-625.

Wohl, E., 2011. Threshold-induced complex behavior of wood in mountain streams. *Geology* 39, 587-590.

Wohl, E., Polvi, L.E., Cadol, D., 2011. Wood distribution along streams draining old-growth floodplain forests in Congaree National Park, South Carolina, USA. *Geomorphology* 126, 108-120.

Wohl, E., Dwire, K., Sutfin, N., Polvi, L., Bazan, R., 2012. Mechanisms of carbon storage in mountainous headwater rivers. *Nature Communications* 3, 1263.

Wolman, M.G., 1954. A method of sampling coarse river-bed material." EOS, *Transactions American Geophysical Union* 35.6, 951-956.

Wood-Smith, R.D., Buffington, J.M., 1996. Multivariate geomorphic analysis of forest streams: implications for assessment of land use impacts on channel condition. *Earth Surface Processes and Landforms* 21, 377-393.

Young, W.J., 1991. Flume study of the hydraulic effects of large woody debris in lowland rivers. *Regulated Rivers: Research & Management* 6, 203-211.

Young, M.K., Haire, D., Bozek, M.A., 1994. The effect and extent of railroad tie drives in streams of southeastern Wyoming. *West. J. Appl. For.* 9.4, 125–130.

Figure 3.1 Aerial reconnaissance of MPB mortality throughout the surveyed watersheds. See Figure 2.1 for background shading.

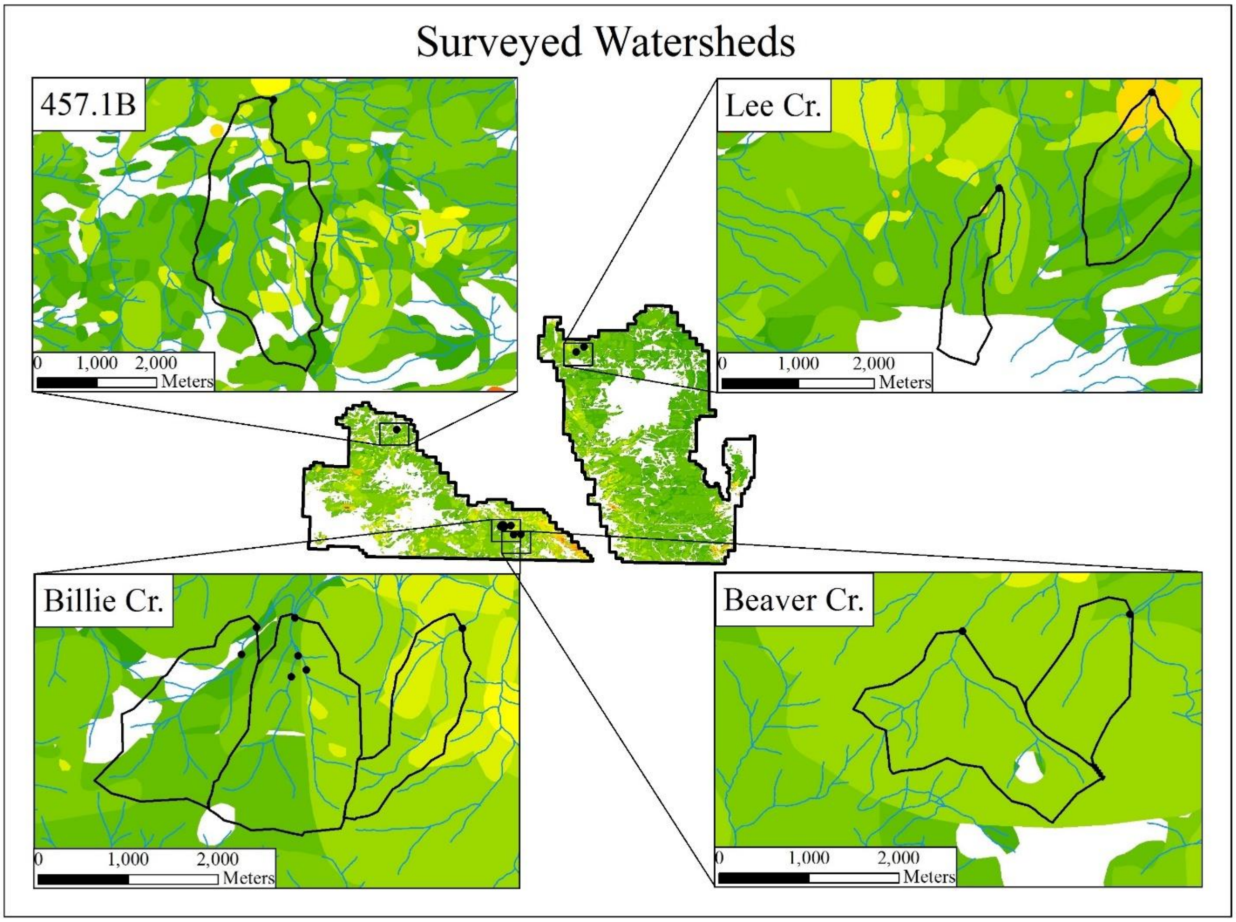


Figure 3.2 Sediment wedge and channel avulsion on West Fork Billie Creek's survey reach. (A) Looking upstream at fallen MPB-killed LW and sediment wedge. (B) Looking downstream at sediment wedge and MPB-killed LW.

(A) (B)

Table 3.1 Summary of LW inventory from Chapter 2.

Early-stage Infestation				
Survey Reach	**Survey Length (m)**	**# MPB pieces**	**# Non-MPB pieces**	**Total # of LW pieces/100m**
Billie Creek - Lower	248.11	4	9	5.2
Billie Creek - Upper	1073	23	101	11.6*
East Fork Soap Creek	155.75	2	40	27.0
Mid NFSR 404 1st Order	1062.45	12	108	11.3
NFSR 404 2nd Order - Unnamed	496.43	10	55	13.1
NFSR 452 - Unnamed	167.17	4	22	15.6
Soap Creek 2nd Order	100.7	2	13	9.0
West Branch Billie Creek Lower	354.4	7	56	17.8*
West Branch Billie Creek Upper	965.2	16	139	16.1*
West Fork Billie Creek Lower	260.52	3	11	5.4*
West Fork Billie Creek Upper	875.89	16	72	10.1*
Middle-stage Infestation				
Billie Creek 2nd Order	343.79	13	41	15.7*
Beaver Creek Lower	132.82	4	23	20.3
Beaver Creek Upper	549.71	14	69	15.1*
Highline - Lower	198.48	6	11	8.6
Lee Creek	468.91	15	88	22.0*
NFSR 261 Lower - Unnamed	267.90	7	62	25.8
West Fork NFSR 404 - Unnamed	491.87	15	25	8.1*
NFSR 414.1A Lower - Unnamed	873.0	30	59	10.2
NFSR 452 Lower - Unnamed	228.38	6	49	24.1
Rankin Creek 2nd Order	281.67	9	50	20.9
Late-stage Infestation				
North Fork Big Creek	63.5	5	14	29.9*
NFSR 136 1st Order	167.42	16	44	35.8
NFSR 136 2nd Order	289.67	16	45	21.1*
NFSR 261 Upper - Unnamed	168.78	20	50	41.5

NFSR 414.1A Upper - Unnamed	224.0	9	35	19.6
NFSR 457.1B	232.65	14	49	27.1*
Rankin Creek 1st Order	280.44	11	50	21.8
West Branch Billie Creek DS Billie Ditch	386.41	15	57	18.6
West Fork Soap Creek	106.31	12	39	48.0

'*' indicates selected for detailed morphological survey.

Table 3.2 Physiometric characteristics for the selected surveyed watersheds.

First-order Channels				
Survey Reach	**Elevation (m)**	**Slope (m/m)**	**Valley Width (m)**	**Area (km^2)**
Billie Creek Upper	2791	0.127	54.90	0.805
Lee Creek	2659	0.244	30.95	0.804
North Fork Big Creek	2829	0.095	67.18	0.971
West Branch Billie Creek Upper	2794	0.276	57.77	1.447
West Fork Billie Creek Lower	2776	0.147	54.49	0.885
West Fork Billie Creek Upper	2792	0.223	61.83	0.852
West NFSR 404 - Unnamed	2742	0.280	63.37	1.021
Second-order Channels				
Beaver Creek	2896	0.066	66.99	1.891
Billie Creek 2nd Order	2749	0.115	50.89	2.028
NFSR 136 - Unnamed	2581	0.126	107.31	1.466
NFSR 457.1B - Unnamed	2600	0.099	84.343	6.070
West Branch Billie Creek Lower	2761	0.160	66.76	1.571

Table 3.3 Average channel dimensions for first and second-order channels across the stages of infestation.

First-order Channels							
Infestation Class	**Survey Reach**	**Width (m)**	**Depth (cm)**	**Max D (cm)**	**W/D**	**Rough**	**XS Area (cm^3)**
Early	Billie Creek Upper	2.98	25.89	34.70	13.091	13.090	6822.0
	West Branch Billie Creek Upper	2.60	28.62	40.18	12.08	17.80	6526.36
	West Fork Billie Creek Lower	2.01	24.90	34.36	8.81	15.194	4453.73
	West Fork Billie Creek Upper	4.03	25.88	39.80	18.45	15.313	10476.8
Middle	Lee Creek	1.69	33.13	41.18	6.079	17.876	5200.46
	West NFSR 404 - Unnamed	2.05	23.50	30.45	9.86	15.615	4395.46
Late	North Fork Big Creek	1.56	23.76	30.64	7.10	12.192	3445.91
Second-order Channels							
Early	West Branch Billie Creek Lower	2.52	26.60	35.70	10.846	14.908	6611.0
Middle	Beaver Creek	3.64	30.38	48.0	13.25	16.94	10029.0
	Billie Creek 2nd Order	2.95	28.25	41.91	13.24	18.0	7049.23
Late	NFSR 136 - Unnamed	1.85	24.40	31.27	8.64	15.53	3884.09
	NFSR 457.1B - Unnamed	3.63	33.20	44.73	12.34	18.23	10880.55

Table 3.4 ANOVA results testing differences in first and second-order channel metrics across the stages of infestation. ANOVA was also utilized to test log-transformed variables that meet assumptions of normality.

First-order Channels				
Variable	**Non-Scaled Metrics**		**Scaled Metrics**	
	F	**Pr(>F)**	**F**	**Pr(>F)**
Width	6.895	0.002**	7.309	0.0013**
Depth	0.628	0.537	0.887	0.416
W/D	4.653	0.013*	3.732	0.0287*
XS Area	3.312	0.042*	3.962	0.0233*
Second-order Channels				
Width	4.812	0.011*	27.356	<0.0001***
Depth	0.320	0.727	7.614	0.001***
W/D	1.591	0.211	11.487	0.0005***
XS Area	1.426	0.247	13.087	0.0001***

'***' indicates significance at the p<0.001 level, '**' at the p<0.01 level, and '*' at the p<0.05 level.

Table 3.5 ANOVA results testing differences in channel metrics across the stages of infestation. ANOVA was also utilized to test variables that meet assumptions of normality.

First and Second-order Channels		
	Non-Scaled Metrics	
Variable	**F**	**Pr(>F)**
Width	1.999	0.139
Depth	1.012	0.366
W/D	2.046	0.133
XS Area	1.053	0.352
	Scaled Metrics	
Variable	**F**	**Pr(>F)**
Width	34.113	<0.0001***
Depth	11.529	<0.0001***
W/D	19.566	<0.0001***
XS Area	18.555	<0.0001***

'***' indicates significance at the p<0.001 level.

Chapter 4 - Effects of Water Conveyance Diversion Structures on Channel Morphology and Aquatic Ecosystem Function in Forested Mountain Headwater Streams, Medicine Bow National Forest, Wyoming.

Abstract

Water diversion ditches traverse mountain hillslopes and transport flow out from one stream channel, typically through a headgate structure, and across a drainage divide. Ditch flow can then be released into an adjacent watershed or continue to traverse drainage divides. Through this process, streamflow can eventually be transported to farm or ranchland. Lawful water rights, typically designated at the state level, give landowners the opportunity to operate water diversion ditches and reservoirs to extract streamflow for use as irrigation. Many of these ditches have been in operation for well over a century and transcend nearly every major watershed, and in some cases divert all natural streamflow. Dewatered stream segments decouple watersheds at various, seemingly random locations while the added flow input at the ditch outlet creates an imbalance in the hydrograph. The implications of this anthropogenic disturbance are potentially catastrophic, however available research is limited in scope and provides only a partial understanding of the impacts of water diversion ditches on aquatic ecosystems. Stream channels were surveyed upstream and downstream from diversion structures that divert natural flow to test for significant differences. Three survey sites were selected encompassing various altered flow patterns created downstream from diversions. Results indicate that stream channels adjust downstream of diversions that limit peak flows. Where peak flows are allowed to pass through the diversion structure, channels show no sign of adjustment.

Introduction

Aquatic ecosystems located in high-alpine forested watersheds are commonly affected by both natural and anthropogenic disturbances at numerous spatial and temporal scales. Natural disturbances, such as atmospheric downbursts and mass movement, are spatially contained within one or two watersheds whereas wildfires, mountain pine beetle infestations and volcanic eruptions affect numerous watersheds simultaneously (Dillon et al., 2005; Wohl, 2005). Similarly, timber harvesting, tie-driving, placer mining, recreational development and other anthropogenic activities can have varying spatial and temporal effects (Dillon et al., 2005; Wohl, 2005). Streams are closely associated with adjacent hillslope processes, and this relationship allows researchers to distinctively link alterations in channel forms and processes with surrounding watershed disturbances.

Historically, research on altered flow regimes mainly focused on damming and channelization (Petts, 1979; Graf, 1980, 1999, 2006). Limited research is available pertaining to the potentially significant morphological, hydrological and biological effects that water diversion ditches have on forested mountain headwater streams. A diversion structure is a headgate that allows water to be removed from a stream channel and moved into a ditch (Marston and Marston., 2017). Barriers are usually placed across stream channels directly downstream from the diversion structures to pool water and reduce stream power, making it easier for water to enter into the ditch through the headgate structure (Marston and Marston, 2017). In some cases, barriers completely span the width of the channel in order to divert 100 percent of natural flow into the ditch. Diversion ditches then follow hillslope contours, transporting water from one watershed to another by transcending drainage divides (Marston and Marston, 2017). Water can be moved across multiple drainages, eventually flowing onto a private farm or ranchland for use as irrigation (Caske et al., 2015; Marston and Marston, 2017).

Normally, some reduced amount of flow is able to continue down the natural channel past the diversion structure (Caske et al., 2015; Marston and Marston, 2017). Ryan (1997) noted that the effects of diversion ditches on runoff patterns is fundamentally different compared to those associated with dams. A dam will reduce peak flow for flood control and increase low flow. Peak flows commonly pass by diversion ditches uncontrolled and can reach and go beyond boundary conditions for the transport of substrate or pieces of large wood (LW).

Ryan (1997) identified the potential impacts of diversion ditches on stream systems in the Colorado Rocky Mountains including an altered flow regime, depleted stream flows, reduced channel capacity, lowered local water tables, encroachment of upland vegetation into riparian zones and degradation of fish and wildlife habitat. Depleted flows alter channel hydraulics in small mountain streams (Baker et al., 2011). Total annual water yield and average annual discharge have been shown to decrease downstream from diversion structures (Ryan, 1997). Also, flow variability was also shown to increase during low-flow years downstream from a diversion (Ryan, 1997).

Ryan (1997) found reduced channel widths below diversion structures due to riparian encroachment, and an overall fining of substrate in Colorado Rocky Mountain streams. Stamp and Schmidt (2006) similarly found channel narrowing and bank accretion with regulated flows. Dominick and O'Neill (1988) measured increases in channel width and width-to-depth ratios in the upper Arkansas River drainage, Colorado. Median particle size was also shown to increase where flows are regulated (Dominick and O'Neill, 1988). Kellerhals et al. (1979) noted a gradual decrease in channel size and capacity due to riparian encroachment and deposition of suspended sediment load. Low-gradient channels in Wyoming were shown to significantly respond to depleted streamflow by narrowing and shallowing (Wesche et al., 1988). However, moderate- to- high-gradient channels, where stream power is high and sediment loading is limited, showed no sign of adjustment to depleted streamflow (Wesche et al., 1988). Caske et al. (2015) found significant differences in channel metrics and vegetation assemblages downstream from diversion structures. Considering the scale upon which these diversion ditches are operating, Caske et al. (2015) suggests that the cumulative effects of ditches on aquatic ecosystems is likely to be significant, and more intense site-level studies are necessary to understand these processes.

It was noted that the frequency of bankfull flows, which are critical for the transport of LW, decreased in stream channels below diversion structures. Wohl (2011) states that regulated flows have the potential to change wood transport dynamics along rivers. A reduction of flow downstream from a diversion could potentially decrease LW transport and increase sediment sequestration and storage. Subsequently, downstream from ditch inputs, amplified flows could increase the transport of LW and sediment, and coarsen overall substrate by flushing out sands and gravels. Alternating between amplified and reduced flows along a stream network due to ditch inputs/diversions could create spatially-unique channel forms and alterations to habitat and channel complexity.

Large diversion ditches may have the ability to transport and input LW from drainage divides directly into stream channels. Usually, riparian zones and forest stands surrounding mountain stream channels are the contributing source for LW being input into the system (Hyatt and Naiman, 2001). Riparian zones are typically composed of a diverse assemblage of vegetation, which transitions to upland species along the hillslopes and drainage divides. LW from non-riparian sources may be able to enter into a ditch at a ridgetop location, then be transported into a natural channel. This process could be important considering the current state of MPB infestation and high number of dead, falling trees. LW dynamics could be significantly altered with this input mechanism in conjunction with alternating amplified then reduced flows along a stream network. Alternatively, LW inputs into a smaller ditch without the capacity to transport those pieces could induce the formation of a debris jam, causing flow to overtop the artificial berm creating a breach. This typically creates some sort of mass wasting event along the hillslope downhill from the breach.

The degree to which flows are altered by diversions has major implications on the ecology of stream channels (Rader and Belish, 1999; Dewson et al., 2007). Flow regulation that reduces discharge can affect water temperature, nutrients and nutrient cycling, and invertebrates (Rader and Belish, 1999; Dewson et al., 2007). Species richness was significantly reduced below water diversions in West St. Louis Creek in Fraser Experimental Forest (Rader and Belish, 1999). Completely dewatered stream segments fragment stream systems (Dynesius and Nilsson, 1994). Natural and/or artificial pollutants could enter into a stream system and be transported across numerous watersheds contaminating each connected stream network.

The Medicine Bow National Forest (MBNF) is a prime location to study the effects of water diversions on channel morphology and LW dynamics. Many of the ditches in the MBNF have been functioning for over 100-years, exposing stream networks to artificial flow patterns during that time. There are a total of 113 ditches in the MBNF, which span a length of 224.70 kilometers (Figure 4.1). That is an average length of 2 kilometers per ditch. Nearly a quarter of all watersheds in the MBNF are impounded by a water conveyance ditch at some location and to varying degrees. A survey by MBNF employees found that stream flows for a third of all perennial stream miles are regulated (Purchase et al., 2004). Findings suggested that though most large streams are regulated, effects from altered streamflow are more likely to be significant in smaller regulated streams. The effects of regulated stream flows by diversion structures on aquatic resources is poorly understood (Purchase et al., 2004).

The Brush Creek-Hayden District of the MBNF began semi-annually inspecting their ditch facilities back in 2002. Inventories include recommendations for maintenance needs, condition and resource concerns for each individual ditch. Permit holders are then sent a letter requesting specific maintenance to be completed within a defined timeframe. In some cases the permit holder will accompany USFS employees on their inspections. In nearly every case, the permit holders have been compliant with maintenance requests and are cooperative as both they and the public management agency recognize the mutual benefit of ditch upkeep. However, little to no effort is made by either party to account for downstream legacy effects of altered regulated flows on channel morphology and aquatic habitat.

The primary research objective of this chapter is to identify the effects regulated flows by diversion structures have on channel morphology and aquatic habitat in forested mountain headwater streams. Stream channels were surveyed upstream and downstream from diversion structures in order to identify any significant differences in stream channel morphology and/or ecosystem function. It is hypothesized that stream channels will significantly adjust downstream from diversion structures that regulate streamflow. Specifically, reducing or eliminating channel-maintaining flows will cause channels to narrow and become shallower, which will reduce width-to-depth ratios and cross-sectional area. It is also hypothesized that substrate will coarsen downstream from a diversion structure, since reduced regulated flows downstream from the diversion lack the power to mobilize larger pieces of substrate. These data will provide preliminary, baseline information for studying the impacts of ditch diversions on aquatic ecosystem function.

Methodology

Study Site Selection

Of the twelve survey reaches from Chapter 3, three of those were located directly upstream from a diversion structure. Billie Creek and West Branch Billie Creek are second-order channels in watersheds experiencing late-stage infestation, while North Fork Big Creek is a first-order channel experiencing middle-stage infestation according to the surveys from Chapters 2 and 3. All three streams were historically tie-driven and have north-facing orientations. The diversion structure for Billie Creek Ditch is located on West Branch Billie Creek at UTM 354687E, 4549212N (NAD83) and allows for some streamflow to continue down the natural channel. Billie Creek Ditch then continues west across the drainage divide and intersect with Billie Creek at UTM 354992E, 4549233N (NAD83), where there is another diversion structure that diverts all streamflow. The ditch then continues west for 2.82 kilometers and dumps into a tributary of Beaver Creek. The diversion structure for Highline ditch is located on McAnulty Creek at UTM 360192E, 4544398N (NAD83). The 5.18 kilometer-long ditch captures 100 percent of flow from North Big Creek at UTM 359436E, 4546946N (NAD83) then continues north and flows into Beaver Creek at UTM 359601E, 4547845N (NAD83). Stream survey reaches on Billie Creek, West Branch Billie Creek, and North Fork Big Creek were located directly downstream from the diversion structure but far enough away so as not to be influenced by the ditch berm. Methods from Chapter 3 were followed to assess watershed conditions at each survey reach.

Data Collection

Survey reaches were installed and measured following the methods from Chapters 2 and 3. Stream reaches were surveyed June through August, 2013, following peak spring runoff. Channel geometry, substrate, LW and meso-habitat were surveyed at the three affected reaches. Physiometric characteristics of the surrounding watershed were measured using ArcGIS, including watershed area, valley width, slope and elevation. Observations were made describing the functionality and current state of the three diversion structures, along with estimates of the percent of flow diverted at each location. There is no record kept, gage or otherwise, on the amount of flow being diverted or released down the natural channel at each structure and at any given time.

Data Analysis

Channel dimensions including width, average depth, width-to-depth ratio, cross-sectional area and roughness were calculated for each cross-section. Cross-sectional and longitudinal roughness values were calculated by taking the standard deviation of rod heights between the tops of the banks for each cross-section and along the longitudinal survey. Total LW volume and number of pieces per 100 meters of stream channel were calculated for MPB and non-MPB killed pieces within each survey reach. Percent of observed channel units, along with D50 and D84 values for substrate within those specified channel units, were calculated for each survey reach.

Analysis of Variance (ANOVA) was used to test for significant differences in channel morphology, LW dynamics, and mesohabitat upstream and downstream from diversion structures. *P*-values were calculated at $\alpha = 0.05$ and $\alpha = 0.01$ to determine significance between upstream and downstream reaches along the same stream network.

Results

All survey reaches were conducted between 2400 and 3000 meters in elevation, throughout primarily (+70%) lodgepole pine forest stands with 80 to 100+ year-old trees. Tree ages coincide with a peak in historic logging activities throughout the region, indicating widespread harvesting activities affected all survey reaches at about the same time. All three stream networks were tie-driven during this time, which resulted in legacy effects such as limited channel complexity and low number of older, entrained LW pieces, uniform gravel particle sizes and no streamside shrub cover (Ruffing et al., 2015; Young et al., 1994).

Channel Morphology

Channel dimensions for survey reaches upstream and downstream from a diversion structure were tested for significant differences. North Fork Big Creek returned the most significant results. Here the diversion structure removes 100 percent of flow out of the natural channel at all times during the flow season. Even peak flows are unable to pass down the natural channel past this diversion point. This channel remains dewatered for less than 300 meters downstream until enough accumulated runoff enters the natural channel from the surrounding hillslopes and groundwater seeps. Channel widths ($p < 0.001$), average ($p = 0.008$) and max ($p = 0.007$) depths and cross-sectional area ($p = 0.001$) for North Fork Big Creek have all been significantly decreased downstream from the diversion structure. Width-to-depth ratios and cross-sectional roughness coefficients were not significantly different downstream. It appears that this stream channel is maintaining its geometric shape while narrowing and becoming shallower overall.

Billie Creek's channel dimensions downstream from the diversion were not significantly different compared to the upstream survey reach. The diversion structure at this location allows for peak spring runoff flows to pass through an emergency spillway back into the natural channel downstream from the ditch crossing (Figure 4.2). Fish passage through this diversion could only occur during peak flows and through the emergency spillway. There is also no mechanism for sediment transfer down the natural channel, causing gravel bars to form directly upstream from the diversion structure.

Channel widths ($p = 0.025$) and cross-sectional area ($p = 0.049$) are significantly decreased downstream from the diversion structure on West Branch Billie Creek. The diversion structure at the beginning of Billie Ditch allows roughly half of low-flow and a quarter of peak flows down the natural channel, exiting the ditch through a culvert pipe (Figure 4.3). The maximum carrying capacity of this culvert pipe therefore represents the maximum amount of flow that can continue down the natural channel at any given time. Water is not diverted during the entire flow season at this location, as evidenced by Figure 4.3. Unfortunately, no records are required to be kept pertaining to the timing or amount of water that is diverted or released down the natural channel.

Longitudinal roughness values are much lower downstream from the diversion structure in North Fork Big Creek and West Branch Billie Creek compared to their upstream counterparts. Similarly, there are slight increases in the percent of riffles downstream from diversion structures at these two survey reaches. As noted earlier, peak flows are unable to pass down the natural channel below these two diversions. Limiting or eliminating peak flows appears to have decreased channel complexity. Peak flows can pass more naturally through the Billie Creek diversion structure's spillway. Longitudinal roughness increases slightly downstream from the Billie Creek diversion, as does the percent of pools.

LW and Habitat

There are no overall significant trends in the volume or number of pieces of LW per 100-meters of stream channel upstream and downstream of diversion structures. In Billie Creek, LW volume increased from 2.76 to 5.74 cubic meters per 100-meters of stream channel while the number of pieces increased from 13.7 to 48.9 downstream from the ditch diversion. North Fork Big Creek and West Branch Billie Creek both show a slight decrease in volume and number of pieces of LW downstream from diversions.

D50 and D84 values for West Branch Billie Creek decreased for both pools and riffles downstream from the diversion. No pools were located on North Fork Big Creek downstream from the diversion point. However, D50 and D84 values both decreased dramatically in representative riffles downstream from the ditch indicating an overall fining of substrate in these channel units. Billie Creek D50 and D84 values increased for both pools and riffles downstream from the diversion structure, though not significantly.

Discussion

North Fork Big Creek has the only diversion structure out of the three survey sites that removes 100 percent of streamflow at all times during the flow season. Downstream channel adjustments on North Fork Big Creek include significant channel narrowing, shallowing, reduced longitudinal roughness and an overall fining of substrate. These results are similar to previous studies that found channels narrowing and shallowing downstream from diversions (Kellerhals et al., 1979; Ryan, 1997; Stamp and Schmidt, 2006). This is due to the lack of channel-maintaining flows since initial diversion. Highline ditch borders both sides of this stream channel, following hillslope contours up along the valley walls. All hillslope runoff is effectively captured by the ditch berm and transported out of the watershed instead of flowing down with gravity to the valley bottom. North Fork Big Creek remains dewatered until enough accumulated runoff downhill from the ditch berm, and groundwater seepage, can replenish the water supply roughly 300 meters downstream. Even during storm events, it is unlikely that channel-maintaining flows are reached. These results serve only as the most extreme examples of channel adjustment to water diversion.

The structure on West Branch Billie Creek allows flow to pass by the diversion at all times during the flow season. Peak flows are limited by the carrying capacity of the culvert directly downstream from the diversion point. This culvert also likely prevents fish passage. West Branch Billie Creek narrows downstream from the diversion structure, causing cross-sectional area to decrease significantly. Without channel-maintaining flows, riparian encroachment causes the channel to narrow. There is also a measureable fining of substrate downstream from the diversion, though not statistically significant. Adjustments measured here are not as extreme as North Fork Big Creek, likely due to the fact that periodically natural flow patterns are maintained, even if only during low-flow months.

Channel metrics for Billie Creek downstream from the diversion structure were not significantly different compared to the upstream survey reach. Longitudinal roughness and substrate sizes increased downstream from the diversion. Though all of low-flows are captured by the diversion structure, peak flows are able to pass down the natural channel. It is likely that channel-maintaining flows annually pass downstream through this diversion, allowing Billie Creek to maintain a more natural channel form.

It appears from these results that channel adjustments downstream from diversion structures could possibly be minimized by allowing peak flows to pass by the diversion structure and continue down the natural channel. However, not every diversion structure in the MBNF is built to accommodate this. Historically, there was no need to build a diversion structure to allow flow, or for that matter fish, to pass down the natural channel if the permittee was allocated 100 percent of the streamflow. Water law in the west in very complex (MacDonnell, 2014), to the point that it commonly deters progress. However, numerous water rights are up for their 100 year renewal. This provides an opportunity for public management agencies and private permittees to work together on a case-by-case basis to reduce the effects of diversions by requiring minimum flows to be released down the natural channel.

Aquatic habitat response to altered flow regimes due to diversion structures is understudied (Ryan, 1997). It is well known that some fish species operate their lives according to seasonal fluctuations in light, nutrient delivery and streamflow (Hynes, 1970). Diversion ditches could affect all three of these variables, or even completely dewater steam segments making them impassable/unlivable for aquatic invertebrates and fish species. Further studies are also necessary to understand how diversion ditches contouring hillslopes affect hillslope hydrology, local groundwater tables and the transport of biological, chemical and/or physical elements or pollutants.

Conclusion

Water diversion ditches located throughout the MBNF function over long temporal scales and create artificial flow patterns. Regulated flows downstream from diversion structures can significantly affect channel morphology. Diversions that limit or eliminate peak flows cause channels to narrow and become shallower downstream. Streams below diversion structures that allow peak flows to continue down the natural channel show no signs of adjustment. Regulated flows will influence LW dynamics, which is especially important considering the recent MPB infestation.

References

Baker, D.W., Bledsoe, B.P., Albano, C.M., Poff, N.L., 2011. Downstream effects of diversion dams on sediment and hydraulic conditions of Rocky Mountain streams. *River Research and Applications* 27, 388-401.

Caske, S.T., Blaschak, T.S., Wohl, E., Schnackenberg, E., Merritt, D., Dwire, K.A., 2015. Downstream effects of stream flow diversion on channel characteristics and riparian vegetation in the Colorado Rocky Mountains, USA. *Earth Surface Processes and Landforms* 40, 586-598.

Dewson, Z.S., James, A.B.W., Death, R.G., 2007. Stream ecosystem functioning under reduced flow conditions. *Ecological Applications* 17, 1797-1808.

Dillon, G.K., Knight, D.H., Meyer, C.B., 2005. Historic range of variability for upland vegetation in the Medicine Bow National Forest, Wyoming. *USDA Forest Service General Technical Report* RMRS-GTR 139.

Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern third of the world. *Science* 266, 753-762.

Graf, W.L., 1980. The effect of dam closure on downstream rapids. *Water Resources Research* 16.1, 129-136.

Graf, W.L., 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* 35, 1305-1311.

Graf, W.L., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology* 79, 336-360.

Hyatt, T.L., Naiman, R.J., 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* 11, 191-202.

Hynes, H.B.N., 1970. The Ecology of Running Waters. Liverpool University Press, Liverpool, England.

Kellerhals, R., Church, M., Davies, L.B., 1979. Morphological effects of interbasin river diversions. *Canadian Journal of Civil Engineering* 6, 18-31.

MacDonnell, L., 2014. The development of Wyoming water law. *Wyoming Law Review* 14.2, 327-378.

Marston, R.A., Marston, B.K., 2017. Mountain hydrology. *The International Encyclopedia of Geography*, 4532-4540.

Petts, G.E., 1979. Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography* 3.3, 329-362.

Purchase, C., Gloss, D., Florich, T., 2004. Managing water facilities on NFS lands – a forest prospective. Presented at Advancing the Fundamental Sciences: *Proceedings of the Forest Service National Earth Science Conference*, 18-22 October 2004, San Diego, CA.

Rader, R.B., Belish, T.A., 1999. Influence of mild to severe flow alterations on invertebrates in three mountain streams. *Regulated Rivers: Research and Management* 15, 353-363.

Ruffing, C.M., Daniels, M.D., Dwire, K.A., 2015. Disturbance legacies of historic tie-drivers persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming. *Geomorphology* 231, 1-14.

Ryan, S.E., 1997. Morphologic response of subalpine streams to transbasin flow diversion. *Journal of the American Water Resource Association* 33, 839-854.

Stamp, M.L., Schmidt, J.C., 2006. Predicting channel responses to flow diversions. *Stream Notes, published by the Stream Systems Technology Center, Rocky Mountain Research Station, US Forest Service.*

Wesche, T.A., Skinner, Q.D., Hasfurther, V.R., Wolff, S.W., 1988. Stream channel response to flow depletion. Abstract WWRC 88-19, In *Proceedings of the Water and the West Symposium*, Wyoming Division American Society of Civil Engineers, Laramie, Wyoming, Wyoming Water Research Center, University of Wyoming.

Wohl, E., Merritt, D., 2005. Prediction of mountain stream morphology. *Water Resources Research* 16.1, 129-136.

Wohl, E., 2011. What should these rivers look like? Historical range of variability and human impacts in the Colorado Front Range, USA. *Earth Surface Processes and Landforms* 36, 1378-1390.

Young, M.K., Haire, D., Bozek, M.A., 1994. The effect and extent of railroad tie drives in streams of southeastern Wyoming. *Western Journal of Applied Forestry* 9.4, 125–130.

Figure 4.1 Water conveyance ditches actively diverting water throughout the study area, and the locations of survey reaches.

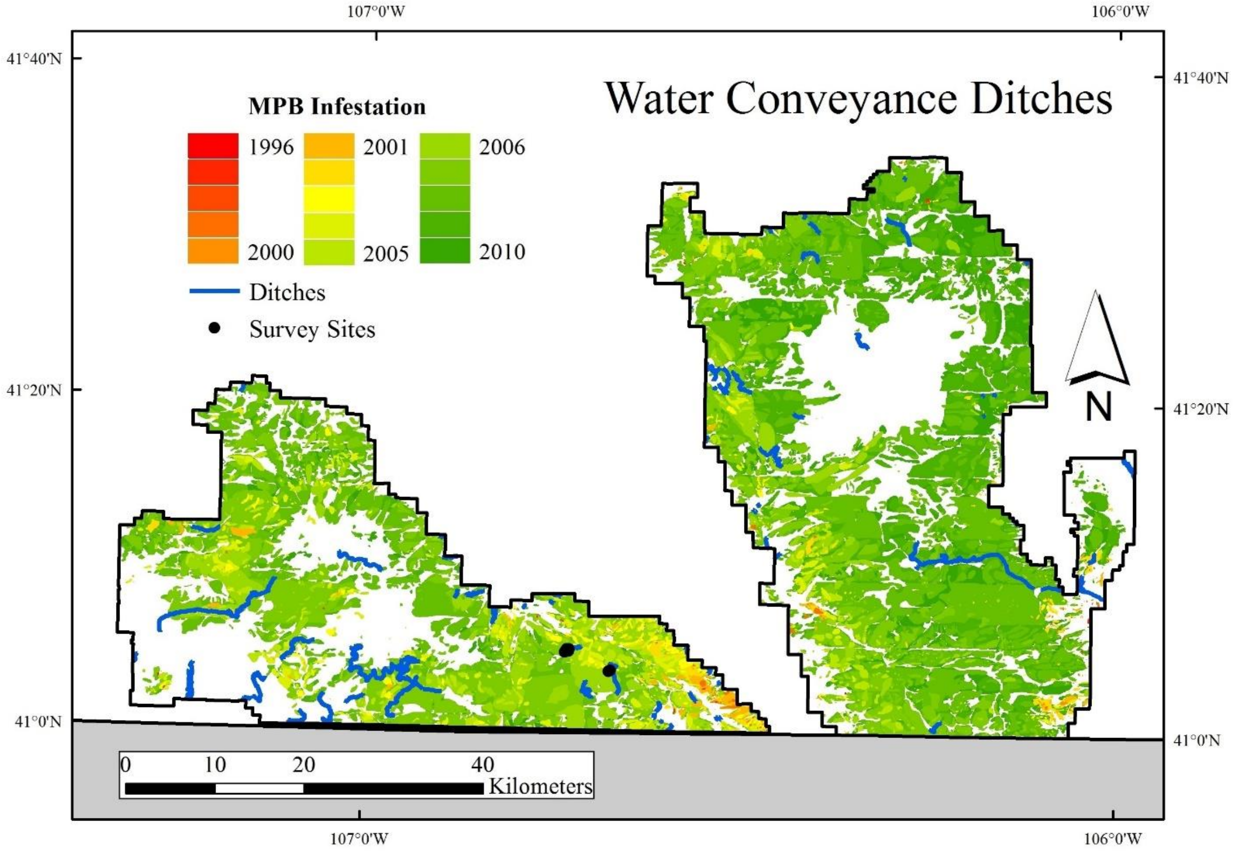


Figure 4.2 Diversion structure on Billie Creek. (A) Approach to diversion structure. (B) Diversion structure/emergency spillway on Billie Creek.

(A) (B)

Figure 4.3 Diversion structure on West Branch Billie Creek. (A) Culvert transports flow through the berm back into the natural channel below the diversion structure. (B) Approach to diversion structure.

(A) (B)

Figure 4.4 Diversion structure on North Fork Big Creek. (A) Confluence of North Fork Big Creek with Highline Ditch. (B) North Fork Big Creek below diversion ditch.

(A) (B)

Table 4.1 Average channel dimensions measured upstream and downstream from a diversion structure.

Survey Reach	Width (m)	Depth (cm)	Max Depth (cm)	W/D	Rough	XS Area (cm^3)
North Fork Big Creek US Diversion	1.56	23.76	30.64	7.10	12.19	3445.90
North Fork Big Creek DS Diversion	0.91	14.83	19.0	6.90	9.82	1172.27
Billie Creek US Diversion	2.95	28.25	41.91	13.24	18.0	7049.23
Billie Creek DS Diversion	2.35	27.88	39.91	10.09	15.72	5870.0
West Branch Billie Creek US Diversion	2.52	26.60	35.70	10.85	14.91	6611.0
West Branch Billie Creek DS Diversion	1.60	21.55	30.18	8.27	13.42	3162.73

Table 4.2 ANOVA results testing differences in channel dimensions between survey reaches located upstream and downstream from a diversion structure.

Stream	Variable	F	Pr(>F)
North Fork Big Creek	Width	22.393	0.00013***
	Depth	8.583	0.0083**
	Max Depth	8.991	0.0071**
	W/D	0.026	0.875
	Roughness	2.590	0.123
	XS Area	14.616	0.0011**
Billie Creek	Width	2.817	0.109
	Depth	0.004	0.948
	Max Depth	0.567	0.460
	W/D	0.756	0.395
	Roughness	0.840	0.370
	XS Area	0.614	0.443

West Branch Billie Creek	Width	5.843	0.026*
	Depth	1.526	0.232
	Max Depth	0.942	0.344
	W/D	1.265	0.275
	Roughness	0.607	0.446
	XS Area	4.381	0.05*

‘*’ indicates significance at the p<0.001 level, ‘**’ at the p<0.01 level, and ‘*’ at the p<0.05 level.

Chapter 5 - Conclusions

This dissertation sought to correlate adjustments in large wood (LW) loading and the geomorphic structure of headwater mountain streams to the temporal spectrum of MPB infestation throughout a disturbance-prone ecosystem. This dissertation also sought to measure geomorphic discontinuities in channel form upstream and downstream from water diversions. The temporal scale for MPB infestation was accounted for by substituting space for time. Three empirical studies presented in this dissertation provide methodologies and data that capture alterations to LW dynamics and the geomorphic structure of headwater streams. This research is unique because it is the first to identify the effects of MPB infestation on in-stream LW and channel form.

Chapter 2, *Large wood loadings in Rocky Mountain headwater streams across an age spectrum of Mountain Pine Beetle infestation, Medicine Bow National Forest, Wyoming*, measures LW loads as a response to time since initial MPB infestation. As time since initial infestation increases, the volume and number of MPB-killed and non-MPB LW pieces also increase. Physiometric characteristics of watersheds did not account for these increases, which is an indicator for disturbance. Physical characteristics of MPB-killed pieces of LW significantly differ from non-MPB-killed pieces. Wood loads will continue to increase as more dead trees fall between the channel margins.

Chapter 3, *Influence of large wood on the geomorphology of Rocky Mountain headwater streams across as age spectrum of Mountain Pine Beetle infestation, Medicine Bow National Forest, Wyoming*, evaluates the effect of an increased LW supply, due to the current MPB infestation, on the ecological function and geomorphic structure of headwater mountain streams. Widths, average depths and width-to-depth ratios are all decreasing with time since initial infestation, which was unexpected. The spatial scale at which detailed morphological surveys were conducted was not large enough to capture the spatially-localized effects of MPB-killed LW. Numerous LW pieces are bridging across the channel and are having only a minimal effect on channel morphology. It is expected that with time, these pieces will eventually ramp down into the channel causing streams to widen and deepen as pools form. This creates a temporal lag in the legacy effects of MPB infestation, indicating a need for future monitoring.

Chapter 4, *Effects of water conveyance diversion structure on channel morphology and aquatic ecosystem function in forested mountain headwater streams, Medicine Bow National Forest, Wyoming*, determines that channel morphology adjusts to flows regulated by diversion structures. Diversion structures that allow peak flows to pass down the natural channel have almost no effect on channel morphology downstream. Channels downstream from diversions that limit peak flows, or that remove 100 percent of natural flow throughout the entire flow season, narrowed significantly, reducing cross-sectional area.

Both natural and anthropogenic disturbances can influence the condition and function of ecosystems at various spatial and temporal scales. In the case of the MPB infestation, roughly 90 percent of killed trees identified in watersheds experiencing the greatest amount of time since initial infestation are still standing. Nevertheless, significant alterations to LW loads and channel form, which are discrete components of an ecosystem, have been measured. This indicates that the temporal scale for the MPB infestation extends much further than the scope of this research. The influence that spatial and temporal scales have on ecosystems are repeated themes throughout the literature on disturbance. System recovery post-disturbance has always been difficult to measure, especially over long periods of time. The amount of carbon in a system is determined by vegetation growth, mortality and re-growth, each of which can operate at their own spatial and temporal scales. Stream channel form represents an interaction between vegetation (i.e. wood loading), geology (i.e. physiometric characteristics of the watershed), and hydrology. Therefore, it should be expected that stream-channel recovery will lag temporally behind carbon regrowth without the influence of other disturbances.