

THESIS

INSTREAM WOOD LOADS IN OLD-GROWTH AND NON-OLD-GROWTH MONTANE
FORESTS

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Karen Jackson

Department of Geosciences

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Fort Collins, Colorado

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Master's Committee:

Advisor: Ellen Wohl

Sara Rathburn
Brian Bledsoe

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ABSTRACT

INSTREAM WOOD LOADS IN OLD-GROWTH AND NON-OLD-GROWTH MONTANE FORESTS

Although several studies document instream wood loads and geomorphic effects in subalpine forests of the southern Rocky Mountain region, little is known of instream wood loads in lower elevation, montane forests of the region. This study focuses on comparing instream wood loads and associated stream geomorphological responses between montane forest stands in the Arapahoe-Roosevelt National Forest of differing age and disturbance history: (i) old-growth forests versus younger, minimally impacted forests, and (ii) healthy forest stands versus stands with greater than 25% of trees infested by mountain pine beetles.

Wood loads of 33 study sites were measured in pool-riffle reaches, along with cross section surveys, pool volume, and sediment volume. Wood loads were standardized to reach length, slope, bankfull width, drainage area, and floodplain area. The significance level was ultimately increased from of $\alpha = 0.05$ to 0.10 and used for all statistical analyses. Using a pairwise t-test, the standardized wood loads were tested based on stand age. There were significantly larger instream wood volumes and jam volumes in old-growth montane forests. Jam frequencies in old-growth forests were significantly higher (Kruskal-Wallis test). Residual pool volume and sediment storage (standardized to slope) were significantly greater in old-growth stands. There was no significant difference between wood loads in mountain pine beetle infested and healthy forest stands. Using the best subset regression method, $\log_{10}(\text{elevation})$, stand age, and mountain pine beetle infestation were the best predictors of all measures of wood volume -

total, instream, and floodplain. Even though infested stand wood loads means were not significantly different than healthy wood load means, multivariate analysis found stand health to be an important predictor of wood loads.

Instream wood loads were comparable to previous Colorado Front Range subalpine values. Jam frequencies were lower in montane streams than Front Range subalpine streams and Pacific Northwest streams. Forest managers should take stand age into consideration when understanding montane streams, whereas recent mountain pine beetle infestation may be less of an issue. Over the next century, beetle infestation may become more relevant, but as of now there is no significant addition of wood to streams.

ACKNOWLEDGMENTS

This project would not have been possible if it had not been for the help and support of many people and organizations. I would like to extend my gratitude to the Colorado State University Geosciences Department, the CSU Memorial Hill Scholarship, the Geological Society of America, and American Water Resource Association for funding. Marry Hattis, the GIS Coordinator at the Arapaho & Roosevelt National Forest and Pawnee National Grasslands, supplied crucial GIS layers of old-growth and mountain pine beetle infested areas in Colorado. I also need to thank Laurie Huckaby at the US Forest Service for taking the time to teach me how to identify and locate old-growth ponderosa trees.

I could not have completed the fieldwork without Joey Matzke, Michael Garcia, and JoJo Mangano. JoJo also helped me with ArcGIS to find field sites, and later make maps. I would have never completed the statistical analysis without the help and guidance of Natalie Anderson. Everyone in the fluvial family has supported me in one way or another over the past two years, and to them I am grateful. Throughout the past two years, Eric Gaver and Rachael McSpadden have also encouraged me and were always there when I needed them the most. Thank you to my committee members, Dr. Sara Rathburn and Dr. Brian Bledsoe, who provided invaluable feedback to complete this thesis. A special thanks goes to Dr. Ellen Wohl, who is the best advisor, mentor, and life coach anyone could ask for.

DEDICATION

I dedicate this thesis to my grandmother, Lois Jackson. You have always encouraged my pursuit of education, and inspire me to keep learning. Thank you for all your love and support.

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1 INTRODUCTION

Mountain streams shape the Rocky Mountain region, and are a vital resource to the ecosystems and communities they support. The behavior of these streams is influenced by more than the surrounding geology (valley shape, substrate, depth to bedrock, etc.). The amount and location of instream wood is also a major influence on the physical and ecological properties of mountain streams (Wohl and Jaeger, 2009). Large instream wood can trap sediment and organic matter (Faustini and Jones, 2003), increase stream boundary roughness (MacFarlane and Wohl, 2003), increase local scour and erosion (Montgomery et al., 1995), and influence channel planform (Wohl, 2011). Wood jams are particularly effective at trapping sediment. Wood jams, defined as three or more large pieces in contact with each other, can create scour pools, and induce other geomorphic effects that are more substantial than those created by single pieces. As a source of aquatic habitat, sufficient wood loads can provide key nutrients and enhance aquatic habitat and biodiversity (Fausch and Northcote, 1992).

Although there have been studies focused on instream wood in the subalpine portion of the Colorado Front Range (~3400-2800 m elevation), wood loads in streams of the montane zone (~2800-1700 m) have not been quantified or analyzed. The subalpine wood dynamics may not transfer to the montane zone, which typically has lower stand density, larger tree species, a different flow regime, and a separate natural disturbance regime (Veblen and Donnegan, 2005). Montane streams now bear the brunt of changing disturbance regimes associated with beetle infestations, wildfire, and warming climate, however, and effective management of these streams and the adjacent riparian forest requires knowledge of instream wood dynamics.

The majority of research on instream wood has been conducted in the temperate rainforests of the Pacific Northwest (Robison and Beschta, 1990; Abbe and Montgomery, 1996; Fox and Bolton 2007). Although some findings from these studies may translate to Colorado Front Range streams, wood dynamics are likely to differ in the drier, heavily disturbed environment (fire, logging, etc.) of the Front Range. Previous instream wood research along Colorado Front Range headwaters has focused on estimating wood volume, distribution, and mobility (Wohl and Goode, 2008; Wohl and Jaeger, 2009; Wohl and Cadol, 2011), primarily within subalpine forests. Investigation of diverse valley, channel, and forest-stand parameters revealed that volume of instream wood correlates with specific aspects of valley and channel geometry and discharge, and individual wood pieces are quite mobile (Wohl and Goode, 2008; Wohl and Jaeger, 2009). Local parameters exert more influence on wood distribution than do overarching downstream trends such as increasing drainage area and discharge (Wohl and Cadol, 2011), and valley geometry can exert a stronger influence than forest age when considered at channel lengths of several kilometers (Wohl and Cadol, 2011). When considering valley segments with similar geometry and differing forest age, however, forest age exerts a significant influence on instream wood characteristics. Old-growth subalpine forests correspond to greater instream wood loads, larger and more closely spaced logjams, and greater instream carbon storage in the form of both logs and finer particulate organic matter (Beckman and Wohl, 2014).

Forest-stand disturbances including logging, wildfire, and mountain pine beetle infestation (Veblen and Donnegan, 2005) also influence instream wood loads. Following a disturbance, wood load increases as trees fall during a period of roughly 30-60 years (Bragg, 2000; Wohl and Cadol, 2011). Once the dead trees have fallen, there is a lapse in recruitment until the living trees are large enough to supply wood to the stream. Reestablishing old-growth

conditions requires at least 200 years (Veblen 1986). Old-growth forests are characterized by older trees with larger diameter, more snags (standing dead trees) and downed wood, and a multi-layered canopy (Richmond and Fausch, 1995; Huckaby et al., 2003). Wood available for recruitment in subalpine disturbed stands ranges from 12-147 m³/ha, which is much smaller than values of 92-254 m³/ha in old-growth stands (Richmond and Fausch, 1995). This difference is particularly important given the demonstrated physical and ecological importance of instream wood, and the potential for substantially reduced wood recruitment in the future as disturbances increase in frequency, extent, and severity. Existing research provides baseline knowledge of instream wood dynamics that can inform management of subalpine streams and riparian forests. The extent to which knowledge of subalpine streams can be extrapolated to montane streams, however, remains unknown.

There are some overarching trends in instream wood in streams of the Colorado Rockies relative to other regions in which instream wood has been studied. In general, less wood is available because Colorado Front Range coniferous stands are less dense and have smaller tree diameters than coniferous forests elsewhere in the world (Wohl and Jaeger, 2009). Less wood, along with a history of logging, may account for the region's low average instream wood volume of 13 m³/100 m of stream (Richmond and Fausch, 1995). Wood volumes were likely larger prior to logging in the 1860s (James, 1823; Fremont, 1845; Wohl and Goode, 2008). Smaller wood volume may also be a factor in shorter wood residence times in the region (Wohl and Goode, 2008). Less wood in turn lessens the odds of jam formation (Bocchiola et al., 2008). Less than 40% of wood pieces in Colorado subalpine streams were located in jams (Wohl and Goode, 2008; Wohl and Cadol, 2011). In conjunction with large and sustained snowmelt floods with

high transport capacities, the low incidence of jamming likely accounts for high wood mobility in Colorado streams.

Old-growth montane stands in Colorado and southern Wyoming are sparse and poorly understood, but these catchments have minimal flow regulation and logging impacts, making them valuable areas in which to observe dynamics of instream wood (Wohl, 2006). In addition to quantifying a baseline for wood loads in disturbed stands, understanding old-growth instream wood dynamics will be crucial for future restoration projects. A spatial model of an intact system can serve as a point of reference for Colorado's highly degraded and regulated stream reaches.

Over the past decade there has been extensive mountain pine beetle (*Dendroctonus ponderosae*) infestation in the Rocky Mountain forests. The beetles infect the pine with blue stain fungi, weakening the tree's health by interrupting water flow. The infestation has spread within significant portions of young and old-growth stands. So far the beetle has impacted 1.3 million hectares in Colorado, with ~64% of that area in the lower elevation (montane) Colorado Front Range (Colorado State Forest Service, 2012). The dead and dying trees may be affecting instream wood recruitment and distribution, but at present there is no knowledge of how beetle kill has affected young and old-growth montane wood loads and channel geometries. The research summarized in this thesis is pertinent to other Rocky Mountain montane ecosystems impacted by the beetle kill, and as climate change widens the areas affected by beetles, insights resulting from this thesis research will be applicable to areas that will experience infestation in future.

1.1 CONCEPTUAL MODEL

Research by other investigators facilitates development of a conceptual model of instream wood dynamics in channels of the Front Range montane zone. This conceptual model

underlies the research design of this thesis, and leads to hypotheses that can be tested using the data collected for this thesis (Fig. 1.1).

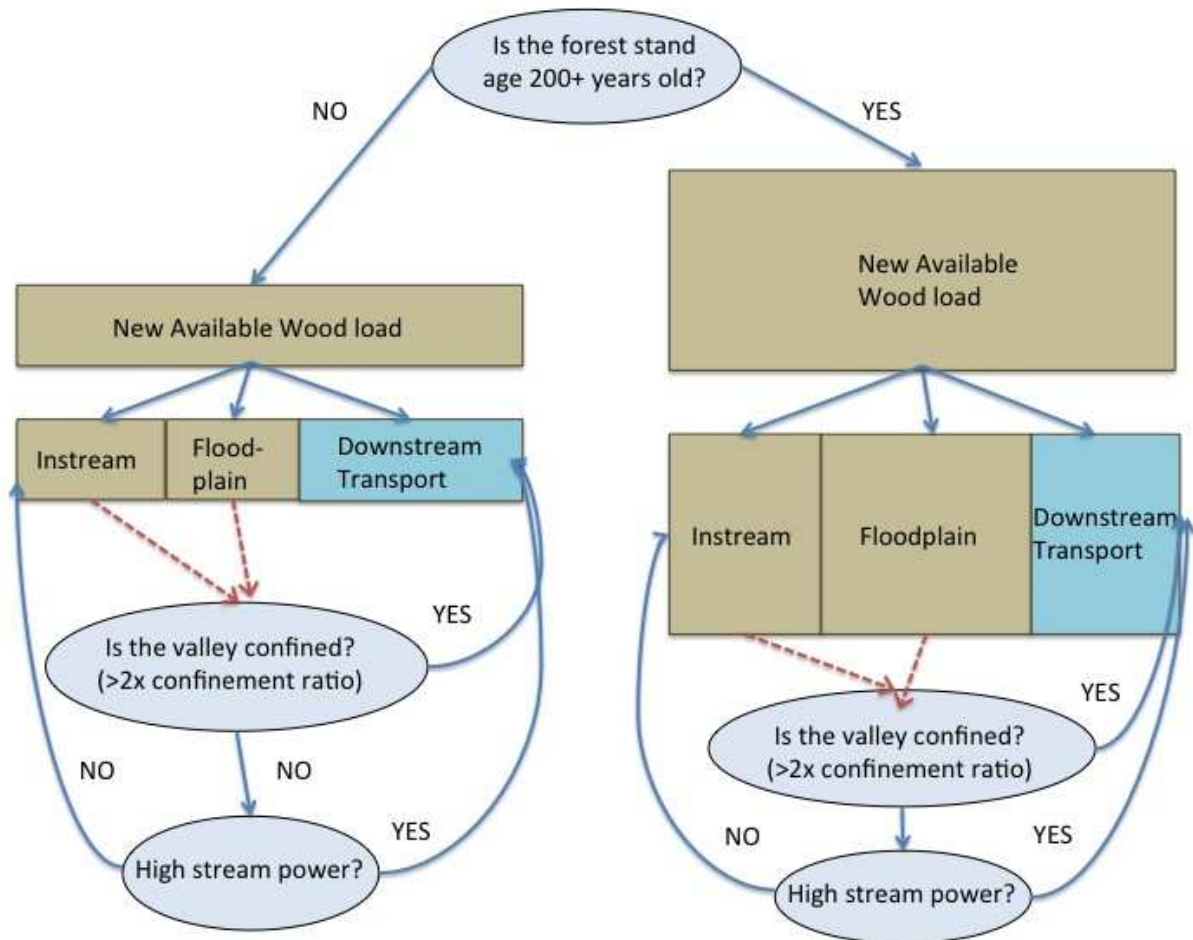


Figure 1.1: Conceptual model for wood retention and transport in headwater streams after a stand-killing disturbance. Rectangle sizes represent relative sizes of wood load. Instream wood includes all wood influenced by bankfull flows. Floodplain wood includes wood that has been deposited by the river, or may be mobilized by the river during high flows. Valley confinement is defined as the ratio of valley bottom width to bankfull width. A confinement ratio of 2x was considered confined, a ratio of 2-10x was partly confined, and >10x was unconfined. This model illustrates how forest stand age and valley geometry interact to influence the conditions under which high and low wood loads can occur in channel and floodplain settings. Note that stand age is a continuum, and new available wood load is a continuum. The stand age threshold is used here solely for illustrative purposes.

After a stand-killing disturbance, newly available wood enters a reach. This wood may be retained in the headwaters or be transported downstream. Factors such as piece size, volume of wood recruited, valley confinement, slope, discharge, and channel complexity influence wood

transport and retention. Highly confined valleys (ratio of valley bottom width to bankfull width > 2) limit floodplain area on the valley floor and contribute to larger stream power and greater flow depth during peak flows, thus limiting wood storage in channels and across the floodplain. Non-confined valleys have the potential for greater floodplain width and greater wood retention within channels and on the floodplain, in part because overbank flow limits total stream power (Ω ; the product of slope, or channel gradient and discharge) and flow depth during peak flows, thus limiting transport capacity for wood. Increased channel complexity also leads to more floodplain area. Multithread channels widen a river's influence on a valley and allow more wood to reside in the channel and floodplain than in a simpler, single thread channel (Wohl, 2011).

Transport of wood out of headwaters is heavily influenced by discharge and slope. Field and flume investigations of wood transport indicate that wood pieces become more mobile as the ratio of flow depth to piece diameter, and the ratio of channel width to piece length, increase (Wohl and Goode, 2008; Bocchiola et al., 2008; Braudrick and Grant, 2000). Higher discharges provide greater flow depth and width, as well as more force to transport wood. Steeper slopes typically correspond to narrower valley bottoms with minimal floodplains, so that high discharges are contained within the channel, maximizing the increase in flow depth, and hence wood mobility, with discharge. Steeper slopes also correspond to more rapid increase in stream power with discharge.

In this conceptual model, more of the newly available wood remains as instream wood in old growth streams. Larger diameter wood pieces from old growth stands are less mobile, and serve as key pieces to form wood jams. The larger pieces and denser forest basal area (greater number of trees that can be recruited to channels) increase jam frequency and size. More jams promote channel avulsion, increasing channel complexity and the ability to retain even more

wood. After the new wood reaches the channel or floodplain, channel geometry, valley geometry, and flow regime determine whether the wood is transported out of the valley segment. Valley confinement and high stream power (steep slopes and high discharges) promote downstream transport of wood. The more complex channels associated with old-growth stands will likely retain more wood given the same valley geometry and discharge. Stream power will diminish as flow encounters more backwater areas, forced wood steps, and pools, which effectively decrease channel gradient.

2 OBJECTIVES AND HYPOTHESES

Although several studies document instream wood loads and geomorphic effects in subalpine forests of the southern Rocky Mountain region, little is known of instream wood loads in lower elevation, montane forests of the region. There are numerous possible objectives that would further the understanding of this region's wood dynamics: this thesis will focus on two objectives.

OBJECTIVE 1: Collect a data set of instream wood loads in four types of montane forest stands: minimally impacted old-growth; minimally impacted non-old-growth; impacted old-growth; and impacted non-old-growth.

In this context, impact refers to degree of mountain pine beetle infestation. Although most of the younger forest stands in the Southern Rockies now have some level of pine beetle infestation, minimally impacted stands are not yet showing extensive tree fall, whereas severely impacted stands have more than 25% of trees falling or dead in association with pine beetle infestation.

- H_{10} : Instream wood loads in old-growth montane forests are not significantly different from instream wood loads in non-old-growth montane forests.
- H_{1A} : Instream wood loads in old-growth montane forests are significantly larger than instream wood loads in non-old-growth montane forests.

I expect the instream wood loads, defined here as volume of wood within the bankfull channel per unit surface area of channel and floodplain (i.e., m^3 wood/ha channel and floodplain), to be greatest in old-growth stands due to the higher probability of finding older (thus larger) wood pieces on the floodplain, within the banks, and in the stream. These larger pieces not only have large wood volume themselves, but also serve as key pieces for jams to form around (Fig. 2.1). If old-growth sites have larger, well-developed floodplains, floodplain wood loads may be biased.



Figure 2.1: Example of instream wood in montane streams. Small log jams (left) and scattered pieces (right) are common.

- H_{2_0} : Wood jam frequency and volume do not vary between forest stand types.
- H_{2_A} : Old-growth montane forests streams have greater frequency and volume of jams than in non-old-growth streams.

Frequency in this context refers to downstream spacing of jams (i.e., number of jams per unit length of channel). Volume of jams is expressed in m^3 of wood per jam. Younger forests may not have large enough wood pieces to form jams, and most wood is likely to be transported downstream in large flows.

- H3₀: Pool volume and sediment storage do not vary between forest stand types.
- H3_A: Old-growth montane forests streams have more wood-created geomorphic effects.

Wood-created geomorphic effects refer to particulate organic matter and sediment finer than the average streambed D_{50} stored in association with instream wood, and to residual pool volume associated with instream wood (Fig. 2.2). Residual pool volume is the volume of water in a pool, below the downstream riffle crest (Hilton and Lisle, 1993). I expect that the greater volumes of instream wood in old-growth forest will correlate with greater sediment storage and/or pool scour in these streams.



Figure 2.2: Example of montane pools. Pools filled with fine sediment (left) and scour pools below forced wood steps (right) are common.

- H4₀: Instream wood loads in minimally impacted montane forests are not significantly different from instream wood loads in beetle-infested montane forests.

- H4_A: Instream wood loads in healthy montane forests are significantly smaller than instream wood loads in beetle-infested montane forests.

I expect instream wood loads to be greater in forest stands where beetle-infested trees have begun to fall. These stands likely supply wood from the floodplain to the stream. Wood pieces may not be large enough to have long residence times, but total wood loads are expected to be larger than in minimally impacted streams. Hassan et al. (2008) found no significant difference between healthy and infested streams in sub-boreal British Columbia. However, the study was done in different climate and latitude, and may be different in the montane Colorado Front Range.

OBJECTIVE 2: Evaluate correlations between instream wood load and associated channel, valley, and forest characteristics.

- H5₀: There is no correlation between instream wood load and any valley, channel, or forest characteristics.
- H5_A: Instream wood load correlates with one or more valley, channel, or forest characteristics.

Wohl and Cadol (2011) found that downstream patterns in local valley and channel geometry influence wood load more than drainage area or time since last forest disturbance. Valley-bottom width, slope, and sequence of longitudinal channel changes had a stronger influence on wood distribution. Fox and Bolton (2007) found wood load to be correlated with

bankfull width, forest type, bedform type, bed slope, and confinement in streams flowing through temperate rainforest in Washington. In a similar study, Wohl and Jaeger (2009) correlated wood loads with drainage area, elevation, channel width, bed slope, and total stream power in streams of the Colorado Front Range. Wohl and Jaeger found wood to decrease with drainage area, but Fox and Bolton found wood to increase with drainage area. Wood loads increased with increasing elevation, decreased with increasing channel width, increased with increasing slope, and decreased with increasing stream power (Fox and Bolton, 2007). Wohl and Jaeger (2009) mainly focused on subalpine regions, and did not include enough montane sites to understand disturbance and age trends within the region. I expect montane streams to exhibit similar trends as subalpine streams, but to have smaller average wood loads.

This objective is, however, secondary to the first objective of this study. Study design focused on comparing stream reaches with differing forest stand age and disturbance history, while attempting to minimize variability in valley and channel geometry between sites. In practice, the limited extent of old-growth forest stands made it difficult to minimize variation in valley and channel geometry, but stream reaches were selected to have pool-riffle sequences or channel gradients close to those associated with pool-riffle bedforms, as opposed to steeper, step-pool sequences and the associated narrow valley geometries.

3 STUDY AREA

Stream reaches were preferentially chosen within the Arapaho and Roosevelt National Forests in Colorado (Fig. 3.1). The forest covers roughly 5250 km², with elevations ranging from 1500 m to 4200 m (Veblen and Donnegan, 2005). Selected stream reaches had the following characteristics: 1) minimal diversions, 2) not subject to recent (last 100 years) fire disturbances, 3) drainage area less than 40 km², and 4) slope less than 8%. Typical land uses in this area include cattle grazing and historical timber harvesting in the mid-1800s. Only small patches (<100 ha) of old-growth stands remain, usually in highly confined river valleys (Fig. 3.1).

3.1 CLIMATE AND VEGETATION

The montane region of the Colorado Front Range has a mean annual precipitation of ~55 cm and a mean annual temperature of 8.3°C (Barry, 1973). Precipitation increases and temperature decreases with increasing elevation along mountain slopes (Fig. 3.2). The montane climate is conducive to ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), and Douglas-fir (*Pseudotsuga menziesii*) forest stands. The Colorado Front Range has lower stand diversity and smaller tree diameters than other coniferous forests (Wohl and Jaeger, 2009).

3.2 HYDROLOGIC CHARACTERISTICS

All streams in this study are snowmelt dominated. Discharge in snowmelt-dominated streams in the Colorado Front Range is less variable than in rainfall-dominated streams such as those in parts of the northwestern United States (Wohl and Jaeger, 2009). However, at elevations lower than 2300 m, intense local thunderstorms can cause flash floods with high peak discharge per unit drainage area between May and September (Jarrett and Costa, 1988). Peak

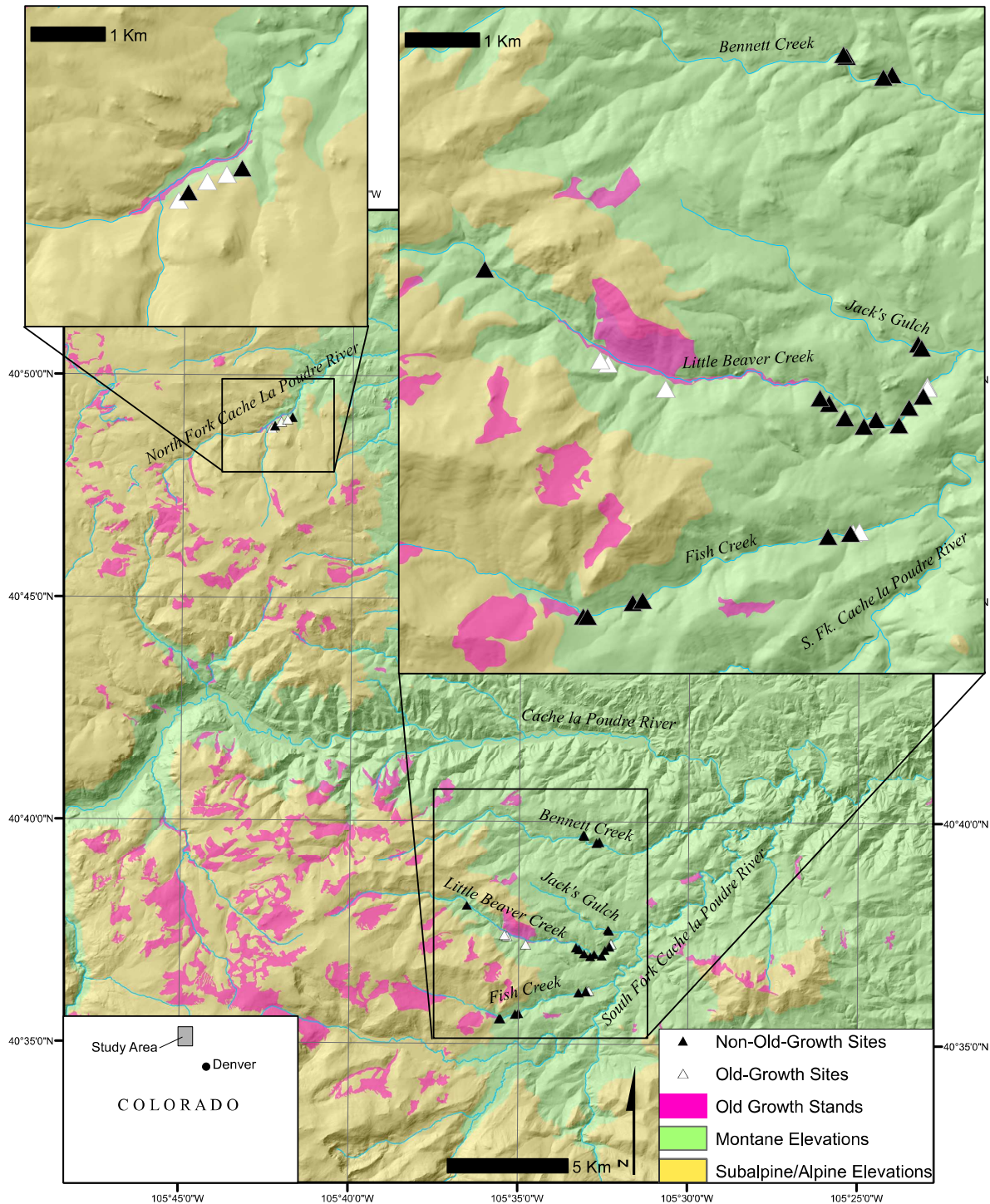


Figure 3.1: Old-growth and non-old growth study sites in the Cache la Poudre River Basin. Pink shading represents old growth stands. Yellow shading indicates elevations above the montane zone. Some old-growth sites were found in sheltered river valleys, outside of the pink shaded areas.

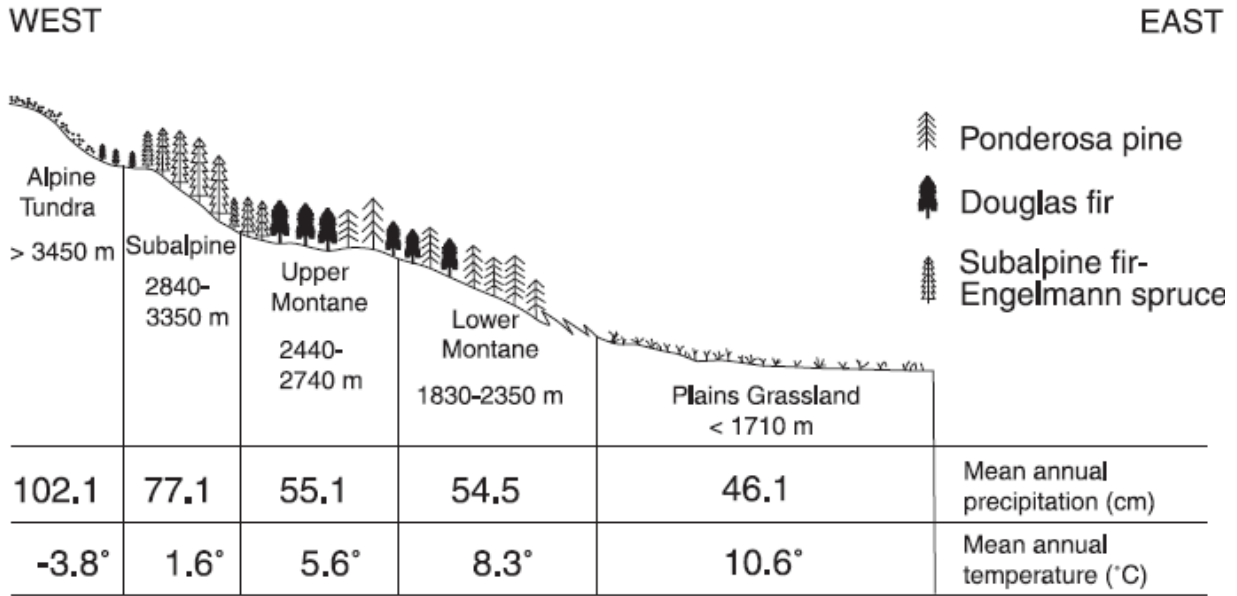


Figure 3.2: Montane elevation range in relation to other hydroclimatic and vegetation gradients with elevation. (Figure from Birkeland et al, 2003 (Fig. 2), who adapted it from Barry, 1973, and Veblen et al, 1991.)

stream flow, minimum stream flow, maximum stream flow, and annual mean stream flow can be estimated using mountain hydrologic regional regression curves created by Capesius and Stephens (2009) and incorporated in the online U.S. Geological Survey program StreamStats (<http://water.usgs.gov/osw/streamstats/>).

3.3 DISTURBANCE HISTORY AND MOUNTAIN PINE BEETLE INFESTATION

The Colorado Front Range is subject to a variety of disturbances: wind, floods, fire, insect infestation, and other pathogens (Veblen and Donnegan, 2005). Minor sources of wood in the montane region are derived from wind, snow, and floods. Strong winds along the Front Range have the capability to cause blowdowns, thus increasing wood availability on floodplains. However, montane zone tree species like ponderosa pine and Douglas-fir have well developed roots, making blowdowns less influential in the montane zone than at higher elevations (Veblen

and Donnegan, 2005). Intense snowfall can cause minor limbs of trees to break, and add smaller pieces to instream wood loads. Floods can transport key pieces of wood from the floodplain into the channel, excavate wood from banks, and mobilize as well as create jams.

Disturbances recently impacting Arapahoe Roosevelt National Forest stream wood load include fires and insect infestation. The fire regime in the Colorado Front Range montane zone is classified as a “variable-severity fire regime” by Veblen and Donnegan (2005). Both ground fires and stand-replacing fires are more common in the montane zone than in the subalpine zone. This is likely due to more herbaceous fuel in the understory. The montane zone fire recurrence interval for low severity ground fires is 10 years at the 100-hectare scale (Veblen and Donnegan, 2005). However, historically, most trees survive fires, and stand-replacing fires are less frequent. The stand-replacing fires are important for large instream wood pieces, because smaller pieces burn, and remaining larger trunks can subsequently be recruited into streams (Bragg et al, 2000). Insect infestation can also produce large amounts of available instream wood. Insects that affect the Colorado Front Range montane zone include the mountain pine beetle, Douglas-fir beetle (*Dendroctonus pseudotsugae*), spruce beetle (*Dendroctonus rufipennis*), pandora moth (*Coloradia pandora*), and the western spruce budworm (*Choristoneura occidentalis*). The bark beetles infect the larger trees and the infestation is usually lethal (Schmid and Mata, 1996). Dead trees may take decades to fall, but once in the stream can provide vital key pieces for jams. The recurrence intervals and extent of beetle and fire disturbances are provided in Figure 3.3 and Table 1 (Veblen and Donnegan, 2005, CSFS, 2012).

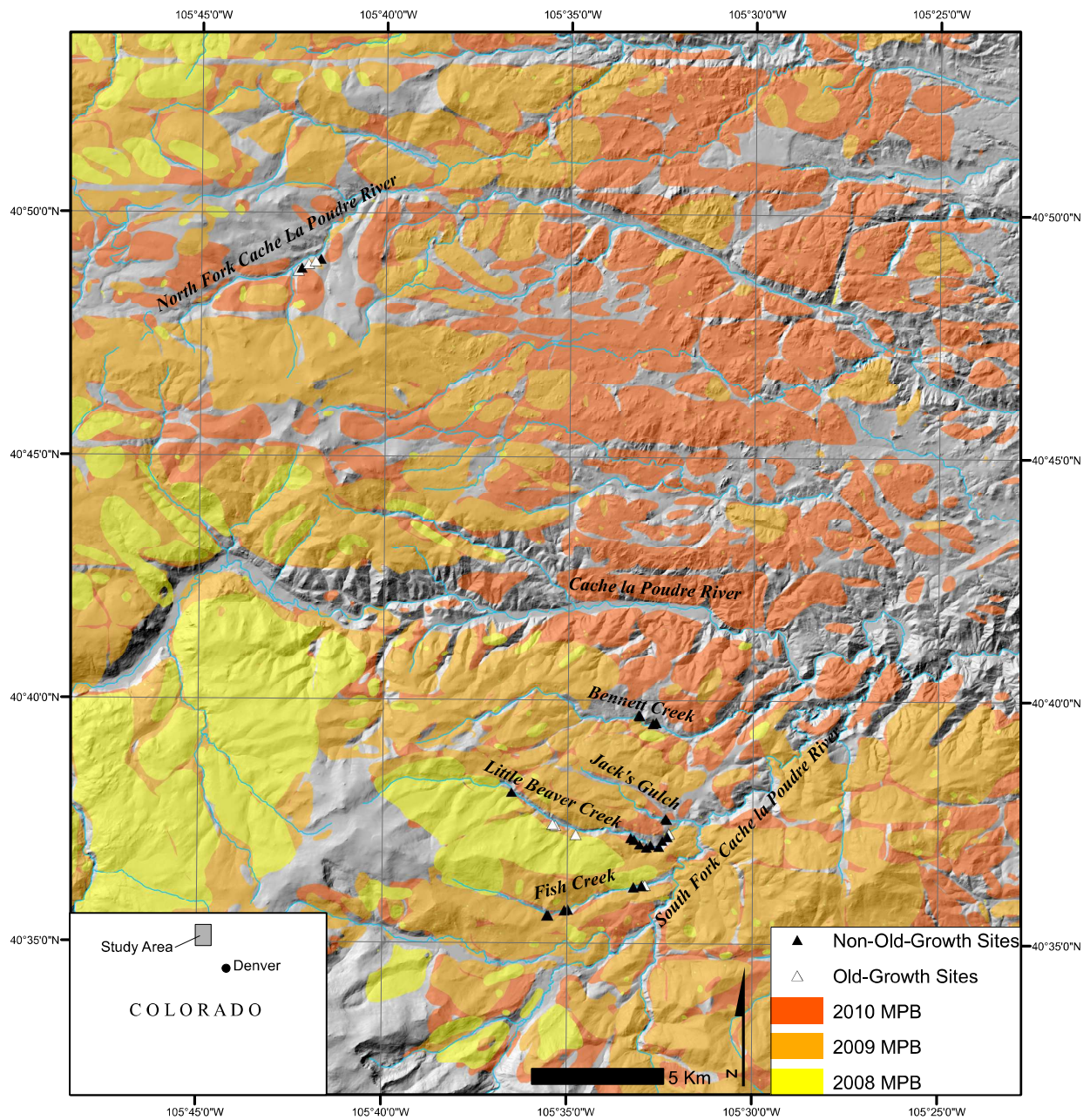


Figure 3.3: Mountain pine beetle infestation of study area. Initial infestation occurred in this region of the Colorado Front Range between 2008 and 2010 (USFS Aerial Detection Survey, 2013).

Table 3.1: Spatial extent, recurrence interval, duration, and impact on wood recruitment of mountain pine beetle (MPB) and fire disturbances in the Colorado Front Range

Disturbance	Area	Recurrence interval	Duration	Hypothesized impacts on wood recruitment
MPB	13,354 km ² (3.3 mil acres)	20-100 years	2-14 years	- may increase fire hazard - more dead trees available to be recruited into streams via individual treefall or mass blowdowns -burns small pieces of wood
Fire	1-400 km ² (10 ² -10 ⁴ acres per event)	10 years	1 season	-can create standing dead trees available for recruitment to streams

3.4 UNDERLYING GEOLOGY

The contemporary configuration of the Colorado Front Range reflects renewed uplift during the Laramide orogeny (~40-70 Ma). The Front Range predominantly consists of Precambrian crystalline basement rock (Cole et al., 2010). Basement rock includes granite, gneiss, schist, pegmatite, granodiorite, and amphibolite (Cole et al., 2010). Outcrops are common near the field sites for this research, as climate does not support thick soil development. As a result, valley walls have steep slopes with colluvium composed of cobble- to boulder-sized clasts. Lack of soil development and limited vegetation on slopes lead to high slope instability (debris flows) during heavy rainfall and in areas of recent fires. Limited weathering in the dry climate also precludes abundant silt and clay introduced to streams.

4 METHODS

4.1 REACH SELECTION

Reaches were selected along streams with minimal human impacts. Streams with a history of diversions or logging were avoided. Old-growth reaches were found using aerial survey data collected by the Arapaho and Roosevelt National Forest Service. Mountain pine beetle-infested reaches were found using Colorado State Forest Service aerial surveys. Both reach types were field checked. Old-growth stands had large (1m+ diameter) trees on both banks for the whole extent of the reach. Ponderosa pines with dead and rounded crowns were also used as indicators of old-growth trees (Fig. 4.1 & Fig. 4.2). Reaches designated as impacted by mountain pine beetle needed at least 25% of the stand dead for the full extent of the reach.

Study reaches needed to satisfy a variety of criteria. First, both banks had to be forested. Reach slope needed to be close to values typically associated with pool-riffle or plane bed morphology (~1-5%), and reaches could not exhibit step-pool morphology (Montgomery and Buffington, 1997). ArcGIS was used to calculate stream gradient and locate reaches with <5% slope. The ArcGIS stream layer for the North Fork and South Fork Poudre were broken up into 1000-m reaches. Gradients for each reach were calculated using a 10-m resolution digital elevation map (Fig. 4.3). Reaches that had evidence of beaver dams were avoided. Reach length was set at 10x bankfull width. Bankfull indicators included depositional bars, bank slope breaks, changes in vegetation, fine sediment deposition on banks, and undercut banks (Harrelson, Rawlins, and Potyondy, 1994). Channel morphology and valley confinement had to be consistent along the whole reach length. Valley confinement was defined as the ratio of valley bottom

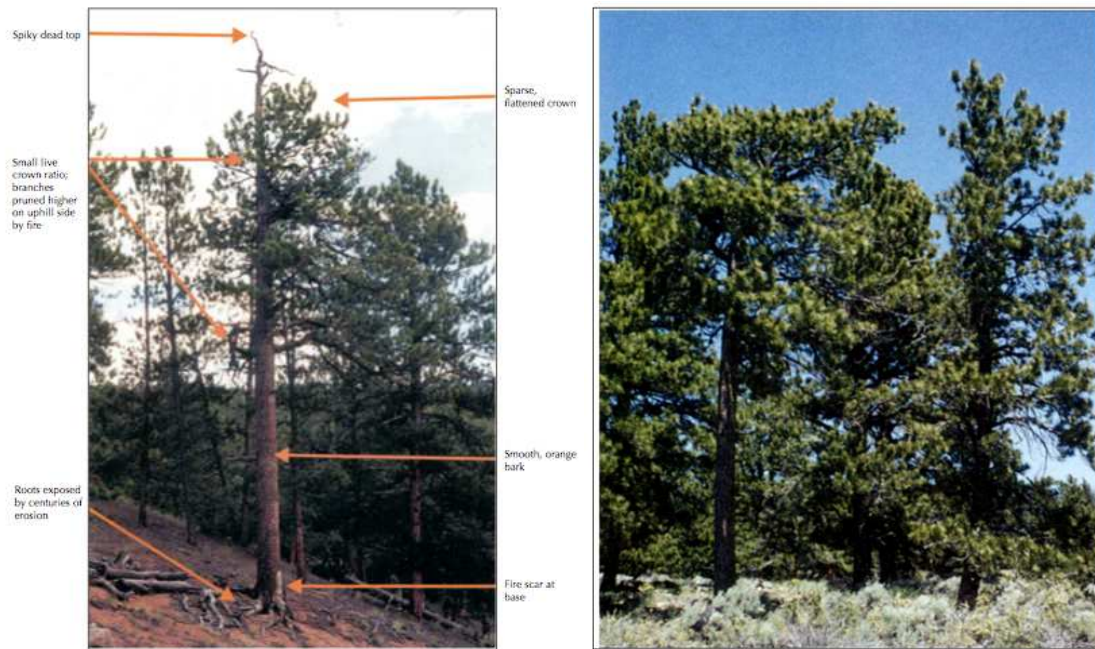


Figure 4.1: Figures from an identification guide to old-growth ponderosa pine trees (Huckaby et al., 2003, Figures 13 and 19). Left: Characteristics of an old ponderosa pine dated to be over 500 years old. Right: A 250 year old ponderosa with a flattened top on the left, and a younger ~125 year old tree. Note in older trees the crown is limited to the upper portion of the tree.



Figure 4.2: Old-growth ponderosa pines found on Little Beaver Creek. Left: Old-growth ponderosa on slope wall with dead crown top. Right: Old-growth ponderosa in valley bottom with flat crown.

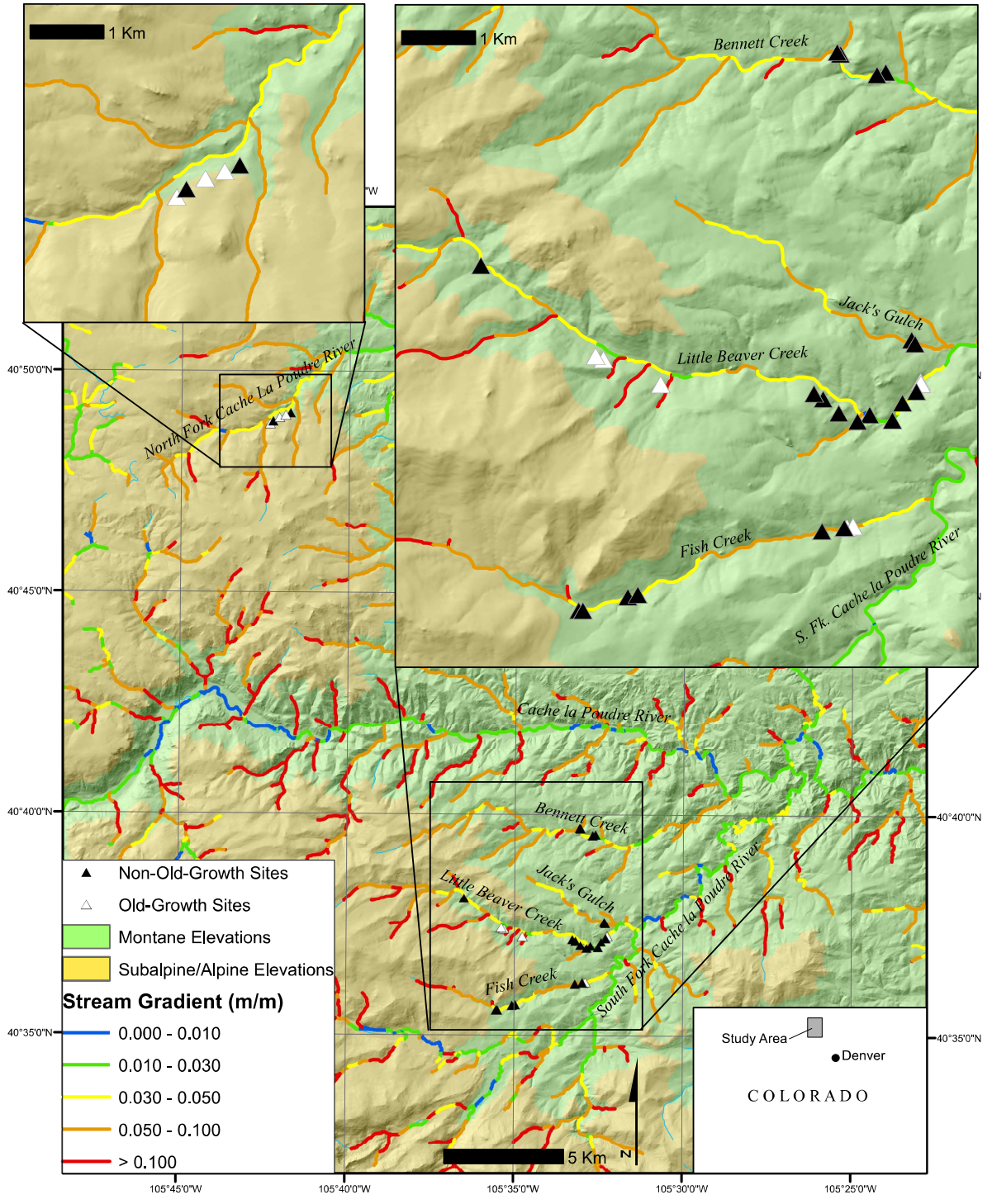


Figure 4.3: Average stream gradient for the North Fork and South Fork Cache la Poudre River basins. Only stream segments shaded in blue, green, and yellow were considered for this study.

width to bankfull width. A confinement ratio of 2x was considered confined, a ratio of 2-10x was partly confined, and >10x was unconfined (Wohl and Beckman, 2012).

4.2 NSTREAM WOOD AND FLOODPLAIN WOOD VARIABLES

Wood variables measured after Wohl et al. (2010) are listed in Table 2. Only wood pieces >1.0 m in length and >0.10 m in diameter were considered in this study. Wood was considered to be in a jam if three or more pieces were in contact with each other. A measuring tape was stretched along the length of the reach, and the meter station of each piece within the floodplain width was recorded. The floodplain was identified using a combination of changes in slope, terraces, valley walls, and debris deposits. Length of each jam was measured using the longitudinal tape. Each piece was given a decay class of rotten, decayed, bare, bark, or needles/leaves present. In-channel wood pieces were given stability classes of unattached, bridge, collapsed bridge, pinned, ramp, or buried (Table 3). All ramp pieces were given an orientation of perpendicular to flow, parallel to flow, angled downstream, or angled upstream. If a wood piece contained a root wad, this was recorded. Geomorphic effects including sediment storage, backwater pools, pool scour, flow deflection, energy dissipation, or bank stabilization were recorded as present or absent.

4.3 GEOMORPHIC VARIABLES

A Laser Technology TruPulse 360 laser range finder (± 0.10 m accuracy) was used for surveys. Three cross sections were measured at the top, middle, and bottom of each reach to obtain an average bankfull width, depth, area, and floodplain width. A tape with 0 m at the left floodplain edge (looking downstream) was stretched to the edge of the right floodplain. The

Table 4.1: Wood, geomorphic, and riparian metrics recorded during fieldwork (after Wohl et al., 2010)

Category	Metric	Description
Wood piece	Length	Piece length in bankfull channel > 1 m
	Diameter	Piece diameter > 0.1 m
	Orientation	Angle with downstream bank
	Root wad present	Presence/absence and orientation with flow
	Decay class	Rotten, decayed, bare, limbs, bark, needles, leaves
	Stability	Unattached/drift, bridge, collapsed bridge, ramp, buried, pinned
	Function	Wood function: storage, backwater pools, pool scour, flow deflection, energy dissipation, bank stabilization
Geomorphic	Valley slope	Valley gradient
	Channel slope	Average water surface gradient
	Channel width	Bankfull width
	Flow depth	Bankfull & time of measurement
	Grain distribution	Wolman pebble count
	Discharge	Bankfull, annual mean, peak annual (from StreamStats)
	Drainage area	Area drained by study reach, measured at downstream end of reach
	Reach length	500-1000 m
	Channel morphology	Cascade, step-pool, plane-bed, pool-riffle, dune-ripple, braided
	Elevation	At study reach and range of elevations for catchment
	Valley side slope	Valley wall gradient
	Confinement	Ratio of channel width to valley bottom width
	Bank scour	Visual estimate of percentage of total stream bank length
Riparian	Dominant species	Forest type/species of trees
	Wood source	Unknown, riparian, hillslope, floated, debris flow, bank undercutting
	Stage age	Young or old growth
	Floodplain survey	Dimensions and spatial density of wood on forest floor
	Basal area	Cross-sectional area of standing trees at breast height

range finder was placed on a walking stick to reduce vertical error. A field assistant holding a stadia rod was used to survey all breaks in slope. At each cross section, floodplain indicators, bankfull indicators, and edges of water were surveyed. Floodplain indicators included breaks in slope and change in vegetation. Bankfull indicators included breaks in slope, flat depositional surfaces, tops of bars if any were present, and sometimes changes in vegetation. Within the

channel, the stadia rod was used to measure the distance from water surface to channel bed for a more accurate measurement. These measurements were ultimately subtracted from the water edge measurements to obtain bankfull channel geometry.

Table 4.2: Piece type classification after Beckmann, 2012

Piece Type	Field Indicators
Bridge	Piece crosses the stream with both ends above bankfull elevation
Left/Right Ramp	One end rests above bankfull elevation on the left/right side of the stream, the other end rests in the stream
Pinned	Piece held in place by semi-stable feature such as a boulder or other wood
Buried	Partially or completely buried by the sediment in the bank for stream bed
Unattached	Floating or loose piece, moves under pressure

Average channel slope was also measured at each cross section using the TruPulse 360 and stadia rod. Channel slope was surveyed upstream and downstream by placing the rod at the water surface in both instances. Valley slope, valley wall slope, confinement and elevation were calculated using ArcGIS digital elevation models. Valley slope was measured over 10x the reach length along the main channel. Valley wall slope was measured from the lateral drainage divide to the stream. Mean basin slope was obtained using StreamStats. Average grain size was visually estimated at each cross section. Grain size classes included clay, silt, sand, gravel, cobble, and boulder. Valley confinement was calculated by taking the ratio of valley width to bankfull width. Valley width was measured using the TruPulse 360. In a few cases where one of

the valley walls was obstructed, digital elevation maps and USGS topographic maps were used to estimate valley bottom width.

Pools were surveyed using a stadia rod and rebar. A cross section and longitudinal profile of pool water depth and sediment depth were measured at each pool to calculate residual pool volume. One longitudinal profile was measured along the thalweg, with a cross section measured every meter (every 0.5 m if pool length < 2 m). Fine sediment deposited in low velocity pools upstream of wood jams was measured using rebar. Coarse gravel and cobble underlay the fine sediment. The rebar was hammered into the substrate until refusal to measure depth of fine sediment at each point on the grid. Pool volume and sediment volume were calculated after Hilton and Lisle (1993).

Once a reach was selected, the upstream and downstream ends of the reach were recorded using a Garmin eTrex 10 handheld GPS (with ± 5 m horizontal accuracy). The downstream GPS point was entered into StreamStats to obtain drainage area, mean basin slope, and bankfull discharge (Ries et al., 2008).

4.4 VEGETATION VARIABLES

The dominant tree types at each cross section were recorded. Possible types include spruce/fir, lodgepole pine, ponderosa pine, willow/deciduous, and aspen. If old-growth (1m+ diameter) trees were present on both banks for the whole extent of the reach, the reach was considered old-growth. If at least 25% of the reach-averaged tree basal area was dead and trees showed sign of beetle infestation (Fig. 4.4), the reach was considered mountain pine beetle infested. Basal area was measured with a Panama Basal Area Angle Gauge. Basal area measurements were taken within 3 m of the left water's edge at each cross section.



Figure 4.4: “Pitch tube” evidence of mountain pine beetle infestation.

4.5 STATISTICAL METHODS

4.5.1 Objective 1 Statistical Methods

For each hypothesis in Objective 1, the normality of relevant data was tested using the Shapiro-Wilk test (H_0 : data are normal), the Kolmogorov-Smirnov test (H_0 : data are normal), and a quantile-quantile graph (QQplot). The variance of the data was analyzed using the Levene’s Test. If data proved to exhibit normality and equal variance, groups were first normalized, and then compared using a pairwise t-test. If data failed to be normal with equal variance, a logarithm transformation (Log_{10}) was attempted. If data were still nonparametric, the Kruskal-Wallis test was used to compare groups. An α of 0.05 was initially used to compare groups. Because the data are part of a complex, multivariate natural system, an α of 0.10 was also considered. The statistical package R was used for the above calculations.

Data were standardized to reach length, slope, bankfull width, floodplain area, and drainage area. After standardization, data were again checked for normality, and transformed if

necessary. If data proved to exhibit normality and equal variance, groups were first normalized, and then compared using a pairwise t-test. If data were still nonparametric, the Kruskal-Wallis test was used to compare groups. An α of 0.05 was initially used to compare groups.

4.5.2 Objective 2 Statistical Methods

For the hypothesis in Objective 2, measured variables were checked for normality. If variables were nonparametric, they were logarithm (Log_{10}) transformed. When variables were highly correlated (>0.80), the variable that correlated best with wood volume was used and the other removed from the data set. The best subsets regression method using a Bayesian Information Criterion (BIC) was used to create regressions in order to determine which channel and valley characteristics best predict wood volumes. Principle component analysis (PCA) was run using all channel and valley characteristics (drainage area, stream power, bankfull width, etc.). The categorical variables of stand age and infestation were included in the best subset regression and PCA. All other variables were continuous.

5 RESULTS

5.1 DATA SUMMARY

Below are tables of basic drainage basin, forest stand, wood load, and geomorphic characteristics for each reach in this study (Tables 4-8). The summary table for all data includes the range and standard deviation of each variable (Table 9). All sites are located between 4493744N to 4518750N, and 440401E to 454511E. There are 33 study sites, with 10 old-growth reaches and 23 non-old-growth reaches. Of these reaches, 12 are mountain pine beetle infested. Only 5 reaches are designated as old-growth and healthy: the remaining reaches are infested. A total of 7 reaches are infested of the non-old-growth sites. Reaches are located within 6 drainages within the larger South Fork and North Fork Poudre drainages (Bennett Creek, Little Beaver Creek, Fish Creek, Jacks Gulch, and North Fork of the Poudre). All reaches are on Strahler (1952) first- and second-order streams.

Many of the study reaches share similar characteristics (slope, topography, grain size, etc.). All sites exhibit a straight planform. Site elevations range from 2400 to 2785 m above sea level, mean annual precipitation ranges from 440 to 770 mm, and bankfull discharge ranges from 0.005 to 0.05 m³/s* (Capesius and Stephens, 2009). Substrates range from gravel to boulder, with most sites comprised of a cobble/boulder mix. Channel types in reaches include plane-bed (3), riffle-run (28), and pool-riffle (2) morphologies. Riffle-run morphologies have slopes comparable to pool-riffle reaches, but pools are only present at forced-wood-steps.

* Note: Discharge regressions in Capesius and Stephens (2009) are valid for slopes 7.6-60.2 percent, higher than slopes chosen for this study.

Table 5.1: Basic drainage basin characteristics for each reach

Site Name	Slope	Bankfull Width Avg (m)	Elevation GPS (m)	Drainage Area (km ²)	Streamstats Bankfull Discharge (cms)	Valley Slope	Side Slope Average	Reach length (m)
Bennet Creek 1	0.041	3.86	2397	20.5	0.019	0.034	0.214	40
Bennet Creek 2	0.019	4.11	2407	20.5	0.019	0.039	0.347	37
Bennet Creek 3	0.023	3.25	2430	19.7	0.018	0.058	0.493	30
Bennet Creek 4	0.035	3.33	2443	18.5	0.017	0.057	0.288	35
Fish Creek 1	0.022	3.38	2534	15.7	0.014	0.051	0.304	36
Fish Creek 2	0.035	3.56	2510	15.7	0.014	0.048	0.271	37
Fish Creek 3	0.037	3.65	2529	15.7	0.014	0.046	0.296	37
Fish Creek 4	0.070	3.62	2548	14.6	0.014	0.051	0.193	35
Fish Creek 5	0.039	3.83	2731	9.7	0.009	0.044	0.285	41
Fish Creek 6	0.041	3.33	2741	9.8	0.009	0.050	0.346	35
Fish Creek 7	0.059	3.58	2683	10.9	0.010	0.048	0.284	35
Fish Creek 8	0.045	3.38	2706	10.9	0.010	0.048	0.319	30
Jacks Gulch 1	0.051	2.55	2483	5.7	0.005	0.075	0.199	25
Jacks Gulch 2	0.060	2.63	2465	5.7	0.005	0.074	0.152	25
Little Beaver Creek 1	0.077	6.13	2447	37.3	0.040	0.034	0.347	57
Little Beaver Creek 10	0.040	5.35	2532	33.2	0.036	0.036	0.405	50
Little Beaver Creek 11	0.020	6.60	2590	29.0	0.033	0.034	0.350	35
Little Beaver Creek 12	0.031	5.03	2652	25.9	0.030	0.035	0.407	65
Little Beaver Creek 13	0.018	4.95	2644	25.8	0.030	0.045	0.438	50
Little Beaver Creek 14	0.025	5.23	2733	18.2	0.022	0.037	0.227	45
Little Beaver Creek 2	0.039	6.48	2456	37.3	0.040	0.034	0.331	73
Little Beaver Creek 3	0.065	5.13	2454	37.3	0.040	0.035	0.308	71
Little Beaver Creek 4	0.075	5.73	2467	37.0	0.040	0.032	0.346	71
Little Beaver Creek 5	0.048	4.98	2485	36.8	0.040	0.033	0.384	52
Little Beaver Creek 6	0.045	5.63	2498	36.3	0.039	0.032	0.301	50
Little Beaver Creek 7	0.037	6.65	2508	36.3	0.039	0.032	0.241	71
Little Beaver Creek 8	0.031	4.99	2510	33.7	0.037	0.036	0.400	56
Little Beaver Creek 9	0.034	5.43	2517	33.4	0.037	0.036	0.442	56
NFK Poudre 1	0.046	5.95	2785	26.7	0.054	0.047	0.191	46
NFK Poudre 2	0.027	6.90	2781	26.9	0.054	0.051	0.250	71
NFK Poudre 3	0.036	6.88	2770	27.2	0.054	0.035	0.248	70
NFK Poudre 4	0.031	4.53	2739	27.5	0.055	0.037	0.283	44.5
NFK Poudre 5	0.049	4.40	2756	27.5	0.055	0.035	0.265	50

Table 5.2: Forest stand characteristics for each study reach by color

Site Name	Stand Type	Stand Health	Basal Area (m ²)	Proportion Dead	Proportion Deciduous
Bennet Creek 1	Non-Old-Growth	Healthy	8.36	0.04	0.19
Bennet Creek 2	Non-Old-Growth	Healthy	7.74	0	0.08
Bennet Creek 3	Non-Old-Growth	Healthy	6.20	0.05	0.05
Bennet Creek 4	Non-Old-Growth	Healthy	8.36	0.11	0.22
Fish Creek 1	Non-Old-Growth	Healthy	7.43	0.04	0.29
Fish Creek 2	Old-Growth	Healthy	10.22	0.15	0.03
Fish Creek 3	Non-Old-Growth	Healthy	8.98	0.14	0.03
Fish Creek 4	Non-Old-Growth	Healthy	6.50	0.19	0.19
Fish Creek 5	Non-Old-Growth	MPB Infested	9.91	0.25	0.16
Fish Creek 6	Non-Old-Growth	MPB Infested	10.84	0.2	0.29
Fish Creek 7	Non-Old-Growth	Healthy	8.98	0.07	0.03
Fish Creek 8	Non-Old-Growth	MPB Infested	4.65	0.33	0
Jacks Gulch 1	Non-Old-Growth	MPB Infested	12.38	0.3	0.03
Jacks Gulch 2	Non-Old-Growth	MPB Infested	7.74	0.28	0
Little Beaver Creek 1	Old-Growth	Healthy	6.81	0.05	0.05
Little Beaver Creek 10	Non-Old-Growth	Healthy	11.45	0.11	0.16
Little Beaver Creek 11	Old-Growth	Healthy	15.79	0.16	0
Little Beaver Creek 12	Old-Growth	Healthy	10.53	0.21	0
Little Beaver Creek 13	Old-Growth	MPB Infested	11.77	0.29	0
Little Beaver Creek 14	Old-Growth	MPB Infested	7.74	0.36	0
Little Beaver Creek 2	Old-Growth	Healthy	10.53	0.03	0.03
Little Beaver Creek 3	Non-Old-Growth	Healthy	10.22	0	0.18
Little Beaver Creek 4	Non-Old-Growth	Healthy	8.05	0.04	0.15
Little Beaver Creek 5	Non-Old-Growth	Healthy	5.27	0.12	0.29
Little Beaver Creek 6	Non-Old-Growth	Healthy	8.67	0.04	0.36
Little Beaver Creek 7	Non-Old-Growth	Healthy	12.70	0.02	0.17
Little Beaver Creek 8	Non-Old-Growth	Healthy	7.74	0.04	0.2
Little Beaver Creek 9	Non-Old-Growth	Healthy	9.29	0.03	0.07
NFK Poudre 1	Old-Growth	MPB Infested	11.15	0.56	0
NFK Poudre 2	Non-Old-Growth	MPB Infested	10.53	0.29	0
NFK Poudre 3	Old-Growth	MPB Infested	9.91	0.66	0
NFK Poudre 4	Non-Old-Growth	MPB Infested	9.29	0.3	0
NFK Poudre 5	Old-Growth	MPB Infested	12.38	0.35	0.03

Table 5.3: Totals for in-channel and floodplain wood loads

Site Name	Total Wood Vol(m3)	Channel Wood Vol(m3)	Total Floodplain Wood Vol (m3)	Total Wood Vol/Area (m3/ha)	Channel Wood Vol/Area (m3/ha)	Total Floodplain Wood Vol/Area (m3/ha)
Bennet Creek 1	1.48	1.26	0.22	19.93	81.55	3.74
Bennet Creek 2	1.47	0.52	0.95	21.50	34.17	17.87
Bennet Creek 3	1.26	0.99	0.27	23.62	101.54	6.19
Bennet Creek 4	0.3	0.03	0.27	4.87	2.58	5.41
Fish Creek 1	5.15	3.88	1.28	118.55	318.56	40.95
Fish Creek 2	12.33	4.42	7.92	207.47	335.32	171.24
Fish Creek 3	16.14	12.66	3.48	314.20	937.43	91.91
Fish Creek 4	12.02	8.72	3.3	370.61	688.87	166.88
Fish Creek 5	7.32	0.57	6.75	100.94	36.27	118.84
Fish Creek 6	6.14	3.44	2.7	96.04	294.86	51.66
Fish Creek 7	9.2	6.08	3.12	150.09	485.24	63.98
Fish Creek 8	12.25	5.78	6.47	288.64	570.02	200.31
Jacks Gulch 1	0.64	0.26	0.38	23.67	40.78	18.39
Jacks Gulch 2	0.69	0.49	0.2	37.13	74.43	16.67
Little Beaver Creek 1	22.62	19.78	2.84	145.36	565.79	23.54
Little Beaver Creek 10	5.89	2.27	3.62	63.85	84.86	55.27
Little Beaver Creek 11	11.04	5.23	5.81	131.61	226.41	95.59
Little Beaver Creek 12	30.78	14.24	16.54	216.56	435.25	151.17
Little Beaver Creek 13	21.46	3.56	17.91	246.90	143.84	288.10
Little Beaver Creek 14	1.7	1.2	0.5	16.36	51.04	6.22
Little Beaver Creek 2	21.57	10.26	11.3	124.19	217.06	89.39
Little Beaver Creek 3	3.28	2.83	0.45	24.72	77.77	4.67
Little Beaver Creek 4	7.47	0.84	6.63	54.30	20.67	68.41
Little Beaver Creek 5	2.41	0.3	2.11	35.72	11.60	50.72
Little Beaver Creek 6	3.17	1.75	1.42	31.82	62.22	19.86
Little Beaver Creek 7	8.58	5.4	3.18	53.83	114.37	28.35
Little Beaver Creek 8	5.34	3.86	1.47	46.47	138.20	16.90
Little Beaver Creek 9	4.43	3.88	0.54	45.31	127.72	8.01
NFK Poudre 1	12.34	5.76	6.58	128.25	210.45	95.57
NFK Poudre 2	7.25	5.08	2.17	44.98	103.69	19.34
NFK Poudre 3	31.65	18.69	12.96	176.33	388.36	98.66
NFK Poudre 4	3.18	2.84	0.34	50.00	141.04	7.82
NFK Poudre 5	16.9	10.35	6.55	153.64	470.45	74.43

Table 5.4: Summary of geomorphic data for each study reach

Site Name	# Jams /100m	Total Wood Vol m ³ /100m	Pool Vol m ³ /100m	Pool Sediment Vol m ³ /100m	V* _w	Avg Floodplain Width (m)	Floodplain Area (m ²)
Bennet Creek 1	0	3.70	4.17	1.56	0.37	14.70	588.00
Bennet Creek 2	0	3.97	5.96	2.20	0.37	14.37	531.57
Bennet Creek 3	0	4.20	2.77	0.89	0.32	14.53	436.00
Bennet Creek 4	2.9	0.86	7.83	0.69	0.09	14.27	499.33
Fish Creek 1	2.8	14.31	0.00	0.00	0.00	8.68	312.60
Fish Creek 2	5.4	33.32	3.14	1.73	0.55	12.50	462.50
Fish Creek 3	5.4	43.62	1.49	0.64	0.43	10.23	378.63
Fish Creek 4	2.9	34.34	5.96	1.47	0.25	5.65	197.75
Fish Creek 5	2.4	17.85	6.46	1.42	0.22	13.85	567.99
Fish Creek 6	8.6	17.54	13.41	3.77	0.28	14.93	522.67
Fish Creek 7	2.9	26.29	3.26	1.04	0.32	13.93	487.67
Fish Creek 8	3.3	40.83	0.00	0.00	0.00	10.77	323.00
Jacks Gulch 1	0	2.56	3.65	1.85	0.50	8.27	206.67
Jacks Gulch 2	0	2.76	2.55	3.07	1.21	4.80	120.00
Little Beaver Creek 1	3.5	39.68	84.63	27.03	0.32	21.17	1206.50
Little Beaver Creek 10	4	11.78	0.00	0.00	0.00	13.10	655.00
Little Beaver Creek 11	8.6	31.54	50.02	1.85	0.04	17.37	607.83
Little Beaver Creek 12	7.7	47.35	0.00	0.00	0.00	16.83	1094.17
Little Beaver Creek 13	2	42.92	25.04	8.06	0.32	12.43	621.67
Little Beaver Creek 14	2.2	3.78	7.49	1.00	0.13	17.87	804.00
Little Beaver Creek 2	2.7	29.55	10.95	3.77	0.34	17.32	1264.12
Little Beaver Creek 3	1.4	4.62	35.30	4.30	0.12	13.57	963.23
Little Beaver Creek 4	1.4	10.52	12.30	1.46	0.12	13.65	969.15
Little Beaver Creek 5	1.9	4.63	0.00	0.00	0.00	8.00	416.00
Little Beaver Creek 6	0	6.34	0.00	0.00	0.00	14.30	715.00
Little Beaver Creek 7	5.6	12.08	4.25	10.14	2.39	15.80	1121.80
Little Beaver Creek 8	3.6	9.54	0.00	0.00	0.00	15.53	869.87
Little Beaver Creek 9	3.6	7.91	5.36	0.43	0.08	12.03	673.87
NFK Poudre 1	6.5	26.83	0.00	0.00	0.00	14.97	688.47
NFK Poudre 2	5.6	10.21	3.50	0.05	0.01	15.80	1121.80
NFK Poudre 3	4.3	45.21	6.87	2.02	0.29	18.77	1313.67
NFK Poudre 4	2.2	7.15	0.00	0.00	0.00	9.77	434.62
NFK Poudre 5	4	33.180	2.85	0.26	0.09	17.60	880.00

Note: V*_w is the weighted mean average of the ratio of fine pool sediment volume to pool water volume.

Table 5.5: Summary of jam characteristics

Site Name	# Jams/ 100m	Total Vol Wood in Jams (m ³)	Avg Wood Vol per Jam (m ³)	% Total Vol in Jams	% Channel Vol in Jams
Bennet Creek 1	0	0.001	0	0.07	0.08
Bennet Creek 2	0	0.001	0	0.07	0.19
Bennet Creek 3	0	0.001	0	0.08	0.10
Bennet Creek 4	2.9	0.001	0	0.33	3.33
Fish Creek 1	2.8	1.5822	1.5822	30.72	40.78
Fish Creek 2	5.4	1.3588	0.67935	11.02	30.74
Fish Creek 3	5.4	11.8629	5.9314	73.50	93.70
Fish Creek 4	2.9	6.311	3.155	52.50	72.37
Fish Creek 5	2.4	0.0984	0.098	1.34	17.26
Fish Creek 6	8.6	0.001	0.16	0.02	0.03
Fish Creek 7	2.9	1.0482	1.0482	11.39	17.24
Fish Creek 8	3.3	4.5839	2.2919	37.42	79.31
Jacks Gulch 1	0	0.001	0	0.16	0.38
Jacks Gulch 2	0	0.001	0	0.14	0.20
Little Beaver Creek 1	3.5	18.3801	9.186	81.26	92.92
Little Beaver Creek 10	4	1.6981	0.84905	28.83	74.81
Little Beaver Creek 11	8.6	3.2403	1.0801	29.35	61.96
Little Beaver Creek 12	7.7	8.6384	1.5308	28.06	60.66
Little Beaver Creek 13	2	1.9271	1.9271	8.98	54.13
Little Beaver Creek 14	2.2	1.2012	1.2012	70.66	100.00
Little Beaver Creek 2	2.7	6.2182	3.1505	28.83	60.61
Little Beaver Creek 3	1.4	0.1958	0.1958	5.97	6.92
Little Beaver Creek 4	1.4	0.001	0	0.01	0.12
Little Beaver Creek 5	1.9	0.1368	0.1368	5.68	45.60
Little Beaver Creek 6	0	0.001	0	0.03	0.06
Little Beaver Creek 7	5.6	3.0353	0.7588	35.38	56.21
Little Beaver Creek 8	3.6	2.3544	2.3544	44.09	60.99
Little Beaver Creek 9	3.6	2.7499	1.37495	62.07	70.87
NFK Poudre 1	6.5	3.8524	1.28412	31.22	66.88
NFK Poudre 2	5.6	3.248	0.811988	44.80	63.94
NFK Poudre 3	4.3	16.4493	5.483098	51.97	88.01
NFK Poudre 4	2.2	0.3226	0.3236	10.14	11.36
NFK Poudre 5	4	9.7859	4.89292	57.90	94.55

Table 5.6: Basic summary of data variables

Variable	Maximum	Minimum	Average	Standard Deviation
Slope	0.077	0.018	0.041	0.016
Bankfull Width Avg (m)	6.9	2.55	4.697	1.279
Elevation GPS (m)	2785	2397	2573.667	126.643
Drainage Area (km ²)	37.296	5.672	23.84	10.206
Streamstats Bankfull Discharge (m ³ /s)	0.055	0.005	0.029	0.016
Valley Slope (StreamStats)	0.075	0.032	0.043	0.011
Side Slope Average (Streamstats)	0.493	0.152	0.308	0.08
Reach length (m)	73	25	47.318	14.722
Total Wood Volume (m ³)	31.65	0.3	9.317	8.483
Channel Wood Volume (m ³)	19.78	0.03	5.067	5.153
Total Floodplain Wood Volume (m ³)	17.91	0.2	4.249	4.666
BA (m ²)	15.8	4.65	9.34	2.34
Proportion Dead	0.66	0	0.176	0.16
Proportion Deciduous	0.36	0	0.099	0.108
Jam Frequency (per 100m)	8.6	0	3.255	2.423
Wood Volume (m ³) / 100m	47.35	0.857	19.14	15.402
Pool Volume (m ³) / 100M	84.63	0	9.369	17.233
Pool Sediment Volume (m ³) / 100M	27.03	0	2.445	4.965
V*w	2.39	0	0.278	0.451
Average Floodplain Width (m)	21.17	4.8	13.556	3.714
Floodplain Area (m ²)	1313.67	120	668.337	323.111

5.2 OBJECTIVE 1 RESULTS

5.2.1 Testing Hypothesis 1: Old-Growth Wood Loads

The logarithm (Log_{10}) total wood load data are normal based on the QQplot (Fig. 5.1A) and the Kolmogorov-Smirnov test p-value of 0.38. The data pass Levene's test of equal variances with an F statistic of 0.99, which is less than the critical F value of 4.16 (Fig.5.1B). A pairwise t-test is used to analyze the data.

- H_{10} : Instream wood loads in old-growth montane forests are not significantly different from instream wood loads in younger montane forests.

- H_{1A} : Instream wood loads in old-growth montane forests are significantly larger than instream wood loads in younger montane forests.

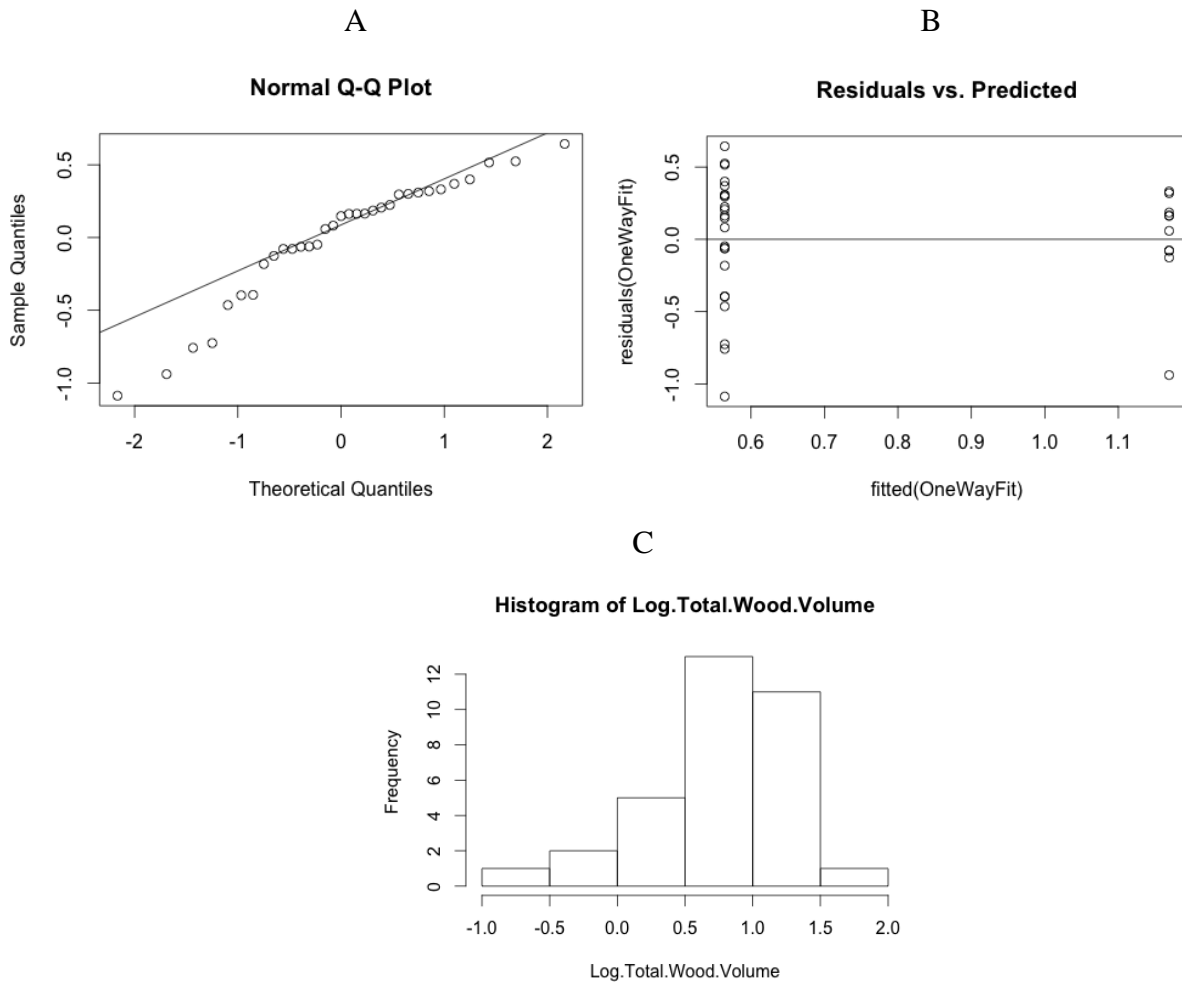


Figure 5.1: Testing assumptions for Hypothesis 1: A) QQplot of normality for the logarithm total wood loads. If data were perfectly normal, data points would fall on the ideal line. B) Residual plot for non-old-growth and old-growth groups. Variance is larger for the non-old-growth group, but acceptable given the small sample size. C) Histogram of the logarithm of total wood volume. Data have a slight heavy negative tail.

Wood volumes used to test Hypothesis 1 are standardized to reach length, slope, drainage area, floodplain area, and bankfull width (Fig. 5.2). Reach length, slope, and drainage area are not significantly different between sites in old-growth and younger montane forests. Floodplain

area and bankfull width data are statistically different when compared to stand age. Old-growth reaches have significantly larger floodplain area and bankfull width.

A larger floodplain area may allow floodplain wood loads to be larger and cause total old-growth wood loads to be larger. Although a wider channel could allow more instream wood to reside in the channel, it is more likely that a wider channel increases transport capacity and wood is transported downstream (Wohl and Jaeger, 2009). During high flows, wood in narrow channels can snag on banks. The wider channels could cause old-growth total wood loads to be smaller. However, it is difficult to separate cause and effect between channel and floodplain width and wood loads. Old-growth forest has the potential to supply greater wood volumes per unit length of channel and valley, and these greater wood loads can facilitate bank erosion and overbank flooding that lead to wider channels and floodplains.

Exploratory analyses suggest a few trends between standardization variables and wood volume (Fig. 5.3 below). Healthy reaches with high wood loads tend to have wider channels, larger drainage areas, larger floodplains, and larger reach lengths. Wood volume does not correlate with slope in this study based on stand age or infestation. Reaches in younger forests plot across the whole range of each standardization variable.

A pairwise t-test is used to compare old-growth and non-old-growth stand wood loads, standardized to reach length, slope, drainage area, floodplain area, and bankfull width. Wood load consists of the volume of all wood in the channel and floodplain of the reach. Old-growth total wood loads are significantly larger in all cases except when standardized to floodplain area. When channel wood load and floodplain wood load are tested, all floodplain wood loads are

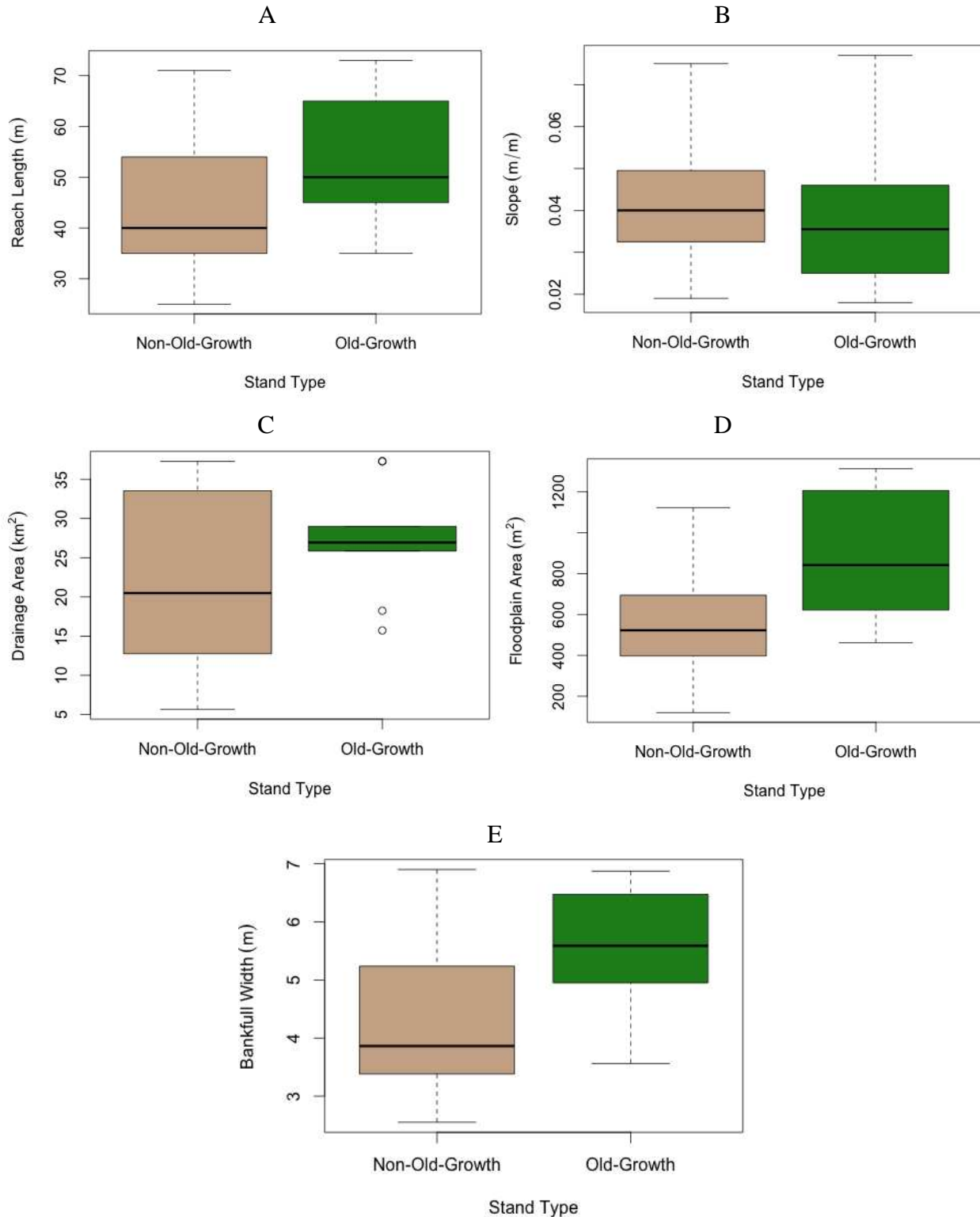


Figure 5.2: Data are standardized to the following variables. Variables A) reach length ($p=0.16$), B) slope ($p=0.43$), and C) drainage area ($p=0.24$) do not vary with stand age at $\alpha = 0.05$. Variables D) floodplain area ($p=0.006$) and E) bankfull width ($p=0.012$) are significantly different at $\alpha = 0.05$.

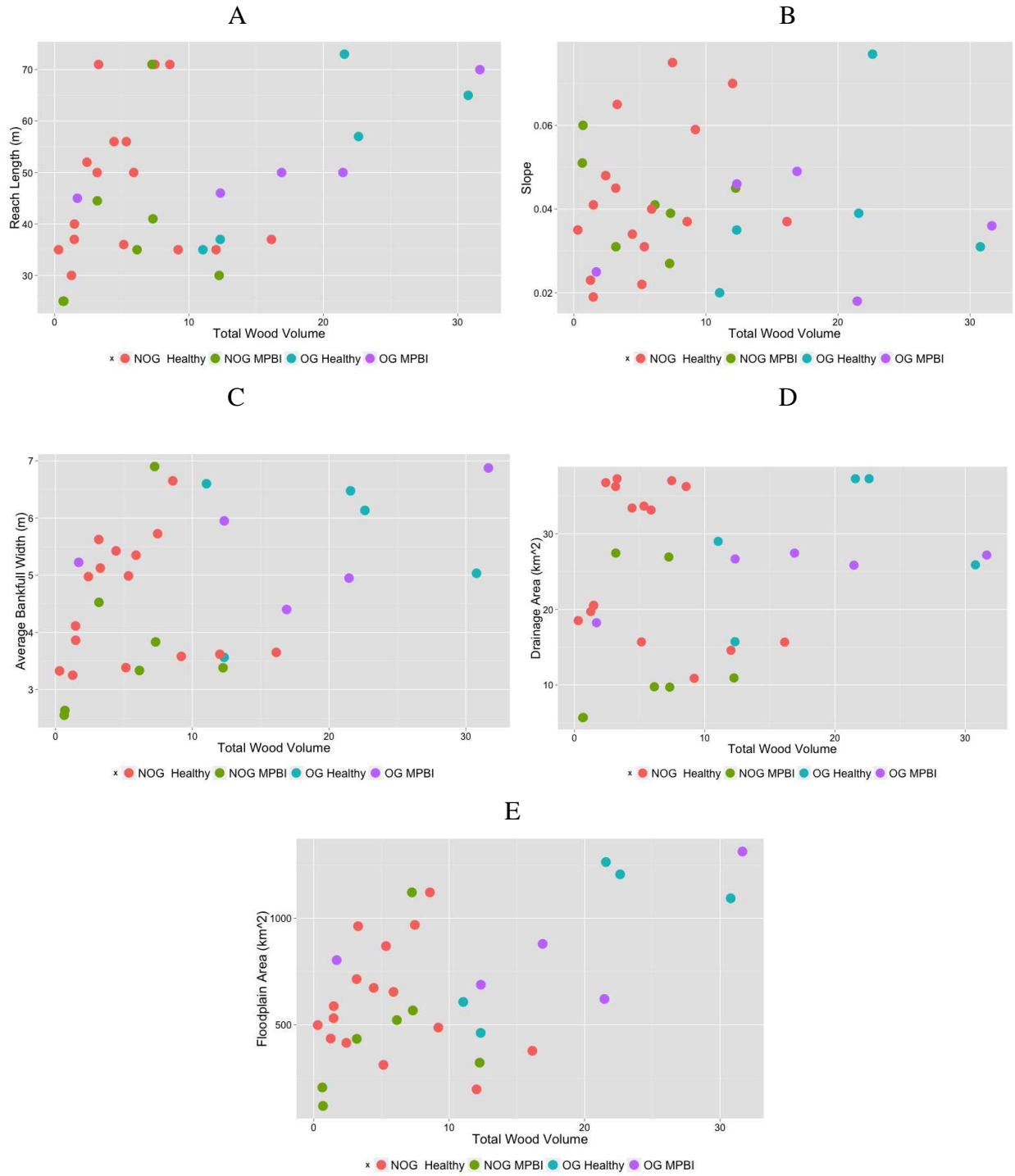


Figure 5.3: Relationship between total wood volume and the standardization variables A) reach length, B) slope, C) bankfull width, D) drainage area, and E) floodplain area.

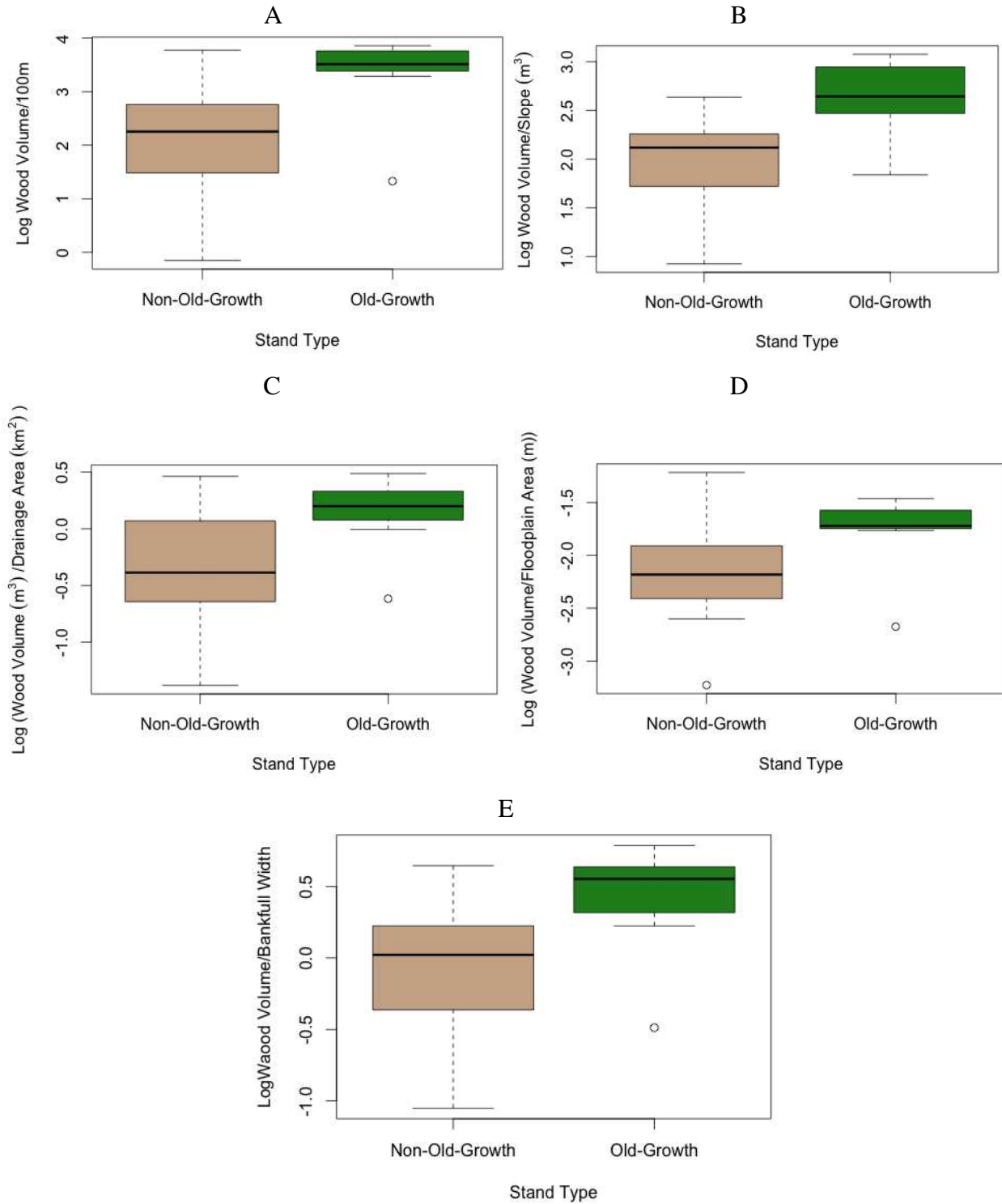


Figure 5.4: Testing Hypothesis 1: Old-growth and non-old growth wood loads standardized to A) reach length ($p=0.0014$), B) slope ($p=0.0003$), C) drainage area ($p=0.0077$), D) floodplain area ($p=0.025$), and E) bankfull width ($p=0.003$) at $\alpha = 0.05$.

significantly larger in old-growth stands (Table 10). When channel wood-loads are standardized to drainage area and floodplain area, old-growth and non-old-growth groups are not significantly different at $\alpha = 0.05$, but are significantly different at $\alpha = 0.10$ (Table 10).

Table 5.7: Wood load pairwise t-test p-values. Shaded value is greater than $\alpha = 0.05$.

Standardized to...	Total	Channel	Floodplain
Nothing	0.00081	0.0061	0.00081
Length (m)	0.0014	0.011	0.0017
Slope (m/m)	0.0003	0.0028	0.0004
Drainage Area (km ²)	0.0077	0.028	0.0078
Floodplain Area (m ²)	0.025	0.07	0.019
Bankfull Width (m)	0.003	0.017	0.003

In summary, the analyses partly support the alternative hypothesis. Total and floodplain wood loads in old-growth forests are significantly larger. Channel wood loads in old-growth forests are significantly larger except when standardized by floodplain area.

5.2.2 Testing Hypothesis 2: Wood Jam Frequency and Volume

The wood jam frequency data are almost normal based on a QQplot (Fig. 5.5A), the Shapiro-Wilk test p-value of 0.03, and the Kolmogorov-Smirnov test p-value of 0.79. The data pass Levene's test of equal variances with an F value of 0.04, which is less than the critical F value of 4.16 (Fig. 5.5B). Data points deviate from normality at the tails. Although the data fail the Shapiro-Wilk normality test, the data do not deviate far from normality on the QQplot. Both parametric (pairwise t-test) and nonparametric (Kruskal Wallis Rank Sum Test) statistical methods are used to cover this ambiguity in the data.

The jam volume data are nonparametric based on a QQplot (Fig. 5.6A) and the Shapiro-Wilk test p-value of 0.0002, but are normal based on the Kolmogorov-Smirnov test p-value of 0.21. The data fail Levene's test of equal variances with an F value of 6.53, which is greater than the critical F value of 4.16 (Fig. 5.6B).

- H_{2_0} : Wood jam frequency and volume do not vary between forest stand types.
- H_{2_A} : Old-growth montane forests streams have greater frequency and volume of jams than in non-old-growth streams.

Using the parametric pairwise t-test to analyze the jam frequency, there are significantly more jams in old-growth reaches than in non-old-growth reaches (Fig. 5.7).

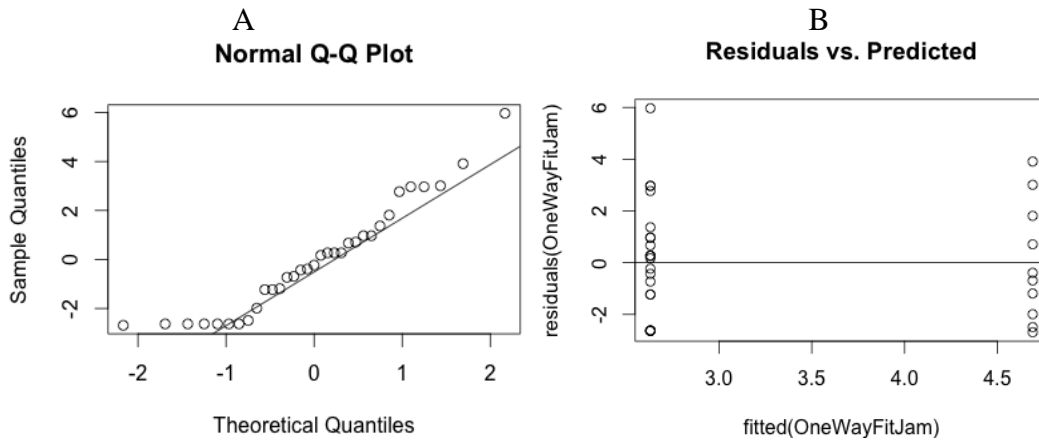


Figure 5.5: Testing assumptions for Hypothesis 2: A) QQplot of normality for jam frequency per 100 m of stream. If data were perfectly normal, data points would fall on the ideal line. B) Residual plot for non-old-growth and old-growth groups. Variance is even for both groups.

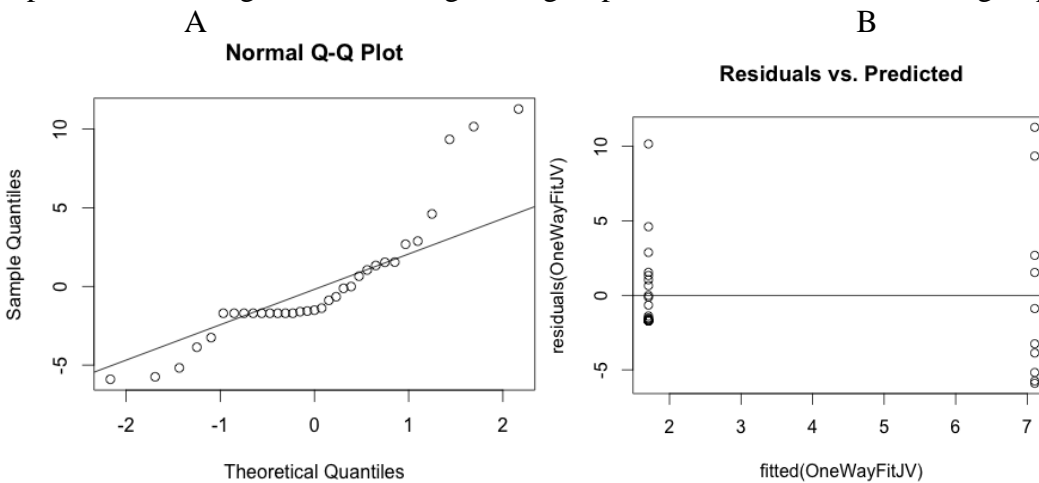


Figure 5.6: Testing assumptions for Hypothesis 2: A) QQplot of normality for jam volume. If data were perfectly normal, data points would fall on the ideal line. B) Residual plot for non-old-growth and old-growth groups. Variance is uneven for both groups.

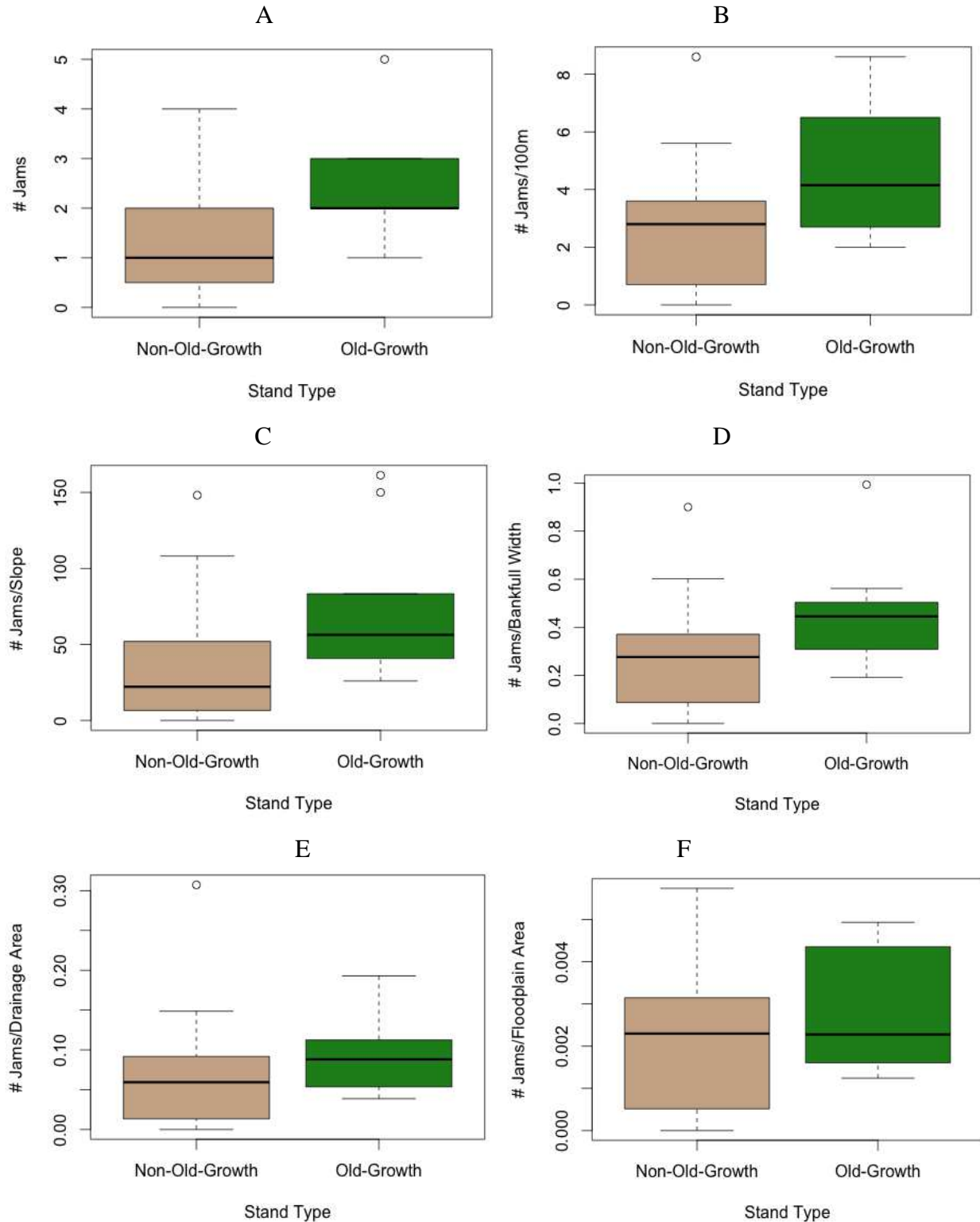


Figure 5.7: Testing Hypothesis 2: A) Old-growth and non-old-growth jam frequency ($p=0.16$), jam frequency standardized to B) reach length ($p=0.033$), C) slope ($p=0.17$), D) bankfull width ($p=0.06$), E) drainage area ($p=0.25$), and F) floodplain area ($p=0.29$) at $\alpha = 0.05$.

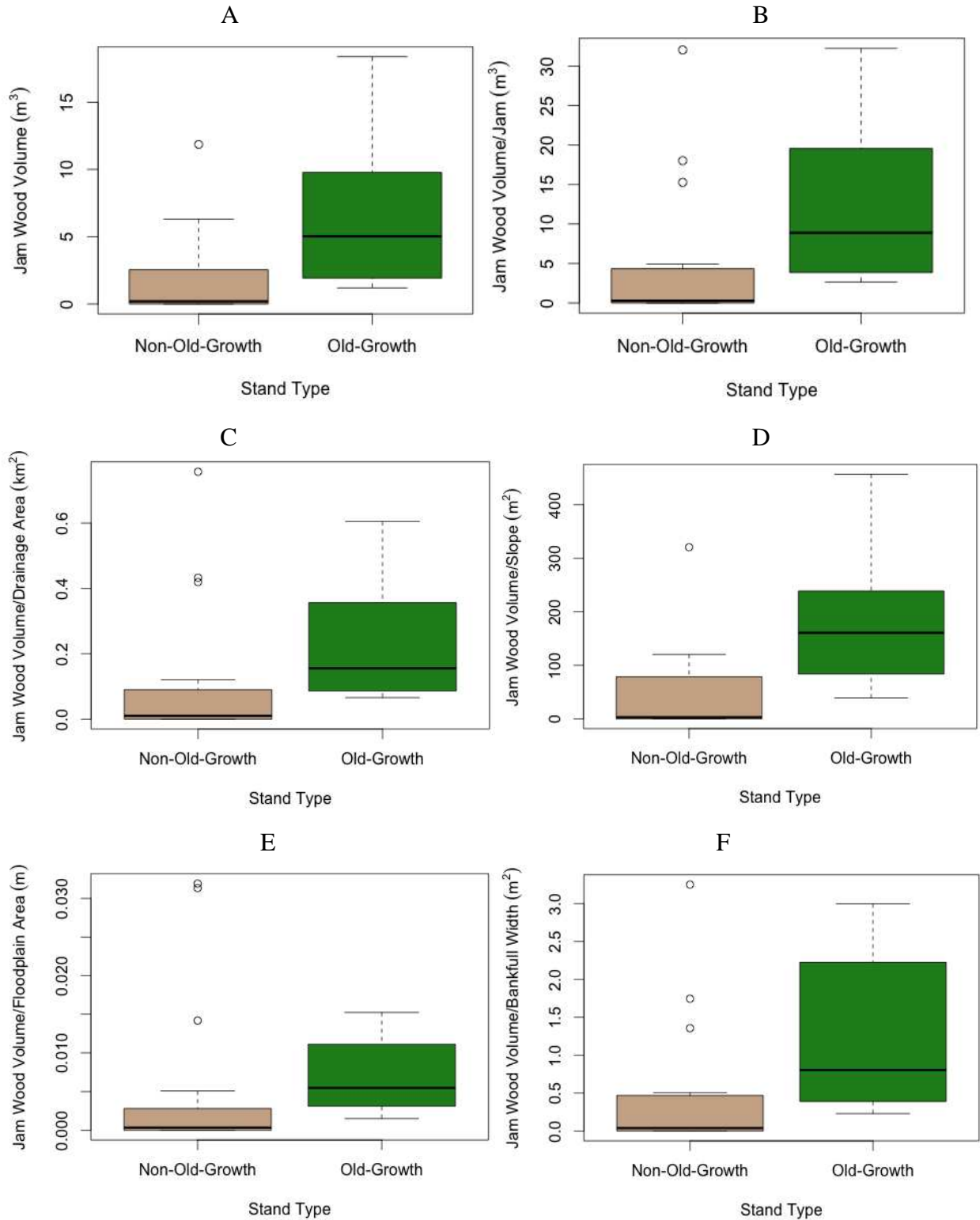


Figure 5.8: Testing Hypothesis 2: A) Old-growth and non-old-growth jam wood volume. Old-growth reaches have significantly more wood in jams ($p=0.0017$ at $\alpha = 0.05$). Jam wood volume standardized to C) number of jams ($p=0.003$), D) drainage area ($p=0.0034$), E) slope ($p=0.00058$), F) floodplain area ($p=0.0034$), and G) bankfull width ($p=0.0034$) at $\alpha = 0.05$.

The nonparametric Kruskal Wallis test is used to compare jam wood volume in old-growth reaches and non-old-growth reaches (Fig. 5.8A). There is significantly more wood in jams in old-growth reaches than in non-old-growth reaches. When standardized to number of jams, there is still significantly more wood in old-growth reaches (Fig. 5.8B).

When individual jam volume is graphed against longitudinal station, old-growth sites have more jams and more wood volume per jam (Appendix A). Figure 5.9 is a subsample of old-growth and non-old-growth sites.

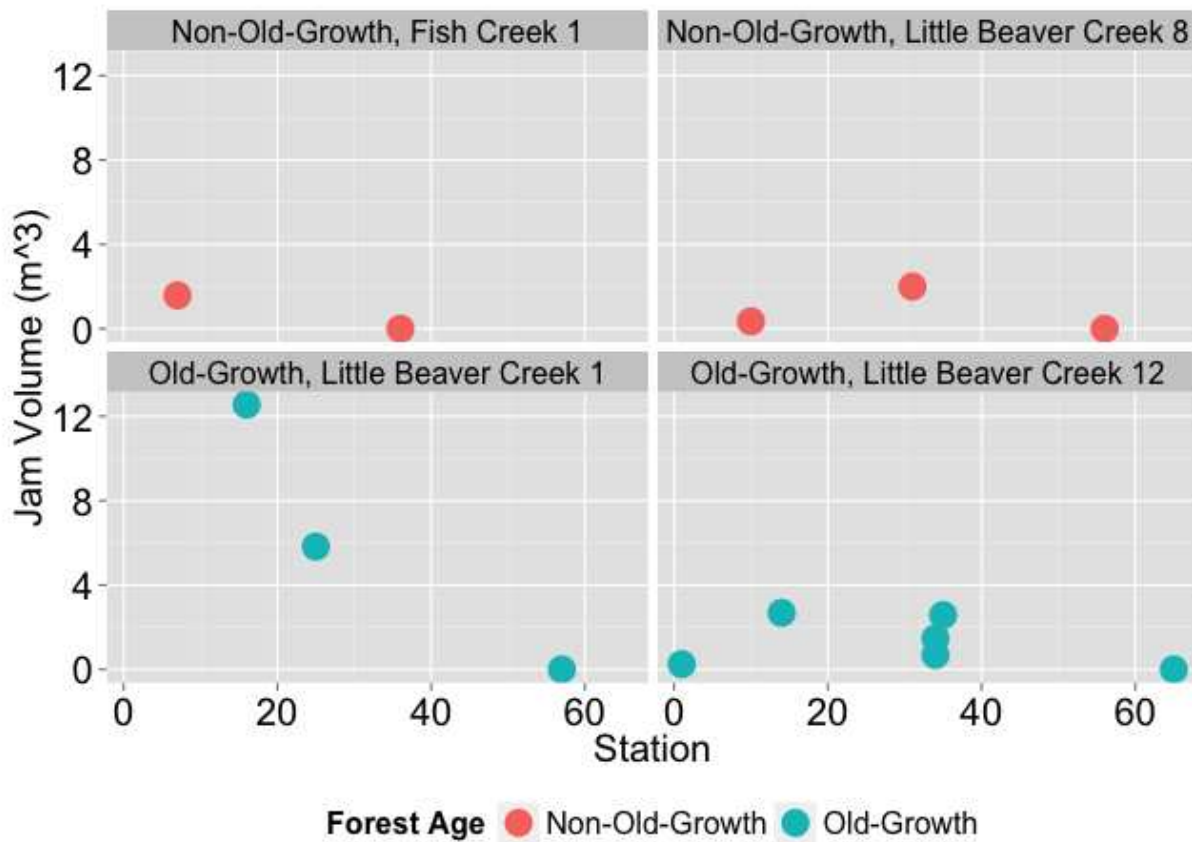


Figure 5.9: Subset of Appendix A. Old-growth sites have more wood in jams, and more total jams per site. Note that the last point in each graph has no wood volume and only signifies the end of the reach to portray reach length.

In summary, the second alternative hypothesis is partly supported. Wood volume is significantly larger in old-growth forests. Wood jam frequency is significantly larger except when standardized by slope, drainage area, and floodplain area.

5.2.3 Testing Hypothesis 3: Geomorphic Effects

Pool volume data are nonparametric, even after a logarithm (Log_{10}) transformation based on a QQplot (Fig. 5.10A), and have a Shapiro-Wilk test p-value of 0.0004. Data are normal based on the Kolmogorov-Smirnov test p-value of 0.13. The data pass the Levene's test of equal variances with an F value of 0.0016, which is less than the critical F value of 4.16 (Fig. 5.10B). Pool volume data standardized to slope yield similar results. After a logarithm (Log_{10}) transformation, data are not normal based on the QQplot and Shapiro-Wilk test ($p=0.0005$), and are normal based on the Kolmogorov-Smirnov test p-value of 0.19. The data pass the Levene's test of equal variances with an F value of 0.0004, which is less than the critical F value of 4.16.

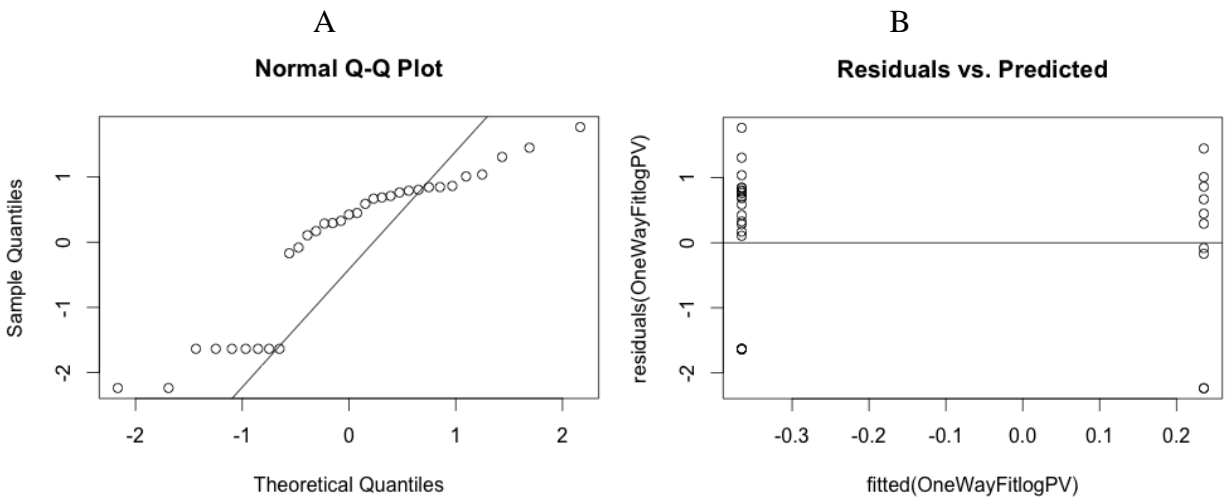


Figure 5.10: Testing assumptions for Hypothesis 3: A) QQplot of normality for pool volume, and B) a residual plot for non-old-growth and old-growth groups. Variance is even for both groups.

- H_{30} : Pool volume and sediment storage do not vary between forest stand types.

- H3_A: Old-growth montane forests streams have more wood-created geomorphic effects.

The nonparametric Kruskal-Wallis test is used to compare pool volume means (Fig. 5.11).

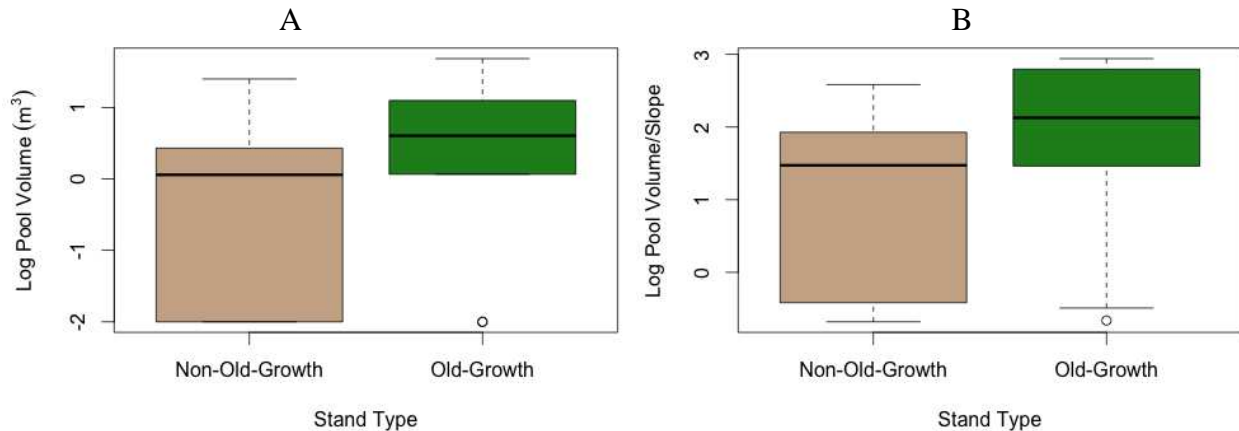


Figure 5.11: Testing Hypothesis 3: A) Logarithm transformed old-growth and non-old-growth pool volumes ($p=0.075$), B) Logarithm transformed old-growth and non-old-growth pool volumes standardized to slope ($p=0.054$). P values are based on the Kruskal-Wallis rank sum test.

Pool sediment volume data are nonparametric, even after a logarithm (Log_{10}) transformation based on a QQplot (Fig. 5.12A), with a Shapiro-Wilk test p-value of 0.017. Data are normal based on the Kolmogorov-Smirnov test p-value of 0.18. The data pass the Levene's test of equal variances with an F value of 0.007, which is less than the critical F value of 4.16 (Fig. 5.12B). Pool sediment volume data standardized to slope yield similar results. After a logarithm (Log_{10}) transformation, data are not normal based on the QQplot and Shapiro-Wilk test ($p=0.02$), and are normal based on the Kolmogorov-Smirnov test p-value of 0.09. The data pass the Levene's test of equal variances with an F value of 0.14, which is less than the critical F value of 4.16.

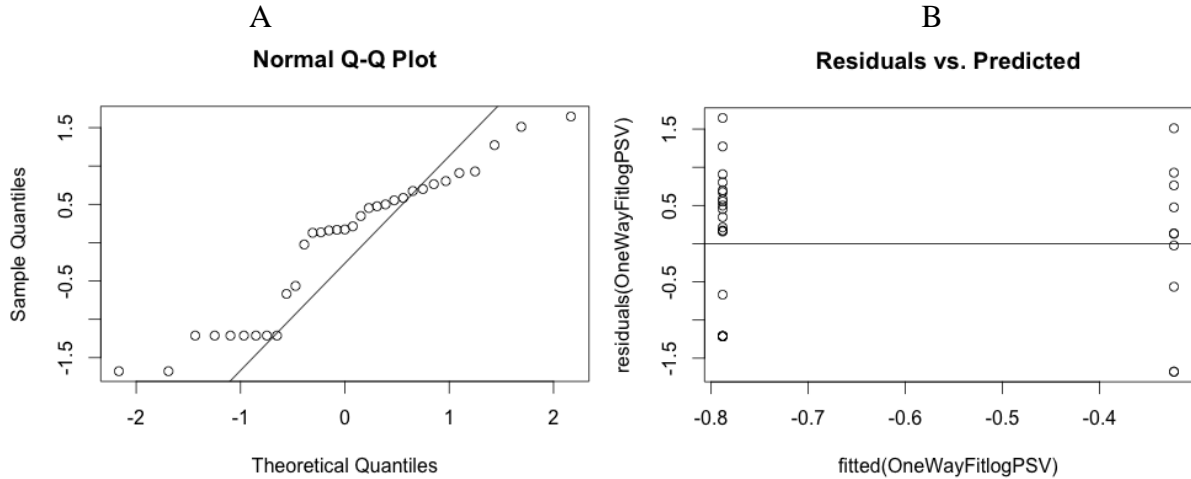


Figure 5.12: Testing assumptions for Hypothesis 3: A) QQplot of normality for sediment volume, and B) a residual plot for non-old-growth and old-growth groups. Variance is even for both groups.

The nonparametric Kruskal-Wallis test was used to compare pool sediment volume means and pool sediment volume means standardized to slope. Both tests fail to reject H_{03} at $\alpha = 0.05$ (Fig. 5.13).

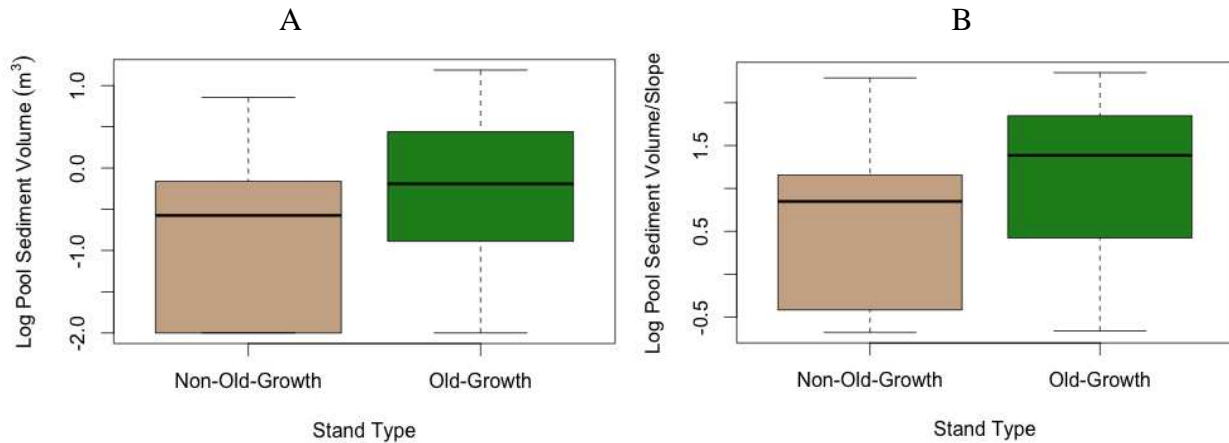


Figure 5.13: Testing Hypothesis 3: A) Logarithm transformed old-growth and non-old-growth pool sediment volumes ($p=0.18$). B) Logarithm transformed old-growth and non-old-growth pool volumes standardized to slope ($p=0.078$). P values are based on the Kruskal-Wallis rank sum test. Both tests fail to reject H_{03} at $\alpha = 0.05$.

Table 5.8: Summary of pool volume and sediment pool volume tests

Variable	p-value	Conclusion
Log ₁₀ (pool volume)	0.075	Fail to reject H ₀ at $\alpha = 0.05$
Log ₁₀ (pool volume/slope)	0.054	Fail to reject H ₀ at $\alpha = 0.05$
Log ₁₀ (pool sediment volume)	0.18	Fail to reject H ₀ at $\alpha = 0.05$
Log ₁₀ (pool sediment volume/slope)	0.078	Fail to reject H ₀ at $\alpha = 0.05$

The Kruskal-Wallis rank sum test fails to reject the null hypothesis. There is no significant difference in pool volume or sediment storage between old-growth and non-old-growth streams.

5.2.4 Testing Hypothesis 4: Mountain Pine Beetle Wood Loads

The wood load data are normal based on a QQplot (Fig. 5.1A), the Shapiro-Wilk test, and the Kolmogorov-Smirnov test shown for hypothesis 1. The data pass Levene's test of equal variances with an F value of 0.14, which is less than the critical F value of 4.16 (Fig. 5.14).

Standardization parameters are not statistically different between healthy and infested stands for reach length ($p=0.40$), slope ($p=0.60$), floodplain area ($p=0.65$), and bankfull area ($p=0.62$) at $\alpha = 0.05$. The standardization parameter drainage area was significantly different between stand types ($p=0.02$), with healthier stands having larger drainage areas.

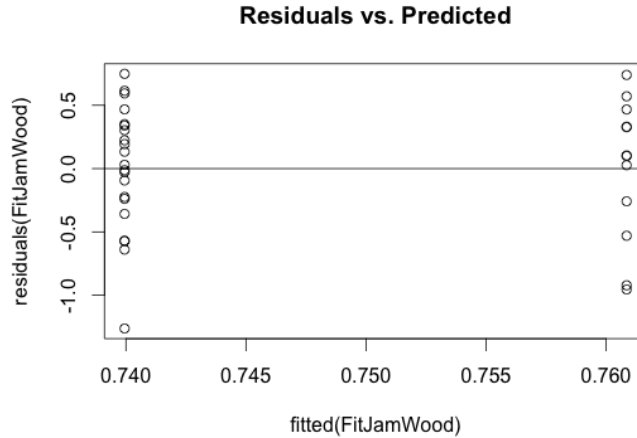


Figure 5.14: Testing assumptions for Hypothesis 4: Residual plot for healthy and pine beetle killed groups. Variance is even for both groups. The between-group variances are very similar, but the within group variance is slightly skewed.

- H_{4_0} : Instream wood loads in minimally impacted montane forests are not significantly different from instream wood loads in beetle-infested montane forests.
- H_{4_A} : Instream wood loads in healthy montane forests are significantly smaller than instream wood loads in beetle-infested montane forests.

A pairwise t-test is used to compare healthy stand wood volumes to beetle-infested wood loads. There is no significant difference between healthy and infested forests, even when standardized to reach length, slope, drainage area, floodplain area, and bankfull width. The pairwise t-test fails to reject the null hypothesis. There is no significant difference between infested and healthy wood loads, even when standardized to reach length, slope, bankfull width, drainage area, and floodplain area.

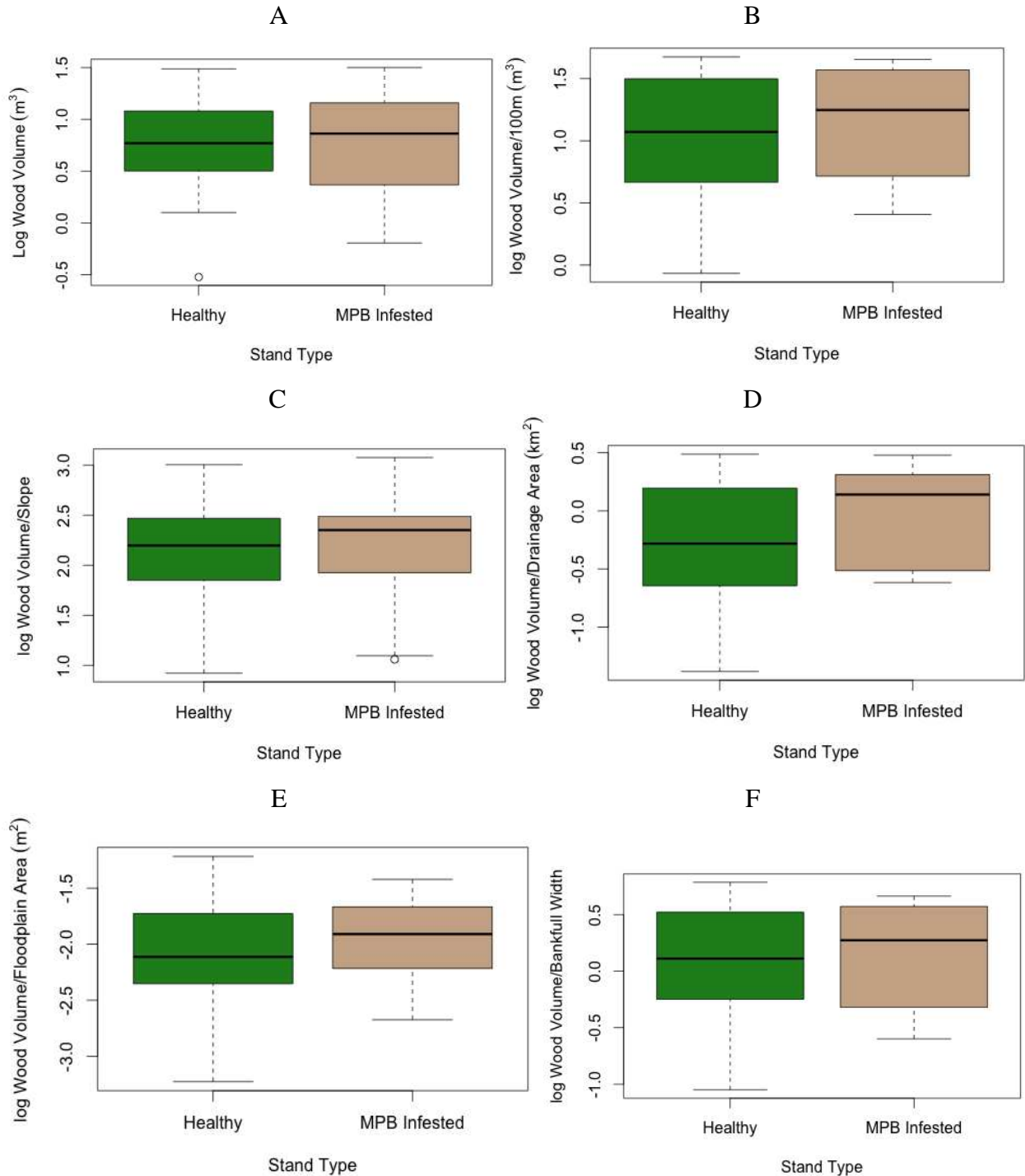


Figure 5.15: Testing Hypothesis 4: A) Healthy and infested wood logarithm volumes. There is no significant difference between the groups ($p=0.91$ at $\alpha = 0.05$). Healthy and infested logarithm wood volumes standardized to B) reach length ($p=0.68$), C) slope ($p=0.83$), D) drainage area ($p=0.21$), E) floodplain area ($p=0.76$), and F) bankfull width ($p=0.70$) at $\alpha = 0.05$.

5.3 OBJECTIVE 2 RESULTS

5.3.1 Testing Hypothesis 5: Instream Wood Load Correlations

- H5₀: There is no correlation between instream wood load and any valley, channel, or forest characteristics.
- H5_A: Instream wood load correlates with one or more valley, channel, or forest characteristics.

In order to best characterize the instream wood volume and floodplain wood volume, principle components analysis (PCA) and best subsets regression are applied to normalized variables. PCA is used to reduce data dimensionality without reducing the data. Variables can roughly be grouped within the first three principle components (Fig. 5.16-5.18). Principle component 1 (PC1) is composed of wood recruitment potential, principle component 2 (PC2) is channel/valley characteristics, and principle component 3 (PC3) is slope.

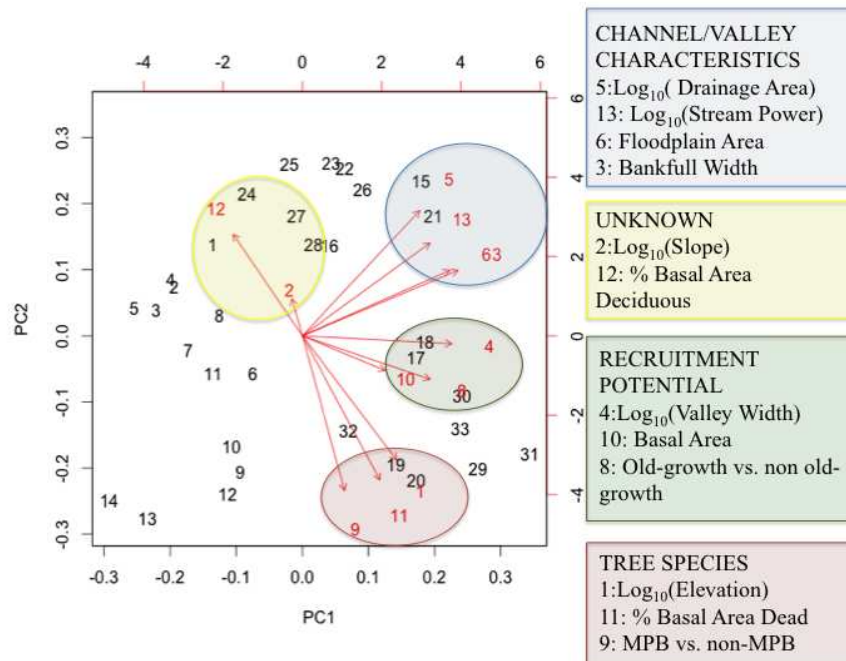


Figure 5.16: Principle component 1: PC1 is composed of wood recruitment potential variables. The variables along PC1 are valley width, basal area, and stand age.

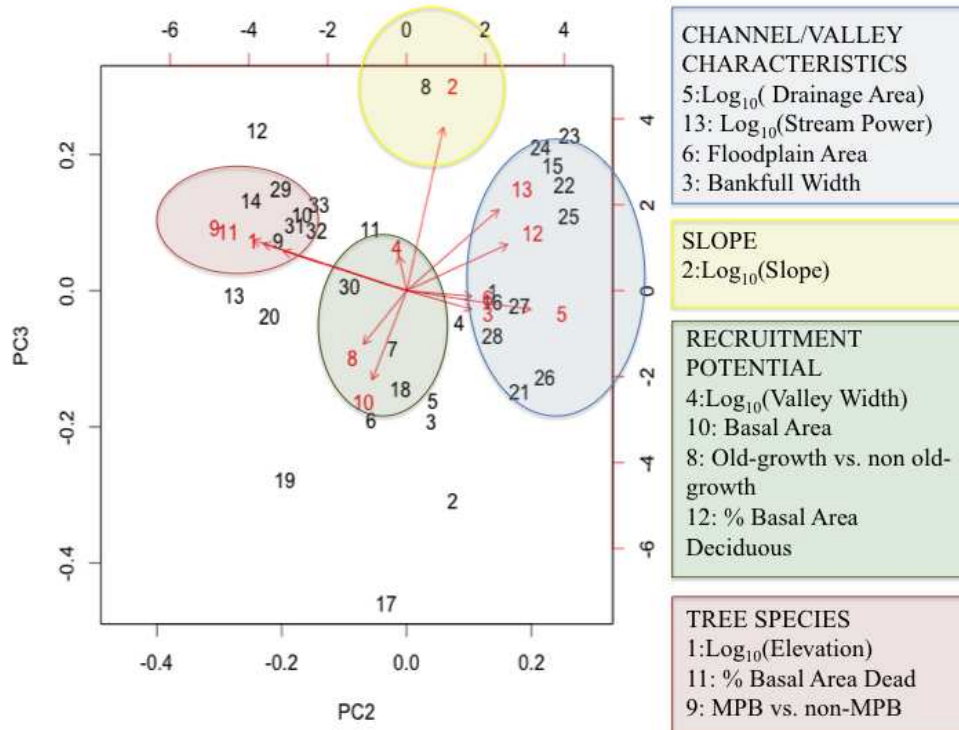


Figure 5.17: Principle component 2: PC2 is composed of channel/valley characteristics. The variables along PC2 are drainage area, stream power, floodplain area, and bankfull width.

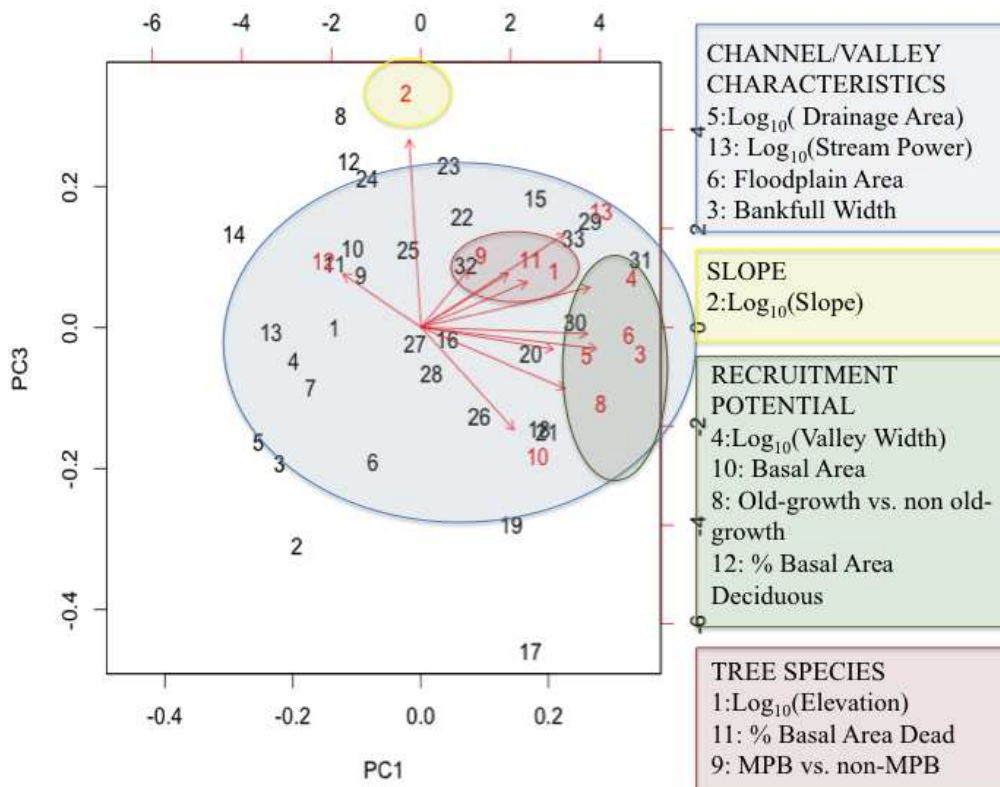


Figure 5.18: Principle component 3: PC3 is primarily composed of the slope variable.

Scree-plot

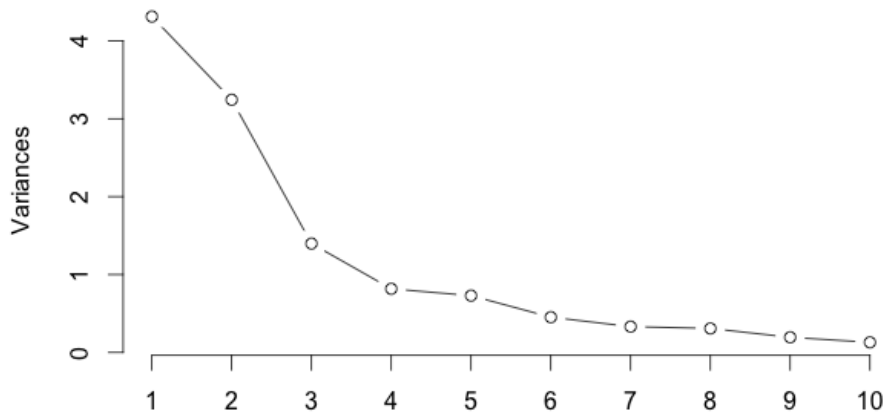


Figure 5.19: Scree-plot of PCA for all variables. PC1 explains 36% of data variation, PC1 with PC2 explains 63% of data variation, and PC1, PC2, and PC3 explain 75% of data variation. PC1 is composed of wood recruitment potential variables, PC2 is channel/valley characteristics, and PC3 is mainly the slope variable.

In order to determine which valley and channel characteristics best related to channel, floodplain, and total wood volume, the best subsets regression method was used. The top three models for each volume based on the best Bayesian information criterion (BIC) are reported below (Table 12).

Wood recruitment (PC1) tends to best describe the data set. Valley/channel characteristics such as drainage area, stream power, floodplain area, and bankfull width describe some data variance as well (PC2). Seventy-five percent of data variation is explained by the first three principle components. The best model predictors of wood volume (channel, floodplain, and total) tend to be elevation, stand age, and beetle infestation.



Figure 5.20: Principle component 1 spectrum in photographs. Along PC1, forest age becomes older, valley width increases, and basal area roughly increases. PC1 is roughly the recruitment potential of the site.



Figure 5.21: Principle component 2 spectrum in photographs. Along PC2 drainage area increases, stream power increases, floodplain area increases, and bankfull width increases. PC2 is roughly the size and slope of the drainage area.

Table 5.9: Top three wood volume regression models

Equation	Intercept	Log ₁₀ (Elevation)	Log ₁₀ (Slope)	Log ₁₀ (Valley Width)	Log ₁₀ (Drainage Area)	Floodplain Area	OG vs. NOG	MPB vs. NMPB	Log ₁₀ (Stream Power)	Proportion Deciduous	BIC	Adj. R ²
Channel Wood Volume 1	= -67.05	19.84					0.45	-0.73			-5.2	0.38
Channel Wood Volume 2	= -54.05	15.77		0.7				-0.78		-1.76	-4.9	0.42
Channel Wood Volume 3	= -1.55			1.15							-3.2	0.24
FP Wood Volume 1	= -56.84	16.79					0.54	0.24			-7.4	0.42
FP Wood Volume 2	= -101.17	30.98	5.11	-0.81	6.41		0.68		-4.37		-6.7	0.52
FP Wood Volume 3	= -77.13	23.5	4.32		5.24		0.55		-3.81		-6.3	0.48
Total Wood Volume 1	= -59.44	17.69					0.45	-0.63			-13	0.51
Total Wood Volume 2	= -60	18.08	0.55				0.48	-0.64			-12	0.54
Total Wood Volume 3	= -56.85	17.08	0.49			0.00027	0.39	-0.58			-11	0.64

* 1= "Non-Old-Growth", 2= "Old-Growth"

**Dead: 1= "Healthy" 2= "MPB Infested"

6 DISCUSSION

6.1 GENERAL DISCUSSION

Overall, wood loads in this study are comparable in magnitude and variation to other old-growth, unmanaged forests around the world (Table 13). Wood loads in this study are similar to unmanaged stand wood loads found by Nowakowski and Wohl (2008) in northern Wyoming, and Richmond and Fausch (1995) in the Colorado Front Range (Table 13). These studies have field sites at higher elevations; however, other factors such as climate, disturbance regimes, types of tree (conifers), and lithology are similar to this study. Wood loads in this study have a smaller variance and are 1-3 orders of magnitude less than those found in the Pacific Northwest (WA, OR, AK, BC in Table 13). The native trees in the Pacific Northwest are large, and primary productivity is higher (Cadot et al, 2009). Although decay rates are lower in the Colorado Front Range, the trees are smaller and the forest stands have lower values of basal area (Bigler et al., 2007). Research in the southern hemisphere is comprised of study sites with deciduous/non-coniferous trees (southern beech, gum, eucalyptus) (Table 13). Front Range wood loads are smaller than the highest values found in South America, but values from Oceania are analogous when compared to this study.

Wood recruitment in the montane zone was heavily dominated by treefall from valley slopes. Evidence of small mass wasting events was present. Spruce, fir, and ponderosa trees were very large compared to the stream, and it is unlikely bankfull flows had the competence to transport any old-growth wood pieces. Lodgepole pine trees from subalpine reaches in the Front Range had smaller diameters, and were more likely to be transported downstream. Lodgepole trees also appeared to be more susceptible to mountain pine beetle infestation. Recruitment of

~0.10 m diameter lodgepole trees could result in wood transported from upstream. Recruitment is less likely to come from a fire disturbance, as trees in the montane zone are more adapted to small fires than subalpine trees. No blowdown areas were encountered in the study areas.

Large key piece sources were channel banks and nearby valley slopes. Because large wood recruitment is so close to the channel, measuring wood within old-growth sites in proximity to each other likely introduces minimal bias. Measureable wood in the stream was assumed to originate mainly from nearby banks, and not significantly from upstream sources. For old-growth sites next to each other, a downstream gap of 100 m or greater was present between sites.

6.2 HYPOTHESIS 1 DISCUSSION

The first null hypothesis, that instream wood loads in old-growth montane forests are not significantly different from instream wood loads in younger montane forests, is rejected. Wood loads (total, channel, and floodplain) are greater in old-growth forest stands when standardized to reach length, slope, bankfull width, drainage area, and floodplain area. Only instream channel wood standardized to floodplain area was not significantly different between stand ages (Table 14). However, old-growth channel wood loads would be significantly greater if the significance level was increased from 0.05 to 0.10. Floodplain area was the least accurately measured variable of the standardizing variables (average floodplain width multiplied by reach length). If a more accurate floodplain area delineation had been done, all wood loads may have been significant at $\alpha = 0.05$. Taking more cross section measurements and calculating an accurate polygon could provide a more accurate delineation of floodplain area.

Table 6.1: Wood loads from unmanaged streams after Cadol et al., 2007

Location	Abbreviation	<i>n</i>	<i>A</i> (km ²)	<i>S</i> (%)	Wood load (m ³ /100 m)	Minimum size: diam/length (m)	Forest type	Source
La Selva, Costa Rica	CR	30	0.1–8.5	0.2–8	3–34.7	0.10/1	Tropical wet	Cadol et al., 2009
Western, WA	WA1	46	0–4	n/r	0–87	0.10/2	Various	Fox and Bolton, 2007
Western, WA	WA2	45	4–20	n/r	3–142	0.10/2	Various	Fox and Bolton, 2007
Cascade Range, WA	WA3	28	2.3–119	<4	1.6–60.7	0.10/2	Western hemlock	Beechie and Sibley, 1997
Western, OR	OR1	46	n/r	0.5–27.4	2–100	0.15/3	Various	Thom et al., 2001
Coast Range, OR	OR2	9	~5–21.5	1.2–3.6	81–262	0.30/3	Spruce-hemlock-fir	Reeves et al., 2003
Southeast Alaska	AK	5	0.7–55.4	0.8–2.5	7–62	0.20/1.5	Sitka spruce-hemlock	Robison and Beschta, 1990
SW British Columbia	BC	4	7.3	1.2–0.5	16.6–85	0.10/1	Douglas- fir	Fausch and Northcote, 1992
Northern Michigan	MI	12	n/r	0.9–5	7–62.3	0.10/1	Hardwood-hemlock	Morris et al., 2007
Front Range, CO	CO1	12	8–270	3–19	0.1–9.7	0.10/1	Mixed conifer	Nowakowski and Wohl, 2008
Front Range, CO	CO2	11	2.4–29.1	0.4–6.4	9.1–27.1	0.10/1	Mixed conifer	Richmond and Fausch, 1995
Bighorn Range, WY	WY1	9	5.7–85	0.7–5.6	0.4–9.5	0.05/1	Pine-spruce-fir	Nowakowski, 2007
Absaroka Range, WY	WY2	10	17–40	2.2	15.3–28.9	0.10/2	Pine-spruce-fir	Zelt and Wohl, 2004
Bridger Teton NF, WY	WY3	13	4.2–100	1.5–10	4.8–54.5	0.10/1	Pine-spruce-fir	Bragg et al., 2000
Southern Andes, Chile	SA	33	9–11	5–8	14.2–64.4	0.10/1	Southern beech	Comiti et al., 2008
Tierra del Fuego, Arg.	TF	32	12.9	6.5	7.2	0.10/1	Southern beech	Comiti et al., 2008
SE Australia	AU	14	187	0.2	27.8	0.10/1	Gum-eucalyptus	Webb and Erskine, 2003
South Island, New Zealand	NZ	5	0.8–1.4	3.2–5.7	0.2–7.4	0.10/1	Southern beech	Baillie and Davies, 2002
Front Range, CO	CO3	10	15.7–37.3	0.02–0.08	2.7–32.2	0.10/1	Old-growth Pine-spruce-fir	This study
Front Range, CO	CO3	23	5.6–37.3	0.02–0.08	0.001–32.0	0.10/1	Non-old-growth Pine-spruce-fir	

6.3 HYPOTHESIS 2 DISCUSSION

The second null hypothesis, that wood jam volume and frequency do not vary between forest stand types, is rejected with respect to wood jam volume. Larger key pieces from older trees easily span entire channel widths in the headwater streams of this study. The key pieces are likely impeding all wood transport downstream, resulting in larger jams. As jams become larger, it becomes increasingly more difficult for wood to be transported downstream. The wood remains in the jam until the jam is washed out.

The null hypothesis is also rejected when jam frequencies are standardized to channel characteristics (bankfull width and reach length). I fail to reject the null hypothesis when jam frequency is standardized to valley characteristics (slope, drainage area, floodplain area). Large key pieces in old-growth stands are likely impeding wood transport immediately downstream. Jam volumes are larger in old-growth stands, making it harder for wood to bypass a jam and form a new jam in the same area.

Comparing jam frequencies to the subalpine region of the Colorado Front Range, montane streams have a lower frequency. Subalpine streams have jam frequency between 0-37 jams/100 m (Wohl and Beckman, 2014) (Table 14). Jam frequencies in this study range from 0.1-8.6 jams/100 m. Jam frequencies fall within the normal range from around the world, but are far less than those measured in the Pacific Northwest (Abbe and Montgomery, 2003) (Table 14).

Although jam frequency is less than in subalpine streams in the Front Range, jam volume is larger in montane streams. The average jam volume for non-old-growth and old-growth stands in the subalpine is 0.9 m^3 and 3.3 m^3 , respectively (Beckman 2013). The average jam volume for non-old-growth and old-growth stands in the montane is 1.7 m^3 and 7.1 m^3 , respectively. Ponderosa and spruce-fir trees of the montane zone have a larger piece diameter, on average,

Table 6.2: Reported values of jam frequency (after Wohl and Beckman, 2014)

Location	Area (km ²)	Length (km)	Characteristics	Jams/km	Jams/Channel Width (W _c)	Reference
Washington, USA	0.5-20	8-20x BKF Width	Old-growth temperate rainforest	15-175	N/A	Abbe and Montgomery (2003)
Poland, Germany	4.5-28.6	2.9-10.8	Second-growth subalpine forest	0.7-6.3	N/A	Kaczka (2003)
Michigan, USA	<50	0.3	Old-growth mixed forest	0.1-0.5	5.6W _c	Morris et al. (2007)
Michigan, USA	<50	0.2-0.3	Second-growth mixed forest	0-0.5	17W _c	Morris et al. (2007)
New York, USA	6.6-128.7	0.7-1	Second-growth mixed conifer-hardwood forest	Nov-51	5W _c	Kraft and Warren (2003)
Argentina*	5-12.9	0.03-0.1	Old-growth Nothofagus forest	16.2	3W _c	Mao et al. (2008)
Ontario, Canada	N/A	0.2-0.6	Second-growth mixed conifer-hardwood forest	0.2-1.8	17W _c	Kreutzweiser et al. (2005)
Colorado, USA	3.8-80.2	0.1-3.6	Old-growth subalpine	0-36	25W _c	Wohl and Beckman (2014)
Colorado, USA	2.6-258	0.08-8.6	Second-growth subalpine	0-37	42W _c	Wohl and Beckman (2014)
Colorado, USA	15.7-37.3	0.04-0.07	Old-growth montane	2-8.6	5W _c	This study
Colorado, USA	5.6-37.3	0.03-0.07	Second-growth montane	0.1-8.6	6W _c	This study

*Included only jams described as log steps

than lodge-pole pine of the subalpine zone. I believe the larger pieces not only add to the jam volume, but also are better at trapping more pieces of wood in jams.

6.4 HYPOTHESIS 3 DISCUSSION

The third null hypothesis, that pool volume and sediment storage do not vary between forest stand types, is retained. However, old-growth pool volume would be significantly greater if α was increased from 0.05 to 0.10. Old-growth sediment volume would be significantly greater if α was increased from 0.05 to 0.10 when standardized to slope. Larger pool volume increases habitat for fish and other species. Larger sediment storage increases nutrient storage and availability. In the montane zone, old-growth reaches tend to have significantly greater fish habitat and thus the potential for healthier aquatic ecosystems.

6.5 HYPOTHESIS 4 DISCUSSION

The fourth null hypothesis, that instream wood loads in minimally impacted montane forests are not significantly different from wood loads in beetle-infested montane forests, is retained. Hassan et al. (2008) found a similar result in a study of streams in British Columbia, Canada. The study found wood loads in infested stands to be within the normal range of wood loads in healthy stands. Infested stands may not provide as much wood to streams as previously assumed. However, time since infestation may play an important role in instream wood recruitment. Trees in the Colorado study area have only been infested since ~2008 (Fig. 3.3). Although there is >25% tree mortality, the majority of the trees are still standing. Dead trees can remain standing >100 years (Mast, 1991; Roovers and Rebertus, 1993). Over the next century,

wood loads in infested stands may become significantly larger, both in this study area and in the areas discussed in the Hassan et al. (2008) study.

6.6 HYPOTHESIS 5 DISCUSSION

The final null hypothesis, that there is no correlation between instream wood load and any valley, channel, or forest characteristics, is rejected. Total, channel, and floodplain wood volumes are related to elevation (Log_{10}), stand age, and beetle-infestation (Table 12). Linear models with valley bottom width (Log_{10}) and slope (Log_{10}) also explain a degree of wood volume variation (based on model BICs). These findings are dissimilar to those from past studies. Wohl and Cadol (2011) found valley-bottom width, slope, and sequence of longitudinal channel changes had a strong influence on wood distribution. Wohl and Jaeger (2009) correlated subalpine wood loads with drainage area, elevation, channel width, bed slope, and total stream power in streams of the Colorado Front Range. Fox and Bolton (2007) found different variables to explain wood load in the Pacific Northwest. They found wood load to be correlated with bankfull width, forest type, bedform type, bed slope, and confinement in streams flowing through temperate rainforest in Washington. Unlike past studies, my results indicate that stand age and beetle infestation have more influence on wood loads in the montane zone than most channel and valley characteristics.

Elevation may be an important variable due to its high correlation with percentage of basal area that is dead (Appendix A). With increasing elevation, the dominant forest type changes from a spruce/fir to lodgepole pine. Lodgepole pine has a higher percentage of dead trees. The higher percentage of dead trees likely adds to the wood volume. Hypothesis 1 supports the inclusion of stand age in the model.

Null hypothesis 4, that wood loads in minimally impacted montane forests are not significantly different from wood loads in beetle-infested montane forests, was retained. It is interesting that whether a study reach is infested or not is significant after multivariate analysis. The coefficients for the beetle infestation variable are small, and mostly negative. This indicates that if a study reach is infested, the wood load will decrease, which is the opposite of the outcome predicted in Hypothesis 4. Because the sign of the coefficient in the multivariate analysis is difficult to interpret, more confidence is placed in the pairwise t-test in Hypothesis 4.

7 CONCLUSIONS

Many of the null hypotheses in this study were rejected at a significance value of 0.10, as initially expected. There are significantly larger instream wood volumes, jam volumes, and jam frequencies in old-growth montane forests. Similarly, residual pool volume and sediment storage when standardized to slope are significantly larger in old growth forests. If restoration or wildlife managers wish to improve or maintain aquatic habitats, areas with old/large trees should be a primary conservation focus. Old-growth stands should not be logged, and streams should be protected from roads, diversions, and dams. Laws, rules, and regulations should be created to protect what little old-growth is left in the montane and subalpine forests. Mountain pine beetle-infested areas may not be as influential to wood dynamics and subsequent ecosystem repercussions as previously thought. I predict that this may change for the Colorado Front Range montane zone, however, over the next century.

7.1 FUTURE WORK

In the meantime, more work is needed to understand the spatial and temporal aspects of montane wood loads. A study with longer reaches could better statistically analyze the wood volume spacing and frequency of jams. Identifying appropriate reaches for such a study will be challenging, however, because only small patches of old-growth forest remain within the montane zone. Wood dynamics could then be more adequately compared to subalpine reaches. Only after further research will it be evident whether mountain pine beetle infestation is a significant instream wood load disturbance. A multiyear study should monitor streams subject to mountain pine beetle infestation, and investigate how wood load changes over time. This type of

study would likely take decades, but as beetle infestations cover more forest, it would provide useful insight into how beetle disturbance affects wood loads.

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9 APPENDICES

9.1 APPENDIX A - JAM VOLUMES AND STATION

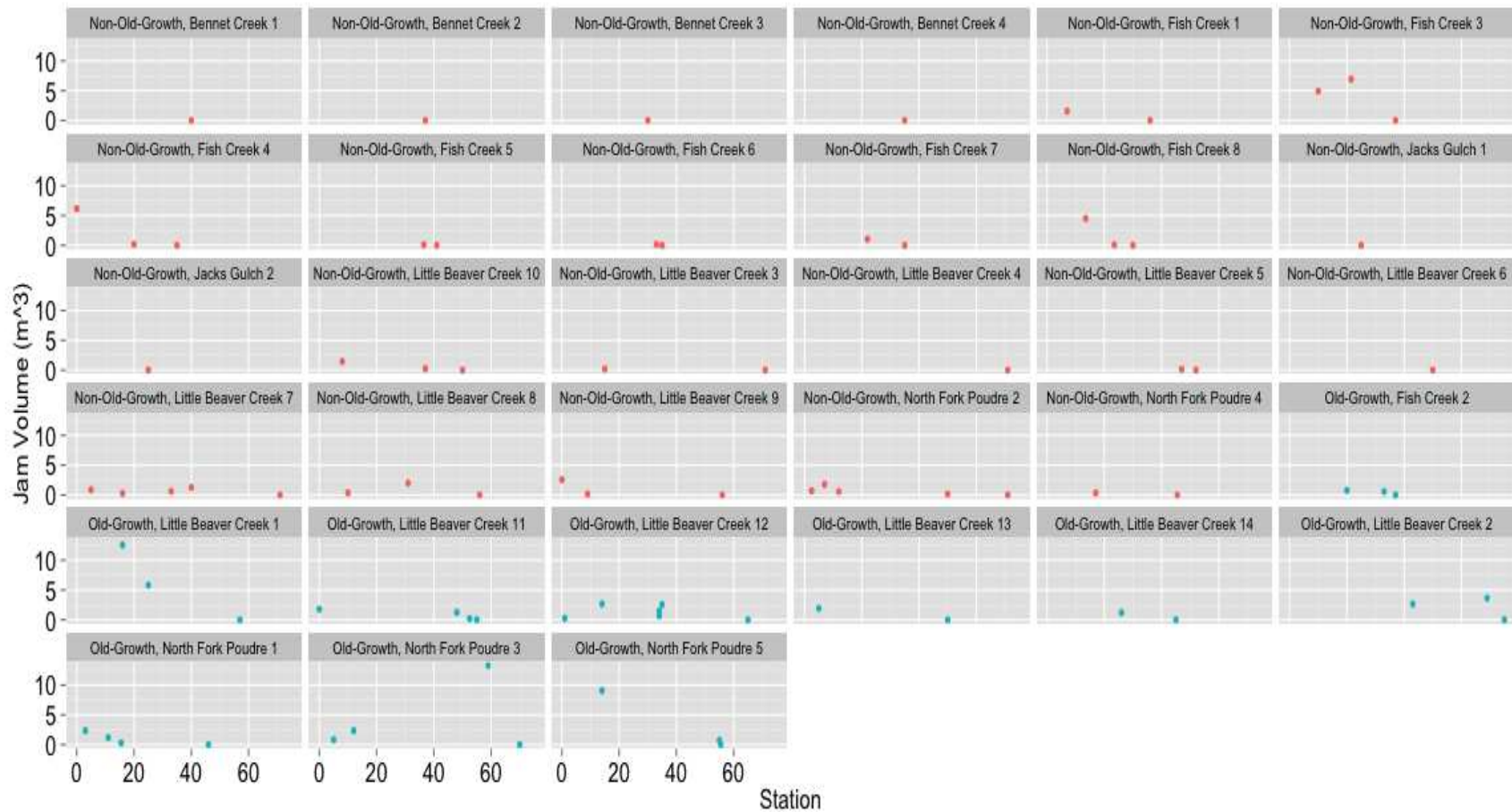


Figure 9.1: Volume of wood in jams with corresponding station downstream. Not the last point in each graph has no wood volume and only signifies the end of reach to portray reach length.

Table 9.1: Volume and station of all wood jams

Site	Jam Volume (m³)	Number Pieces	Station	Stand Age	Health
Bennet Creek 1	0.00	0	40	Non-Old-Growth	Healthy
Bennet Creek 2	0.00	0	37	Non-Old-Growth	Healthy
Bennet Creek 3	0.00	0	30	Non-Old-Growth	Healthy
Bennet Creek 4	0.00	0	35	Non-Old-Growth	Healthy
Fish Creek 1	1.58	4	7	Non-Old-Growth	Healthy
Fish Creek 1	0.00	0	36	Non-Old-Growth	Healthy
Fish Creek 2	0.78	4	20	Old-Growth	Healthy
Fish Creek 2	0.58	4	33	Old-Growth	Healthy
Fish Creek 2	0.00	0	37	Old-Growth	Healthy
Fish Creek 3	4.94	4	10	Non-Old-Growth	Healthy
Fish Creek 3	6.93	3	21.5	Non-Old-Growth	Healthy
Fish Creek 3	0.00	0	37	Non-Old-Growth	Healthy
Fish Creek 4	6.15	4	0	Non-Old-Growth	Healthy
Fish Creek 4	0.16	3	20	Non-Old-Growth	Healthy
Fish Creek 4	0.00	0	35	Non-Old-Growth	Healthy
Fish Creek 5	0.10	3	36.5	Non-Old-Growth	MPB Infested
Fish Creek 5	0.00	0	41	Non-Old-Growth	MPB Infested
Fish Creek 6	0.16	3	33	Non-Old-Growth	MPB Infested
Fish Creek 6	0.00	0	35	Non-Old-Growth	MPB Infested
Fish Creek 7	1.05	11	22	Non-Old-Growth	Healthy
Fish Creek 7	0.00	0	35	Non-Old-Growth	Healthy
Fish Creek 8	4.51	3	13.5	Non-Old-Growth	MPB Infested
Fish Creek 8	0.08	3	23.5	Non-Old-Growth	MPB Infested
Fish Creek 8	0.00	0	30	Non-Old-Growth	MPB Infested
Jacks Gulch 1	0.00	0	25	Non-Old-Growth	MPB Infested

Jacks Gulch 2	0.00	0	25	Non-Old-Growth	MPB Infested
Little Beaver Creek 1	5.82	13	25	Old-Growth	Healthy
Little Beaver Creek 1	12.55	5	16	Old-Growth	Healthy
Little Beaver Creek 1	0.00	0	57	Old-Growth	Healthy
Little Beaver Creek 2	3.65	11	69	Old-Growth	Healthy
Little Beaver Creek 2	2.65	6	43	Old-Growth	Healthy
Little Beaver Creek 2	0.00	0	75	Old-Growth	Healthy
Little Beaver Creek 3	0.20	6	15	Non-Old-Growth	Healthy
Little Beaver Creek 3	0.00	0	71	Non-Old-Growth	Healthy
Little Beaver Creek 4	0.00	0	71	Non-Old-Growth	Healthy
Little Beaver Creek 5	0.14	4	47	Non-Old-Growth	Healthy
Little Beaver Creek 5	0.00	0	52	Non-Old-Growth	Healthy
Little Beaver Creek 6	0.00	0	50	Non-Old-Growth	Healthy
Little Beaver Creek 7	1.27	14	40	Non-Old-Growth	Healthy
Little Beaver Creek 7	0.62	6	33	Non-Old-Growth	Healthy
Little Beaver Creek 7	0.28	4	16	Non-Old-Growth	Healthy
Little Beaver Creek 7	0.87	4	5	Non-Old-Growth	Healthy
Little Beaver Creek 7	0.00	0	71	Non-Old-Growth	Healthy
Little Beaver Creek 8	2.00	3	31	Non-Old-Growth	Healthy
Little Beaver Creek 8	0.35	3	10	Non-Old-Growth	Healthy
Little Beaver Creek 8	0.00	0	56	Non-Old-Growth	Healthy
Little Beaver Creek 9	0.17	3	9	Non-Old-Growth	Healthy
Little Beaver Creek 9	2.58	5	0	Non-Old-Growth	Healthy
Little Beaver Creek 9	0.00	0	56	Non-Old-Growth	Healthy
Little Beaver Creek 10	0.24	3	37	Non-Old-Growth	Healthy
Little Beaver Creek 10	1.46	6	8	Non-Old-Growth	Healthy
Little Beaver Creek 10	0.00	0	50	Non-Old-Growth	Healthy
Little Beaver Creek 11	1.79	3	0	Old-Growth	Healthy

Little Beaver Creek 11	1.26	7	48	Old-Growth	Healthy
Little Beaver Creek 11	0.20	6	52.5	Old-Growth	Healthy
Little Beaver Creek 11	0.00	0	55	Old-Growth	Healthy
Little Beaver Creek 12	0.25	4	1	Old-Growth	Healthy
Little Beaver Creek 12	2.68	15	14	Old-Growth	Healthy
Little Beaver Creek 12	0.68	4	34	Old-Growth	Healthy
Little Beaver Creek 12	2.58	7	35	Old-Growth	Healthy
Little Beaver Creek 12	1.47	3	34	Old-Growth	Healthy
Little Beaver Creek 12	0.00	0	65	Old-Growth	Healthy
Little Beaver Creek 13	1.93	10	5	Old-Growth	MPB Infested
Little Beaver Creek 13	0.00	0	50	Old-Growth	MPB Infested
Little Beaver Creek 14	1.20	10	26	Old-Growth	MPB Infested
Little Beaver Creek 14	0.00	0	45	Old-Growth	MPB Infested
North Fork Poudre 1	0.31	5	15.5	Old-Growth	MPB Infested
North Fork Poudre 1	1.18	17	11	Old-Growth	MPB Infested
North Fork Poudre 1	2.36	15	3	Old-Growth	MPB Infested
North Fork Poudre 1	0.00	0	46	Old-Growth	MPB Infested
North Fork Poudre 2	0.17	6	50	Non-Old-Growth	MPB Infested
North Fork Poudre 2	0.58	11	12	Non-Old-Growth	MPB Infested
North Fork Poudre 2	1.80	17	7	Non-Old-Growth	MPB Infested
North Fork Poudre 2	0.70	7	2.5	Non-Old-Growth	MPB Infested
North Fork Poudre 2	0.00	0	71	Non-Old-Growth	MPB Infested
North Fork Poudre 3	13.27	47	59	Old-Growth	MPB Infested
North Fork Poudre 3	2.35	11	12	Old-Growth	MPB Infested
North Fork Poudre 3	0.82	4	5	Old-Growth	MPB Infested
North Fork Poudre 3	0.00	0	70	Old-Growth	MPB Infested
North Fork Poudre 4	0.32	3	17	Non-Old-Growth	MPB Infested
North Fork Poudre 4	0.00	0	45.5	Non-Old-Growth	MPB Infested
North Fork Poudre 5	0.72	6	55	Old-Growth	MPB Infested
North Fork Poudre 5	9.07	22	14	Old-Growth	MPB Infested
North Fork Poudre 5	0.00	0	55.5	Old-Growth	MPB Infested

9.2 APPENDIX B - SITE GPS COORDINATES

Table 9.2: GPS coordinates of upstream and downstream end of each reach.*

Site Name	Downstream UTM N	Downstream UTM E	Upstream UTM N	Upstream UTM E	Type	Dead
Bennet Creek 1	4501069	454032	4501037	453954	Non-Old-Growth	Healthy
Bennet Creek 2	4501034	453912	4501029	453880	Non-Old-Growth	Healthy
Bennet Creek 3	4501315	453417	4501337	453395	Non-Old-Growth	Healthy
Bennet Creek 4	4501343	453373	4501359	453351	Non-Old-Growth	Healthy
Fish Creek 1	4494871	453504	4494863	453481	Non-Old-Growth	Healthy
Fish Creek 2	4494887	453587	4494885	453552	Old-Growth	Healthy
Fish Creek 3	4494869	453468	4494853	453440	Non-Old-Growth	Healthy
Fish Creek 4	4494824	453163	4494856	453133	Non-Old-Growth	Healthy
Fish Creek 5	4493746	449857	4493819	449829	Non-Old-Growth	MPB Infested
Fish Creek 6	4493744	449915	4493753	449888	Non-Old-Growth	MPB Infested
Fish Creek 7	4493931	450526	4493929	450493	Non-Old-Growth	Healthy
Fish Creek 8	4493960	450660	4493962	450624	Non-Old-Growth	MPB Infested
Jacks Gulch 1	4497425	454384	4497404	454347	Non-Old-Growth	MPB Infested
Jacks Gulch 2	4497372	454430	4497376	454416	Non-Old-Growth	MPB Infested
Little Beaver Creek 1	4496855	454507	4496855	454507	Old-Growth	Healthy
Little Beaver Creek 10	4496697	453058	4496697	453017	Non-Old-Growth	Healthy
Little Beaver Creek 11	4496822	450970	4496827	450932	Old-Growth	Healthy
Little Beaver Creek 12	4497162	450192	4497191	450155	Old-Growth	Healthy
Little Beaver Creek 13	4497207	450088	4497195	450127	Old-Growth	MPB Infested
Little Beaver Creek 14	4498442	448526	4498456	448488	Old-Growth	MPB Infested
Little Beaver Creek 2	4496827	454511	4496755	454481	Old-Growth	Healthy
Little Beaver Creek 3	4496724	454449	4496691	454404	Non-Old-Growth	Healthy
Little Beaver Creek 4	4496570	454260	4496513	454240	Non-Old-Growth	Healthy
Little Beaver Creek 5	4496334	454123	4496320	454093	Non-Old-Growth	Healthy
Little Beaver Creek 6	4496407	453815	4496418	453772	Non-Old-Growth	Healthy
Little Beaver Creek 7	4496315	453648	4496348	453620	Non-Old-Growth	Healthy
Little Beaver Creek 8	4496430	453393	4496461	453362	Non-Old-Growth	Healthy
Little Beaver Creek 9	4496623	453181	4496647	453139	Non-Old-Growth	Healthy

* NOTE: GPS coordinates were taken in river valleys with poor reception. Many points do not plot exactly on the stream.

NFK Poudre 1	4518317	440438	4518292	440401	Old-Growth	MPB Infested
NFK Poudre 2	4518426	440571	4518404	440528	Non-Old-Growth	MPB Infested
NFK Poudre 3	4518572	440828	4518546	440758	Old-Growth	MPB Infested
NFK Poudre 4	4518750	441299	4518724	441284	Non-Old-Growth	MPB Infested
NFK Poudre 5	4518668	441093	4518659	441045	Old-Growth	MPB Infested