DISSERTATION

INSTREAM WOOD LOADS AND CHANNEL COMPLEXITY IN HEADWATER SOUTHERN ROCKY MOUNTAIN STREAMS UNDER ALTERNATIVE STATES

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer 2016

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ABSTRACT

INSTREAM WOOD LOADS AND CHANNEL COMPLEXITY IN HEADWATER SOUTHERN ROCKY MOUNTAIN STREAMS UNDER ALTERNATIVE STATES

Small, forested streams are symbiotic with riparian processes, and thus land use changes to their riparian forests can have lasting effects on stream channel form and function. The first part of this dissertation evaluates the legacy effects of land use on stream channels of forested, subalpine streams of the Southern Rockies, with particular interest in the correlations between stream geomorphic complexity and characteristics of the adjacent riparian forest, valley geometry, and land use history. The study uses field data from the Southern Rocky Mountains of Colorado and Wyoming in streams flowing through old-growth forests (OU), younger-growth, naturally disturbed forests (YU), and forests that have undergone past land use changes (YM, management) such as logging. Field sites also have varied valley geometry (lateral confinement). Field data are used to evaluate measures of geomorphic complexity based on cross-sectional, planform, and instream wood piece and logjam variables. Significant differences in geomorphic stream complexity between OU, YU, and YM result primarily from differences in wood characteristics, which correlate strongly with pool volume and organic matter storage. Unconfined OU streams have the largest wood loads and the greatest complexity in form and function, whereas legacy effects of logging, tie-drives, and channel simplification create lowest complexity in YM streams. The second part of this dissertation proposes that the geomorphic concepts of thresholds, river metamorphosis, and complex response are the geomorphic analog to alternative states in ecology, which recognize that biotic community structure and function can exist in multiple states under the same environmental conditions. This concept is used in conjunction with field data from relatively laterally unconfined valley bottoms in the first part of this dissertation, in addition to wood data from the montane zone, to demonstrate how land use can drive streams across a threshold to induce an alternative state of significantly reduced complexity of stream form, function, and carbon storage in large wood and instream particulate organic matter. This is illustrated by threshold differences between unmanaged and managed stream segments, regardless of current forest stand age, implying that the legacy effects of past land use on riparian forest characteristics result in an alternative state of reduced stream complexity and retention. High complexity can maintain aquatic-riparian ecosystem functions through positive feedbacks, and the reduced state of managed watersheds implies an alternative ecologic state with reduced carbon storage, ecosystem productivity, and biotic diversity. The cumulative effects of reduced carbon storage in mountainous environments experiencing analogous human alteration may have large implications for global carbon budgets. Alternative states driven by land use changes likely apply to watersheds in other forested, mountain environments. Maintenance of riparian forest buffers around streams in laterally unconfined valley segments is a recommended first-order restoration technique for physical and ecological recovery.

ACKNOWLEDGMENTS

I extend many thanks to the people who supported me throughout my dissertation project. First, I would like to thank the National Science Foundation Grant DEB-1145616 for funding support throughout this project, as well as the Colorado State University Warner College of Natural Resources, Department of Geosciences, and scholarship donors for funding, all of which was imperative to my success and experience as a graduate student. Thank you to Rocky Mountain National Park, Arapahoe-Roosevelt National Forest, and Medicine Bow National Forest for allowing access to field sites and supporting field work and research. None of this could have been achieved without the dedicated help of my field assistants: Gus Womeldorph, whose positive attitude and interest in learning made long days of data collection and nights of camping something to look forward to; and Reed Waldon, my cousin and partner in field season 2 – we really took family bonding to a new level. I saw so much growth in him as a person and geoscientist; he was a pleasure to work with, and it meant more to me than he will ever know to have him as a part of this. I want to thank the Franklin Graybill Statistical Laboratory at Colorado State University for statistical consulting and comments of two anonymous reviewers who substantially helped Chapter 2.

Special thanks also go out to my fluvial family of graduate students who provided constant support, feedback, and differing perspectives all along the way, particularly Nicholas Sutfin, my buddy in international travel, field work, and sense of humor; Natalie Anderson for help with statistics, morale, and inspiration; Katherine Lininger and JoJo Mangano for help with GIS, emotional support, and laughter; Karen Jackson, Derek Schook, and Dan Scott for their time and insight. Being a part of this lab was a once in a lifetime experience, and I know that the caliber of this group that I had the pleasure of sharing this time with cannot be found anywhere else. You are all my friends and colleagues for life.

Thank you to my committee members, Dr. Sara Rathburn, Dr. Tim Covino, and Dr. Michael Gooseff, who provided me with valuable perspectives and feedback on my research, and who challenged me to think outside my intellectual box by providing me thoughtful questions in preliminary exams and beyond, and who genuinely wanted to see me succeed. I particularly thank Sara for all our conversations, and for her support and life advice when I needed it.

Endless gratitude goes out to my family, particularly my grandmothers, whose support and love was felt throughout this learning process and who were always there when I needed encouragement. And to my friends: I have the most amazing friends on this planet, and distance never limited their ability to support me. Thank you so much for understanding, listening, encouraging me, making me laugh, keeping me grounded, and constantly reminding me of who I am, how I got here, and why science is my passion.

I thank my husband, Alex, who came into my life right as I began this journey. Your support over this time is immeasurable. You have given me more strength and been more patient than I ever could have imagined. We have weaved back and forth through the trials and tribulations of finishing our doctorates, while also planning a wedding, getting jobs, and moving across the country. I am blessed to share this life with you, and maybe the next few years will be less exciting than these last few.

But most of all I want to thank my advisor, Dr. Ellen Wohl, whose mentorship, friendship, expertise, humor, insight, generosity, and belief in me made this dissertation happen. Every day I am grateful you took a chance by accepting me, and you have changed the course of my life in the most positive way imaginable. Your genuine interest in the success and well-being of your students cannot be matched. I am continually and incredibly grateful for the opportunity to work with such an accomplished scientist. I can only hope to make the kind of impact on my future students that you have made on my life. I hope this is only the beginning of many years of friendship and collaboration and look forward to the many things the future holds for us.

DEDICATION

I dedicate this dissertation to my grandmothers, Betty Rachell and Jeanette. You are incredible role models and you shaped who I am as a person, but more importantly, your unwavering support and belief in me has been my foundation during my years away from home and graduate school. Betty Rachell: you live your life to the fullest and are more worldly than anyone I know. I inherited your curiosity, strength, and boldness, which allow me to challenge and push myself toward my dreams and forge ahead in life no matter what challenges come my way. Jeanette: you are the sweet and spicy Southern gal in my life, and your thoughtfulness, love, and humor are the reason I come to you when I need support the most. You always listen, you always care. Every day I am grateful to have you amazing women in my life, and the moments I get to spend with you are the most cherished moments of my life. This is for you.

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Chapter 1: Introduction

First- to third-order, small, forested streams have a disproportionately important impact on entire watersheds because they: can constitute the majority of stream length; are more coupled with riparian processes; promote hydrologic connectivity; readily transmit sediment downstream; and have unique habitat and nutrient sources for food webs [*Milliman and Syvitski*, 1992; *Gomi et al.*, 2002; *Freeman et al.*, 2007; *Meyer et al.*, 2007]. The symbiotic nature of riparian and stream ecosystems in small, forested streams implies that exchanges of material and energy between these environments can impact ecosystem function at all levels, and that, in turn, disruption of the flow of these exchanges can impact both stream and riparian dynamics [e.g. *Baxter et al.*, 2005].

Prior to European settlement of the Southern Rocky Mountains, watersheds in subalpine and montane elevation zones had a patchwork of riparian forest stand ages, with old-growth (>200 years) trees occurring where natural disturbances were rare, and younger-growth (<200 years) forests occurring where natural disturbances, such as fire, blowdowns, debris flows, and insect infestations, led to death, fall, and movement of large wood (LW) pieces to be stored on hillslopes, floodplains, in stream channels, or floated downstream, while forests slowly regrew. Thus, rates of LW recruitment to streams varied through time in response to natural disturbances.

Valley width and channel geometry in the Southern Rockies can alternate through the longitudinal profile at scales of $10^2 – 10^3$ m because of the history of alpine glaciation [*Anderson et al.*, 2007] and valley width and canyon development from bedrock jointing patterns [*Ehlen and Wohl*, 2002]. Laterally unconfined valleys, or valleys where the floodplain is at least eight times the bankfull width of the stream channel, can allow the formation of multithread channels when biotic drivers such as beaver dams or logjams pool enough backwater to promote overbank flow and avulsion to form secondary channels [*John and Klein*, 2004; *Wohl*, 2011a; *Collins et al.*, 2012]. Multithread channels in the Southern

Rockies retain much more instream wood and closely-spaced logjams than confined or single-thread stream segments [*Wohl*, 2011a; *Wohl and Cadol*, 2011; *Wohl and Beckman*, 2014].

Because of very slow rates of wood decay in the Southern Rockies, instream LW likely was historically always present, resulting in wood-rich, multithread streams in unconfined valley segments [*Beckman and Wohl*, 2014]. Instream LW affects channel complexity by creating zones of flow separation and scour. This effect is most pronounced with channel-spanning structures such as logjams that greatly reduce flow velocities, enhance hyporheic exchange, and trap and store fine sediment and organic matter in pools and areas of irregular banks, equating to greater opportunities for nutrient processing and biological uptake at a range of discharges [*Lautz et al.*, 2006; *Battin et al.*, 2008; *Hester and Doyle*, 2008]. Overbank flows caused by logjams can promote channel avulsion and initiation of secondary channels in unconfined valleys, furthering wood recruitment [*Collins et al.*, 2012] and making stream reaches ever more complex. Because of the role that channel-spanning logjams have in retention and nutrient processing, their frequency and distribution could strongly influence nutrient processing and biological metabolism and production in streams, particularly headwater streams.

In the mid-1800s, land use change began in the Southern Rockies; activities included beaver trapping, placer mining, removal of instream wood, timber harvesting and log floating, and building roads. Collectively, these activities changed the spatial and temporal characteristics of riparian forests and stream channels, having lasting effects and reducing instream wood recruitment, instream wood loads, and hydraulic roughness in stream channels [*Wohl and Jaeger*, 2009; *Wohl and Cadol*, 2011; *Wohl and Beckman*, 2014]. Channel-spanning logjams were much more common in forested Southern Rockies streams before land use change and thus streams are assumed to no longer function as they did historically [*Wohl*, 2011b]. Although some of these activities have long since ceased, reduced wood loads in managed streams persist due to the time required for trees to reach old-growth status (>200 years) [*Veblen*, 1986; *Kaufmann*, 1996] and removal of instream wood to maintain infrastructure.

The primary objective of this study is to evaluate the legacy effects of land use on stream channels of the Southern Rockies, with particular interest in the relationship between riparian forest characteristics and physical stream form and function (complexity) and organic carbon storage in relatively unconfined valley bottoms. Field data were collected from 24 subalpine stream reaches in the Colorado Front Range (Rocky Mountain National Park and Arapaho-Roosevelt National Forest) and the Medicine Bow Mountains of Wyoming over two field seasons in order to address this objective. Stream reaches are categorized into three treatments, old-growth unmanaged forests (OU), younger unmanaged forests (YU), and younger managed forests (YM), based on watershed land use and management history and include a range of lateral valley confinements from unconfined to confined.

The research in this dissertation is divided into two main chapters designed to address the primary objective through two main components: 1) developing metrics of physical channel complexity, evaluating different forms of complexity and differences in complexity in relation to treatment and valley geometry, and inferring processes that create and maintain complexity; and 2) using geomorphic concepts and field data to evaluate the evidence for alternative states of stream form, function, and organic carbon storage as a result of historical land use. Chapter 2 links potential control variables of valley geometry (confinement), forest stand age, and land use in the Southern Rockies to response variables of instream LW characteristics and channel complexity by evaluating all variables between treatments and different levels of confinement. I then relate overall channel complexity, which includes LW characteristics, to riparian forest stand age and history in order to determine the effects of land use on overall stream channel complexity. I determine which measures of complexity are related to certain control variables, and discuss which complexity metrics appear to be most valuable to ecologic complexity. The legacy effects of land use appear to result in reduced physical complexity relative to streams with no land use history flowing through similarly-aged forest and old-growth forest. The greater physical heterogeneity provided by LW and multithread planform likely leads to greater potential habitat and nutrient retention in pools and irregular banks, as well as greater biomass and biodiversity, although I do not directly test this hypothesized relationship.

The history of land use that changed LW recruitment and storage characteristics in the study area has led to significantly reduced levels of channel complexity and LW characteristics, dictating a threshold of complexity and retention of water and organic carbon, and in turn ecosystem dynamics, in the Southern Rockies. In Chapter 3, I use geomorphic concepts of thresholds, river metamorphosis, and complex response to discuss the relationship between physical alternative states and alternative states in ecology. Thresholds in LW storage and channel complexity in my field data, and additional data from the montane zone, are used to demonstrate the existence of alternative states of stream form, function, and organic carbon storage in small Southern Rocky Mountain streams with relatively unconfined valleys. The results suggest that historical land use drove stream ecosystems into an alternative state. Unconfined, unmanaged streams are interpreted as being in a positive feedback cycle of wood recruitment via logjams and channel complexity, while younger-growth, managed streams are thought to be in a positive feedback cycle of limited wood recruitment or retention due to lack of logjams or channel complexity. The alternative states of stream form, function, and organic carbon storage induced by land use in the Southern Rockies imply a reduced alternative state of ecological function.

The research in this dissertation is a component of a larger project that aims to link physical habitat to animal production and ecosystem function in relation to stream management history, and the geomorphic data will be used as baseline data to ultimately provide the first landscape-scale assessment of the effects of wood removal on stream processes, with broad implications for stream ecosystems. This project involved collaboration with scientists across multiple biological and physical scientific disciplines at other educational institutions. Co-investigators evaluated biogeochemical processing of nitrogen, instream macroinvertebrate and riparian spider mass and diversity, and fish mass, growth, and age distribution. The research thus fills in key knowledge gaps on the effect of logjam loss across a spectrum of stream ecosystem processes. We expect logjam loss to result in decreased animal production, decreased biogeochemical processing and increased export of nutrients downstream. Given the importance of small mountain streams on entire watersheds, this loss potentially affects mountain ecosystems over larger spatial and temporal scales. This research thus links instream wood recruitment and formation of logjams and the role of large wood in stream ecosystem function and structure. Streams in semiarid regions, particularly the Colorado Front Range, are undergoing significant alteration and stress due to increasing population as well as climate change, which may in turn change flow regimes due to earlier or less snowmelt, or forest dynamics due to insect infestations and increased frequency of fires. The research thus provides critical information as to how changes in semiarid regions may affect logjam formation and stream processes in headwater streams. The National Park Service and US Forest Service aim to understand the historical characteristics of the distribution and function of instream wood as part of developing restoration and resource management goals.

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Chapter 2: Sources and interpretation of channel complexity in forested subalpine streams of the Southern Rocky Mountains

Summary

We evaluate correlations between stream geomorphic complexity and characteristics of the adjacent riparian forest, valley geometry, and land use history in forested subalpine streams of the Colorado Front Range. Measures of geomorphic complexity focus on cross-sectional, planform, and instream wood piece and logjam variables. We categorize adjacent riparian forests as old-growth unmanaged forest (OU), younger unmanaged forest (YU), and younger managed forest (YM), and valley geometry as laterally confined, partly confined, or unconfined. Significant differences in geomorphic stream complexity between OU, YU, and YM result primarily from differences in wood pieces and logjams, and these differences correlate strongly with pool volume and organic matter storage. Significant differences in planform and cross-sectional complexity correlate more strongly with valley geometry, but do not explain as much of the observed variability in complexity between streams as do the wood variables. Unconfined OU streams have the largest wood loads and the greatest complexity, whereas legacy effects of logging, tie-drives, and channel simplification create lower complexity in YM streams, even relative to YU streams flowing through similarly-aged forest. We find that management history of riparian forests exerts the strongest control on reduced functional stream channel complexity, regardless of riparian forest stand age. This chapter has been accepted for publication in Water Resources Research.

2.1 Introduction

Small streams, defined here as having drainage area < 100 km^2, can occupy two-thirds or more of the total length of stream networks [*Freeman et al.*, 2007]. These streams are heavily influenced by terrestrial processes and play a key role in hydrologic connectivity and biotic diversity [*Freeman et al.*, 2007; *Meyer et al.*, 2007]. Small streams are areas of sediment production and are essential in delivering nutrients downstream through channel networks [*Milliman and Syvitski*, 1992; *Gomi et al.*, 2002; *Benda et al.*, 2005]. Small mountain streams have heterogeneous forms, habitats, and species compositions because of their diversity of physical characteristics such as gradient, light, chemistry, temperature, and substrate [*Meyer et al*., 2007]. Despite their abundance and their influence on the whole river network, small streams can be underestimated and inadequately acknowledged in natural resources management [*Gomi et al.*, 2002]. Given the importance of small streams, it would be useful to characterize their physical complexity with respect to different forms of complexity (e.g., bed versus banks) and degree of complexity in relation to characteristics such as valley geometry and land use history.

Stream channel complexity has been defined in many ways [*Palmer et al.*, 2010], but generally refers to heterogeneity of physical stream geometry or habitat. We distinguish geomorphic complexity, which is spatial heterogeneity of channel substrate, bedforms, cross-sectional geometry, planform, and downstream gradient [e.g., *Gooseff et al*., 2007; *Bertoldi et al*., 2009; *Legleiter*, 2014; *Tuttle et al*., 2014], from habitat complexity, which relates to niche diversity [*Peipoch et al.*, 2015]. Geomorphic complexity does not necessarily correlate to habitat complexity. Although many investigators assume that geomorphic complexity links to habitat complexity and thus ecological function [*Pinay et al*., 1999; *McClain et al*., 2003], few studies thus far have demonstrated a correlation between geomorphic complexity or habitat heterogeneity and biodiversity and abundance at the reach scale [e.g., *Lepori et al.*, 2005]. This may reflect the fact that biotic communities are influenced by other controls beyond habitat characteristics, such as competition from introduced species and limited connectivity [e.g., *Palmer et al.*, 2010]. Or, the lack of correlation between geomorphic complexity and biota could reflect a focus on the wrong measures of geomorphic complexity [*Lepori et al.*, 2005]. Similarly, degradation of geomorphic complexity is believed to lead to reduced biodiversity, biomass, and ecological functioning in streams [e.g., *Violin et al.*, 2011], but this relationship has been difficult to demonstrate in the field [*Palmer et al.*, 2010]. Although previous studies have related geomorphic complexity of floodplain and instream units to riparian plant species in natural watersheds [*Harris*, 1988] and watersheds disturbed by human activity [*Hupp and Rinaldi,* 2007; *Gumiero et al.*, 2015; *Sitzia et al.*, 2015], they do not evaluate such complexity in relation to variations in valley geometry and forest disturbance history. In this paper, we evaluate correlations between different measures of geomorphic complexity in small mountain streams of the

Colorado Front Range and characteristics of the adjacent riparian forest, valley geometry, and land use history.

Exchanges of water, sediment, and organic matter within and between terrestrial and stream environments influence physical and biological stream dynamics, as well as ecological food webs [*Baxter et al*., 2005], in turn influencing geomorphic complexity. In this context, riparian forest stand age can exert a particularly important indirect influence on channel complexity by serving as a control on the recruitment of large wood ($\geq$ 10 cm diameter and 1 m length) to channels. Trees in old-growth forests ($\geq$200 years stand age) are larger in diameter and thus greater in volume than trees in younger growth forests. Trees with greater diameter are less likely to be transported downstream in small streams due to the relative dimensions of wood pieces and channels [*Braudrick et al.*, 1997; *Braudrick and Grant*, 2001; *Martin and Benda*, 2001; *Gurnell et al.*, 2002; *Cordova et al.*, 2007; *King et al.*, 2013; *Dixon and Sear*, 2014] and are thus retained close to where they fall in the stream [*Lienkaemper and Swanson*, 1986; *Wohl and Jaeger*, 2009] and have greater potential to trap mobile wood and form channel-spanning logjams [*Beckman and Wohl*, 2014b].

Any source of irregularities in stream channel boundaries (e.g., boulders or uneven stream banks) can create zones of flow separation in which areas of lower velocities can facilitate retention of suspended sediment and particulate organic matter and increase opportunities for nutrient processing and biological uptake [*Gomi et al.*, 2002; *Battin et al.*, 2008]. Instream wood in the form of channel-spanning logjams, however, is particularly effective at creating flow separation [*Bocchiola*, 2011; *Davidson and Eaton*, 2013] and backwaters with large residual pool volume that retain fine sediment and organic matter, as well as scour pools below the logjam [*Robison and Beschta*, 1990; *Richmond and Fausch*, 1995; *Buffington et al.*, 2002; *Montgomery et al.*, 2003]. Logjams may be needed to establish a threshold of organic matter retention and processing, as individual logs or non-channel spanning logjams may not effectively increase organic matter storage [*Entrekin et al.*, 2008].

In addition to creating backwaters, channel-spanning logjams promote overbank flow during high discharges, which in laterally unconfined valleys can lead to channel avulsion and initiation of secondary channels, further increasing stream complexity [*Wohl*, 2011a; *Collins et al.*, 2012]. Additional wood recruitment can occur in newly initiated channels. Thus, we expect greater wood loads to promote greater channel complexity. The effect of morphology and channel irregularities on instream processes is most pronounced with channel-spanning structures such as logjams that greatly reduce flow velocities, enhance hyporheic exchange, and trap and store fine sediment and organic matter at a range of discharges [*Lautz et al.*, 2006; *Hester and Doyle*, 2008].

Valley geometry can indirectly influence channel complexity by influencing (i) the extent of riparian forest and the volume of wood available for recruitment to the channel, (ii) the space available for the development of channel sinuosity, multithread channel planform, and a floodplain, and (iii) substrate grain size and bank erodibility. Unconfined valley bottoms correspond to greater sources of wood recruited to a channel via bank erosion and floodplain exhumation, particularly if the stream is sinuous or has multithread channels. The larger valley bottom also allows for a broader floodplain with greater retention of large wood. Because wider valley segments typically correspond to lower gradient and more overbank flow, substrate is typically slightly finer grained than in adjacent steep, narrow valley segments [*Wohl et al.*, 2004; *Livers and Wohl*, 2015], facilitating bank erosion and development of heterogeneous channel widths.

Land use history is important in the context of geomorphic complexity as it influences the size and abundance of wood available for recruitment to streams (forest stand age, proximity of road corridors that correspond to reduced riparian forest cover) and the ability of streams to retain recruited wood (history of instream wood removal) [*Swanson et al.*, 1976; *Richmond and Fausch*, 1995; *Hedman et al.*, 1996; *Nowakowski and Wohl*, 2008; *Wohl and Beckman*, 2014]. Channel-spanning logjams were much more common in streams and rivers prior to European settlement in North America and thus small streams likely no longer function as they did historically [*Wohl*, 2011b, 2014]. Previous studies in the Colorado Front Range show that contemporary streams flowing through old-growth, unmanaged forests have up to ten times more wood volume than streams flowing through younger-growth, managed forests [*Beckman and Wohl*, 2014; *Wohl and Jaeger*, 2009; *Wohl and Cadol*, 2011; *Wohl and Beckman*, 2014b].

Although some of these management activities have long since ceased, reduced wood loads in managed streams persist due to the time required for trees to reach old-growth age (>200 years) [*Veblen*, 1986; *Kaufmann*, 1996] and removal of instream wood to maintain infrastructure. The widespread changes in mountain streams due to these activities have led to reduced frequencies of natural channel-spanning logjams in managed streams. Younger forests with a history of natural disturbances such as wildfire, insect infestations, and blowdowns occur in the study area. These natural disturbances, however, do not typically remove all dead and downed trees from the channel and floodplain, in contrast to land uses such as timber harvest or log floating [*Young et al.*, 1994; *Ruffing et al.*, 2015]. We expect managed streams with a history of timber harvest, tie drives, and wood removal to have lower riparian and instream wood loads than unmanaged streams, and thus lower geomorphic complexity.

Our understanding of the influences of forest stand age, valley geometry, and land use on geomorphic complexity leads to a conceptual model and a series of hypotheses (Figure 2.1). We hypothesize that the three independent variables of forest characteristics, valley geometry, and land use correlate with instream wood abundance and other measures of geomorphic complexity in small streams of the Southern Rockies (*H1*) (Figure 2.1A). We hypothesize that streams flowing through old-growth forest in laterally unconfined valley segments will exhibit the greatest geomorphic complexity, whereas streams flowing in managed stream corridors will exhibit the least geomorphic complexity, regardless of confinement (*H2*). Because laterally confined channels are typically steeper, have correspondingly higher stream power to flush out instream wood and logjams, have fewer wood recruitment sources, and have less floodplain with which to meander and create viable habitat, *H2* also hypothesizes that confined channels will have lower instream wood and geomorphic complexity than their less confined counterparts, and thus managed and confined stream reaches will be similar in wood and complexity metrics. We further hypothesize that the relationship between forest characteristics, land use, and

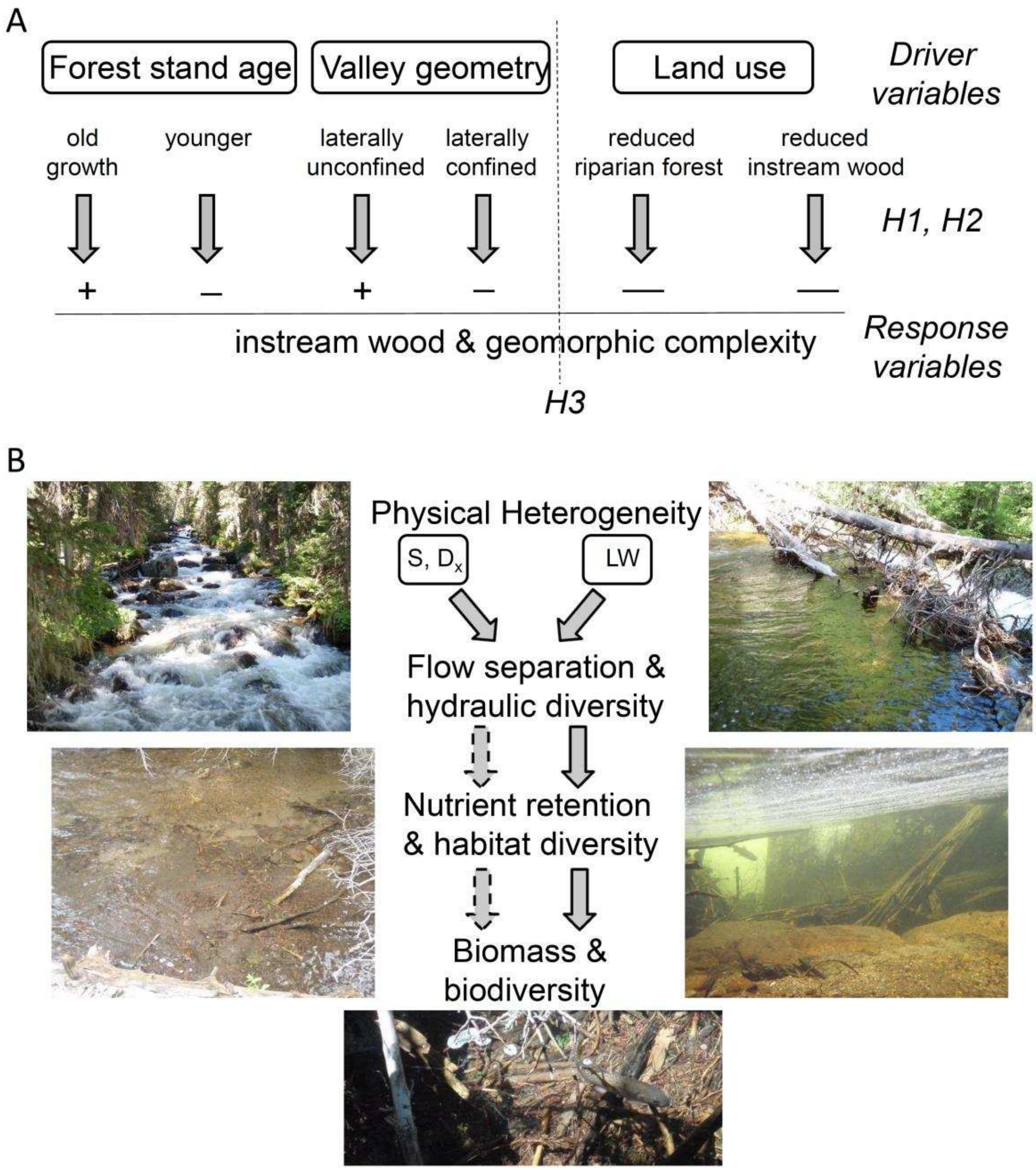


Figure 2.1 Conceptual model and hypotheses to be tested for small streams in the Southern Rocky Mountains. (A) We hypothesize that the combined effects of forest stand age, valley geometry, and land use correlate with instream wood load and geomorphic complexity in a manner that will create significant correlations between the driver and response variables (H1). We hypothesize that old-growth forest and laterally unconfined valleys will correlate with the greatest wood loads and geomorphic complexity, indicated by plus symbols, whereas valley confinement and land use will correlate with lower values of wood load and geomorphic complexity, indicated by minus symbols (H2).We hypothesize a threshold effect such that natural streams differ significantly from managed streams, symbolized by the vertical dashed line (H3). (B) We hypothesize that physical heterogeneity associated with large wood (LW) is greater than that associated with gradient (S) or grain size (Dx) (H4), as indicated by solid rather than dashed outlines for arrows. We expect this greater heterogeneity to result in greater flow separation, retention of fine sediment and organic matter, habitat diversity, and biomass and biodiversity, although we do not test these assumptions in this paper.

geomorphic complexity exhibits a threshold such that streams in old-growth forest and in younger, naturally disturbed forest differ significantly from managed streams (*H3*).

Implicit in this conceptual model and hypotheses are the assumption that instream wood load is the primary instream source of geomorphic complexity. Physical heterogeneity within a channel can also result from differences in substrate grain size or downstream variations in local gradient associated with bedforms, each of which can correspond to differences in substrate, channel width, bed elevation, and cross-sectional shape. We hypothesize that, in the context of promoting nutrient retention, biomass, and biodiversity, physical heterogeneity directly associated with instream wood in the study streams is more effective than heterogeneity associated with factors such as grain size in the absence of wood (*H4*) (Figure 2.1B). Another way to express this conceptualization is to distinguish structural complexity, which includes all forms of physical heterogeneity in the channel, from functional complexity, which includes physical heterogeneity that promotes a specified function such as nutrient retention. In the context of this study, *H4* states that we expect functional complexity to be greatest in wood-rich streams.

Our objectives in this paper are to (i) determine whether there are significant differences in wood characteristics and geomorphic complexity among streams with differing forest stand age, valley geometry, and land use; (ii) identify scenarios that result in greatest functional geomorphic complexity; and (iii) test the conceptual model and hypotheses outlined above.

2.2 Study Area

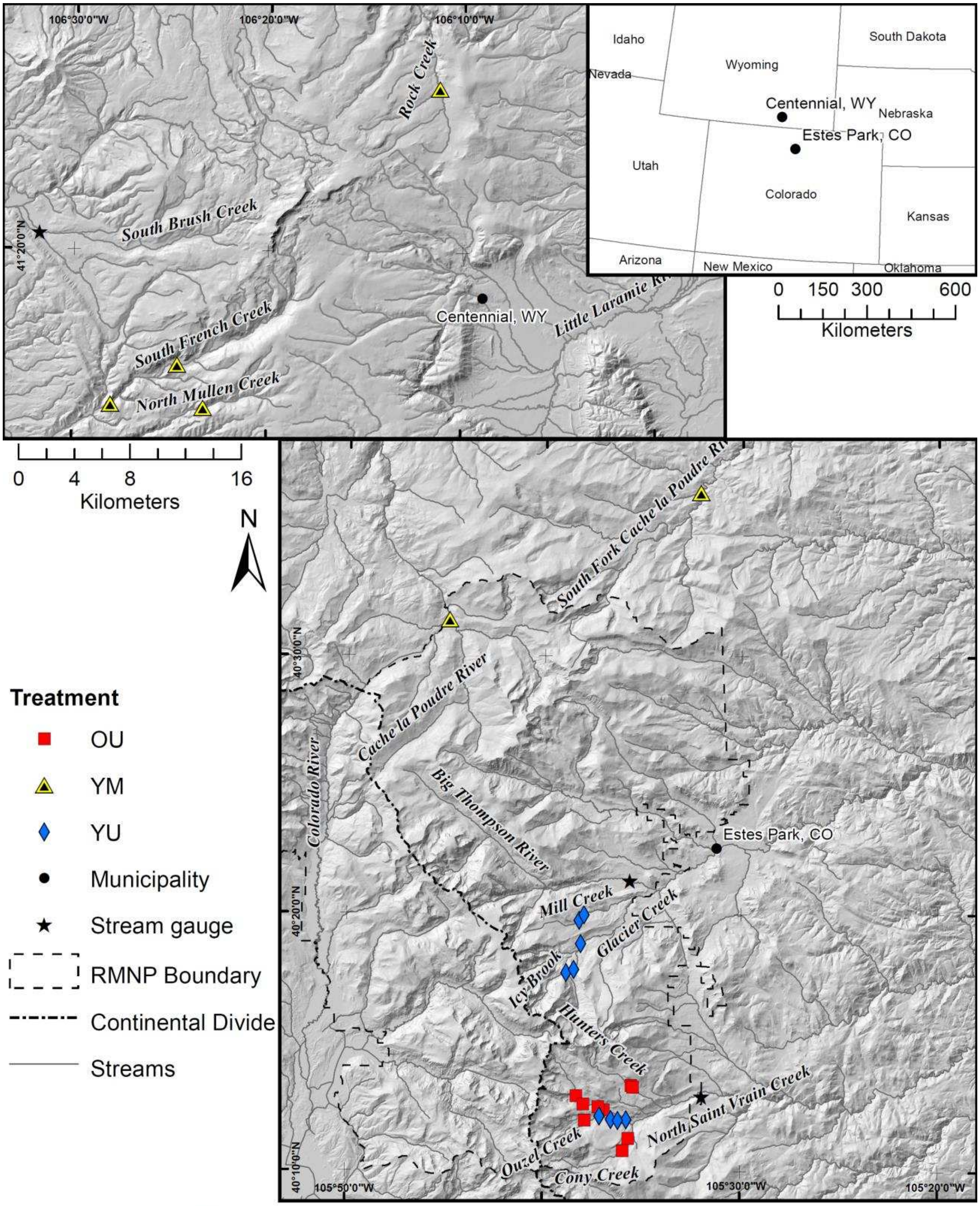
Study reaches are in the Big Thompson, Cache la Poudre, and North St. Vrain drainages in northern Colorado, USA and the North Platte River drainage in southern Wyoming, USA (Figure 2.2). The Colorado drainages, which constitute the majority of stream channels in this study, head on the east side of the continental divide in Rocky Mountain National Park at ~4050 m in elevation and flow eastward through Roosevelt National Forest, eventually flowing into the South Platte River beyond the mountain front at ~1500 m in elevation [*Anderson et al.*, 2006]. The drainages for the Wyoming streams head in the mountains of Medicine Bow National Forest at lower elevations than those in Rocky

Mountain National Park, flowing west, then north to east through Medicine Bow National Forest before meeting the North Platte River.

Precambrian Silver Plume granitic crystalline rocks are the dominant core of the study area, and consist of granite with some biotite schist and granodiorite [*Braddock and Cole*, 1990]. Tectonic activity in the Front Range has been uncommon since the end of the Tertiary [*Anderson et al.*, 2006]. The headwaters of the catchments in this study were glaciated during the Pleistocene epoch. The last major glaciation in the central Rocky Mountains, the Pinedale glaciation, extended down to approximately 2430 m elevation, leaving a prominent terminal moraine [*Polvi et al.*, 2011; *Wohl et al.*, 2004]. Pleistocene glacial advance and retreat removed bedrock and sediments in pulses associated with glacial-interglacial cycles, and glacial erosion widened and deepened valleys, leaving steep valley walls and headwalls and flattened valley bottoms, as well as steps in the longitudinal profile at tributary junctions [*Anderson et al.*, 2006].

In addition to glaciation, valley width and canyon development in the study area are the consequence of patterns of bedrock jointing, with wider valleys corresponding to greater joint density [*Ehlen and Wohl*, 2002]. Spatial variations in joint density within the Colorado Front Range have led to canyons with significant longitudinal variability in valley width and gradient. Stream segments with wide valleys typically have lower gradients and minimal stream-hillslope coupling, whereas stream segments with narrow, bedrock-confined valleys typically have steeper gradients and high stream-hillslope coupling.

Valley width and channel geometry in the study area can alternate through the longitudinal profile at scales of $10^2 – 10^3$ m. Lower-gradient stream segments (0.01-0.03 m/m) with wide valleys can have single- or multithread channels with sand- to cobble-size sediment (Figure 2.3). If the floodplain is at least eight times the bankfull width of the stream channel, these segments are referred to as unconfined (with respect to potential floodplain development). Unconfined valleys can allow the formation of multithread channels throughout a floodplain (Figure 2.3A), and have been shown to retain much more instream wood



Base map: modified from U.S. Geological Survey 10-meter resolution DEM
Hydrology: U.S. Geological Survey National Hydrography Dataset
Projection: UTM, Zone 13N, NAD 1983

Figure 2.2 Location map of the study area showing the location of stream channels in southern Wyoming and northern Colorado and the distribution of treatment categories within the Medicine Bow National Forest and the Colorado Front Range.

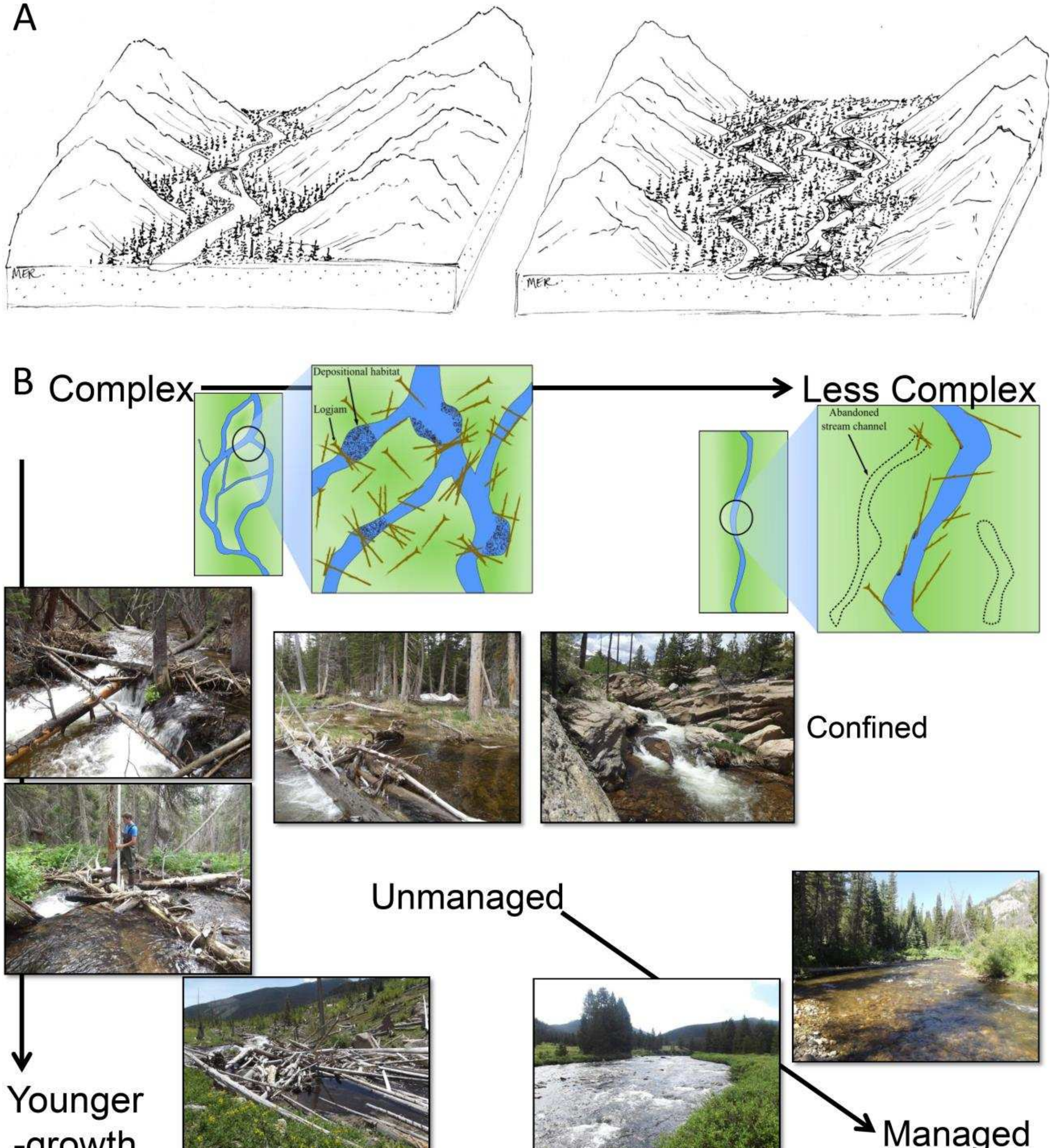


Figure 2.3 Depiction of stream types. (A) Illustration of laterally confined and unconfined valleys. (Drawing courtesy of Mariah Richards.) (B) Detailed views of channel planform and wood loads in complex to less complex streams (left to right). Multithread, unmanaged to single-channel, unmanaged streams, both with high wood loads, occur on left side as a gradient from old-growth to younger-growth forests, respectively. Confined and managed streams on the right side represent less complex streams.

and closely-spaced logjams than confined or single-thread stream segments [*Wohl*, 2011a; *Wohl and Cadol*, 2011; *Wohl and Beckman*, 2014]. Multithread stream channels only occur when biotic drivers such as beaver dams or logjams create obstructions to flow and sufficient backwater to promote overbank flow and avulsion that lead to secondary channels (Figure 2.3B) [*John and Klein*, 2004; *Wohl*, 2011a; *Collins et al.*, 2012]. Conversely, relatively steep stream segments (> 0.03 m/m) in the study area with bedrock-confined valleys (valley width < 2x bankfull width) only have single-thread channels with cobble- to boulder-sized sediments and cascade or step-pool morphology (Figure 2.3B) [*Montgomery and Buffington*, 1997].

Mean annual precipitation for the upper North St. Vrain Creek catchment is 70-80 cm and the hydrograph is dominated by snowmelt, peaking in May-June [*Wohl et al.*, 2004]. Characteristic subalpine forest species in the unmanaged portion of the study area are Engelmann spruce *(Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*Pinus contorta*) with stand-killing fires that recur ca. 300-400 years [*Veblen and Donnegan*, 2005]. Debris flow disturbances are rare. A gaging station on North St. Vrain Creek catchment in Rocky Mountain National Park (1926-2011) had a mean annual peak discharge of 20 m^3/s and peak unit discharge of 0.24 $m^3/s/km^2$ [*Wohl and Beckman*, 2014]. The Big Thompson River below Moraine Park (1995-1997, 2001-current) has a mean annual peak discharge of 16.7 m^3/s and peak unit discharge of 0.16 $m^3/s/km^2$ [*USGS NWIS*, 2015a]. A USGS gaging station (06622900) located on South Brush Creek, Wyoming that has the most representative drainage area and location for reaches in Medicine Bow National Forest, was maintained during 1960-1972, 1976, 1989-1990, and 2002-2014. It has a mean annual peak discharge of 12.3 m^3/s with a peak unit discharge of 0.21 $m^3/s/km^2$ [*USGS NWIS*, 2015b]. All of these gages are within the glaciated zone.

Management history in our study reaches specifically refers to a history of timber harvest and tie-drives associated with logging operations. In the Colorado Front Range and southern Wyoming, accessible riparian forests were clear-cut, large boulders and instream wood pieces were removed from stream channels, and timber was sent en masse downstream. Although timber harvest in our managed study reaches ceased by the mid-20th century and forests in some places have regrown, tie-drives simplified stream channels by homogenizing channel geometry and sediment size and removing any instream wood present before these land use changes.

2.3 Methods

2.3.1 Field methods

Field reaches were chosen based on land use and management history (human activity), as well as natural disturbance history. Surveyed channel reaches were located on second- to fourth-order streams in subalpine forests of Rocky Mountain National Park (RMNP) and Arapaho-Roosevelt National Forest (ARNF), Colorado and the Medicine Bow Mountains, Wyoming (Figure 2.2). Channel segments were categorized into three treatments: old-growth unmanaged forests (OU), younger-growth unmanaged forests (YU), and younger-growth managed (YM) forests. These categories are based on watershed land use, management history, and history of natural disturbance. Riparian stand age in OU forests is 200 years or more and there is no history of timber harvest, flow regulation, or placer mining. YU forests have a riparian stand age less than 200 years because of natural, stand-killing disturbances such as wildfire, blowdown, or insect infestation. YM forest streams have a riparian stand age less than 200 years and historical timber harvest (all YM forests are at least 50 years in age) and/or log floating. Some of the streams also have contemporary flow regulation or road corridors.

We collected field data over the two summer field seasons of 2013 and 2014. The first field season involved detailed assessments of five stream segments with each treatment represented (“intensive” reaches), while the second field season involved fewer measurements of 19 stream segments with each treatment represented (“extensive” reaches). The five intensive reaches included three reaches in OU: one confined reach and two unconfined reaches. A confined reach was chosen in order to evaluate how hydraulic differences, represented by confinement, affected wood storage and complexity given abundant wood recruitment sources from OU forest. The other two intensive reaches represented YU and YM treatment types.

Site selection was based on knowledge of watershed land use and management history, as well as accessibility. We aimed to have an even number of streams for each treatment, along with a range of valley confinement between reaches. Stream segments were chosen to have similar elevation, drainage area, gradient, and climate to the greatest extent possible. However, forest disturbance history made it impossible to find OU stream reaches with drainage area greater than 18 km^2 and YU stream reaches with drainage area less than 20 km^2.

Table 2.1 provides a detailed summary of the methods used to characterize each variable. Valley bottom width was determined in the field using indicators such as change in slope, vegetation, and area likely to be inundated in higher flows or digitally using changes in slope.

Lengths of individual reaches were variable, ranging from about 150-1000 m in valley length, depending on channel width and the total length of the valley segment before geometry changed downstream. Some reaches were comprised of a single channel whereas other reaches had multithread planform. For streams evaluated during the intensive field season, bankfull was surveyed on 100 m subreaches using field indicators such as changes in bank geometry, slope, or vegetation, in order to record the coordinates of bankfull at each meter along each subreach. Bankfull was surveyed for both stream banks, where vegetation density and space on the stream bank permitted. The coordinates and elevation of the thalweg of subreaches were surveyed similarly.

Streams evaluated during the extensive field season were measured at 4-5 subreaches with approximately equal spacing along the reach. For each reach, endpoints and sampling points were mapped using a handheld GPS device (Garmin eTrex, typically 3-5 m horizontal accuracy). At each sampling point, a number of quantitative variables were measured: bankfull width, water-surface gradient, bankfull depth, valley width, and basal area of the riparian forest (henceforth referred to as forest cover). For multithread channels, each channel was sampled across a transect perpendicular to the valley, aligned with the original sampling point. Because of the predominance of multithread channels in our study, bankfull width measurements were used to create two mean width variables for each reach: mean width of an individual channel and mean total width of all channels across transects. Type of stream morphology

Table 2.1 Field Methods and Calculations for Measured Variables in this study.

Group of Variables	Variable	Methods
Control variables	Treatment	Forest stand age, occurrence or no occurrence of logging and tie-drive activites
	Forest cover (basal area, m^2/ha)[a]	Panama basal area angle gage; ~3x/reach
	Drainage area (km^2)	USGS StreamStats for CO reaches[b]; 10-meter DEMs in ArcGIS 10 for reaches in WY
	Gradient (m/m)	Laser rangefinder[c], measured water-surface gradient ~5 times/reach
	Valley width (m)	Laser rangefinder[c], 10-m DEMs in ArcGIS 10, or Google Earth; measured ~5x/reach
	Confinement	Categorical: confined: valley bottom width (vbw) <3x bankfull width (w); partly confined: vbw ~3-8x w; unconfined: vbw >8x w; continuous: vbw/w
Bed and bank surveys[d]	Bank Survey	Total station, using tape stretched to follow bankfull (banks left and right) location, surveyed bankfull at 1m increments for ~100m, 2-3 surveys/reach
	Thalweg survey	Total station, surveyed thalweg elevation at 1m increments for ~100m, 2-3 surveys/reach
	Longitudinal roughness	(Σ(thalweg residuals))/n [*Gooseff et al.*, 2007]
Cross section variables	Bankfull depth	Stadia rod to measure bankfull depth using indicators mentioned in text; 3 measurements/sample, equally spaced across channel
	Bankfull width	Laser rangefinder[c] using bankfull indicators mentioned in text
	Width coefficient of variation	Width SD/mean width [*Laub et al.*, 2012]
Planform variables	Total channel length and valley length (m)	Followed each channel with GPS, converted to length in ArcGIS 10 or Google Earth, or used GPS endpoints to measure lengths in Google Earth; lengths of individual channels summed for multithread reaches; valley length digitally calculated using GPS endpoints
	Channel area (m^2)	Total channel length * mean bankfull width for each channel
	Valley area (m^2)	Followed valley edges with GPS, converted to area in ArcGIS 10 or Google Earth, or mean valley width * valley length
Wood piece and jam variables	Large wood pieces	All pieces >0.1m diameter (*d*) and >1m length (*l*): measured *d*, *l*, orientation, decay class
	Jams	GPS location, measured average length, depth, width with measuring tape, visually estimated porosity and % particulate organic matter (OM), measured LW pieces
	Jam backwater pools	Measured average length (*l*), depth (*d*), and width (*w*) of pools, estimated volume POM finer than minimum wood piece size by measuring average *l*, *d*, and *w* stored POM

[a]These field methods and associated variables only evaluated on extensive sites; [b]http://water.usgs.gov/osw/streamstats/colorado.html; [c]TruPulse 350B, horizontal accuracy +/- 0.1m; [d]These field methods and associated variables only evaluated on intensive sites

[*Montgomery and Buffington*, 1997] was noted at each subreach, as well as the predominant substrate size (e.g., boulder, cobble). With the exception of forest cover, all variables were also collected several times at all intensive sites.

Bankfull width and valley width data collected in the field were used to create two continuous variables for confinement: confinement using mean width of individual channels and confinement using mean total width of all channels across transects. We calculated both because of the arbitrary nature of the category designations; multithread channels may be considered unconfined when evaluating individual channel widths compared to valley width, but are nearly confined when all channel widths across the valley are summed and compared to valley width. Category of lateral valley confinement was then assigned to each reach based on the categorical designations in Table 2.1.

For each reach, the total channel length and valley length were calculated (Table 2.1). We calculated the ratio of total channel length to valley length, which is different from sinuosity only in that it accounts for multithread channels. Bankfull channel area and valley area were then calculated for each reach and were used to calculate ratio of channel area to valley area.

For all of the reaches in this study, we evaluated all large instream wood pieces (Table 2.1), including orientation in the stream and decay class. Orientation types were: bridge, ramp, buried, pinned, and unattached. Pieces were assigned to one of three decay classes based on presence of bark, limbs, cones, and needles, and whether the piece was decayed or rotten. If three or more large wood pieces were clustered together, we considered this a logjam and recorded a number of measurements, including backwater pool characteristics (Table 2.1).

2.3.2 Statistical analyses

For variables that cumulatively reflect characteristics throughout a reach, such as wood and pool metrics, the totals of the data were normalized for each reach by dividing quantities to achieve the quantity per 100 m of valley length. This was done to account for multithread and sinuous channels because differences of these variables between treatments are a function of greater stream length rather than greater retention per channel length (Appendix F). For each reach, the *proportion of bridge and ramp* *wood pieces*, which are believed to be essential for jam formation [*Beckman and Wohl*, 2014], relative to other orientation types was calculated. In order to calculate the average drop in longitudinal profile caused by logjams, a metric of average logjam height divided by frequency of logjams per 100 m of valley was calculated for each reach that had at least one logjam. Variables representing geomorphic complexity were organized into cross section variables, planform variables, wood piece, and logjam variables (supporting information Table 1).

For the 22 raw quantitative variables in supporting information Table 1, we calculated mean, range, and standard deviation for the three treatments (supporting information Table 2). Using all individual measurements of bankfull depth, bankfull width, and water-surface gradient, the standard deviation of each of the three variables for each reach was calculated. In addition, the coefficient of variation of width was calculated for each reach (Table 2.1) [*Laub et al.*, 2012].

Variables were divided into control and response variables. Wood and complexity variables (response variables) are potentially regulated by individual or a combination of control variables, which includes our hypothesized controls (treatment, confinement, and forest cover), as well as other possible controls such as drainage area, gradient, and bankfull and valley widths (supporting information Table 2; Table 2.1).

All statistical analyses were performed using the statistical software RStudio version 3.2.2. For most variables, a log transformation, square root transformation, or either plus a constant was sufficient to attain normality; but *logjams/100 m valley, proportion of bridge and ramp pieces, length ratio, and volume of organic matter in backwater pools /100 m valley* did not have a straightforward transformation to attain normality. For these four variables, we used nonparametric statistical tests for analyses. For all analyses, we determined significance at an α value of 0.05, but we also evaluated results below a *p*-value of 0.10 in order to determine large-scale patterns in the data.

We ran a correlation matrix using all variables and used Pearson's correlation test to determine significant correlation between variables (supporting information Table 3). To address whether the three treatment types exhibit significantly different mean values of control and response variables, we performed an ANOVA test for each of the transformed variables to determine whether there was a significant difference in means of that variable between treatments. Tukey's HSD test was then run for pairwise comparisons to determine which groups had significant differences [*Ott and Longnecker*, 2010]. For variables that were not normally distributed, we performed the nonparametric Kruskal-Wallis analysis of variance test to determine whether there was a significant difference in that variable between treatments, followed by Dunn's test with Bonferroni adjustment to test significant differences in pairwise comparisons [*Dunn*, 1964; *Ott and Longnecker*, 2010]. We performed the same tests between the three confinement types regardless of treatment category for each variable in order to evaluate which variables are specifically influenced by confinement and not just forest history and management. Boxplots for each variable between the three treatments, as well as box plots between the three confinement types for each variable, were created in order to visualize the differences between treatments and confinement types.

Total station data collected at intensive reaches were used to evaluate thalweg and stream bank complexity. The small number of intensive reaches (n=5) limits evaluating differences in bed and bank survey data between treatments. In plotting the data, determining the characteristics of their best fit, and comparing among treatments, we aimed to provide a means of evaluating differences in small-scale channel complexity. For thalweg surveys, elevation data were plotted by distance and the best-fit linear line was fit to the coordinates. We then calculated the standard deviation of the residuals between data points and the best-fit line for each thalweg survey for each intensive reach as a complexity metric. We also calculated longitudinal roughness using each thalweg survey. After transformation, if possible, we ran the same analyses as above to determine whether there were significant differences of *thalweg SD* and longitudinal roughness between treatments.

Stream bank data were plotted by their x-y coordinates for each individual bank that was surveyed with the total station. Because of the large-scale complexity associated with meandering, we fit polynomial lines to the data points that appeared to best fit the meandering shape of the stream channel in order to capture the smaller-scale complexity of stream banks unassociated with meandering. Fourth level polynomial lines were the highest polynomial level used. We then calculated the standard deviation of residuals and ran the same tests as we did for thalweg data to determine significant differences between treatments.

In order to determine how complexity and wood variables relate to one another and to sampled streams, we ran three principal components analyses (PCAs): on all wood and complexity variables; on all wood variables; and on all complexity variables. PCA reduces dimensions of data by creating components, or new variables, that combine variables that have redundant explanation of variance in data. The components rotate data to account for this variance, with variables centered and scaled before analysis. Each PCA produces an equal number of principal components (PC) to the number of variables analyzed. However, generally only the first two to three PCs are retained for further analyses, as they explain the most variance in the original data. For each of the PCAs, we retained variance explained for each PC and produced a biplot which displays the location and magnitude of each variable, as well as the location of each sampled reach, in PCA space.

Results of PCAs were used as response values to evaluate how the nine potential control variables relate to wood and complexity variables, as well as the role of wood as a control or response variable. For each of the three PCAs, reach scores from the first two PCs were first run through a varimax rotation, which rotates the data to produce new, independent scores for each PC. The new set of PC reach scores were then used as the response variable in multiple linear regressions; the first two PCs for each of the three PCAs were retained, for a total of six variables. Using both forward and backward stepwise selection, linear regressions were run for each of these six response variables using all six possible control variables to select significant control variables. The control variables in the model with the lowest Akaike Information Criterion (AIC) were chosen for each linear regression [*Akaike*, 1973]. These models were then run, and the model's *p*-value and *p*-values for each of the control variables used in the model were retained and evaluated to determine controls on response variables. This analysis was also run for complexity PCs with wood variables as the control to determine whether wood variables exerted more control on complexity response than watershed control variables.

2.4 Results

2.4.1 Instream wood and channel complexity differences between treatments

A total of 24 reaches were evaluated: nine OU reaches, nine YU reaches, and six YM reaches (Appendices A, B, and C). *Mean total channel width*, *valley width*, and confinement variables are not significantly different between the three treatments, but *mean individual channel width* is significantly higher in YM reaches (Table 2.2; Appendix D). *Forest cover* is significantly different between all treatments, with OU reaches having the greatest forest cover and YM reaches having the least forest cover (Table 2.2; Figure 2.4, left panel). This is the general trend of nearly all wood and complexity variables (Figure 2.4, left panel): OU has the highest mean values for wood storage and complexity, whereas YM has the lowest mean values (Appendix D). OU multithread reaches have the greatest channel length to valley length ratio, logjam backwater pool volumes, logjam organic matter storage, and backwater pool organic matter storage, whereas YM single-channel reaches and confined reaches have the smallest values of these variables. With respect to other control variables, *drainage area*, *gradient*, and *mean individual channel width* are significantly different between some of the treatments, whereas *mean total channel width*, *valley width*, and continuous measures of confinement are not. OU reaches tend to have small drainage areas, steep gradients, smaller individual channel widths, and variation in confinement, whereas YM reaches have larger drainage areas, flatter gradients, and are consistently partly confined. Trends for some of the variables, particularly cross section variables related to width, depth, and gradient, are better defined between confinement types rather than treatment types (Figure 2.4, right panel). Width and confinement variables are significantly correlated with many wood and complexity variables (Appendix E).

Table 2.2 Significant Differences of Wood and Complexity Variables Between Treatments[a]

Group of Variables	Variable	Trans.	ANOVA/ KW p-value	Pairwise Comparison		
				OU-YU	OU-YM	YU-YM
Control variables	Confinement (ind. ch. width) (m/m)	log	0.74	1.00	0.77	0.76
	Confinement (tot. ch. width) (m/m)	log	0.11	0.35	0.10	0.65
	Forest cover (basal area, m^2/ha)[b]	normal	**<<0.01**	**<<0.01**	**<<0.01**	**0.01**
	Drainage area (km^2)	1/log	**<<0.01**	0.95	**<<0.01**	**<0.01**
	Gradient (m/m)	log+0.01	**0.03**	0.82	**0.03**	0.08
	Valley width (m)	log	0.09	0.99	0.13	0.11
	Mean individual channel width (m)	log	**0.04**	0.99	**0.05**	0.06
	Mean total channel width (m)	log	0.08	0.17	0.88	0.10
	Ind. ch. width/depth	log	**<0.01**	0.83	**0.02**	**<0.01**
	Tot. ch. Width/depth	log+.01	**0.04**	0.08	0.90	0.06
Wood piece variables	Jams/100 m valley (#)		**<0.01**	0.77	**<0.01**	**0.01**
	Wood volume/100 m valley (m^3)	log	**<0.01**	0.27	**<0.01**	0.10
	Pieces/100 m valley (#)	log+10	**<0.01**	0.75	**<0.01**	**0.02**
	Proportion of bridges & ramps		**0.02**	0.61	0.06	**<0.01**
	Bridges & ramps/100 m valley (#)	log+1	**<0.01**	0.69	**<0.01**	**0.03**
Planform variables	Area ratio (m^2/m^2)	normal	**0.03**	0.11	**0.04**	0.72
	Length ratio (m/m)		0.09	0.06	0.17	1.00
Cross section variables	Depth SD	log	0.69	0.99	0.69	0.76
	Width SD	1/sqrt	0.56	0.54	0.92	0.83
	Width CV	log	0.10	0.45	0.07	0.50
	Gradient SD	sqrt	**0.01**	0.65	0.06	**0.01**
Jam variables	Pool volume/100m valley (m^3)	log+1	**<<0.01**	0.14	**<<0.01**	**0.01**
	Jam OM volume/100 m valley (m^3)	log+0.1	**0.04**	0.45	**0.03**	0.23
	Pool OM volume/100 m valley (m^3)		**0.04**	1.00	**0.04**	**0.04**
	Avg jam height/jam frequency (m/#)	log+0.1	**<0.01**	0.67	**<0.01**	**0.03**

	Variable	Trans.	ANOVA p-value	OU-YM	YU-YM	YM-C	OU-C
Bed and bank surveys[c]	Bank SD	log	0.06	0.07	0.12	0.75	0.77
	Thalweg SD	log	0.15	0.60	0.82	0.12	0.38
	Longitudinal roughness		0.08	0.97	1.00	0.37	0.03

[a]ANOVA was performed on variables that could be transformed to normal distribution while Kruskal-Wallis was performed on variables with no tranfsformation. Bolded *p*-values indicate statistically significant differences. OU: Old-growth, unmanaged; YU: Younger-growth, unmanaged; YM: Younger-growth, managed; C: Confined; [b]Only extensive sites evaluated; [c]Only intensive sites evaluated and only displaying pairwise comparisons with relatively low *p*-values

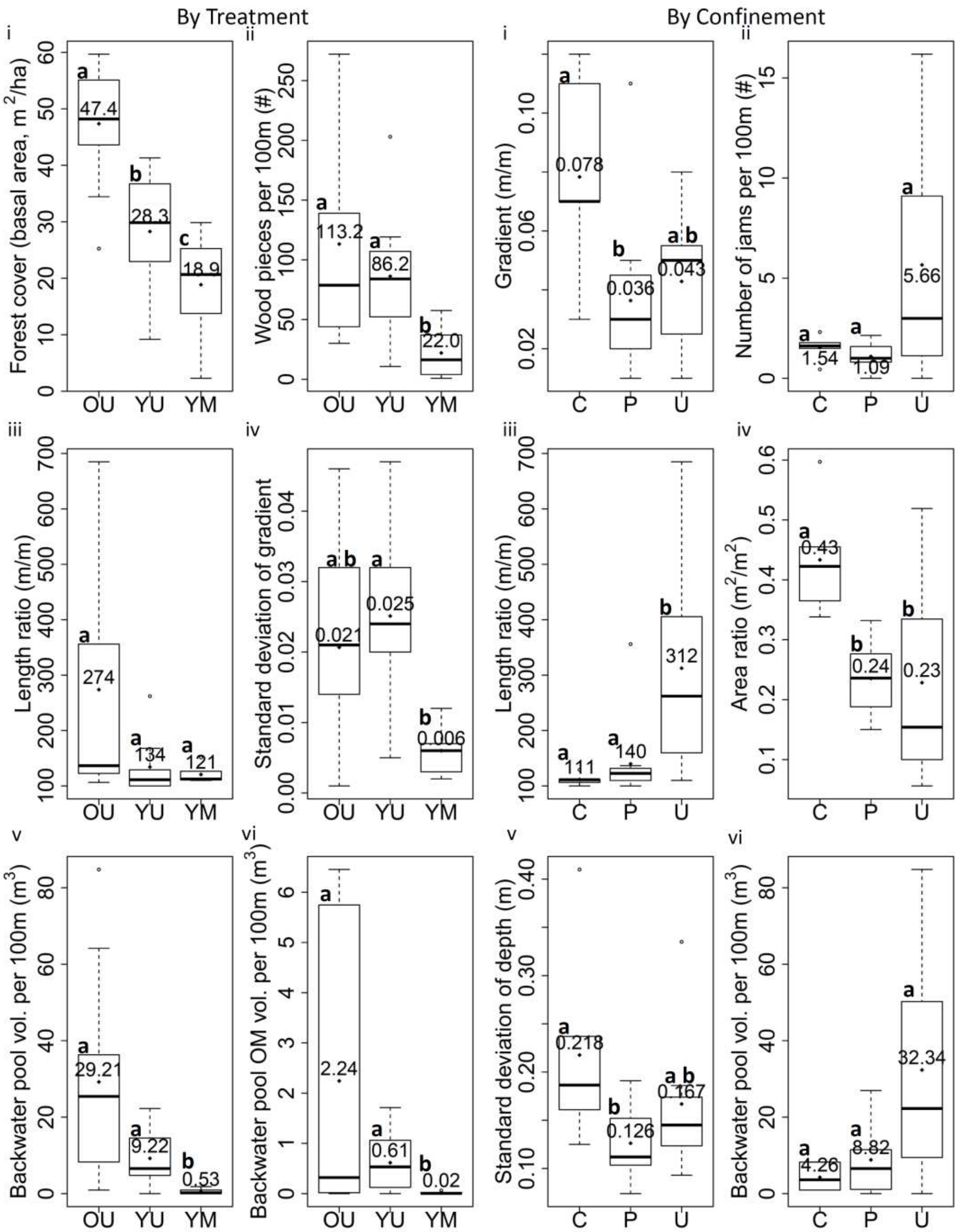


Figure 2.4 Box and whisker plots of selected wood-related and complexity variables, with mean labeled for each group and letters above boxes indicating statistically significant groupings. (Left panel) Patterns between streams in the three treatment categories of old-growth, unmanaged streams (OU), younger growth, unmanaged streams (YU), and younger growth, managed streams (YM); i: forest cover as basal area; ii: number of wood pieces per 100 m valley length; iii: length ratio (total length of all channels/length of valley); iv: standard deviation of gradient; v: backwater pool volume per 100 m valley; vi: backwater pool organic matter volume per 100 m. (Right panel) Patterns between streams in the three lateral valley confinement categories of confined (C), partly confined (PC), and unconfined (U) (confinement categories defined in Table 2.1); i: gradient; ii: number of logjams per 100 m valley; iii: length ratio; iv: area ratio (total area of all channels/valley area); v: standard deviation of depth; vi: backwater pool volume per 100 m valley.

All wood piece and logjam variables have significant differences between at least two of the treatment categories, but cross section variables typically do not (Table 2.2). Despite significant differences in forest cover, OU versus YU reaches do not have significant differences in other control variables, wood variables, or complexity variables. However, both of the unmanaged treatments typically are significantly different than the managed reaches in wood and complexity variables, with the exception of cross section variables. The strength and occurrence of significant differences between OU and YM reaches are almost always greater than differences between YU and YM reaches, indicating a gradient of wood storage and complexity across the treatments.

2.4.2 Bed and streambank complexity analyses of intensive reaches

Data from bed and bank surveys (Appendix G), as well as calculated longitudinal roughness, did not indicate significant differences between treatments at α of 0.05, but a few of the comparisons with *p*-values between 0.05 and 0.10 are notable (Table 2.2). Standard deviation of bankfull surveys between OU and YM reaches are significant at α values of 0.10. Longitudinal roughness between OU and confined reaches are also significant at α of 0.10. Results of the thalweg surveys had the least significance among survey data.

2.4.3 Multivariate analyses of variables that control stream complexity

Figure 2.5 shows the orientation of the response variables and the location of reaches in PCA space for the three possible combinations of response variables. Table 2.3 explains the patterns seen in Figure 2.5: it displays the proportion of variance explained for each PC in Figure 2.5, R^2 values for the linear regression models, and the significant control variables for each linear regression on individual PC axes. *P*-values in Table 2.3 are only listed for the control variables used in that linear regression, as chosen by stepwise regression and AIC values described in statistical methods; *p*-values in bold denote statistical significance for that control variable in the regression, whereas non-bold *p*-values were not significant in the linear regression. Reaches in Figure 2.5 are labeled by their treatment, categorical confinement, and presence of multithread planform, respectively.

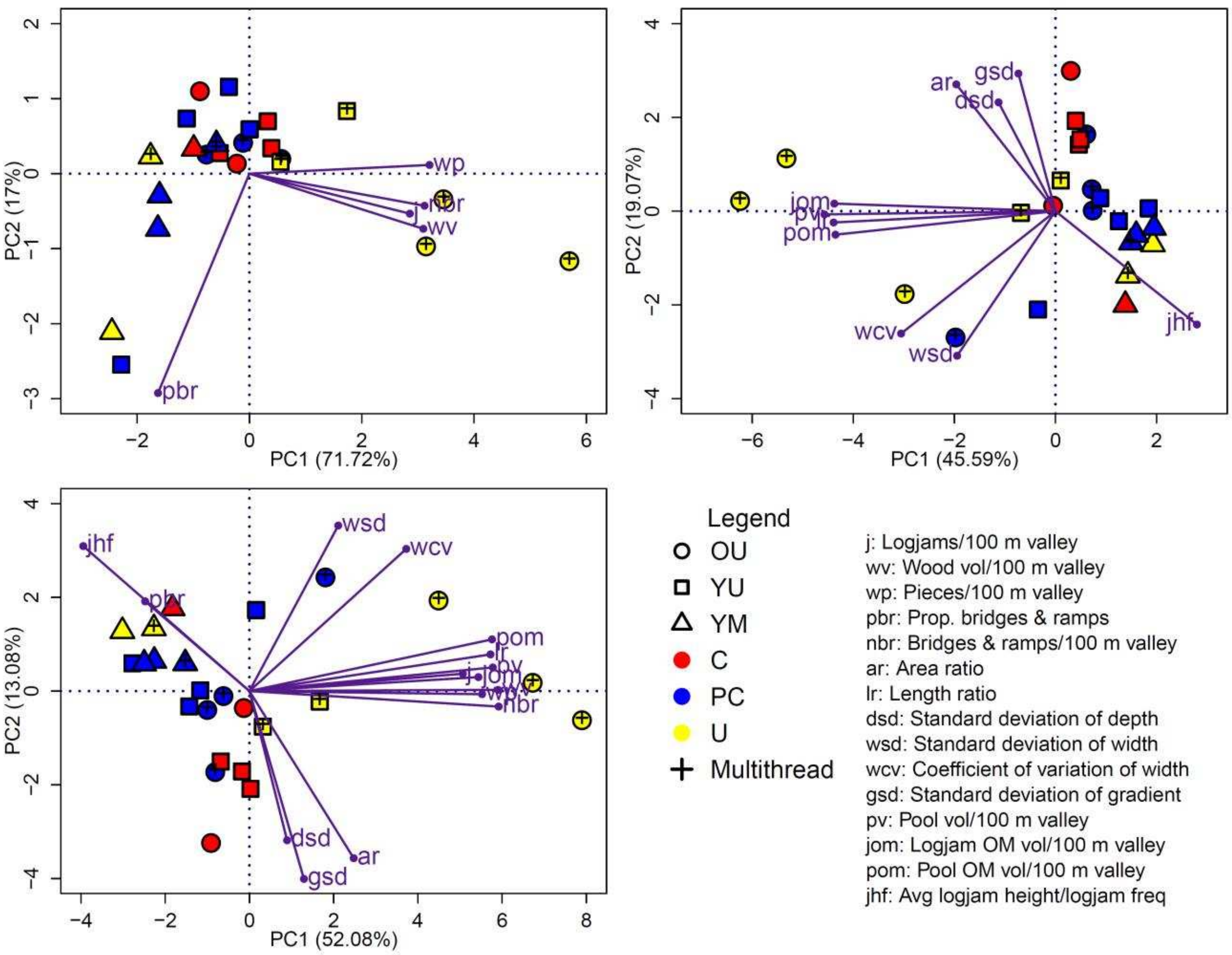


Figure 2.5 PCA biplots with variables and reaches plotted in PCA space. (Top left) Biplot using all wood variables. (Top right) Biplot using all complexity variables. (Bottom left) Biplot using all wood and complexity variables. In each biplot, the lengths of lines correspond to magnitude of influence of variable. Shapes designate treatment, fill color of shapes designate confinement as defined in Table 2.1; plus sign in the symbol designates presence of multithread planform. Response variable abbreviations defined in legend.

In each plot in Figure 2.5, PC1 is the x-axis and PC2 is the y-axis, and reaches and response variables are plotted using their PC1 and PC2 scores, respectively. Significant control variables in Table 2.3 for each axis influence reach PC scores and thus their locations on each plot, as well as the response variable PC scores and their locations on each plot. For example, in Figure 2.5, bottom left, *depth SD*, *gradient SD*, and *area ratio* are oriented with PC2, with low values of PC2 corresponding to high values of these response variables and high PC2 values corresponding to low values of these response variables. Because PC2 is significantly controlled by *mean gradient* (Table 2.3), the response variables that orient with the PC2 axis and the y-values (PC2 scores) for reaches are controlled by *mean gradient* (Figure 2.5, bottom left); confined reaches have the highest mean gradient (Figure 2.4, right panel). Many of the longitudinal complexity variables and wood variables are oriented on PC1 and are significantly controlled by a combination of confinement and management history (Table 2.3; Figure 2.5), with relatively confined reaches and managed reaches having low x-values (PC1 scores) and low values of longitudinal complexity and wood variables.

Management history, or treatment YM, and confinement are the most significant controls on wood and complexity, as they influence all PC1 axes that explain the greatest proportion of variance and have greater R^2 values than analyses on PC2 axes; channel width variables also control complexity variables when control variables are modeled against the complexity-only PC (Table 2.3). PC2 axes are controlled by *mean gradient* or *drainage area*, which are significantly correlated to one another (Appendix E) and are significantly different for YM reaches (Table 2.2). When complexity-only PCs are regressed using wood variables as controls, wood variables are only significant for PC1 (Table 2.3). Many of the complexity variables are oriented with PC2 (Figure 2.5), indicating that wood variables alone cannot explain many of the complexity variables.

Response variables have opposing influences on complexity, as seen by their orientation to one another on the biplots in Figure 2.5. For example, high values of complexity related to width correspond to low values of depth SD, gradient SD, and area ratio. Wood piece variables, with the exception of proportion of bridge and ramp pieces, have the same influence in PCA space as many of the logjam variables and length ratio, meaning those complexity and wood variables are redundant in explaining complexity. Many of these variables are significantly correlated (Appendix E).

Table 2.3 Control Variables on Wood and Complexity Responses as PC Data[a]

					p-values for control variables								
Analysis	PC	Prop. Variance Expl.	*p*-value	R^2	YU	YM	Conf., total width (m/m)	Conf., ind. ch. width (m/m)	Mean total ch. width (m)	Mean ind. ch. width (m)	DA (km^2)	Mean gradient (m/m)	Mean valley width (m)
Wood PC ~control	1	0.72	**<<0.01**	0.88	0.93	0.08	**<<0.01**	**<<0.01**	0.06	0.07			
	2	0.17	**<0.01**	0.29							**<0.01**		
Comp. PC ~control	1	0.46	**<<0.01**	0.92	0.21	**<0.01**	**<<0.01**	**<<0.01**	**0.03**				
	2	0.19	**<<0.01**	0.60						**0.03**		**<0.01**	**0.02**
Wood+ Comp. PC ~control	1	0.52	**<<0.01**	0.90	0.48	**0.02**	**<<0.01**	**<<0.01**					
	2	0.13	**<<0.01**	0.60								**<<0.01**	0.06

Analysis	PC	Prop. Variance Expl.	*p*-value	R^2	Jams/ 100 m valley (#)	Wood vol/ 100 m valley (m^3)	Pieces/ 100 m valley (#)	Prop. bridges & ramps	bridges & ramps/ 100 m valley (#)
Comp. PC ~ Wood Variables	1	0.46	**<<0.01**	0.94	**<0.01**	0.19	**<0.01**	0.13	**<<0.01**
	2	0.19	0.16	0.16			0.12	0.08	

[a]PC axes and proportion variance explained correspond to data in Figure 2.5. Variables with bolded *p*-values indicate statistically significant control on the response PC. YU: Younger-growth, unmanaged; YM: Younger-growth, managed; DA: drainage area.

2.5 Discussion

2.5.1 Instream wood and channel complexity differences between treatments

The results support *H1* by indicating significant differences in wood load and other measures of geomorphic complexity in relation to forest stand characteristics, valley geometry, and land use. The results also support *H2* in that streams flowing through old-growth forest in laterally unconfined valley segments have the largest wood loads and the greatest functional geomorphic complexity as indicated by backwater pool volume, storage of organic matter in backwater pools, standard deviation of channel width and depth, and the ratio of channel area to valley area (Table 2.2; Figure 2.4, left panel; Figure 2.5).

The greater volumes of wood in OU reaches confirm previous work on streams in unmanaged and managed forests in the study area [*Beckman and Wohl*, 2014b]. Wood loads in YU reaches are not different from OU but do differ significantly from YM, indicating that forest cover does not control wood loads. The same pattern is typical of complexity variables that have significant differences, with YM having significantly less complexity than unmanaged streams (Table 2.2; Figure 2.4, left panel). These results support *H3* and suggest that legacy effects of logging and removal of instream wood lead to lower wood loads and complexity in managed streams, even when managed streams are compared to streams flowing through natural forest of an age similar to the riparian forest in the managed streams.

The *proportion of bridge and ramp pieces* is highest in YM and confined streams and lowest in OU streams despite the opposite trend in *number of bridge and ramp pieces/100m* (Figure 2.5; Appendix D). This indicates that the frequency of bridge and ramp pieces, rather than proportion of those pieces relative to wood with other orientations, results in greatest wood storage and complexity. Average *logjam height/jam frequency* is also greatest in YM reaches because of the low frequency of logjams (Figure 2.5). This variable, like *proportion of bridge and ramp pieces*, is lowest in OU reaches because it represents the inverse of how much elevation drop is caused by logjams. These two variables are redundant in PCA space but represent a different measure of complexity from other categories due to their independence from other groups of variables on a biplot. Small values of *logjam height/jam frequency* result in a high longitudinal drop from logjams, and this complexity metric is a separate longitudinal metric from others such as pool volume and organic matter storage.

The location of cross section variables in PCA space explains why there are few significant differences in these variables between treatments. Cross section variables are loaded on PC2, meaning they explain less of the variability in the data than variables loaded on PC1, which supports *H4* (Figure 2.5). In addition, PC2 is generally explained by gradient and valley width, both of which correlate significantly to confinement (Appendix E). Greatest values of *depth SD* and *gradient SD* are found in confined channels regardless of treatment, which is likely a reflection of greater clast sizes and steepness of confined channels. Cross section variables thus represent structural complexity, but may not contribute to functional complexity in the study reaches. Complexity variables related to width are greatest in multithread, relatively unconfined channels because there are multiple channels in each reach that can have a greater range of widths than a single channel sampled many times; the significantly smaller individual channel widths in OU and YM also contribute to the retention of greater wood volumes, as large wood pieces are less likely to be mobile in smaller channels.. *Polvi et al.* [2014] also found that cross section variables were not significant in analyzing complexity across a gradient of treatments related to management history. Even where variables were not significant between treatments in the ANOVA, there are larger ranges of values in OU reaches than in YM, indicating greater complexity through variability in complexity values (Figure 2.4, left panel).

Confinement plays a role in the ANOVA results (Figure 2.4, right panel), as all three confinement categories occurred in each treatment. Because confinement, which is dependent on valley width, influences gradient and potential for multithread planform, having a range of confinements in each treatment prevents *length ratio*, *valley width*, and cross section variables from being significantly different between treatments. More channel measurements of width, depth, and gradient for each reach could also help in understanding how cross section variables contribute to channel complexity.

In summary, the significant differences in geomorphic stream complexity depend on the complexity metric being evaluated. Significant differences between treatments appear to result primarily from differences in individual channel widths, individual wood pieces and logjams within the streams, and to a lesser extent from differences in the ratio of channel area to valley area (which primarily reflects the presence of multithread channels in OU reaches). Significant differences in geomorphic complexity as measured by the ratio of channel length to valley length, and the cross-sectional metrics of standard deviation of channel gradient, bankfull width, and depth, correlate more strongly with differences in valley lateral confinement than differences between treatments. Measures of functional complexity related to stream retention (pool volume and organic matter storage) correlate more strongly with wood and logjam variables than with cross-sectional metrics.

2.5.2 Bed and streambank complexity analyses of intensive reaches

ANOVA analyses for surveys and *longitudinal roughness* were run with low *n* values for treatments, which is one explanation for why significant differences were difficult to achieve. More surveys per treatment, including confined reaches as a separate treatment, could provide more insights into differences reflected in bed and bank surveys. We expected confined channels to have greater values of *thalweg SD* and *longitudinal roughness* because of steeper gradients (Figure 2.4, right panel), step-pool and cascade morphology, and clast sizes of confined channels. Although *thalweg SD* differences between the four groups were not statistically significant, the confined reach had the greatest value, followed by OU, YU, and YM, suggesting thalweg complexity has the expected pattern between treatments.

At α of 0.10, bankfull surveys exhibit the expected patterns in that unmanaged reaches have greater *bank SD* values than the managed reach, which is most similar to the confined reach. Because of methods used in total station surveys, we were unable to use bankfull measurements as a means to evaluate *width SD*, which we believe may have produced more statistically significant results. Large-scale complexity such as meanders may have hindered our ability to capture smaller-scale complexity found in stream bank irregularities. As in extensive sites, we expect that a greater sample of widths may result in greater statistical significance between treatments.

2.5.3 Multivariate analyses of variables that control stream complexity

Results of the PCA biplots and linear regression analyses indicate that treatment and confinement are the dominant controls on stream channel complexity, and YM, or a history of management, results in low values of complexity variables. The analysis also revealed that the variables we analyzed represent four different groupings of complexity measures, related to wood pieces, channel width, other cross-sectional measures (depth, gradient, area), and logjams (Figure 2.5, bottom left). Most wood piece variables represent the same complexity characteristics as *backwater pool volume/100m valley*, both organic matter storage variables, and *length ratio*. Wood characteristics appear to directly influence these complexity variables and could represent a mediator between forest history and complexity (Table 2.3). However, these are the only complexity variables that appear to be directly influenced by wood characteristics.

Complexity variables associated with width measurements represent the second group of complexity characteristics, while *depth SD*, *gradient SD*, and *area ratio* represent the third. These two groups represent different aspects of complexity, but share an axis in PCA space. This axis is controlled by gradient, *mean individual channel width*, and *valley width* (Table 2.3), all of which are dominated by the influence of confinement and multithread channel planform (Figures 2.4, right panel and 2.5). Confined channels have the greatest variability in gradient and depth, hence their location in PCA space. *Area ratio*, or the amount of valley space the stream occupies, is high in confined channels and in multithread channels (Figure 2.4, right panel), which is why that variable loads between these two channel types in PCA space. This complexity metric is thus not very useful in determining high levels of complexity. Width variables are highest in multithread channels, likely because of the variation in widths associated with measuring many separate channels rather than multiple width measurements from a single-channel stream. Because multithread planform equates to high complexity, but is different than how width changes in a single channel, a braiding index applied to anastomosing channels, or average number of anabranch channels, may be a more appropriate measure of complexity than *width SD* or *width CV*. Greater numbers of individual channels in a valley likely equate to greater opportunities for pools, nutrient storage, and habitat diversity for aquatic biota (Figure 2.1B). The fourth grouping includes *proportion of bridge and ramp pieces* and *logjam height/jam frequency*, and distinguishes low-wood managed and confined streams; in other words, these variables define low-complexity channels. Mean gradient is a significant control variable for PC2 axes assessing complexity variables in Table 2.3, but because YM has a significantly lower slope from other treatments, corresponding to greater drainage area, we believe these results may be responding more to treatment and confinement rather than high gradients corresponding to high complexity and wood storage.

Although Figure 2.4, left panel appears to suggest a uniform gradient of wood characteristics and channel complexity based on forest age and management history, the two unmanaged treatments are not typically significantly different from one another, whereas both are typically significantly different from managed reaches (Table 2.2). In addition, all three biplots show YM reaches clearly distinguished in PCA space from the other two treatments, suggesting a threshold effect related to management history (Figure 2.5). In order to evaluate the relevance of YM reaches for channel complexity, we ran the same PCAs and regressions against control variables without YM reaches and found that PCs explained less variance in the data and only PC1 was ever significant. Thus, patterns of complexity are more difficult to discern without YM reaches, which represent a baseline for non-complex stream channels in our analyses. Despite gradient of forest cover (Figure 2.4, left panel), management history creates a threshold, and the effect on complexity of removing wood and wood sources is greater than the effect of natural disturbances to previously undisturbed forests (Figure 2.1A). In other words, old-growth riparian forests are not required for greater complexity as long as wood is not removed from stream channels.

We find that high levels of complexity and wood storage in mountain streams of the Southern Rockies are related to high forest cover, lack of human disturbance, and relatively unconfined valleys. Some complexity variables represent different aspects of heterogeneity which are trade-offs, such as variation of depth and variation of width, indicating the need for explicit ecological and functional complexity goals in stream restoration projects. The greater physical heterogeneity provided by wood through flow separation and hydraulic diversity hypothetically leads to greater potential habitat and nutrient retention in pools and irregular banks, as well as greater biomass and biodiversity (Figure 2.1B): whether our measures of complexity lead to these responses is a possibility that will be tested in subsequent papers.

2.6 Conclusions

The results of this investigation of small mountain streams in subalpine forests of the Southern Rockies suggest that riparian forest stand age and management history, along with valley geometry, significantly influence instream wood load and characteristics of wood pieces, such as number of bridges and ramps and number of channel-spanning logjams. Wood load and wood characteristics in turn influence variables such as pool volume, organic matter storage, and the ratio of channel length to valley length (Figure 2.5; Table 2.3). Despite slightly lower wood loads and complexity values in younger versus old-growth forests in unmanaged streams, we find that management history of riparian forests exerts the strongest control on reduced functional stream channel complexity, regardless of riparian forest stand age. Lateral valley confinement is a primary influence on cross-sectional variables such as the standard deviation of bankfull depth and local gradient, and on the ratio of channel area to valley-bottom area. Overall, the most geomorphically complex streams are those in old-growth forest with laterally unconfined valleys and multithread planform. Streams in younger unmanaged riparian forest and laterally unconfined valleys are more similar to these streams than are streams in younger riparian forest with some history of land use. The results also support our initial conceptual model (Figure 2.1) and suggest that instream wood is a primary driver of physical heterogeneity in these streams.

Our results also indicate that the legacy effects of removal of riparian forests and instream wood have resulted in long-lasting reductions of instream wood loads and geomorphic complexity in small stream channels within subalpine forests of the Southern Rockies. Management or restoration projects aiming to restore wood loads and functional geomorphic complexity should focus on maintaining or allowing growth of riparian forests, which is of particular importance in stream channels with relatively unconfined valley bottoms that have the potential to form a multithread planform. Our results indicate that natural disturbances are as important as old-growth forest in sustaining geomorphic complexity, suggesting that retaining dead wood in the stream corridor is a key passive restoration technique for streams. Any restoration technique that involves addition of wood should focus on number of bridge and ramp pieces, which are key in trapping additional instream wood [*Beckman and Wohl*, 2014b], particularly if management goals involve greater backwater pool volumes and storage of particulate fine organic matter.

Although stream restoration can be explicitly designed to increase geomorphic complexity [*Wohl et al*., 2015], there is currently no consensus on how to characterize complexity, let alone quantify metrics of complexity. As noted by *Polvi et al*. [2014], this suggests that restoration designed to increase complexity should consider diverse forms of complexity that reflect site-specific constraints such as valley geometry and riparian vegetation, and focus on functional complexity designed to foster specific goals of restoration.

Ongoing changes to forest ecosystems associated with warming climate have the potential to alter the magnitude of geomorphic complexity of subalpine forest streams by changing the recruitment of wood to channels via wildfire, insect infestations, and blowdowns [*Wohl*, 2013; *Dennison et al.*, 2014], as well as the ability of streams to transport wood via changes in flow and sediment regimes [*Goode et al.*, 2012]. Consequently, it is particularly important to document existing levels of geomorphic complexity and relations between complexity and potential driver variables.

The relations among forest stand age, valley geometry, land use, and channel complexity investigated in this study likely apply to many other small, forested streams in diverse environments. Investigations of geomorphic complexity of headwater streams in Sweden, for example, indicate that large-scale factors of valley and channel gradient, as well as land use, drive differences in complexity [*Polvi et al*., 2014], and assessments of complexity in headwater streams of the Southern Appalachians indicate that forested streams containing wood exhibit greater complexity than meadow streams [*Jackson et al*., 2015]. More limited studies link these reach-scale differences in geomorphic context and associated complexity to differences in the dynamics of stream ecosystems [e.g., *Bellmore and Baxter*, 2014]. As we continue to expand our understanding of how geomorphic context, forest history, and land use govern geomorphic complexity and ecosystem function, we may be able to develop more quantitative metrics that can be used to assess whether stream restoration incorporates an appropriate level of complexity for a particular stream segment.

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Chapter 3: Alternative states for stream form, function, and carbon storage in forested mountain watersheds as a result of historic land use

Summary

The concept of alternative states in ecology recognizes that biotic community structure and function can exist in multiple states under the same environmental conditions. Multiple physical states, induced naturally and from human changes to watersheds, have been demonstrated in streams in a number of studies, but have not always been described explicitly as alternative states or supported by field data. We propose that the geomorphic concepts of thresholds, river metamorphosis, and complex response are the geomorphic analog to alternative states in ecology. We use field data from the Southern Rocky Mountains of Colorado and Wyoming in streams flowing through relatively unconfined valleys with old-growth forests, younger-growth, naturally disturbed forests, and forests that have undergone past land use changes such as logging to demonstrate how land use can drive streams across a threshold to induce an alternative state of significantly reduced complexity of stream form, function, and carbon storage in large wood and instream particulate organic matter. Field data show a threshold of differences between unmanaged and managed stream segments, regardless of current forest stand age, supporting our hypothesis that the legacy effects of past land use on riparian forest characteristics leave affected watersheds in an alternative state of stream complexity and carbon storage. Such complexity can maintain aquatic-riparian ecosystem functions, suggesting that the reduced state of managed watersheds can be the physical template for an alternative ecologic state with reduced carbon storage, ecosystem productivity, and biotic diversity. The cumulative effects of reduced carbon storage in mountainous environments experiencing analogous human alteration may have large implications for global carbon budgets. Maintenance of riparian forest buffers around streams in laterally unconfined valley segments is a recommended first-order restoration technique.

3.1 Introduction

Our primary objectives in this paper are to evaluate the evidence for alternative states for mountain streams in forested portions of the Southern Rockies, and to evaluate the influence of potential control variables, including land use, in causing streams to develop alternative states. We define alternative states primarily with respect to channel planform geometry, but we also examine how alternative planform geometries correspond to differences in stream function, as reflected in pool volume, which provides critical habitat for salmonids [*Fausch and Northcote*, 1992; *Richmond and Fausch*, 1995] and other aquatic organisms, and storage of organic carbon in the form of large wood and particulate organic matter (POM). We use field sites from the Southern Rockies of Colorado and Wyoming to address these objectives, but the fundamental nature of the processes that we examine suggests that our results are likely to be broadly applicable to forested mountain streams.

3.2 Background

3.2.1 Forested mountain streams of the Southern Rockies

Valley geometry in streams of the Southern Rocky Mountains varies longitudinally at lengths of $10^1 – 10^3$ m between relatively steep, narrow valley segments and lower gradient, wider valley segments as a result of the history of Pleistocene valley glaciation [*Anderson et al.*, 2006] and spatial differences in the density of bedrock jointing [*Ehlen and Wohl*, 2002]. Stream segments with wide valleys typically have broader and more longitudinally continuous floodplains and lesser stream-hillslope coupling, whereas stream segments with narrow, bedrock-confined valleys typically have minimal floodplains and high stream-hillslope coupling.

Forested streams in the region can exhibit four general morphologies based on valley geometry and the abundance of large wood (LW) (> 10 cm in diameter and 1 m in length) within the bankfull channel. In laterally unconfined valleys, where the floodplain width is at least eight times the width of a single stream channel, streams can exhibit (i) multithread planform as a result of abundant instream LW and channel-spanning logjams that facilitate overbank flows, channel avulsion, and formation of secondary channels; (ii) single-thread planform with low to moderate instream wood loads and lower riparian forest density as a result of groundwater-fed wet meadows on the valley bottom; or (iii) single-thread planform with low instream wood loads and drier floodplains. Here, we test the idea that the first two morphologies occur primarily in old-growth or naturally disturbed valley segments [*Wohl and Beckman*, 2014; *Livers and Wohl*, 2016] and the third morphology, which we interpret as an alternative state, occurs in valley segments with a legacy of human disturbance. The fourth morphology is found in laterally confined valleys, where single-thread streams with higher peak stream power caused by higher gradients and lack of floodplains regularly remove temporarily stored instream wood. Laterally confined valleys appear to have single-thread streams regardless of disturbance history. Land use at the study sites primarily involves timber harvest and log floating between circa 1860 and 1935 AD, although a few of the human-disturbed sites have continuing land use in the form of adjacent roads and/or flow diversions.

In this paper, we evaluate the possibility that land use resulting in reduced wood recruitment to streams and/or historical removal of instream wood has driven small, multithread streams with high wood loads in laterally unconfined valley segments into an alternative state of single-thread channels with low wood loads (Figure 3.1). We propose that this alternative single-thread channel corresponds to an alternative state of stream form, ecological function, and carbon storage that persists for several decades to a century after the last removal of instream wood. We use field data from the Colorado Front Range and the Medicine Bow Mountains of Wyoming to test this idea (Appendices A, B, and C). We focus on streams with potential to be densely forested in laterally partly confined to unconfined valley segments, because 1) we assume that controls on riparian wood strongly influence stream form, function, and carbon storage [*Livers and Wohl*, 2016] and 2) laterally confined stream segments in the region appear to be less responsive to changed riparian inputs [*Wohl*, 2011a].

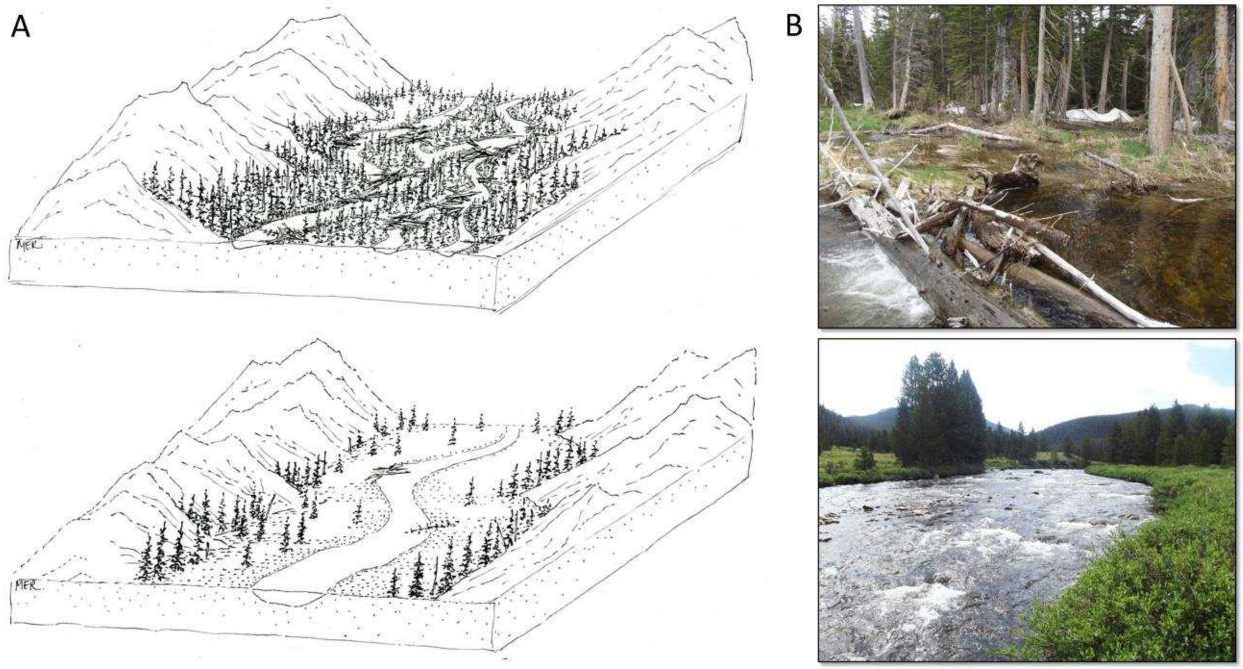

Figure 3.1 Depiction of alternative states of stream form, function, and carbon storage in laterally unconfined valley segments of forested mountain streams. The two states are i) multithread planform with high riparian forest density, wood load, and complexity, and ii) single-thread planform with low riparian forest density, wood load, and complexity. (A) Idealized drawings of alternative states (Drawing courtesy of Mariah Richards) (B) Field photographs of alternative states.

3.2.2 Alternative stable states in ecology

The concept of alternative stable states in ecology proposes that ecological systems can exist in multiple, distinct, and self-reinforcing states in equilibrium under equivalent environmental conditions [*Holling*, 1973; *May*, 1977]. Although the existence of alternative stable states in ecosystems has typically been evaluated based on biologic community structure [*Scheffer et al.*, 2001; *Beisner et al.*, 2003; *Scheffer and Carpenter*, 2003], stable states continue to be controversial because of the difficulty in demonstrating long-term stability and the lack of field-based empirical evidence to support theoretical arguments of existing alternative stable states [*Schröder et al.*, 2005].

In order for alternative stable states to occur, a disturbance or a threshold in response to ongoing changing conditions must be capable of driving an ecosystem into an alternative state or basin of attraction. Once a threshold is reached, the ecosystem then takes a different pathway of recovery, or displays hysteresis, in response to natural disturbances to the ecosystem, which ultimately leads to reorganization of ecosystem structure that becomes self-sustaining in positive feedbacks over time and a new average range of conditions. Evaluation of alternative states largely focuses on biotic communities, but changes to the physical structure of ecosystems can be directly responsible for changes to biota, particularly in systems where there are strong feedbacks between biotic factors and physical attributes of an ecosystem [*Suding et al.*, 2004].

The challenge of demonstrating long-term stability associated with alternative stable states has led to the related concept of alternative states, which can be stable or transient over varying time scales [*Suding et al.*, 2004]. Because the concept of alternative stable states does not have a specific temporal definition, we refer from here forward to alternative states and explicitly discuss potential time spans for the stability of different states.

3.2.3 Geomorphic analogs to alternative states

The concepts of thresholds, complex response, and river metamorphosis are key in geomorphic understanding of how river systems can abruptly change their physical form and function. When a geomorphic threshold is crossed, for example, stream channels can quickly change from transport-limited to supply-limited, causing incision or change in channel planform [*Schumm*, 1973]. This can occur even in the absence of changes in external variables, when gradual changes within a system eventually cause instability in stream functions and an intrinsic threshold is crossed. Complex response describes how channel change (i) can be asynchronous throughout a river basin, with tributaries incising while the mainstem channel is aggrading, for example, and (ii) can repeatedly alternate between aggradation and erosion in response to a single initial perturbation [*Patton and Schumm*, 1975]. River metamorphosis proposes that rivers can undergo an almost complete change in morphology when natural or human-induced changes in water and sediment yield force the river across a threshold [*Schumm*, 1969].

Although not explicitly described in this manner, thresholds, complex response, and river metamorphosis are geomorphic analogs to alternative states in ecology. Geomorphic thresholds are analogous to thresholds that ecosystems cross into other basins of attraction, complex response is analogous to the hysteresis seen in ecological response to these perturbations, and river metamorphosis ultimately describes an alternative state of a river system, which could result in alternative ecological states. Could river metamorphosis provide a template for alternative ecological states in stream systems?

3.2.4 Alternative states in river systems

Alternative states of physical structure and carbon storage have been documented in relatively undisturbed river ecosystems including the Florida Everglades, where adjacent ridges and sloughs create alternative stable patches [*Watts et al.*, 2010], and the deserts of the southwestern United States, where wetlands and deserts form alternative stable states with differing vegetation density [*Heffernan*, 2008]. Land use may also lead to alternative states in stream ecosystems. Wide, shallow, braided, intermittent rivers of the Great Plains were transformed to single-channel, sinuous, perennial rivers with denser riparian vegetation as a result of flow regulation [*Nadler and Schumm*, 1981]. Similarly, human and natural causes pushed streams in the southwestern United States into an alternative state of incised channels [*Webb and Leake*, 2006]. In the Everglades, draining floodplains and impounding streams drove aquatic ecosystems into an alternative state with different hydrology and vegetation [*Watts et al.*, 2010]. Construction and abandonment of milldams along streams in the U.S. Mid-Atlantic Piedmont changed multithread, wet valleys into wider, single-channel streams disconnected from the historical water table [*Walter and Merritts*, 2008]. In these examples, internal positive feedbacks maintained the alternative state after land use changes ceased.

3.2.5 Biotic drivers and multithread planform in mountain streams

The loss of biotic drivers – organisms that strongly influence river process and form – may drive river metamorphosis and create alternative states of riparian-stream ecosystems. Biotic drivers in the form of beavers and old-growth forests in laterally unconfined valley segments of the Southern Rockies can create multithread channel planform via dams and logjams, respectively. Their removal from stream ecosystems can change streams [*Polvi and Wohl*, 2013; *Wohl*, 2013].

Although both beaver meadows and old-growth forests can occur within a single watershed, beaver meadows occur in lower gradient valley segments that retain stream flow and groundwater seepage, limiting conifer growth [*Wohl*, 2013]. The high riparian water table favors deciduous woody riparian species that form an important part of the diet of beavers and beavers build multiple dams that divert water across the floodplain, creating a stable, multithread channel planform [*Polvi and Wohl*, 2012, 2013]. Elk grasslands in Yellowstone National Park exemplify the alternative state of beaver meadows. Elk grasslands developed from beaver meadows after wolves were extirpated from the park, allowing overgrazing of riparian areas by elk. Riparian overgrazing limits deciduous woody riparian species, so beaver populations decline, beaver dams fall into disrepair, and peak stream flows are more likely to be contained within a single channel [*Wolf et al.*, 2007]. A similar scenario has occurred within the past century in the Southern Rockies, particularly in Rocky Mountain National Park, where elk hunting is prohibited.

The floodplain large-wood hypothesis [*Collins et al.*, 2012] describes the historical context of LW as a biotic driver of alternative riparian-stream states in the U.S. Pacific Northwest. Historical LW loads in streams promoted multithread planform with vegetated islands and high diversity and productivity, whereas timber harvest and removal of LW from streams after European settlement resulted in single-channel or braided planforms with altered channel dynamics and reduced habitat diversity. Empirical evidence for these alternative states was described in *Collins et al.* [2002]. The floodplain large-wood hypothesis neatly outlines the feedbacks that promote wood-rich and biologically productive streams or wood-poor streams with minimal productivity [*Collins et al.*, 2012]. A similar scenario has likely occurred within the past century in small watersheds of the Southern Rockies that experienced timber harvest and removal of instream LW [*Wohl*, 2011a].

Nadler and Schumm [1981], *Walter and Merritts* [2008], *Collins et al.* [2012], *Wohl* [2013], and *Wohl* [2014] all find that pre-disturbance, multithread, complex streams became less physically complex, single-thread streams after human alteration of forests, valley bottoms, and/or hydrology. Similarly, *Young et al.* [1994], *Wohl and Beckman* [2014], and *Ruffing et al.* [2015] proposed that 19th-century timber harvest and log floating in forests of the Southern Rockies reduced instream wood loads in a manner that has persisted for more than a century, leading to an alternative state of wood-poor streams in contrast to wood-rich streams of unaltered watersheds. Differences in riparian forests and LW recruitment to streams drive large differences in stream channel complexity, such that streams in watersheds that underwent land use changes are significantly less physically complex (Figure 3.1) [*Livers and Wohl*, 2016]. Could Southern Rocky Mountain streams exist in an alternative state of form, function, and carbon storage after logging and other land use changes?

Prior to European settlement of the Southern Rockies, forested watersheds included a mosaic of forest stand ages, with old-growth patches and stands of younger forest as a result of natural disturbances such as wildfire or blowdowns. Rates of wood recruitment to streams varied through time in response to natural disturbances, but because of very slow rates of wood decay, some wood likely was always present, resulting in wood-rich, multithread streams in valley segments with appropriate geometry (Figure 3.1A). During approximately 1860-1935, accessible riparian forests in the region were clear-cut to supply railroad ties and mining timbers [*Wohl*, 2001]. Existing instream wood and obstructions such as large boulders were removed from stream channels and cut timber was floated downstream to sawmills and collection booms during snowmelt floods. The seasonal pulses of cut logs eroded channel boundaries and removed riparian vegetation, simplifying and homogenizing riparian forests, channel geometry, and clast size distributions within the channel [*Young et al*., 1994; *Ruffing et al.*, 2015]. In homogenizing the stream channel, natural obstructions which would have trapped and stored newly recruited wood within the stream channel were removed. Sources of wood recruitment were limited pending regrowth of riparian forests. As wood recruitment and retention were altered, the mechanisms that once controlled and maintained channel form, function, and carbon storage in these altered watersheds were effectively removed, creating a positive feedback for wood-poor, low-complexity stream channels in the Southern Rocky Mountains (Figure 3.1B) [*Wohl and Beckman*, 2014]. Although *Wohl and Beckman* [2014] proposed this scenario of alternative states for mountain streams in the Colorado Front Range, they did not test it with quantitative field data as we do in this paper.

3.3 Study Area

The dominant geology of the study area is Precambrian Silver Plume crystalline rocks consisting of granite, biotite schist, and granodiorite [*Braddock and Cole*, 1990]. Tectonic activity in the area has been uncommon since the end of the Tertiary [*Anderson et al.*, 2006]. Headwaters were glaciated during the Pleistocene epoch and the last major glaciation in the central Rocky Mountains, the Pinedale glaciation, extended down to approximately 2430 m elevation, leaving prominent terminal moraines [*Wohl et al.*, 2004; *Polvi et al.*, 2011]. Pleistocene glacial advance and retreat in the Southern Rockies removed bedrock and sediment in pulses associated with glacial-interglacial cycles, widening and deepening valleys, and leaving steep valley walls and headwalls and flattened valley bottoms [*Anderson et al.*, 2006]. These broad, flat valley bottoms with unsorted glacial sediments can have relatively low-gradient streams that continue to adjust to inherited glacial terrain and sediments [*Livers and Wohl*, 2015].

Wide valleys in the study area can have lower-gradient stream segments (0.01-0.03 m/m) with single- or multithread planform and sand- to cobble-size sediment (Figure 3.1). The formation of multithread stream channels in association with beaver dams or logjams [*John and Klein*, 2004; *Wohl*, 2011a; *Collins et al.*, 2012; *Wohl*, 2013] creates greater stream area, greater retention of instream wood, and more closely spaced channel-spanning logjams than present in confined or single-thread stream segments, which are relatively steep (> 0.03 m/m) [*Wohl*, 2011a; *Wohl and Cadol*, 2011; *Wohl and Beckman*, 2014; *Livers and Wohl*, 2016].

Study reaches in northern Colorado are within the Big Thompson, Cache la Poudre, and North St. Vrain drainages, and reaches in southern Wyoming are in the North Platte River drainage (Figure 3.2). The Colorado drainages originate east of the continental divide in Rocky Mountain National Park at ~4050 m in elevation and flow eastward, eventually flowing into the South Platte River beyond the mountain front at ~1500 m in elevation [*Anderson et al.*, 2006]. The Wyoming drainages originate in the mountains of the Medicine Bow National Forest at lower elevations than those in Rocky Mountain National Park, flowing west, then north to east before meeting the North Platte River.

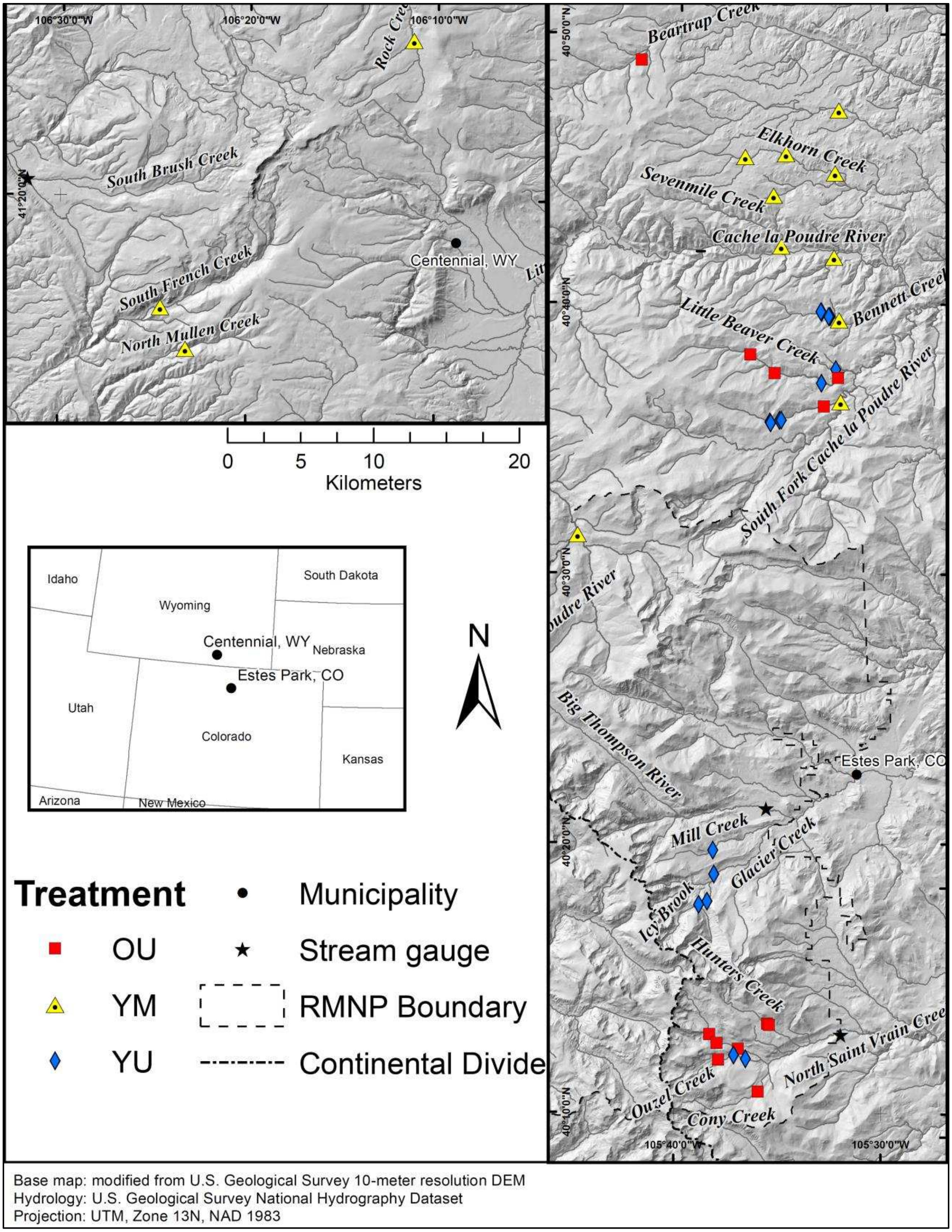

Figure 3.2 Location map of the study area showing the location of montane and subalpine stream channels in southern Wyoming and northern Colorado and the distribution of treatment categories within the Medicine Bow National Forest and the Colorado Front Range.

The lower limit of Pleistocene glaciation also corresponds to a boundary between hydroclimatic regimes. Streamflow at higher elevations is dominated by annual snowmelt floods, whereas streamflow below this limit undergoes annual snowmelt floods but also has larger, less frequent flood peaks associated with lower-elevation summer convective storms [*Jarrett*, 1990]. Mean annual precipitation for the upper North St. Vrain Creek catchment is 70-80 cm and streamflow peaks in May-June [*Wohl et al.*, 2004]. Gaging stations on North St. Vrain Creek, the Big Thompson River, and South Brush Creek, Wyoming in the study areas have mean annual peak discharge and peak unit discharge values of 20 m^3/s and 0.24 $m^3/s/km^2$, 16.7 m^3/s and 0.16 $m^3/s/km^2$ [*USGS NWIS*, 2015a], and 12.3 m^3/s and 0.21 $m^3/s/km^2$ [*USGS NWIS*, 2015b], respectively. All three gages are within the glaciated zone.

Conifer forests dominate the Southern Rocky Mountains [*Peet*, 1998]. Characteristic subalpine forest species include Engelmann spruce *(Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) with stand-killing fires that recur ca. 100-400 years, whereas at lower elevations montane forests include lodgepole pine (*Pinus contorta*) and ponderosa pine (*Pinus ponderosa*) and have fire frequencies of 2-70 years [*Veblen et al.*, 2000; *Veblen and Donnegan*, 2005]. Stand-replacing fires have greater effects on wood recruitment to streams than more frequent fires that burn smaller areas [*Veblen and Donnegan*, 2005].

Natural disturbances in the study area include fires, insect-induced mortality of trees, wind-throw or blowdowns, and mass movements. Debris flows and landslides are rare and are most likely to occur following wildfire. Disturbances in these forests can be very localized, sometimes only affecting one to several trees, leaving downed wood on forest floors and in stream channels within otherwise old-growth forest. Hence, instream wood volumes can be high while old-growth forest remains. Although fires and tree mortality from insects contribute LW to streams, dead trees can stand for decades after mortality and have very slow contributions to instream wood and logjams [*Jackson and Wohl*, 2015]. Conversely, wind-throw and mass movements can immediately introduce LW into stream channels, including dead trees affected by fire and insects. The patterns created by the variations in valley geometry and disturbance regime can be delineated via process domains [*Montgomery*, 1999] that differentiate mountain stream segments with different planforms and ecosystem productivity.

Human changes to these watersheds began with beaver trapping during the first decades of the 19^{th} century, resulting in the loss of beaver dams and the indirect alteration of the hydrology of broad, unconfined valley bottoms that beaver historically occupied [*Wohl*, 2001]. When railroads reached the region after 1859, forests were clear-cut to provide timber for railroad ties and log floating in streams was used to deliver timber downstream. These land use practices directly and indirectly reduced or removed biotic drivers, thus reducing geomorphic complexity in streams. Mining, grazing, and water diversions have also created lasting effects on stream channels [*Hilmes and Wohl*, 1995; *Ryan*, 1997; *Wohl*, 2001; *Caskey et al.*, 2015]. Collectively, land use changes in the region have led to altered channel morphology and flow regimes that potentially alter aquatic and riparian ecological processes.

Data collection was designed to sample stream reaches from natural (unmanaged) areas and areas affected by land use (managed) that were otherwise comparable in terms of elevation, drainage area, gradient, climate, forest type, and natural disturbance regimes, while maintaining an equal distribution of unmanaged and managed sites with respect to valley confinement. However, forest disturbance history created limitations for study design, sampling, and statistical analyses. Logging and log floating occurred primarily in areas that were easy to access. Consequently, only small patches of old-growth subalpine or montane forests (stand age >200 years) remain in small, steep drainages that are difficult to access. Managed streams occur primarily at larger drainage areas and lower elevations that correspond to a different hydroclimatic regime and forest composition, meaning managed streams undergo different natural disturbance regimes of fires and floods than their unmanaged counterparts. However, because we assume that forests in managed watersheds would have included old-growth patches before land use, we believe that inferences drawn from our analyses are broadly applicable across the study area.

3.4 Methods

3.4.1 Field methods

Field methods and metrics measured are described in detail in *Livers and Wohl* [2016]. Surveyed reaches were second- to fourth-order streams in subalpine forests of Rocky Mountain National Park (RMNP) and the Medicine Bow Mountains, Wyoming and montane forests of Arapaho-Roosevelt National Forest (ARNF), Colorado (Figure 3.2). Channel segments were categorized into three treatments based on watershed land use and history of natural disturbance: old-growth unmanaged forests (OU), younger-growth unmanaged forests (YU), and younger-growth managed (YM) forests. Riparian stand age in OU forests is $\geq$ 200 years and there is no history of timber harvest, flow regulation, or placer mining. YU forests have a riparian stand age < 200 years because of natural, stand-killing disturbances such as wildfire, blowdown, or insect infestation. YM forest streams have a riparian stand age of 50-200 years and historical timber harvest and/or log floating. Some of the streams also have contemporary flow regulation or road corridors. We evaluated data from 18 laterally unconfined or partly confined reaches in subalpine forest (7 OU, 6 YU, 5 YM) and from 23 reaches in montane forest (5 OU, 10 YU, 8 YM). This includes floodplain wood volume estimates from overlapping sites in *Sutfin* [2016], LW data from unmanaged montane sites from *Jackson and Wohl* [2015], and additional LW data from unconfined managed (YM) montane sites (Appendix H). Surveyed stream reaches were 150-1000 m in valley length, depending on channel width and longitudinal extent of the segment of consistent channel geometry.

Table 3.1 displays variables and units used in this evaluation. Data collected in the field and additional data from 10-m DEMs and calculations were used to evaluate potential differences in stream channel form, function, and carbon storage between process domains. In addition to treatment and valley confinement, several potential control variables were collected for every surveyed stream reach (Table 3.1). For all study reaches, we evaluated all instream LW pieces, including length, diameter, orientation in the stream, and decay class. If three or more LW pieces were clustered together, we considered this a logjam and recorded measurements such as volume of backwater pool and stored POM. Variables associated with channel cross-section and planform were evaluated for each reach and spatial variability of stream bed and stream banks was evaluated in a subset of reaches. Because of sinuosity and multithread planform, raw data that were continuously collected in surveyed reaches were normalized by valley length. Data that were collected as repeat measurements were evaluated based on their variability throughout a reach, such as standard deviation. Wood, logjam, planform, cross section, and bed and bank surveys are considered response variables of stream form and function.

Table 3.1 Variables used to evaluate stream form and function in this study.

Group of Variables	Variable
Control variables	Confinement (using individual channel width) (m/m)
	Forest cover (basal area, m^2/ha)
	Drainage area (km^2)
	Gradient (m/m)
	Valley width (m)
	Mean individual channel width (m)
Wood piece variables	Logjams/100 m valley (#)
	Wood volume/100 m valley (m^3)
	Pieces of wood/100 m valley (#)
	Proportion of bridge & ramp pieces
	Number of bridge & ramp pieces/100 m valley (#)
Logjam variables	Pool volume/100m valley (m^3)
	Logjam organic matter volume/100 m valley (m^3)
	Pool organic matter volume/100 m valley (m^3)
	Average jam height/jam frequency (m/#)
Planform variables	Area ratio (total channel area/total valley area) (m^2/m^2)
	Length ratio (total channel length/valley length) (m/m)
Cross section variables	Depth standard deviation
	Width standard deviation
	Width coefficient of variation
	Gradient standard deviation
	Variable
Bed and bank surveys[a]	Bank standard deviation
	Thalweg standard deviation
	Longitudinal roughness

[a]Only intensive sites evaluated, n=5.

To evaluate quantities of carbon storage, we assumed an average wood density of 450 kg/m^3 for all wood pieces [*Forest Products Laboratory*, 2010] and that approximately 50% of the mass of wood is composed of carbon [*Lamlom and Savidge*, 2003]. For subalpine streams, we collected ~5 POM samples each from logjams and backwater pools in a reach from each of the three treatments. We measured loss on ignition and assumed 50% of burned mass was organic carbon. Using the value of bulk density for POM from *Beckman and Wohl* [2014a] (1330 kg/m^3), we converted total sediment volumes to mass, then used average percent carbon in each location (logjams and pools) for each treatment to calculate total mass of carbon stored in instream sediments. Components of carbon storage were normalized by valley length and by area of floodplain or channel.

3.4.2 Statistical analyses

Statistical analyses were designed to effectively illustrate how the hypothesized alternative states differ in process and form. If true alternative states exist, we expect to see a clear threshold of variable values between reaches in managed versus unmanaged watersheds, with a spread of unmanaged reaches not defined by forest stand age. *Livers and Wohl* [2016] found that streams in forests that had undergone natural disturbances remained as complex as streams in old-growth forests, despite a gradient of significant differences in forest cover between all three treatment types, suggesting that the removal of wood in managed watersheds had lasting impacts on stream ecosystems. However, that analysis included laterally confined reaches, which dampened the differences between treatments.

We first tested for significant differences in response variables between the OU and YU streams, or unmanaged treatments, to establish whether riparian forest age drove differences in stream form and function in partly- to unconfined valley segments. Lumping all unmanaged sites together, we then tested for significant differences in response variables between unmanaged and managed stream reaches. All statistical analyses were performed using the statistical software RStudio version 3.2.2. For variables that were normally distributed, we ran student’s t-tests to evaluate whether the means between groups were significantly different. For variables that were not normally distributed, we ran nonparametric Wilcoxon Rank Sum statistical tests for analyses. For all analyses, we determined significance at an α value of 0.05. Additionally, boxplots for each variable between the three treatments were created in order to visualize the differences between treatments.

In order to evaluate whether channel form and function variables collectively exhibit a threshold of differences from land use changes, we ran principal components analyses (PCA) using all response variables. PCA allowed us to visualize where all study reaches plot when all variables are combined, as it creates components that combine variables to reduce dimensions of data. Each new component represents a single variable that integrates all the other variables, with the first component explaining the most variability in the data, and each additional component explaining progressively less variability in the data. Each PCA produces a number of principal components (PC) equal to the number of variables analyzed. Because the first two to three PCs explain the majority of variation in response variable values, we plotted our study reaches as PC1 versus PC2 to visualize how similar or different reaches are in terms of channel form and function by evaluating their relative positions in PC space. We retained variance explained for each PC and produced a biplot which displays the location and magnitude of each variable, as well as the location of each sampled reach in PCA space.

PC1 and PC2 scores were used to evaluate a threshold in form and function from land use by determining 1) whether significant differences in PC scores exist between unmanaged and managed sites, using the same statistical methods used to evaluate differences in response variables; and 2) which of the six potential control variables best predict the location, or PC values, using linear models, with treatment expected to predict these values if land use drives threshold changes. Reach scores were first run through a varimax rotation in order to produce new, independent scores for each PC. The new sets of PC scores were then used as the response variable in multiple linear regressions. Using stepwise selection, linear regressions were run for both PC sets using all six possible control variables to select significant control variables. The model with the lowest Akaike Information Criterion (AIC) was chosen for each regression [*Akaike*, 1973]. These models were then run, and the model's *p*-value and *p*-values for each of the control variables were evaluated to determine controls on response variables.

3.5 Results

3.5.1 Differences in instream wood and channel form and function between treatments

Significant differences in wood and complexity characteristics rarely exist between the two unmanaged treatments (Table 3.2). Differences in area ratio occur because of the prevalence of multithread channels in OU sites and fewer multithread channels in YU sites, which in turn impacts total pool volumes between the treatments.

Table 3.2 *p*-values for tests of significant differences of form and function variables.

Variable	Old vs Young Unmanaged		Unmanaged vs Managed	
	p-value	Higher group[c]	*p*-value	Higher group[d]
Forest cover (#)[ab]	**0.001**	O	**<0.001**	U
Valley width (m)[b]	0.943		0.153	
Width/depth (m/m)	0.836		**0.035**	U
Logjams/100m valley (#)	0.234		**0.005**	U
Wood vol/100m valley (m^3)	0.138		**0.014**	U
Pieces/100m valley (#)[b]	0.309		**0.010**	U
Proportion bridge & ramp pieces[b]	0.174		**0.016**	M
Bridges & ramps/100m valley (#)	0.234		**0.010**	U
Area ratio (m^2/m^2)[ab]	**0.008**	O	0.101	
Length ratio (m/m)	0.053		0.237	
Depth SD	**0.011**	O	0.849	
Width SD	0.628		0.566	
Width CV[b]	0.366		0.059	
Gradient SD[b]	0.774		**0.005**	U
Pool vol/100m valley (m^3)	**0.035**	O	**0.005**	U
Pool OM vol/100 m valley (m^3)	0.474		**0.013**	U
Logjam OM vol/100mvalley	0.295		**0.020**	U
Avg logjam height/logjam frequency (m/#)[ab]	0.229		**<0.001**	M
Bank SD residuals[ab]	0.645		**0.019**	U
Thalweg SD residuals	1.000		0.727	
Longitudinal Roughness	0.191		0.727	
PC1	0.101		**0.003**	U

[a]Variable is normally distributed for unmanaged sites; [b]variable is normally distributed for all sites; [c]O: old-growth forest, Y: younger-growth forest; [d]U: unmanaged watershed, M: managed watershed.

Differences in wood and complexity characteristics between unmanaged and managed treatments, however, are nearly always significant. Although there are not significant differences in some cross-sectional and planform variables between these groupings, the variables that most affect stream ecological function and carbon storage, such as wood and logjam characteristics, pool habitat, and POM storage, are significantly reduced in managed stream reaches.

Table 3.3 Mean, minimum, and maximum values of carbon storage by category, treatment, and elevation zone

		Subalpine				Montane			
		OU	YU	YM	*p* value[a]	OU	YU	YM	p value[a]
Basal area (m^2/ha)[b]	mean	46.9	28.3	18.9	**<<0.01**	23.6	21.0	16.6	**0.04**
	min.	43.6	16.1	11.5		16.8	11.5	11.5	
	max.	52.8	36.7	25.3		30.6	30.6	23.0	
Floodplain wood OC (Mg/ha)	mean	40.6	44.6	4.0	-	4.9	3.4	1.2	0.09
	min.	31.2	24.1	4.0		0.1	0.3	0.3	
	max.	47.5	62.5	4.0		16.1	9.3	2.5	
Instream wood OC (Mg/ha)	mean	49.9	31.0	9.4	**0.03**	83.6	40.2	4.2	**<<0.01**
	min.	34.3	3.7	0.2		11.5	0.6	0.9	
	max.	94.9	62.2	35.8		127.3	128.3	9.5	
Logjam Sediment OC (Mg/ha)	mean	10.79	6.62	1.55	**0.03**				
	min.	3.32	0.00	0.00					
	max.	27.50	19.71	6.30					
Pool Sediment OC (Mg/ha)	mean	3.20	1.32	0.04	**0.01**	23.63	7.29	4.28	0.27
	min.	0.00	0.00	0.00		0.00	0.00	0.00	
	max.	8.22	2.47	0.19		101.2	20.96	11.00	
Total OC (Mg/ha)[c]	mean	104.5	83.6	15.1		112.2	50.9	9.7	
	min.	68.9	27.8	4.2		11.6	0.9	1.2	
	max.	94.9	62.5	35.8		127.3	128.3	11.0	
Living tree		70-127	111			62	62		

[a]*p*-value of t-test (Wilcoxon Rank Sum test) between unmanaged and managed reaches; [b]In units of area/area, not converted to carbon content; [c]Does not include basal area (standing wood C); [d]Estimated standing wood carbon estimates for forests in Colorado and Wyoming [*Bradford et al.*, 2008]

There are large differences in total carbon storage across the three treatments in both elevation zones (Figure 3.3, Table 3.3), with unmanaged reaches having ~6-7x and ~5-12x greater estimated mean carbon storage per hectare than managed sites in subalpine and montane zones, respectively. When carbon is evaluated by length of valley rather than area, subalpine unmanaged reaches store ~5-9x more carbon than managed or montane reaches. This is a consequence of multithread planform in unconfined valleys, which are more prevalent in unmanaged subalpine watersheds. Unconfined reaches in old-growth montane forest do not appear to exist in the study area because they either had land use changes or were formerly, or are currently, occupied by beavers. Because of variable tree height throughout our study area, basal area was not converted to carbon storage and is not included in Figure 3.3, but basal area and published estimates of carbon in living trees are listed in Table 3.3. Evaluation of carbon content in

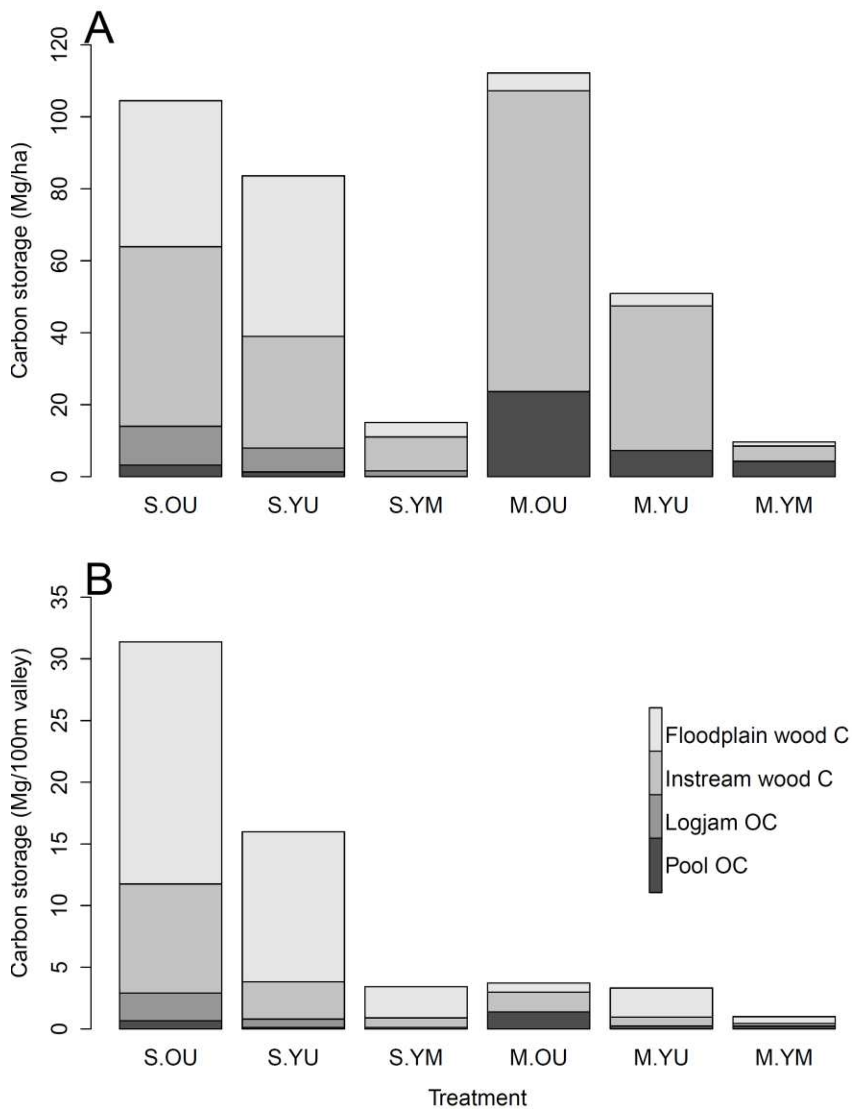

Figure 3.3 Minimum mean organic carbon estimates between treatments and elevation zones by category of storage. Elevation zones: subalpine (S) and montane (M); three treatment categories: old-growth, unmanaged streams (OU), younger growth, unmanaged streams (YU), and younger growth, managed streams (YM). Montane carbon totals are underestimates because of missing logjam OC data. Living tree OC is not listed. (A) Carbon storage in Mg/ha; ha of floodplain for floodplain wood estimates and ha of stream for instream estimates. (B) Carbon storage in Mg/100 m valley.

instream POM showed no significant differences between treatments, but significant differences in total carbon storage in POM do occur between treatments because of the much greater total volume of POM between treatments (Table 3.3) [*Livers and Wohl*, 2016]. Floodplain wood data were only available for ten of our subalpine sites [*Sutfin*, 2016], only one of which was a managed reach, and logjam POM data were not available for montane sites [*Jackson and Wohl*, 2015]. Because of this, Figure 3.3 provides the best summary mean estimates of total carbon storage across treatments, but statistical analyses were not performed.

3.5.2 PC analyses and presence of a threshold from land use

The PCA plot (Figure 3.4) shows that unconfined and multithread channels have the highest values for wood and complexity variables, with the two unmanaged treatments overlapping in PCA space. Managed reaches plot in one specific location of the PCA space and do not overlap with either treatment of unmanaged reaches, despite the presence of multithread planform and variations in confinement of managed reaches. The clustering of managed reaches in the PCA plot indicates that these stream reaches are more similar to each other, in terms of form and function, than they are to unmanaged reaches. PC1 explains ~58 percent of the variance in the data, and the pattern of the location of managed versus unmanaged reaches on this plot is oriented along this axis, with the exception of one partly confined YU reach. Treatment and confinement are the only control variables that significantly influence stream form and function variables (Table 3.4), and land use history (YM) has the strongest control (Table 3.4) on

Table 3.4 Control variables on stream form and function as PC data[a]

				p-values for control variables		
PC	Prop. Variance Expl.	*p*-value	R^2	YU	YM	Confinement, ind. ch. width (m/m)
1	0.58	**<<0.01**	0.61	**<0.01**	**<<0.01**	**<0.01**
2	0.11	0.18	0.14	0.48	0.07	0.17

[a]PC axes and proportion variance explained correspond to data in Figure 3.4. Variables with bolded *p*-values indicate statistically significant control on the response PC. YU: Younger-growth, unmanaged; YM: Younger-growth, managed.

PCA location of reaches. Variables associated with this axis include wood, planform, and habitat characteristics, indicating that differences in values for these variables distinguish the threshold between managed and unmanaged stream channels.

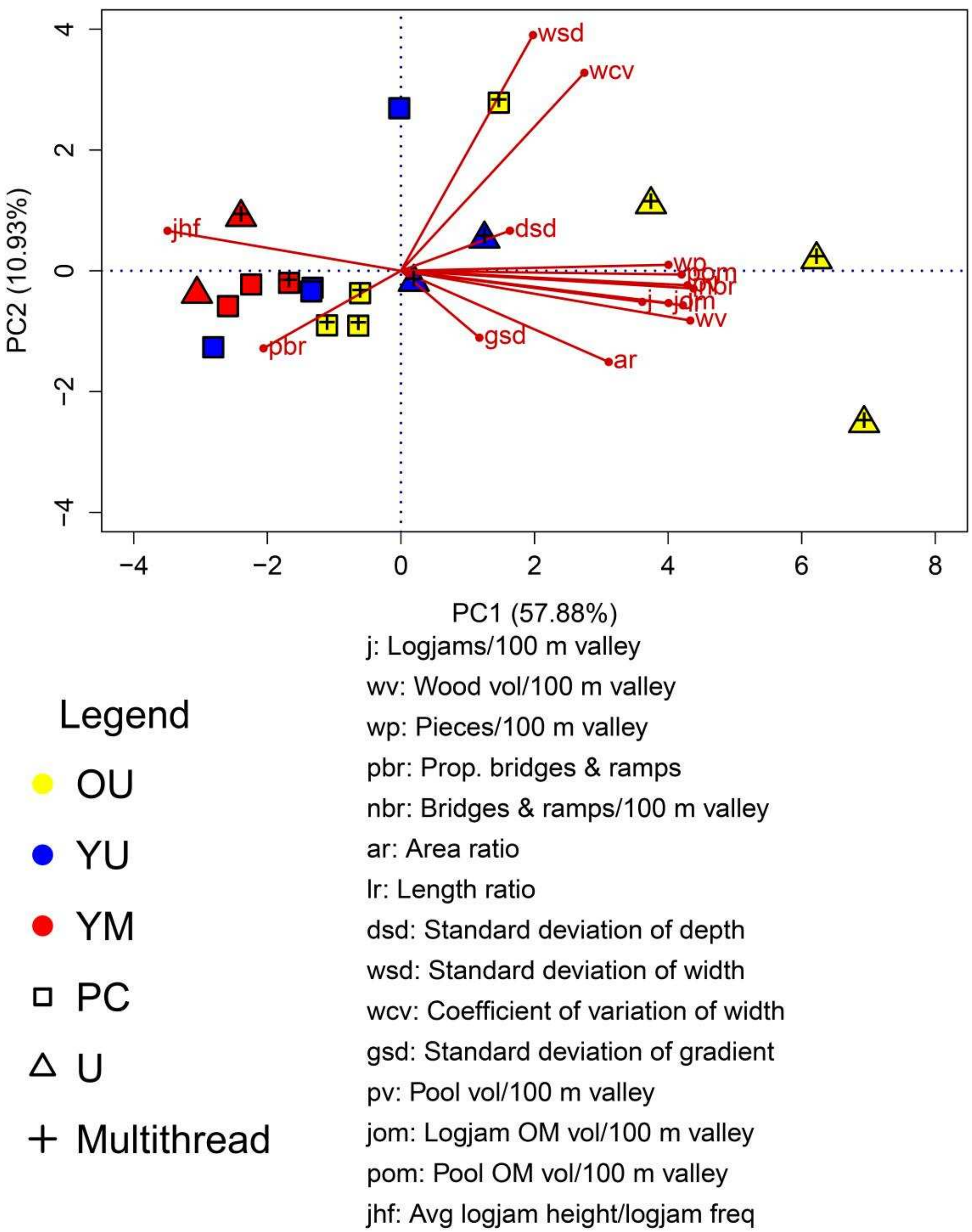

Figure 3.4 PCA biplot of all wood and complexity (form and function) variables and reaches plotted in PCA space. The lengths of lines correspond to magnitude of influence of variable. Fill colors of shapes designate treatment, shapes designate confinement; plus sign in the symbol designates presence of multithread planform. Response variable abbreviations defined in legend.

3.6 Discussion

3.6.1 Alternative states of complexity as form and function

Streams in unmanaged watersheds have significantly greater complexity of form and function than streams in managed watersheds and exhibit a threshold of differences when evaluated through PCA, supporting the hypothesis that land use results in alternative states of stream form and function in the Southern Rockies. Although a few complexity variables related to cross-section and planform are not significantly different in watersheds with land use, the mechanisms that maintain complexity of channel form and function, and which are the most relevant to stream ecology, no longer operate fully in watersheds with historical land use (Figure 3.5).

Multithread planform with vegetated islands forms in relatively unconfined valleys of the Southern Rockies as a result of abundant logjams; this results in smaller individual channels that can more effectively trap and retain LW pieces. Streams that underwent logging and tie-drives are simplified, with straighter, wider channels and fewer obstructions such as channel-spanning logjams that could trap individual LW pieces. These two alternative states of stream form and function have opposing positive feedback systems in states of quasi-equilibrium (Figure 3.5). Because wood is a driver for channel complexity and habitat potential for stream biota [*Livers and Wohl*, 2016], historical land use changes in the Southern Rockies have driven affected streams into an alternative state lacking wood, complexity, and ecological potential found in unmanaged streams.

The most complex and unaltered natural streams in our study also correspond to the channels with greatest stream gradients, suggesting that the multithread planform and complexity caused by instream LW is a mechanism for energy dissipation in these steep, unconfined, mountainous valleys. Much as braided streams effectively dissipate energy in conditions of high-gradient and high-sediment load, multithread planform forced from LW dissipates energy in the study streams, allowing for greater attenuation of downstream fluxes of water and organic carbon. In the absence of wood, these streams would behave more like laterally confined streams in the region, in which flow incises a single channel, enhancing sediment mobility and reducing instream and floodplain retention of water, solutes, and POM.

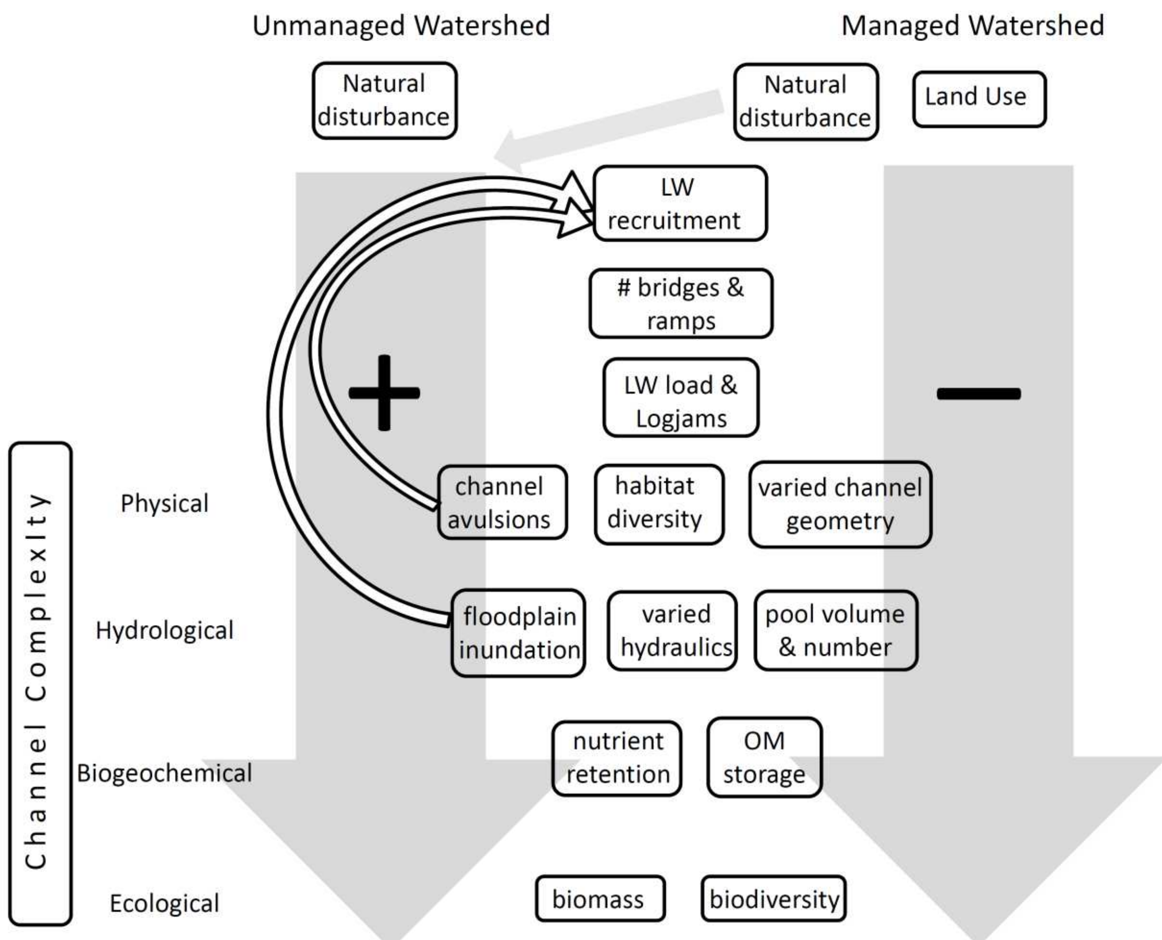

Figure 3.5 Conceptual model of stream form and function variables, and their internal feedbacks, affected by riparian forest characteristics. Arrows denote positive feedbacks, with the largest arrows, pointing down, indicating that each successive level has potential to influence levels below it via feedbacks. In unmanaged watersheds, each level has a positive influence on the levels below it, while in managed watersheds, top levels are significantly reduced, having a negative influence on all levels below. Feedbacks to higher levels only operate in unmanaged watersheds.

With time, historically managed watersheds might re-cross a threshold back into their former alternative state, but this is unlikely at many sites. Although some areas that underwent past logging have had regrowth of native conifers, some stream segments currently support different vegetation communities (e.g., *Salix* spp. and grasses; Figure 3.1B) and native conifer forests have not regrown in the riparian zone. Even where conifers have regrown, some streams continue to be constrained by roads that are maintained for forest access or recreation, which precludes streams from meandering or migrating across their floodplains and requires instream wood removal or bank stabilization to avoid damage to roads. Relatively slow rates of recruitment of instream wood and low retention capacity in channels that were historically cleared of LW and other natural irregularities of the channel boundaries also limit retention of LW that is recruited to contemporary channels. The combined effects of persistent changes in riparian vegetation communities, limited retention of LW, and continuing management of streams appear to constrain the ability of formerly or currently managed streams to return to a physically complex, retentive state.

Allowing riparian forests to regrow and undergo natural senescence, or tree mortality, and natural disturbances could speed recovery of managed stream channels to more natural, complex states (Figure 3.5). Natural disturbances such as insect infestations and fire can leave standing dead wood that persists for decades, slowly introducing LW into channels and creating delayed responses of form and function in stream channels [*Jackson and Wohl*, 2015]. In contrast, blowdowns and mass movements cause fast, direct inputs of LW into stream channels, with more immediate and drastic effects on stream form and function. However, streams with historical land use in the Southern Rockies are significantly wider than the individual channels of their unaltered, multithread counterparts [*Livers and Wohl*, 2016] and lack bridge and ramp pieces that facilitate formation of channel-spanning logjams [*Beckman and Wohl*, 2014b], so LW pieces entering stream channels would have to be very long to span channels and initiate logjams that would result in the channel avulsions needed to promote multithread planform. Also, slower inputs of LW in wider and simplified streams that lack obstructions to trap individual pieces of wood could result in downstream transport of recruited LW. *Bragg* [2000] estimated that at least 200-250 years are required for LW loads in streams to reach a steady state after anthropogenic or natural disturbances in the Southern Rockies, but this assumes that forests are left without further human disturbances and does not account for unknowns such as climate change that could affect forest growth. Even if the natural state of all the physical components of form and function of Southern Rockies streams were to be restored, a return to the original stable state requires that the biota and ecological structure return to their natural states, which will not necessarily occur.

The impacts from natural disturbances to riparian forests on managed streams are unknown and have a range of possible outcomes. Because of this uncertainty, combined with the difficulty in demonstrating ecosystem stability, we believe that streams in the Southern Rockies that have undergone land use changes exist in an alternative transient state [*Didham et al.*, 2005; *Schröder et al.*, 2005; *Fukami and Nakajima*, 2011]. Our study represents a snapshot in time, while full recovery from land use changes may take hundreds of years. Forest succession takes longer than the time since logging and tie-drive activities in the Southern Rockies, and succession and recovery within riparian-stream ecosystems could take even longer in ecosystems with strong disturbance regimes [*Didham et al.*, 2005].

Another argument for transience is that stability of stream ecosystems is difficult to demonstrate. Streams are continually adjusting to varying flow magnitudes and other disturbances, even over the course of a season, and individual observations do not capture the whole range of stream ecosystem conditions. The presence of positive feedbacks that maintain physical stability could help create stability for the entire ecosystem. *Fukami and Nakajima* [2011] infer that the greater presence of positive feedbacks equates to a greater chance of alternative stable states, but strong disturbance regimes maintain transience. Unmanaged streams in the Southern Rockies could be considered stable states in that, even though LW recruitment fluctuates through time, sufficient LW remains present in the stream to create substantial physical complexity and retentiveness, whereas managed streams are in a transient state of lower physical complexity and retentiveness. However, stream substrate and morphology in formerly-glaciated terrain of the Southern Rockies are still responding to glacial retreat [*Livers and Wohl*, 2015], and thus the disturbance regimes associated with process domains [*Montgomery*, 1999] in the region may dictate the existence of stable or transient states even in environments not altered by human activities. Although positive feedbacks can help maintain complex form and function in unmanaged watersheds, intact positive feedbacks in a degraded state (managed streams) can increase the resistance of a system and make it more resistant to restoration efforts [*Suding et al.*, 2004].

Past studies that have introduced potential alternative stable states do not address the difficulty in demonstrating stability, and may have been more properly defined as transient states. For example, streams in Mid-Atlantic Piedmont watersheds affected by milldams are currently incising, moving large amounts of sediment as they adjust to the milldam sediments deposited throughout former floodplains [*Walter and Merritts*, 2008]. Braided Great Plains rivers that became single-thread after irrigation changed river hydrology [*Nadler and Schumm*, 1981] rely on the regulation of flow that reduces flood peaks and increases base flows to maintain single-thread planform.

Streams in unmanaged forests of the Southern Rockies are significantly more complex in form and function than streams with riparian forests that have undergone land use changes [*Livers and Wohl*, 2016]. Greater complexity means greater variety and availability of habitats and food sources for aquatic and riparian biota, particularly in valleys with multithread channels. Greater opportunities for habitat and resources in streams with complex form and function could equate to higher resilience and recovery for the ecosystem, and hence stability, in these disturbance-driven environments.

3.6.2 Alternative states of carbon storage

All carbon storage estimates in this study represent a minimum mean value, as many wood pieces can be buried in channels and floodplains, and smaller quantities of instream POM can be stored in local flow separation zones such as those caused by backwaters of bank irregularities; we did not attempt to quantify carbon in such locations. The valleys of unmanaged stream segments store large amounts of organic carbon in standing forests, dead wood on the floodplain, floodplain sediments [*Sutfin*, 2016], instream wood, and POM in logjams, pools, and bank irregularities. Because our dataset lacked unconfined, unmanaged montane sites, significant differences in carbon stored within floodplain wood and pool POM were difficult to document, but mean and maximum values of these variables illustrate the large differences between treatments (Table 3.4). The significant reduction in carbon storage observed in managed watersheds (Table 3.4, Figure 3.3) [*Beckman and Wohl*, 2014a] indicates an alternative state of carbon storage induced by historic land use in the Southern Rockies.

Figures 3.6 illustrates the transient state of instream and floodplain wood loads, the main components of carbon storage in this study, through recovery time of different types and degrees of natural and human disturbances. Natural disturbances to riparian forests and valley bottoms in the

Southern Rockies can increase wood recruitment, or storage of carbon for some period of time before stability, or average state, can be reached, but human disturbances in these areas can lead to transient low carbon storage or stable (permanent) low carbon storage, depending on degree and duration of disturbance (Figure 3.6A). Streams in unconfined valley bottoms are more susceptible to this hypothesized sequence of changes (Figure 3.6B) than more confined stream segments. Confined streams have less floodplain area in which to store wood and are less altered by disturbances that influence wood recruitment because LW in confined streams is regularly moved during peak flows confined to a limited cross sectional area. Carbon storage is transient because LW and POM decay or are transported downstream, but the effects of land use can lead to a permanent reduction in overall organic carbon storage in watersheds of the Southern Rockies, limiting available organic carbon for riparian-aquatic biota and altering long-term carbon sinks. The cumulative effects of such changes in the first- to third-order streams that constitute the great majority of channel length within a watershed [*Freeman et al.*, 2007] could be significant for the global carbon cycle [*Cole et al.*, 2007]. Figure 3.7 demonstrates the alternative transient states in illustrating the range of state conditions induced by disturbances.

Climate change is likely to affect carbon storage in headwater stream networks in the Southern Rockies. Fires are expected to be more frequent and intense [*Dennison et al.*, 2014], exacerbated by increased tree mortality from insect infestations and drought stress [*van Mantgem et al.*, 2009]. Warming in high elevation areas could alter snowmelt hydrology and increase decomposition of stored carbon in wood and sediment within floodplains. Although the detailed effects on carbon storage are unknown, the greater magnitude of carbon storage in old-growth forest streams (Figure 3.3) suggests that an increase in disturbance frequency and magnitude will decrease carbon storage.

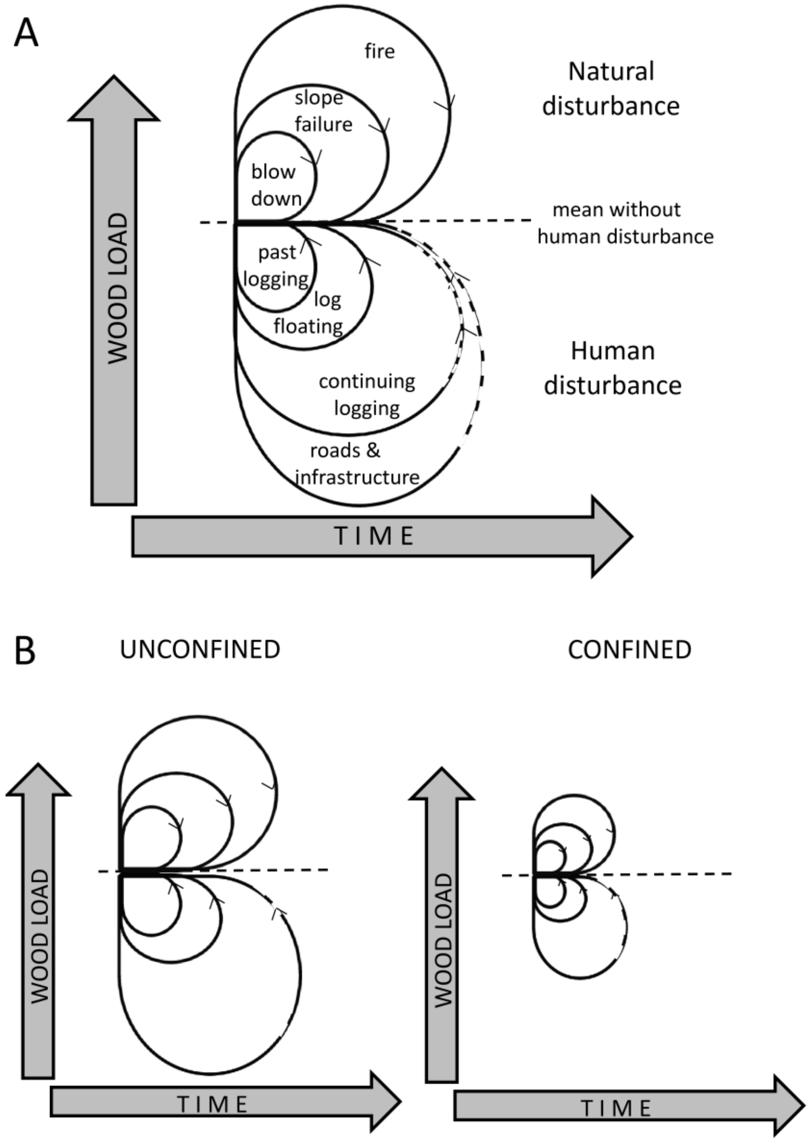

Figure 3.6: Conceptual model of influence of disturbances on instream and floodplain wood load (carbon storage) over time, or the transient state caused by disturbances. Vertical length of each loop reflects the magnitude of disruption and the horizontal length reflects the time needed to return to an 'average' state, or recovery time. Human disturbances typically decrease wood recruitment and loading, and the dashed line indicates that the system may not be able to return to a 'natural average' value if the human disturbance continues. (A) Generalized influence of disturbance on wood load. (B) Magnitude and recovery time differences between laterally unconfined versus confined stream segments; unconfined stream segments are more affected by disturbances to riparian forests than confined stream segments.

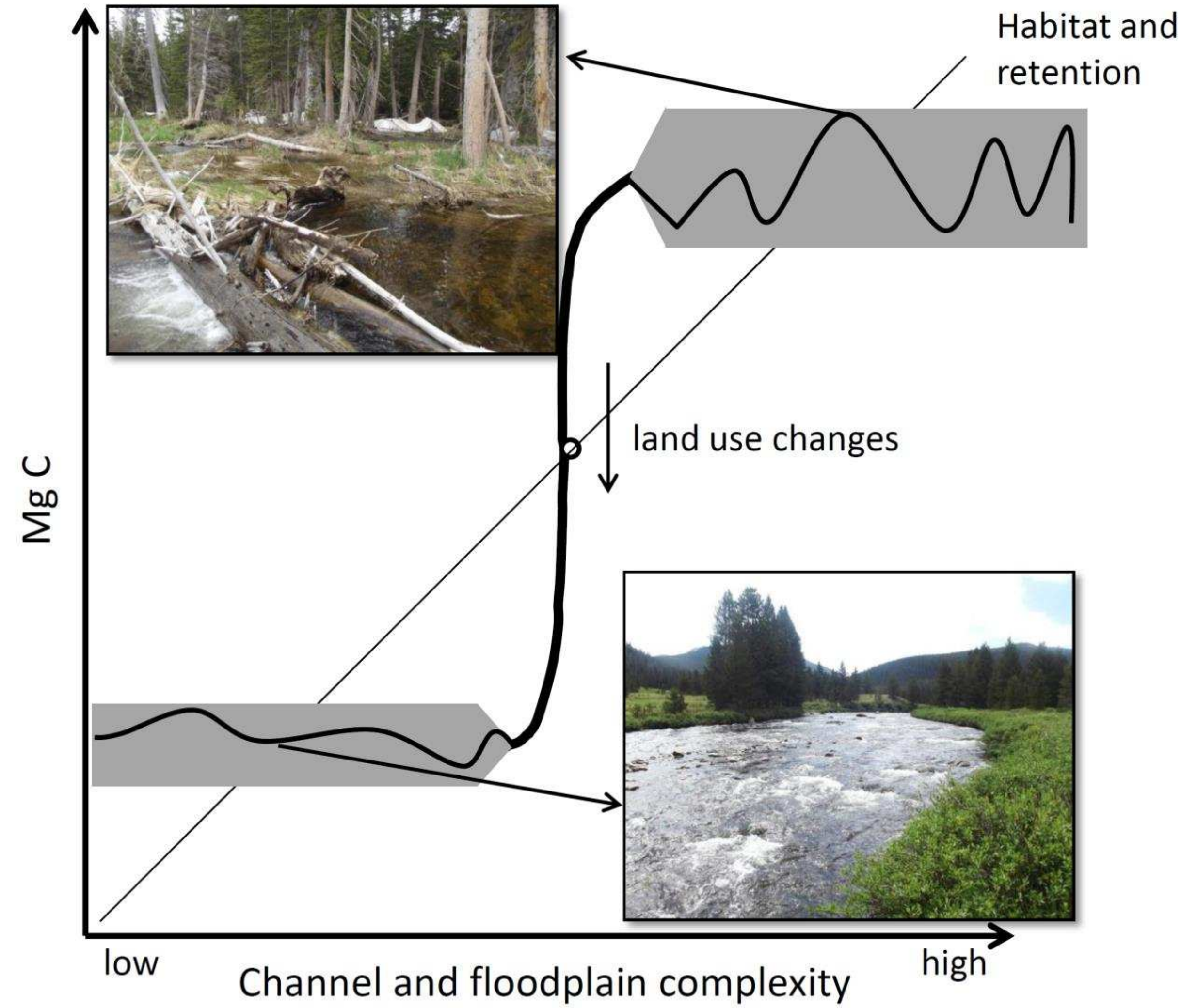

Figure 3.7: Conceptual diagram of alternative states of channel and floodplain complexity and carbon retention and the threshold induced by land use changes. Transience within a state is illustrated by the range of possible conditions (blue boxes) induced by natural disturbances, with larger range of conditions in the more complex, retentive state.

3.6.3 Management implications

Increasing appreciation for the ecosystem services that small streams provide has promoted restoration projects on watersheds degraded by land use. Watershed management commonly focuses on restoring physical factors of streams in order to create the template needed for native biota, but typically the focus of restoration is on instream factors rather than riparian forests. The USDA Forest Service has implemented watershed conservation practices for national forests of the Southern Rockies, but these are generalized, lack quantitative objectives particular to stream environments, and do not prohibit riparian logging [*USDA Forest Service*, 1999; *Fausch and Young*, 2004]. Thus, specifying forest management practices that incorporate the need to maintain riparian forest corridors and leave standing and downed wood within the riparian zone is one passive restoration technique that would allow managed watersheds to move toward their unaltered physical and ecological state, as also suggested for streams elsewhere [e.g., *Jackson et al.*, 2015].

The loss of logjams, high instream wood loads, and the ecologic benefits they provide to mountain stream channels has made streams leaky with respect to storage of water and POM necessary for the base of the stream trophic system, as well as the carbon in wood and POM that was historically stored in these mountain valleys [*Wohl and Beckman*, 2014]. Although small-scale disconnectivity provided by logjams is important for mountain stream ecosystems, large-scale, or landscape, connectivity is fragmented in the Southern Rockies due to human structures such as dams and water diversions. Restoring landscape connectivity [*Freeman et al.*, 2007] and internal positive feedbacks in aquatic-riparian environments would facilitate the restoration of watersheds with historic land use.

Tie-drives, in particular, changed the channel geometry and clast-size distributions that facilitated and maintained multithread planform and complex stream form and function via trapping of LW pieces. *Polvi et al.* [2014] found that stream restoration activities in northern Sweden that included additions of coarse sediments had significantly greater wood volumes than analogous unrestored streams after at least a few years following restoration, suggesting that the addition of boulders and a variety of clast sizes could be a viable restoration technique in Southern Rocky Mountain streams with reduced wood loads from land use changes. Restoration of physical channel complexity and ecologic potential does not guarantee restoration of the biologic community structure found in natural, unmanaged streams of the Southern Rockies. It is possible that a third ecosystem state, an intermediate state with intermediate levels of functional complexity, could be achieved through restoration, imagined in the central area of Figure 3.7; this could also be the state of watersheds that had only partial or less intense land use change. If wood loads can be restored and riparian buffers maintained, intermediate complexity of pool habitat and nutrient retention could be possible; in a future of unknown changes to these systems, this may be an acceptable level of functional complexity. This highlights the need to evaluate watersheds in the Southern Rockies and elsewhere that have intermediate levels of land use change rather than the watersheds we have evaluated here, in which forests were clear-cut. For example, evaluating watersheds that had only partial clearing of riparian forests would not only gain insight into a third alternative state, but could provide more reasonable management techniques for forest resources and minimum functional complexity needed to restore stream channels.

Riparian logging and tie-drives caused catastrophic changes to stream and riparian biota, and any surviving biota may have relocated due to lost access to nutrients and habitat. Furthermore, native cutthroat trout in the region have been significantly reduced and even eradicated in streams of the Southern Rockies, with introduced non-native rainbow and brown trout occupying former cutthroat habitat [*Fausch and Young*, 2004]. Changes in dominant salmonid species have likely affected food webs between aquatic and riparian ecosystems in the Southern Rockies [*Baxter et al.*, 2005]. Unless native biota are reintroduced or gradually return to managed stream segments, and introduced and non-native species are removed, restoration of naturally occurring stable states of Southern Rockies stream ecosystems will not occur.

3.7 Conclusions

Geomorphic thresholds, river metamorphosis, and complex response are the geomorphic analog to alternative states in ecology. Could Southern Rocky Mountain streams exist in an alternative state of form, function, and carbon storage after logging and other land use changes? This study suggests that they can, with disturbed watersheds in an alternative transient state which is simplified and less retentive of water and organic carbon. Could river metamorphosis provide a template for alternative ecological states in stream systems? We believe that river metamorphosis caused by land use changes led to substantial changes in stream form and function that likely led to alternative ecologic states, as demonstrated by concurrent research evaluating stream metabolism, insect diversity and biomass, and fish characteristics in our study reaches. Stream segments in old-growth, unmanaged forests with unconfined valley bottoms in the Southern Rockies can store over 100 Mg/ha of organic carbon in dead wood and instream POM.

This storage is significantly reduced in watersheds with human alterations (< 20 Mg C/ha), suggesting that land use changes in riparian areas here and in other regions could impact the global carbon cycle and characterization of river corridors as carbon sinks. Because legacy riparian land use changes have had widespread and persistent impacts to stream form, function, and carbon storage in the study region, and we believe that this has in turn impacted riparian-aquatic ecosystems, we recommend maintaining existing riparian forests or facilitating regrowth of such forests as a first-order restoration technique to improve the degraded alternative state of streams in the Southern Rockies.

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Chapter 4: Conclusions

4.1 Summary

This study describes the legacy effects of land use, and the role of land use in initiation of alternative states, on stream channels of the Southern Rocky Mountains, particularly with respect to the relationship between riparian forest characteristics and physical stream form and function (complexity) and organic carbon storage in relatively unconfined valley bottoms in the region. When LW wood recruitment and retention in channels were altered during riparian land use activities, the mechanisms that once controlled and maintained channel form, function, and carbon storage were effectively changed, creating a positive feedback for an alternative transient state of wood-poor, low-complexity stream channels in the Southern Rocky Mountains. Meanwhile, streams in unmanaged (no land use history), unconfined valleys of the region are significantly more complex in form and function, and represent a natural state of high carbon storage and complexity. This greater complexity means greater variety and availability of habitats and food sources (nutrient retention) for aquatic and riparian biota, leading to theoretically greater biomass and diversity, particularly when multithread planform is dominant. Greater opportunities for habitat and resources in streams with complex form and function could equate to higher resilience and recovery for riparian-aquatic ecosystems, and hence stability, in these disturbance-driven environments.

Management history of riparian forests exerts the strongest control on reduced functional stream channel complexity and carbon storage in this study, regardless of riparian forest stand age. Other land use activities in the region, such as mining, grazing, and water diversions, have also been shown to have lasting effects on stream channels, implying that land use changes in the region have collectively led to altered channel morphology and flow regimes that potentially caused widespread changes to aquatic and riparian ecological processes. Because unconfined valley segments can constitute up to 25% of stream length in watersheds of the Southern Rockies [*Wohl et al.*, 2012], and they appear to be hotspots for functional stream complexity and carbon storage and are expected to have equivalent impact on stream ecology, unconfined valleys affected by land use changes are an ideal target for stream restoration activities.

Resource managers seek target values of wood load for active and passive stream restoration techniques because of the many beneficial effects of instream wood on physical, biological, and ecological processes in aquatic-riparian ecosystems [*Gurnell et al.*, 2002; *Wohl*, 2011], including those for salmonid fish. This study provides detailed estimates of instream wood characteristics from natural to disturbed watersheds that can be used as guidelines to promote or reestablish internal feedbacks associated with LW which are vital to these ecosystems. Because this study indicates that wood characteristics appear to represent a mediator between forest history and complexity in stream form and function, focusing on riparian forests is a key element to sustaining restoration efforts.

The patterns between riparian forest characteristics and channel functional complexity observed in this research likely apply to other small or headwater forested segments of watersheds of different regions, particularly in watersheds that have unconfined valley segments due to glaciation or other processes. Such patterns are likely restricted to smaller streams that are narrow enough to store, rather than transport, LW, or larger-order streams that are sufficiently small to store LW as a result of a multithread planform. Climate and temperature may also influence how LW is stored in stream channels in watersheds from different regions due to differing decomposition rates and flow regimes. The Southern Rockies are semiarid and flows in streams in this study are dominated by snowmelt, and the dry climate and cold temperatures can restrict decomposition of wood that maintains channel complexity and multithread planform. Therefore, the patterns in this study may be restricted to the temperate zone, where trees can grow relatively fast and tall, and climate limits decomposition of instream LW. Similar studies in different physiographic regions of the temperate zone, with differing dominant tree species, differing elevations and disturbance regimes, and with both similar and varied types and extents of land use, could further test the proposed conceptual model of alternative states of channel complexity and organic carbon storage induced by land use changes. The effect of loss of LW loads from land use is one possible cause for driving alternative physical states of stream channels, but other land use changes could directly or indirectly alter hydrologic regimes, sediment regimes, room for stream migration, water quality, and other characteristics of streams that may also drive alternative states with reduced ecological potential.

4.2 Future Work

The research in this dissertation makes inferences based on a relatively low sample size, with disclaimers based on ability to sample certain types of streams. Unmanaged and managed watersheds in the Southern Rockies are typically different with respect to drainage area, stream gradient, and forest characteristics. In order to more fully characterize LW characteristics, channel complexity, organic carbon storage in LW and instream sediments, and the long-term effects of land use on whole watersheds and regions, more reaches need to be sampled across a range of forest stand ages and valley confinements. Furthermore, the primary land uses evaluated in this study relate to former logging and tie-drive operations, and it would be useful to extend the dataset to include streams affected by additional land use activities in the region, such as placer mining. Research on the effects of loss of beaver on stream channels in the Southern Rockies is ongoing.

Other measures of complexity could enhance interpretation of the alternative states driven by land use changes. For example, detailed surveys of substrate size throughout stream channels could provide insight into how wood, or lack thereof, affects substrate size distribution in the Southern Rockies; it could also aid in quantifying the legacy effects of boulder removal by evaluating the current distribution of boulders in managed stream channels. More detailed surveys of stream banks and cross-sectional geometry could be used to evaluate changes in bankfull width and depth at smaller scales to evaluate whether these complexity metrics are really a function of confinement rather than management history. The loss of high LW loads could also affect hyporheic exchange in the Southern Rockies, and a detailed study of the differences in hyporheic exchange between unmanaged and managed watersheds could both reinforce results from biogeochemical analyses performed by co- investigators in this study and enhance understanding of the hydrological differences imposed by land use changes in the region.

Data collected in this study have the potential to be used for further research of LW characteristics and their effect on stream channel processes in the Southern Rocky Mountains. The coordinates for each logjam could be used to analyze spatial distribution and density of logjams across treatments in the region. Visual and back-calculated logjam porosity estimates could be used to address inconsistent reporting of logjam porosity values in the literature and to propose a field methodology to efficiently determine logjam porosity in the field. Instream LW piece decay classes and orientation types could be used in conjunction with logjam porosities to evaluate the transience of LW distribution across treatments and confinements under the assumption that logjams with low porosities and more decayed LW pieces have longer residence times. LW data could also be used to evaluate the distribution of LW piece sizes in logjams versus free pieces across treatments and confinements to enhance the dataset from *Beckman and Wohl* [2014]. Finally, stream POM data could be used to describe organic carbon storage in multithread versus single-thread, unconfined valley bottoms of the Colorado Front Range in conjunction with data from *Sutfin* [2016].

4.3 Future of LW in Watersheds

Although this study is useful in describing the natural, complex, and retentive state of subalpine streams of the Southern Rockies, ongoing changes and maintenance to watersheds preclude streams in altered states from returning to historical states. Furthermore, finding streams that are unaffected by some kind of land use or flow control is difficult, particularly in regions that have high populations, and stream restoration is not always an option.

Riparian forests, in both managed and unmanaged watersheds, may change over time, and the research in this study may provide clues into expected changes in stream channels from such changes. In managed watersheds in this study, some reaches had regrowth of native conifers while others did not have riparian forest regrowth, and instead had grasses and shrubs in the riparian zone. In many areas, the forests are currently changing. The widespread outbreak of native pine beetle (*Dendroctonus ponderosae*) in the Rocky Mountains, believed to be exacerbated by higher winter temperatures, is decimating forests in the region [*Kaufmann et al.*, 2008], and will result in slow wood recruitment to channels over the next several decades [*Jackson and Wohl*, 2015]. Similar effects of native and non-native insect infestations on instream LW loads in small streams have been documented in other mountainous regions [e.g., *Costigan* *et al.*, 2015]. While insect infestations provide LW to stream channels over delayed times, death of entire forests would limit LW recruitment once all standing dead wood has left the riparian zone. A total reduction in riparian forests, some of which is already seen in managed watersheds in this study, could lead to overall transport of LW out of river corridors before wood recruitment mechanisms are restored, leading to permanent changes in the riparian zone, channel complexity and retention, and ultimately ecological potential. Other indirect changes to watersheds associated with climate change, such as increased forest fire frequency, blowdowns, and drought stress, can alter the geomorphic complexity of streams by altering LW recruitment patterns to channels [*van Mantgem et al.*, 2009; *Goode et al.*, 2012; *Wohl*, 2013; *Dennison et al.*, 2014].

As forests senesce, forest succession is expected; the regrowth of new forest species could result in changes to soil moisture and hydrology, which indirectly affect channel complexity and retention, in addition to changes in riparian flora unaccustomed to changed hydrology, as well as riparian fauna and ecological structure [e.g., *Ford and Vose*, 2007]. In the Southern Rockies and in other regions, different riparian species after succession could mean shorter or longer life spans of trees with varying forest turnover rates; different sizes of LW recruited to the channel; and different time spans for LW storage or decomposition. Fast-growing and short-lived riparian trees could result in a quicker recovery to the natural state if wood pieces are large enough and streams are otherwise left unaltered, but in the Southern Rockies subalpine zone, conifers are slow to regrow, and recovery to the historical natural state could take hundreds of years, if it occurs.

4.4 Alternative transient states of forested headwater Southern Rocky Mountain streams

The concepts of thresholds, complex response, and river metamorphosis allow geomorphologists to understand how river systems can abruptly change their physical form and function, and in this study I relate these concepts to the analogous concept of alternative states in ecology. It is my hope that in unifying these concepts, which likely apply to additional scientific fields, applied river scientists can approach research and restoration more holistically, integrating physical and ecological goals into common overarching objectives. While some ecological studies discuss alternative states as being stable, many river systems are more properly described as being in a state of physical transience because of constant motion of materials (water, sediment, organic matter and biota), and because surrounding mountainous uplands undergo disturbance regimes that can disrupt stability and recovery over varied timescales. Land use changes evaluated in this study do not simply disrupt the ecosystem in the manner of a disturbance from which the stream can recover to some historical mean; instead, land use changes can cause the stream to cross a threshold beyond which stream responses to movement of materials and recovery from natural disturbances may be similar, but recovery to a complex ecosystem, the historical mean, is unlikely to occur and a reduced mean is established.

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Chapter 5: Appendices

5.1 Appendix A: Field data

Table 5.1 Channel geometry data by sampling location for extensive reaches.

Reach	Loc.	BF Width (m)	BF Depth (m)	Valley width (m)	Conf.	Gradient (m/m)	Cover (#)	Grain size	Morph.	Coordinates	Notes
HUNTc	1	5.9	0.83	11.9		0.19		c/b	Cas	40.222319, 105.592116	Only 240m
HUNTc	2	6.5	0.67	47		0.12	24	g/c	SP	40.222025, 105.591626	
HUNTc	2	8.9	0.52	47		0.08	24	g/c	SP		
HUNTc	3	6.8	0.57	14		0.10	11	c/b	SP	40.221624, 105.591015	
HUNTc	4	4.4	0.85	26.7		0.05	21	c/b	RR	40.22147, 105.59065	
HUNTu	1	3.7	0.50	29		0.07	24	c/b	RR		J3, 2 channels
HUNTu	1	4.0	0.57	29		0.08	24	c/b	RR		J3, 2 channels
HUNTu	2	4.3	0.63		U/I	0.03		c	RR	40.2206061, 105.589780	
HUNTu	3	4.3	0.70	21	PC	0.04	20	b/c	RR	40.220011, 105.588721	
HUNTu	4	5.1	0.73	22	PC	0.02		c	RR	40.219082, 105.588721	above trail
HUNTu	5	6.0	0.68		U	0.03		s/c	RR	40.21871, 105.58769	
CONYu	1	6.2	0.48		U	0.02	21	c	PB	40.18063, 105.59812	Some side channels, lots of OM everywhere, behind single pieces
CONYu	2	8.3	0.43		U	0.02		c	PB	40.18084, 105.59741	
CONYu	3	11.0	0.47		U	0.01	25	c/g	PB/PR	40.18185, 105.59703	
CONYu	4	7.0	0.57		U	0.01		c/g	PB/PR	40.18245, 105.59688	
CONYu	5	6.2	0.57	19		0.01	19	c	RR/PB	40.18310,	

Reach	Loc.	BF Width (m)	BF Depth (m)	Valley width (m)	Conf.	Gradient (m/m)	Cover (#)	Grain size	Morph.	Coordinates	Notes
										105.59646	
CONYc	1	6.3	0.66	24		0.14	26	b	Cas	40.18824, 105.59455	Too crazy to get in, all measurements from bank right; lots of OM
CONYc	2	18.2	0.57	24.1		0.09		b/c	Cas/SP	40.18916, 105.59366	Same as J1, where channel is very wide with island and jams
CONYc	3	9.3	0.58	25.1		0.16	22	b	Cas	40.18985, 105.59280	Where channel narrows
CONYc	4	6.8	0.75	21		0.08		b/c	Cas	40.19099, 105.59194	Before split
CONYc	5	7.0	0.57	15.2		0.14	15	b	Cas	40.19138, 105.59125	
OUZELu	1	10.8	0.48		PC	0.02	23	c	PR/PB	40.19989, 105.62980	~40m from top
OUZELu	2	20.7	0.47	38.8	C	0.07		b/c	RR	40.19982, 105.62808	multiple channels, all one in the part, whole valley
OUZELu	3*	2.6	0.53	50		0.05	22	c	SP	40.19986, 105.62678	wood forced; multiple channels, side channels have lots of OM, at J4
OUZELu	4*	2.6	0.47		U	0.05		g/c	SP	40.20014, 105.62627	wood forced; right below J6, at least 5 channels
OUZELu	5	6.5		28.1	PC	0.05	15	c	RR	40.200095, 105.625104	lots of woody flood debris not necessarily jams; side channel leaves valley at 40.20027, 105.62604
NSVH	1*	1.6	0.33		U	0.07	18	c	SP	40.21545, 105.63854	reach is 275 m; wood volumes a min. est. trib enters river right halfway down reach
NSVH	1*	4.3	0.45		U	0.09		c	RR		2 major channels for entire reach length (each about 4-5 m wide), but up to 8 subparallel channels (mostly 1-3 m wide, 50-100 m long)
NSVH	1*	3.0	0.40		U	0.14		c	RR		
NSVH	2*	3.8	0.48		U	0.07		c/b	RR	40.21516, 105.63807	probably one more channel
NSVH	2*	3.0			U			c	SP		
NSVH	2*	3.0	0.33		U	0.11		c	SP		
NSVH	3*	3.9	0.37		U	0.06	19	bed/c	RR	40.21479, 105.63776	5 channels!
NSVH	3*	2.2	0.25		U	0.12		c	RR		

Reach	Loc.	BF Width (m)	BF Depth (m)	Valley width (m)	Conf.	Gradient (m/m)	Cover (#)	Grain size	Morph.	Coordinates	Notes
NSVH	3*	1.2	0.30		U			cl	PR		
NSVH	3*	1.0			U	0.02			SP		
NSVH	3*	4.2	0.38		U	0.06		c/b	RR		
NSVH	4*	5.4	0.37		U	0.06		c	RR	40.21431, 105.63744	2 channels, kind of confined on both individually
NSVH	4*	4.0	0.48		U	0.06		c/b	RR		
NSVH	5	5.5	0.40		PC		19	c/b	RR	40.21397, 105.63716	PC only because hugging valley wall
NSVpc	1	5.4	0.82	25	PC	0.12	15	b	Cas/RR	40.20031, 105.59602	400m reach; lots of OM not in jams or backwater pools, ton of floodplain wood and debris
NSVpc	2	8.0	0.60		PC	0.09		b/c	Cas	40.199657, 105.595227	
NSVpc	3	10.3	0.58	30	PC	0.07	18	c/b	Cas/SP	40.198831, 105.594912	below junction with Ouzel
NSVpc	4	8.1	0.80	19	C	0.07		b/c	Cas	40.198741, 105.594011	large boulders, deep pools
NSVpc	5	10.2	0.75	19	C	0.03	11	c/b	RR/Cas	40.198353, 105.593287	stopped surveying here
OUZELa	1	6.5	0.82	66.7		0.05	6	c	RR	40.200354, 105.608309	wet side channels, all pieces from burn
OUZELa	2	5.8	0.85	54		0.08		c/b	SP/RR	40.200340, 105.607214	
OUZELa	3	5.8	0.67	55		0.03	5	c	RR	40.200276, 105.605740	
OUZELa	4	7.2	0.73	63		0.03		c	RR	40.199881, 105.604757	
OUZELa	5	20.8	0.50	33.6		0.03	11	c	PB	40.19967, 105.60336	whole valley
OUZELb	1	7.3	0.68	73.2		0.04	16	g/c	PR	40.202659, 105.618106	above where channel splits
OUZELb	2	3.5	0.38	64	U	0.03		g/c	PR	40.202970, 105.617914	5 channels, width averaged
OUZELb	3	6.8	0.63	75		0.01	14	c	PR/PB	40.202806, 105.616206	end of multithread reach
OUZELb	4	5.7	0.80	41		0.04		c/b	RR	40.202598,	2 channels, width averaged

Reach	Loc.	BF Width (m)	BF Depth (m)	Valley width (m)	Conf.	Gradient (m/m)	Cover (#)	Grain size	Morph.	Coordinates	Notes
										105.615202	
OUZELb	5	6.0	0.78	30		0.11	5	b	RR/Cas	40.20245, 105.61398	
OUZELc	1	6.5	0.68	36		0.03	4	c/b	RR	40.199612, 105.60274	
OUZELc	2	7.7	0.72	11.5		0.07		c/b	RR/Cas	40.19915???, 105.6019	
OUZELc	3	7.0	0.77	12.7		0.07	9	br/c	SP	40.199259, 105.601483	
OUZELc	4	10.1	0.47	14.7		0.10	10	c/b	SP	40.198852, 105.600653	
MILLu	1	2.8	0.35	13.3		0.03	17	c/g	PB	40.32928, 105.63638	irregular banks, lots OM behind logs everywhere, lots algae, split channels, baby fish!
MILLu	2	5.2	0.47		U	0.00		g	PR	40.32964, 105.63583	above J2
MILLu	3	3.2	0.50		U	0.00	17	g/s	PR	40.33035, 105.63547	deep pools
MILLu	4	3.9	0.45	31		0.02		g/c	PR/PB	40.33092, 105.63438	
MILLu	5	3.3	0.42	18		0.01	11	g/c	PB	40.33143, 105.63446	last two close together
GLACIERu	1	7.9	0.62	25	PC	0.11	18	b/c	SP	40.29557, 105.64761	top of Icy Brook
GLACIERu	2*	4.0	0.40		U	0.02		c	PB/RR	40.29613, 105.64619	Icy Brook multithread, 3 channels, may be below GC confluence
GLACIERu	3*		0.43		U	0.02	13	g/s	PR	40.29646, 105.64486	Whole valley is wet with channels
GLACIERu	4	4.4	0.75		PC	0.00	14	c/g	PB/PR	40.29651, 105.64371	lowest on reach, one channel
GLACIERu	5	10.4	0.51	38		0.05	15	c/b	PB	40.29525, 105.64619	top of Glacier Creek
GLACIERc	1	4.3	0.50		PC	0.07	11	c/b	RR	40.29754, 105.641026	river birch hell, bedrock confined river right
GLACIERc	2	3.9	0.62		C	0.01		c/b	RR	40.29767, 105.64069	river birch hell, bedrock confined river right

Reach	Loc.	BF Width (m)	BF Depth (m)	Valley width (m)	Conf.	Gradient (m/m)	Cover (#)	Grain size	Morph.	Coordinates	Notes
GLACIERc	3	5.7	0.56		C	0.02	10	c	PB/RR	40.29792, 105.64010	river birch hell, bedrock confined river right
GLACIERc	4	4.0	0.50		PC	0.02	15	br/c	RR	40.29807, 105.63985	opening up again, no bedrock
MILLc	1	7.5	0.47		C	0.19	16	b	Cas/SP	40.33309, 105.63264	260m reach
MILLc	2	4.7	0.47		C	0.15		b	Cas/SP	40.33354, 105.63238	below J1
MILLc	3	4.8	0.37		C	0.10	16	b/c	RR	40.33373, 105.63223	above J4, valley is less confined but channel is incised
MILLc	4	3.2	0.43		C	0.08		c/b	RR/SP	40.33445, 105.63182	below where it has multiple channels
MILLc	5	4.8	0.47		C	0.05	11	c/b	RR	40.33459, 105.63112	reach incised or confined
SFREN1	1	14.1	0.51		PC	0.01	11	c/b	PB	41.25892, 106.4154	bottom of reach
SFREN1	2	12.9	0.42		PC	0.02		c	PR	41.25874, 106.41403	cobble bar
SFREN1	3	11.6	0.52		PC	0.02	10	c/b	PB/RR	41.25914, 106.41254	bigger clasts
SFREN1	4	12.3	0.52		PC	0.02		c	PB	41.25940, 106.41139	
SFREN1	5	14.9	0.55		PC	0.05	12	c/b	PB/RR	41.25943, 106.41044	
SFREN2	1	19.6	0.65		C	0.03	6	c	PB/RR	41.23342, 106.46697	top of reach, jam above, forced pool here
SFREN2	2	9.5	0.68		PC	0.03		c/b	RR	41.23303, 106.46817	below J1
SFREN2	3	17.9	0.67		C	0.03	8	c	PR/PB	41.23238, 106.46960	below big step, above where channel splits
SFREN2	4	9.7	0.55		PC	0.03		c	PB	41.23182, 106.46996	above second split
MULL	1	7.5	0.47		PC	0.03	13	c	PB	41.23178, 106.38751	top of reach
MULL	2	5.1	0.43		PC	0.02		c	PB/RR	41.23137, 106.38872	
MULL	3*	3.8	0.35		PC	0.02	11	c	PR/PB	41.23098,	4 channels

Reach	Loc.	BF Width (m)	BF Depth (m)	Valley width (m)	Conf.	Gradient (m/m)	Cover (#)	Grain size	Morph.	Coordinates	Notes
										106.38990	
MULL	4	4.5	0.47		C	0.03		c	RR/PB	41.23099, 106.39066	all one channel
MULL	5	4.8	0.58		PC	0.04	9	c/b	RR	41.23043, 106.39211	stopped here; valley wall alternates
ROCK	1	5.8	0.54		PC	0.02	5	c	PB	41.43994, 106.18787	
ROCK	2*	3.9	0.35		PC	0.02		c	PR/PB	41.44112, 106.18864	2 channels
ROCK	3	7.8	0.43		PC	0.03	4	c	PB/RR	41.44176, 106.18853	
ROCK	4	9.5	0.42		PC	0.02		c	PB	41.44238, 106.18874	
ROCK	5	5.5	0.60		C	0.04	7	c/b	RR	41.44335, 106.18880	

Table 5.2 Jam and backwater pool data for all reaches.

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
NSVS1	S1	36	2.2	0.9	0.72	0.60	0.40	0.60	0.23	0.35	3.7	4.0	14.7	0.39	5.7	0.10	1.1	70
NSVS1	S2	40-45	4.4	0.5	0.62	0.40	0.50	0.50	0.39	0.39	2.8	2.2	6.2	0.28	1.7	0.07	0.1	25
NSVS1	S3	47	3.1	0.6	0.60	0.70	0.30	0.70	0.10	0.23	1.5	1.4	2.1	0.22	0.5	0.08	0.1	40
NSVS1	S4	68	4.5	1.2	1.00	0.70	0.00	1.00	0.00	1.58	1.5	2.2	3.4	0.49	1.7	0.00	0.0	0
NSVS1	WDJ	107	0.3	0.3	0.34	0.40	0.30	0.70	0.01	0.02								
NSVS1	S5	108	1.4	0.6	0.60	0.70	0.00	1.00	0.00	0.14								
NSVS1	S6	122	2.0	0.7	0.52	0.40	0.50	0.50	0.23	0.23	1.9	2.4	4.5	0.32	1.4	0.07	0.1	30
NSVS2	S7	0	1.0	0.4	0.45	0.20	0.10	0.90	0.01	0.13	2.5	1.9	4.7	0.20	1.0	0.00	0.0	0
	S7										2.9	1.0	3.0	0.26	0.8	0.06	0.2	100
	S7										2.0	0.5	1.0	0.22	0.2	0.02	0.0	30
	S7										1.3	0.6	0.7	0.10	0.1	0.03	0.0	75
NSVS2	WD	17	1.6	0.6	0.30	0.60	0.10	0.90	0.01	0.09	2.5	1.7	4.2	0.25	1.0	0.06	0.1	60
NSVS3	S8	7	1.4	0.9	0.32	0.30	0.30	0.70	0.08	0.20	1.6	1.0	1.7	0.14	0.2	0.06	0.1	100
NSVS3	WD	12	0.5	0.3	0.30	0.50	0.00	1.00	0.00	0.02								
NSVS3	S9	22	0.6	0.4	0.51	0.40	0.50	0.50	0.04	0.04								
NSVS3	S10	39	1.7	1.5	0.62	0.70	0.40	0.60	0.18	0.28	2.3	1.6	3.5	0.21	0.7	0.07	0.2	100
NSVS5	S13	4	4.3	0.9	0.57	0.70	0.40	0.60	0.26	0.39	1.2	1.9	2.3	0.32	0.7	0.09	0.1	70
NSVS5	S12	15	2.8	0.7	0.65	0.30	0.35	0.65	0.29	0.54	2.1	1.6	3.2	0.15	0.5	0.22	0.5	75
NSVS5	S11	25	2.7	0.6	0.61	0.40	0.30	0.70	0.18	0.42	2.0	1.1	2.2	0.18	0.4	0.13	0.3	100
	S11										2.8	3.0	8.4	0.27	2.2	0.08	0.5	70
NSVS6	S14	0	5.1	0.8	0.69	0.40	0.30	0.70	0.51	1.18	2.4	3.6	8.8	0.29	2.5	0.00	0.0	0
NSVS6	WD	2	1.8	0.2	0.30	0.40	0.40	0.60	0.03	0.04								
NSVS6	no#	5	1.9	0.9	0.65	0.40	0.20	0.80	0.13	0.53								
NSVS7	WD	8	1.4	0.5	0.41	0.60	0.30	0.70	0.03	0.07								
NSVS7	S15	16	2.4	1.7	0.51	0.70	0.40	0.60	0.24	0.36	1.5	0.6	1.0	0.25	0.2	0.06	0.0	30

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
NSVS7	S16	18	3.3	1.2	0.41	0.45	0.40	0.60	0.34	0.51	2.6	2.9	7.5	0.21	1.6	0.21	1.6	100
NSVS7	S17	27	4.9	2.1	0.82	0.70	0.40	0.60	1.01	1.52	2.7	4.5	12.1	0.23	2.8	0.13	1.5	100
NSVS9	S19	12	1.6	0.5	0.57	0.40	0.50	0.50	0.15	0.15	2.7	2.6	7.0	0.20	1.4	0.06	0.2	45
	S19										3.9	2.6	10.2	0.19	2.0	0.16	1.1	70
NSVL	J1	4450675, 447669	3.0	1.0	0.83	0.50	0.20	0.80	0.25	1.00	1.8	0.5	0.9	0.41	0.4	0.02	0.0	25
NSVL	J2	4450670, 447668	2.6	0.5	0.37	0.50	0.10	0.90	0.02	0.21	1.2	1.7	2.1	0.21	0.4	0.04	0.0	50
NSVL	J3	4450669, 447677	2.4	0.9	0.63	0.40	0.35	0.65	0.27	0.51								
NSVL	J4	4450654, 447678	1.9	1.6	0.80	0.30	0.35	0.65	0.58	1.08	5.8	3.4	19.5	0.38	7.4	0.12	1.8	75
NSVL	J5	4450658, 447684	3.2	0.8	0.45	0.45	0.30	0.70	0.19	0.44	2.8	4.4	12.5	0.39	4.8	0.07	0.5	60
NSVL	J6	4450654, 447685	3.4	0.6	0.81	0.40	0.30	0.70	0.30	0.69	2.8	1.1	3.0	0.30	0.9	0.01	0.0	15
NSVL	J7 (S21)	4450638, 447707	2.2	1.8	0.66	0.60	0.25	0.75	0.25	0.76	3.0	2.1	6.2	0.24	1.5	0.40	2.5	100
NSVL	J8	4450641, 447706	9.8	1.1	1.51	0.30	0.25	0.75	2.85	8.55	5.2	6.0	31.2	0.83	26.0	0.04	0.4	30
	J8										2.7	2.5	6.7	0.64	4.2	0.05	0.1	30
NSVL	J9	4450633, 447736	3.9	0.9	0.59	0.35	0.20	0.80	0.26	1.05	1.6	1.7	2.8	0.19	0.5	0.12	0.3	100
NSVL	J10	4450640, 447749	4.7	2.7	1.56	0.70	0.00	1.00	0.00	5.85	2.1	1.2	2.4	0.68	1.6	0.00	0.0	0
NSVL	J11	4450651, 447779	2.9	0.5	0.45	0.30	0.10	0.90	0.05	0.45								
NSVL	J12	4450655, 447788	1.6	0.6	0.55	0.45	0.15	0.85	0.04	0.24								

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
NSVL	J13	4450670, 447830	3.0	0.4	0.80	0.60	0.10	0.90	0.03	0.30								
NSVL	J14	4450682, 447856	5.2	3.5	0.90	0.60	0.20	0.80	1.30	5.20								
GC	J1	4462427, 446049	3.0	0.9	0.82	0.50	0.25	0.75	0.28	0.83								
GC	J2	4462488, 446027	2.8	0.4	0.50	0.60	0.20	0.80	0.04	0.16								
GC	J3	4462502, 446025	3.0	1.5	1.15	0.40	0.40	0.60	1.22	1.83	2.8	1.9	5.3	0.31	1.6	0.00	0.0	0
GC	J4	4462524, 446032	3.0	1.3	4.10	0.70	0.25	0.75	1.20	3.60	3.4	2.7	9.2	0.25	2.3	0.03	0.1	40
GC	J5	4462555, 446060	8.6	1.0	1.20	0.50	0.30	0.70	1.55	3.61	3.2	5.3	17.0	0.59	10.0	0.03	0.1	25
GC	J6	4462558, 446069	5.0	0.9	0.85	0.30	0.40	0.60	1.07	1.61	5.0	4.5	22.5	0.34	7.6	0.04	0.4	40
	J6										4.3	1.8	7.7	0.60	4.7	0.00	0.0	20
GC	J7	4462562, 446076	6.3	0.9	0.95	0.60	0.20	0.80	0.41	1.63								
GC	J8	4462589, 446146	1.8	0.8	0.75	0.40	0.45	0.55	0.29	0.36								
GC	J9	4462680, 446213	2.0	0.4	0.50	0.40	0.45	0.55	0.11	0.13								
GC	J10	4462697, 446241	1.1	3.0	1.40	0.50	0.15	0.85	0.33	1.87								
GC	J11	4462754, 446267	5.4	0.9	1.00	0.10	0.60	0.40	2.62	1.75	4.0	4.3	17.2	0.36	6.2	0.25	4.2	100
GC	J12	4462787, 446307	3.7	0.3	0.40	0.40	0.45	0.55	0.10	0.12	3.2	3.5	11.2	0.42	4.7	0.04	0.1	30
GC	J13	4462803, 446323	4.7	1.8	0.90	0.70	0.30	0.70	0.69	1.60								

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
GC	J14	4462843, 446391	1.4	0.4	0.50	0.50	0.50	0.50	0.07	0.07								
GC	J15	4462916, 446487	4.0	0.5	0.45	0.70	0.40	0.60	0.11	0.16								
NSVC	J1	4450886, 447274	4.3	0.3	0.58	0.50	0.10	0.90	0.04	0.33	1.9	2.5	4.6	0.49	2.3	0.02	0.0	20
NSVC	J2	4450868, 447305	6.0	0.5	0.70	0.65	0.10	0.90	0.07	0.66								
NSVC	WD		1.0	0.3	0.30	0.50	0.25	0.75	0.01	0.03								
NSVC	J3	4450804, 447438	2.5	0.7	0.65	0.60	0.10	0.90	0.04	0.40								
NSVC	J4	4450806, 447452	2.3	0.8	0.35	0.50	0.40	0.60	0.13	0.19	2.0	2.0	3.9	0.43	1.7	0.04	0.1	35
NSVC	J5	4450802, 447455	1.6	0.3	0.68	0.25	0.60	0.40	0.16	0.11								
NSVC	J6	4450799, 447476	2.6	0.6	0.50	0.60	0.10	0.90	0.03	0.28								
NSVC	J7	4450700, 447628	2.6	0.9	0.80	0.45	0.10	0.90	0.10	0.88								
SFP	J1	4435027, 454696	13.0	1.5	1.30	0.50	0.30	0.70	3.80	8.87								
SFP	WD		0.9	1.4	0.90	0.65	0.10	0.90	0.04	0.36								
SFP	J2	4495278, 454739	2.2	1.3	0.50	0.40	0.40	0.60	0.34	0.51								
SFP	J3	4495328, 454807	2.0	0.4	0.55	0.50	0.60	0.40	0.13	0.09	1.8	2.2	3.9	0.46	1.8	0.03	0.0	30
SFP	J4	4495291, 455058	2.4	0.9	0.50	0.60	0.15	0.85	0.06	0.37								
SFP	J5	4495314, 455082	3.7	0.9	0.60	0.45	0.25	0.75	0.27	0.82								

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
SFP	WD	4495452, 455091	4.8	0.8	0.30	0.50	0.35	0.65	0.20	0.37								
SFP	WD		0.5	0.5	0.50	0.40	0.40	0.60	0.03	0.05								
SFP	J6	4495480, 455041	4.5	1.4	1.10	0.50	0.20	0.80	0.69	2.77								
SFP	J7	4495479, 455038	9.1	0.6	0.90	0.75	0.20	0.80	0.25	0.98	2.4	1.7	3.9	0.43	1.7	0.03	0.0	30
NSVU	JA	40.21031, 105.63077																
NSVU	JB		4.5	1.5	0.80	0.40	0.15	0.85	0.49	2.75	2.5	0.7	1.8	1.80	3.2			
NSVU	J1	40.21008, 105.63196	15.0	1.5	1.50	0.35	0.05	0.95	1.10	20.84								
NSVU	J2	40.21014, 105.63184	12.0	2.0	1.00	0.25	0.10	0.90	1.80	16.20	3.5	4.0	14.0	0.55	7.7		0.3	
NSVU	JC	40.21023, 105.62855	2.5	1.0	0.50	0.20	0.10	0.90	0.10	0.90	1.2	1.0	1.2	0.48	0.6		0.0	
NSVU	JD	40.2101, 105.6284	6.0	0.8	0.70	0.10	0.40	0.60	1.21	1.81	2.5	2.0	5.0	0.40	2.0		0.1	
NSVU	JE	40.21013, 105.62852	4.0	1.1	0.60	0.25	0.10	0.90	0.20	1.78								
NSVU	JF	40.21014, 105.62817	7.0	0.5	0.50	0.20	0.15	0.85	0.21	1.19	2.0	2.0	4.0	0.48	1.9		0.0	
NSVU	JG	40.21006, 105.62766	3.0	2.0	0.50	0.30	0.10	0.90	0.21	1.89								
NSVU	J3	40.20976, 105.62926	3.1	1.4	1.10	0.10	0.65	0.35	2.79	1.50	4.2	3.8	16.0	0.60	9.6		0.8	
NSVU	J4	40.20976, 105.629242	3.6	1.6	2.40	0.10	0.50	0.50	6.22	6.22	7.4	9.5	70.3	1.70	119.5		12.0	
NSVU	J5	40.20975, 105.62967	8.0	1.7	2.10	0.30	0.50	0.50	10.00	10.00	4.0	8.0	32.0	2.10	67.2		1.4	

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
NSVU	J6	40.20976, 105.62994	8.0	3.5	1.20	0.20	0.60	0.40	16.13	10.75	2.0	6.0	12.0	2.70	32.4		1.2	
NSVU	J7	40.20975, 105.63056	6.1	1.4	1.50	0.60	0.30	0.70	1.54	3.59	4.0	2.0	8.0	1.40	11.2		0.0	
NSVU	J8	40.20973, 105.6311	3.6	1.5	1.60	0.20	0.50	0.50	3.46	3.46	2.5	3.0	7.5	1.50	11.3		0.6	
NSVU	J9	40.20977, 105.63133	5.5	4.8	1.90	0.50	0.60	0.40	15.05	10.03	6.0	2.5	15.0	1.10	16.5		0.9	
NSVU	J10	40.20982, 105.63155	6.0	1.9	0.90	0.70	0.30	0.70	0.92	2.15	2.0	2.0	4.0	0.70	2.8			
NSVU	J11	40.20985, 105.63161	6.5	4.5	2.00	0.50	0.40	0.60	11.70	17.55	5.2	3.6	18.7	0.90	16.8		1.4	
NSVU	J12	40.21001, 105.63134	4.3	1.2	1.00	0.10	0.30	0.70	1.39	3.25	3.0	4.5	13.5	0.60	8.1		1.9	
NSVU	J13	40.21004, 105.63149	12.0	1.0	1.50	0.10	0.10	0.90	1.62	14.58								
NSVU	J14	40.21003, 105.6316	9.5	5.5	1.50	0.50	0.40	0.60	15.68	23.51	7.0	5.5	38.5	1.50	57.8		3.6	
NSVU	J15	40.20982, 105.63062	5.5	1.0	1.00	0.40	0.50	0.50	1.65	1.65	3.5	3.0	10.5	0.70	7.4		0.5	
NSVU	J16	40.20999, 105.63112	3.5	1.0	0.70	0.10	0.20	0.80	0.44	1.76	5.1	1.7	8.7	0.50	4.3		0.7	
NSVU	J17	40.21, 105.63119	4.1	1.5	2.00	0.30	0.40	0.60	3.44	5.17	2.0	2.5	5.0	0.50	2.5		0.2	
NSVU	J18	40.21, 105.63125	2.5	1.0	0.80	0.10	0.40	0.60	0.72	1.08	3.5	2.0	7.0	0.60	4.2		0.3	
NSVU	J19	40.21001, 105.63132	6.5	2.0	1.30	0.20	0.60	0.40	8.11	5.41	3.0	3.5	10.5	0.70	7.4		1.0	
HUNTc	J1	40.221485, 105.590865	4.3	2.5	0.50	0.40	0.00	1.00	0.00	3.23	3.8	1.9	7.2	0.83	6.0		0.0	
HUNTc	J2	40.2225, 105.592009	3.3	3.0	1.30	0.25	0.15	0.85	1.45	8.20	2.6	2.2	5.7	0.65	3.7		0.0	

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
HUNTc	J3	40.2225, 105.592009	6.3	1.5	1.50	0.50	0.00	1.00	0.00	7.09	0.0	0.0	0.0	0.00	0.0		0.0	
HUNTc	J4	40.221773, 105.591244	5.5	1.5	1.25	0.40	0.10	0.90	0.62	5.57	3.4	3.0	10.2	0.70	7.1		0.0	
HUNTu	J1	40.221316, 405.590629	4.8	1.0	1.20	0.60	0.15	0.85	0.35	1.96	2.7	2.4	6.3	0.50	3.2			
HUNTu	J2	40.221273, 105.590462	5.5	1.7	1.50	0.60	0.15	0.85	0.84	4.77	2.7	1.2	3.2	0.93	3.0			
HUNTu	J3	40.221088, 105.590299	9.3	0.8	0.50	0.75	0.15	0.85	0.13	0.74								
HUNTu	J4	40.22755, 105.58959	4.0	0.5	0.60	0.40	0.10	0.90	0.07	0.65							0.1	
HUNTu	J5	40.219648, 105.587994	3.3	1.0	0.50	0.60	0.15	0.85	0.10	0.56	4.7	2.8	13.2	0.70	9.2		0.0	
HUNTu	J6	40.219213, 105.587921	5.5	1.6	1.30	0.40	0.05	0.95	0.34	6.52								
HUNTu	J7	40.218938, 105.587324	9.0	2.0	0.75	0.40	0.30	0.70	2.43	5.67	11.1	12.0	133.2	0.70	93.2		0.4	
CONYu	J1	40.18022, 105.59896	6.0	1.0	0.70	0.15	0.50	0.50	1.79	1.79	5.0	6.0	30.0	0.63	19.0		0.5	
CONYu	J2	40.18058, 105.59805	2.5	2.0	0.60	0.25	0.20	0.80	0.45	1.80	1.0	1.5	1.5	1.15	1.7			
CONYu	J3	40.18062, 105.5974	4.0	2.0	0.60	0.40	0.15	0.85	0.43	2.45	3.0	1.0	3.0	0.57	1.7			
CONYu	J4	40.18137, 105.59691	5.0	2.0	0.50	0.35	0.30	0.70	0.98	2.28	9.0	2.0	18.0	0.53	9.6		0.8	
CONYu	J5	40.18137, 105.59696	4.0	1.0	0.50	0.40	0.15	0.85	0.18	1.02								
CONYu	J6	40.18143, 105.59644	6.0	1.5	0.40	0.35	0.15	0.85	0.35	1.99								
CONYc	J1	40.18976, 105.59366	4.5	4.0	0.40	0.15	0.15	0.85	0.92	5.20								

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
CONYc	J2	40.18934, 105.59355	4.0	0.8	0.50	0.30	0.05	0.95	0.05	1.00								
CONYc	J3	40.18962, 105.59344	6.0	0.8	1.00	0.35	0.10	0.90	0.29	2.63								
CONYc	WD		1.0	1.0	1.00	0.25	0.15	0.85	0.11	0.64								
CONYc	J4	40.18964, 105.59304	3.5	0.5	1.00	0.45	0.10	0.90	0.10	0.87	3.5	2.0	7.0	1.00	7.0			
CONYc	J5	40.18972, 105.59303	4	0.5	0.75	0.45	0.05	0.95	0.04	0.78								
CONYc	J6	40.1907, 105.59204	6.0	0.4	0.50	0.35	0.05	0.95	0.04	0.74								
OUZELu	J1	40.19992, 105.62904	9.0	1.2	0.40	0.35	0.12	0.88	0.34	2.47								
OUZELu	J2	40.19981, 105.62872	6.5	2	0.6	0.3	0.2	0.8	1.092	4.368	1	1	1	0.88	0.9			
OUZELu	J3	40.199801, 105.62852	17.0	2.0	1.70	0.15	0.15	0.85	7.37	41.76	12.0	9.5	114.0	0.97	110.2		6.0	
OUZELu	J4	40.19986, 105.62678	5	1	0.5	0.2	0.15	0.85	0.3	1.7	3	2	6	0.57	3.4	0.06		
OUZELu	J5	40.20001, 105.62653	6	1.75	0.5	0.3	0.15	0.85	0.551	3.1238	2	3.5	7	0.62	4.3	0.50		
OUZELu	J6	40.20014, 105.62627	6.0	2.0	1.00	0.15	0.20	0.80	2.04	8.16	3.0	3.0	9.0	0.93	8.3		0.1	
NSVH	J1	40.21552, 105.63881	2.4	1.5	0.4	0.3	0.05	0.95	0.05	0.9576								
NSVH	J2	40.21534, 105.63866	5.0	3.0	1.50	0.10	0.15	0.85	3.04	17.21	1.5	2.6	3.9	0.40	1.6		0.1	
NSVH	J3	40.21503, 105.63869	7.5	2.5	2	0.3	0.5	0.5	13.13	13.125	9.0	4.7	42.3	1.20	50.8	1.88		
NSVH	J4	40.21484, 105.63876	7.0	1.5	1.50	0.70	0.20	0.80	0.95	3.78	3.0	2.5	7.5	0.40	3.0		0.4	

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
NSVH	J5	40.21462, 105.63878	4.5	1.5	1	0.2	0.3	0.7	1.62	3.78	3.5	1.5	5.3	0.50	2.6	0.38		
NSVH	J6	40.21462, 105.63869	5.5	2.5	1.50	0.50	0.20	0.80	2.06	8.25	4.0	3.0	12.0	1.00	12.0		0.9	
NSVH	J7	40.2146, 105.63851	6.0	2.5	1.00	0.70	0.10	0.90	0.45	4.05								
NSVH	J8	40.2136, 105.63794	5.0	2.0	1.00	0.50	0.20	0.80	1.00	4.00								
NSVH	J9	40.21403, 105.6373	8.0	1.8	0.90	0.60	0.50	0.50	2.59	2.59	3	3.0	9.0	1.50	13.5	0.60		
NSVH	J10	40.21494, 105.63867	4.2	0.9	0.80	0.45	0.15	0.85	0.25	1.41	3	1.5	4.5	0.50	2.3	0.24		
NSVH	J11	40.21486, 105.63869	2.3	0.8	1.00	0.10	0.60	0.40	0.99	0.66	4.5	2.0	9.0	2.00	18.0		2.4	
NSVH	J12	40.21484, 105.63863	2.6	1.2	0.80	0.30	0.40	0.60	0.70	1.05	6.2	2.0	12.4	0.60	7.4		2.4	
NSVH	J13	40.21462, 105.63849	4.7	1.4	0.60	0.05	0.05	0.95	0.19	3.56	3.0	2.5	7.5	0.70	5.3		0.5	
NSVH	J14	40.21461, 105.63843	2.8	2.0	0.60	0.15	0.10	0.90	0.29	2.57	4.0	4.0	16.0	0.70	11.2		0.6	
NSVH	J15	40.21494, 105.6383	3.4	1.6	0.70	0.40	0.50	0.50	1.14	1.14	2.0	2.5	5.0	0.50	2.5		0.6	
NSVH	J16	40.21509, 105.63837	4.1	1.3	1.10	0.30	0.25	0.75	1.03	3.08								
NSVH	J17	40.21514, 105.63837	4.2	1.0	0.60	0.20	0.10	0.90	0.20	1.81	3.0	3.5	10.5	0.60	6.3		0.3	
NSVH	J18	40.21529, 105.63837	3.6	1.5	1.00	0.30	0.50	0.50	1.89	1.89	3.0	2.5	7.5	0.50	3.8		1.3	
NSVH	J19	40.21532, 105.63848	2.7	0.9	0.70	0.25	0.10	0.90	0.13	1.15	0.5	1.2	0.6	0.40	0.2		0.1	
NSVH	J20	40.21532, 105.63828	3.4	0.9	0.80	0.10	0.25	0.75	0.55	1.65	3.5	2.5	8.8	0.60	5.3		1.5	

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
NSVH	J21	40.21522, 105.63816	2.6	0.9	0.70	0.60	0.05	0.95	0.03	0.62	1.0	1.0	1.0	0.60	0.6		0.0	
NSVH	J22	40.21534, 105.63829	3.5	1.0	0.75	0.25	0.50	0.50	0.98	0.98	3.5	0.2	0.5	0.29	0.2		0.0	
NSVH	J23	40.21504, 105.63799	3.0	1.0	0.80	0.35	0.05	0.95	0.08	1.48								
NSVH	J24	40.21487, 105.63776	4.0	2.0	0.50	0.30	0.30	0.70	0.84	1.96								
NSVH	J25	40.21462, 105.63762	2.5	1.0	0.40	0.45	0.05	0.95	0.03	0.52								
NSVH	J26	40.21431, 105.63744	4.0	1.0	0.70	0.35	0.10	0.90	0.18	1.64	2.0	1.0	2.0	0.50	1.0			
NSVH	J27	40.21436, 105.63737	7.0	1.0	1.50	0.35	0.30	0.70	2.05	4.78								
NSVH	J28	40.21432, 105.63718	6.0	1.5	0.70	0.35	0.20	0.80	0.82	3.28	1.0	1.0	1.0	0.20	0.2		0.0	
NSVH	WD		1.0	1.0	1.00	0.40	0.40	0.60	0.24	0.36								
NSVH	J29	40.21407, 105.63718	2.0	0.5	0.70	0.20	0.20	0.80	0.11	0.45								
MILLc	J1	40.3335, 105.63242	3.2	0.4	0.35	0.45	0.15	0.85	0.04	0.21								
MILLc	J2	40.33356, 105.6324	5.0	0.7	1.00	0.10	0.20	0.80	0.63	2.52	4.0	1.5	6.0	0.52	3.1		0.1	
MILLc	J3	40.3337, 105.6323	5.0	0.6	0.60	0.10	0.20	0.80	0.32	1.30	3.0	1.0	3.0	0.50	1.5			
MILLc	J4	40.33373, 105.6322	1.5	0.7	0.60	0.30	0.05	0.95	0.02	0.42								
MILLc	J5	40.33398, 105.63216	3.5	2.0	0.70	0.15	0.30	0.70	1.25	2.92	1.3	1.5	2.0	0.20	0.4		0.1	
MILLc	J6	40.33427, 105.63197	5.0	1.0	1.00	0.10	0.20	0.80	0.90	3.60	3.2	4.2	13.4	0.55	7.4		0.4	

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
NSVpc	J1	40.199907, 105.59544	9.0	1.8	0.50	0.45	0.22	0.78	0.98	3.47	2.6	2.0	5.2	0.72	3.7		0.1	
NSVpc	J2	40.199796, 105.595397	4.6	0.4	0.40	0.20	0.30	0.70	0.18	0.41	3.7	4.9	18.1	1.20	21.8		0.1	
NSVpc	J3	40.199346, 105.594922	7.0	2.5	0.50	0.40	0.05	0.95	0.26	4.99								
NSVpc	J4	40.199089, 105.595041																
NSVpc	J5	40.198691, 105.593493	9.0	1.5	0.60	0.40	0.05	0.95	0.24	4.62								
OUZEL a	J1	40.200421, 105.608779	15.1	5.0	1.50	0.45	0.20	0.80	12.46	49.83	6.8	3.7	25.2	0.80	20.1		2.4	
OUZEL a	J2	40.200308, 105.607303	4.0	1.7	0.60	0.60	0.10	0.90	0.16	1.47	3.8	1.0	3.8	0.50	1.9		0.0	
OUZEL a	J3	40.200375, 105.606525	13.7	3.0	1.00	0.20	0.20	0.80	6.58	26.30	6.6	8.0	52.8	0.70	37.0		2.7	
OUZEL a	J4	40.200258, 105.605649	8.4	1.0	0.50	0.50	0.10	0.90	0.21	1.89	2.2	3.5	7.7	0.58	4.5		0.0	
OUZEL a	J5	40.199745, 105.604472	5.0	2.0	1.20	0.40	0.20	0.80	1.44	5.76	4.0	6.0	24.0	0.38	9.2		0.2	
OUZEL b	J1	40.20031, 105.59602	5.7	1.1	0.60	0.45	0.15	0.85	0.31	1.76	7.0	1.0	7.0	0.60	4.2		0.0	
OUZEL b	J2	40.202691, 105.618422	4.9	0.8	0.50	0.60	0.05	0.95	0.04	0.70	2.0	3.5	7.0	0.60	4.2			
OUZEL b	J3	40.202661, 105.618272	3.1	0.6	0.40	0.40	0.15	0.85	0.07	0.38	1.8	0.5	0.9	0.38	0.3		0.0	
OUZEL b	J4	40.202707, 105.618343	11.0	3.0	0.60	0.30	0.40	0.60	5.54	8.32			0.0		0.0			
OUZEL b	J5	40.202784, 105.618053	3.5	1.6	0.60	0.30	0.15	0.85	0.35	2.00	4.1	3.4	13.9	0.43	6.0		0.4	
OUZEL b	J6	40.20297, 105.617914	3.5	1.0	0.50	0.40	0.10	0.90	0.11	0.95	9.5	5.1	48.5	0.70	33.9		0.0	

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
OUZEL b	J7	40.202775, 105.616185	6.1	1.0	0.60	0.50	0.15	0.85	0.27	1.56	2.1	3.0	6.3	0.52	3.3		0.1	
OUZEL b	J8	40.20258, 105.61578	5.8	1.0	0.50	0.45	0.05	0.95	0.08	1.52	6.8	6.0	40.8	0.78	32.0			
OUZEL b	J9	40.20242, 105.61428	3.0	2.0	0.70	0.30	0.30	0.70	0.88	2.06								
OUZEL b	J10				0.56								124.4					
OUZEL c	J1	40.19967, 105.60336	3.9	1.0	0.90	0.45	0.25	0.75	0.48	1.45	1.0	2.0	2.0	0.52	1.0			
OUZEL c	J2	40.199255, 105.602422	6.0	3.0	0.70	0.35	0.10	0.90	0.82	7.37								
OUZEL c			5.0	2.0	1.50	0.15	0.20	0.80	2.55	10.20								
OUZEL c	J3	40.199155, 105.601335	1.7	2.0	0.50	0.40	0.10	0.90	0.10	0.92								
OUZEL c	J4	40.198887, 105.600583	8.0	3.5	1.00	0.55	0.15	0.85	1.89	10.71	3.0	1.0	3.0	1.50	4.5			
MILLu	J1	40.32927, 105.6366	5.0	0.5	0.40	0.30	0.40	0.60	0.28	0.42	5.0	1.5	7.5	0.47	3.5		0.1	
MILLu	J2	40.32967, 105.63589	5.0	0.7	0.50	0.15	0.25	0.75	0.37	1.12	4.5	7.0	31.5	0.62	19.4		1.8	
MILLu	J3	40.33143, 105.63446	2.7	0.5	0.40	0.35	0.20	0.80	0.07	0.28								
GLACu	WD		2.0	1.0	0.50	0.25	0.20	0.80	0.15	0.60								
GLACu	J1	40.29586, 105.64675	2.0	1.7	1.00	0.15	0.10	0.90	0.29	2.60	3.0	1.5	4.5	0.43	2.0		0.2	
GLACu	J2	40.29582, 105.64689	2.5	0.8	0.50	0.20	0.15	0.85	0.11	0.64								
GLACu	WD		2.0	1.0	0.30	0.15	0.10	0.90	0.05	0.46								
GLACu	J3	40.295, 105.646	3.0	1.0	0.40	0.10	0.15	0.85	0.16	0.92	1.0	1.0	1.0	0.40	0.4		0.1	

Reach	Jam	N, E (or m)	Len. (m)	Wid. (m)	Dep. (m)	Void (prop)	OM (prop)	Wood (prop)	OM vol. (m^3)	Wood vol. (m^3)	Pool len. (m)	Pool wid. (m)	Pool area (m^2)	Pool dep. (m)	Pool vol. (m^3)	OM Dep. (m)	OM vol. (m^3)	Pool OM cover (%)
GLACu	J4	40.29567, 105.6465	5.0	0.8	0.50	0.25	0.15	0.85	0.21	1.20	4.0	1.5	6.0	0.45	2.7		0.0	
GLACu	J5	40.29574, 105.64665	2.5	0.5	0.50	0.10	0.25	0.75	0.14	0.42								
GLACu	J6	40.29664, 105.64557	4.0	2.0	0.50	0.15	0.20	0.80	0.68	2.72	4.0	3.0	12.0	0.67	8.0		1.2	
GLACu	J7	40.29615, 105.64471	3.5	1.3	1.00	0.10	0.25	0.75	1.02	3.07	4.0	2.0	8.0	0.50	4.0		0.4	
GLACu	J8	40.29536, 105.646	5.0	1.5	1.00	0.20	0.05	0.95	0.30	5.70								
GLACu	J10	40.29587, 105.64508	7.0	1.0	1.00	0.10	0.15	0.85	0.95	5.36	1.0	3.0	3.0	0.30	0.9		0.0	
GLACu	J11	40.29616, 105.64484	2.7	0.7	0.50	0.15	0.05	0.95	0.04	0.76	3.0	3.0	9.0	0.43	3.9		0.6	
GLACu	J12	40.29618, 105.6445	17.0	1.5	0.60	0.10	0.25	0.75	3.44	10.33	13.2	7.5	99.0	0.76	74.9		5.0	
GLACu	J13	40.29635, 105.64445	2.8	1.5	0.50	0.35	0.05	0.95	0.07	1.30								
SFREN 2	J1	41.23311, 106.46784	6.8	1.0	0.70	0.30	0.25	0.75	0.83	2.50	5.0	2.0	10.0	0.42	4.2		0.1	
SFREN 3	J2	41.23225, 106.46967	13.7	1.3	0.90	0.20	0.15	0.85	1.92	10.90			0.0		0.0			
MULL	J1	41.2316, 106.38819	8.0	1.0	0.70	0.20	0.15	0.85	0.67	3.81			0.0		0.0			
MULL	J2	41.23135, 106.8895	7.0	4.0	1.00	0.40	0.10	0.90	1.68	15.12			0.0		0.0			
MULL	J3	41.23093, 106.38984	6.0	3.0	1.00	0.35	0.30	0.70	3.51	8.19	5.0	3.0	15.0	0.60	9.0		0.3	
MULL	J4	41.23102, 106.3902	6.0	2.0	1.00	0.20	0.10	0.90	0.96	8.64								

Table 5.3 Non-jam related pools and their organic matter at intensive sites.

Reach	Meter	Pool length (m)	Pool width (m)	Pool area (m^2)	Pool depth (m)	Pool vol. (m^3)	OM depth (m)	OM vol. (m^3)	Pool OM cover (%)	Notes
NSVSC 1	30-35	3.05	1.60	4.88	0.20	0.97	0.04	0.07	35	
NSVSC 1	30-35	2.78	2.68	7.45	0.22	1.66	0.07	0.26	50	
NSVSC 1	121	1.60	2.93	4.69	0.42	1.97	0.00	0.00	0	
NSVSC 3	19-21	1.96	1.96	3.84	0.22	0.83	0.09	0.35	100	
NSVSC 3	36	1.29	0.40	0.52	0.22	0.11	0.09	0.05	100	
NSVSC 3	46-48	1.30	2.22	2.89	0.17	0.50	0.15	0.42	100	
NSVSC 4	15-17	3.80	2.34	8.89	0.32	2.84	0.13	1.19	100	
NSVSC 4	11-14	2.93	1.66	4.86	0.31	1.50	0.08	0.22	60	
NSVSC 8	0	3.15	2.91	9.17	0.28	2.58	0.08	0.51	70	
NSVSC 8	0	4.00	2.47	9.88	0.25	2.49	0.12	1.03	90	
NSVSC 9	3	1.72	1.81	3.11	0.23	0.71	0.05	0.04	30	
NSVL	25	1.28	2.08	2.66	0.20	0.52	0.03	0.04	50	
NSVL	30	1.57	1.03	1.62	0.36	0.59	0.01	0.00	20	
NSVL	140-145	3.70	7.20	26.64	0.26	6.99	0.07	1.07	55	
NSVL	155	1.13	1.50	1.70	0.22	0.37	0.14	0.16	70	
NSVL	220	1.70	1.70	2.89	0.22	0.64	0.04	0.06	45	
NSVL	230	3.06	1.90	5.81	0.38	2.21	0.01	0.02	20	
GC	-435	3.30	1.05	3.47	0.39	1.34	0.00	0.00	0	
GC	-430	1.77	0.88	1.56	0.38	0.60	0.00	0.00	0	
GC	-420	3.60	1.95	7.02	0.46	3.21	0.00	0.00	0	
GC	-415	2.08	1.20	2.50	0.36	0.89	0.00	0.00	0	
GC	-412	1.58	1.15	1.82	0.27	0.49	0.00	0.00	0	
GC	-410	1.40	1.26	1.76	0.22	0.39	0.00	0.00	0	
GC	-405	2.30	2.00	4.60	0.19	0.87	0.05	0.07	35	
GC	-402	1.88	2.19	4.12	0.35	1.45	0.00	0.00	15	
GC	-400	1.32	1.50	1.98	0.42	0.83	0.00	0.00	0	
GC	-400	2.80	1.50	4.20	0.25	1.07	0.11	0.20	45	
GC	-390	3.60	3.00	10.80	0.81	8.80	0.00	0.00	0	
GC	-375	2.80	1.30	3.64	0.47	1.71	0.00	0.00	0	
GC	-370	2.40	2.50	6.00	0.43	2.58	0.00	0.00	0	
GC	-365	2.90	2.70	7.83	0.52	4.09	0.00	0.00	0	
GC	-350	2.00	2.80	5.60	0.41	2.27	0.00	0.00	0	

Reach	Meter	Pool length (m)	Pool width (m)	Pool area (m^2)	Pool depth (m)	Pool vol. (m^3)	OM depth (m)	OM vol. (m^3)	Pool OM cover (%)	Notes
GC	-275	1.70	1.80	3.06	0.49	1.50	0.00	0.00	0	
GC	-255	1.30	1.50	1.95	0.60	1.16	0.00	0.00	0	
GC	-235	3.80	1.70	6.46	0.53	3.42	0.00	0.00	0	
GC	-210	2.50	2.00	5.00	0.36	1.78	0.01	0.01	10	
GC	-170	6.30	3.50	22.05	0.39	8.50	0.01	0.03	20	
GC	-140	7.70	9.40	72.38	1.06	76.64	0.00	0.00	0	
GC	-120	3.80	4.30	16.34	0.38	6.14	0.06	0.25	25	
GC	-75	2.40	0.20	0.48	0.39	0.19	0.00	0.00	0	
GC	-50	3.90	1.80	7.02	0.44	3.10	0.00	0.00	0	
GC	-10	4.50	4.10	18.45	0.50	9.29	0.06	0.31	30	
GC	38	5.20	2.70	14.04	0.42	5.85	0.04	0.19	30	
GC	50	3.80	3.20	12.16	0.52	6.38	0.04	0.12	25	
GC	78	2.90	2.00	5.80	0.43	2.49	0.01	0.02	30	
GC	115	3.20	2.20	7.04	0.54	3.78	0.00	0.00	0	
GC	260	3.00	3.20	9.60	0.47	4.47	0.00	0.00	0	
GC	310	2.90	2.30	6.67	0.37	2.44	0.03	0.06	25	
NSVC	32	2.90	1.45	4.21	0.22	0.93	0.04	0.08	50	
NSVC	40	2.05	2.10	4.31	0.53	2.30	0.00	0.00	0	
NSVC	80	1.00	1.15	1.15	0.42	0.48	0.00	0.00	10	
NSVC	131	1.65	2.30	3.80	0.29	1.11	0.01	0.01	30	
NSVC	205	2.60	1.75	4.55	0.45	2.05	0.03	0.05	30	
NSVC	205	2.10	1.60	3.36	0.39	1.32	0.06	0.15	80	
NSVC	290	2.20	1.70	3.74	0.38	1.43	0.02	0.02	20	
NSVC	350	3.00	1.75	5.25	0.40	2.08	0.01	0.01	10	
NSVC	365	1.10	2.00	2.20	0.39	0.85	0.00	0.00	0	
NSVC	430	3.55	2.40	8.52	0.37	3.18	0.05	0.22	50	
SFP	0	1.40	1.60	2.24	0.26	0.59	0.06	0.14	100	
SFP	15	2.85	2.40	6.84	0.42	2.90	0.00	0.00	0	
SFP	32	3.40	2.40	8.16	0.59	4.85	0.00	0.00	0	
SFP	175	1.15	1.50	1.73	0.22	0.38	0.05	0.04	50	above weir
SFP	250	4.00	1.90	7.60	0.27	2.06	0.01	0.01	10	
SFP	315	3.30	2.00	6.60	0.31	2.07	0.00	0.00	0	
SFP	365	2.20	2.50	5.50	0.54	2.99	0.00	0.00	0	below weir
SFP	370	1.90	1.40	2.66	0.47	1.26	0.04	0.02	20	
SFP	405	8.00	2.50	20.00	0.41	8.11	0.07	0.40	30	
SFP	410	2.40	2.70	6.48	0.35	2.29	0.03	0.06	30	
SFP	525	8.00	3.60	28.8	0.55	15.7	0.05	0.77	50	

Reach	Meter	Pool length (m)	Pool width (m)	Pool area (m^2)	Pool depth (m)	Pool vol. (m^3)	OM depth (m)	OM vol. (m^3)	Pool OM cover (%)	Notes
				0		1				
SFP	550	2.80	2.60	7.28	0.40	2.90	0.00	0.00	20	below weir
SFP	705	4.40	2.50	11.00	0.48	5.30	0.01	0.02	25	
SFP	900	2.05	1.90	3.90	0.39	1.51	0.03	0.05	50	
SFP	920	6.80	6.35	43.18	0.75	32.48	0.03	0.36	25	above weir
SFP	950	8.00	4.75	38.00	0.69	26.26	0.03	0.38	30	above weir
SFP	965	4.70	3.10	14.57	1.00	14.57	0.00	0.00	0	above weir
SFP	980	4.40	3.70	16.28	0.73	11.83	0.00	0.00	0	above weir
NSVU		1.90	3.00	5.70	1.20	6.84				
NSVU		1.90	1.80	3.42	0.60	2.05				
NSVU		3.30	2.90	9.57	0.70	6.70				
NSVU		2.50	4.90	12.25	0.70	8.58		0.36		
NSVU		1.50	4.90	7.35	1.10	8.09				
NSVU		4.30	2.00	8.60	1.00	8.60				
NSVU		2.30	3.10	7.13	1.40	9.98				
NSVU		5.00	2.50	12.50	1.80	22.50				
NSVU		1.60	2.50	4.00	0.60	2.40				
NSVU		4.10	5.30	21.73	0.90	19.56		2.25		
NSVU		3.00	4.00	12.00	1.50	18.00				
NSVU		2.50	3.00	7.50	0.90	6.75				
NSVU		3.00	2.50	7.50	1.00	7.50				
NSVU		4.00	4.00	16.00	2.00	32.00				
NSVU	500-400	1.50	1.00	1.50	0.50	0.75	*For pools in 500-400m, RIVER LEFT, one channel evaluated; multiply all following data by 2 (for 2 channels) then normalize by the 500m			
NSVU	500-400	2.00	6.00	12.00	0.50	6.00				
NSVU	500-400	1.00	0.50	0.50	0.50	0.25				
NSVU	500-400	1.50	0.50	0.75	0.40	0.30				
NSVU	500-400	1.00	1.50	1.50	0.50	0.75				
NSVU	500-400	1.00	1.50	1.50	0.60	0.90				
NSVU	500-400	1.00	1.50	1.50	0.50	0.75				
NSVU	500-400	1.00	1.50	1.50	0.50	0.75				
NSVU	500-400	1.50	1.50	2.25	0.60	1.35				
NSVU	500-400	1.30	1.00	1.30	0.80	1.04				
NSVU	500-400	1.50	5.00	7.50	0.45	3.38		0.25		
NSVU	100-0	5.00	2.00	10.00	0.80	8.00	*For pools in 100-0m, RIVER LEFT, one channel evaluated; multiply all following			

Reach	Meter	Pool length (m)	Pool width (m)	Pool area (m^2)	Pool depth (m)	Pool vol. (m^3)	OM depth (m)	OM vol. (m^3)	Pool OM cover (%)	Notes
NSVU	100-0	2.00	1.20	2.40	0.30	0.72	data by 2 (for 2 channels) then normalize by the 500m			
NSVU	100-0	3.50	2.00	7.00	0.80	5.60				
NSVU	100-0	3.00	2.00	6.00	0.80	4.80				
NSVU	100-0	2.00	1.00	2.00	0.30	0.60				
NSVU	100-0	3.00	2.00	6.00	0.60	3.60				
NSVU	100-0	2.00	2.00	4.00	0.60	2.40				
NSVU	100-0	3.00	3.00	9.00	1.00	9.00				
NSVU	100-0	5.00	5.00	25.00	0.60	15.00				
NSVU	100-0	3.00	1.50	4.50	0.50	2.25		0.45		
NSVU	100-0	4.00	3.00	12.00	0.60	7.20		0.30		
NSVU	100-0	2.00	1.00	2.00	0.30	0.60		0.10		
NSVU	100-0	3.00	1.00	3.00	0.60	1.80		0.10		
NSVU	100-0	3.00	2.00	6.00	0.30	1.80				
NSVU	100-0	6.00	1.50	9.00	0.60	5.40		0.10		

Table 5.4 Organic matter data from irregular banks and zones of flow separation in intensive reaches.

Reach	Meter	OM length (m)	OM width (m)	OM depth (m)	OM vol. (m^3)	Notes
NSVSC1	25	0.48	0.21	0.07	0.01	
NSVSC1	29	0.75	0.40	0.29	0.09	
NSVSC1	96	1.11	0.50	0.10	0.06	
NSVSC9	3	1.17	1.26	0.10	0.15	
NSVSC9	23-27	5.70	1.05	0.14	0.83	
NSVSC9	31-34	3.16	1.52	0.16	0.77	
NSVL	15	5.10	2.75	0.21	2.90	
NSVL	37	5.60	1.00	0.12	0.65	
NSVL	40	5.10	0.85	0.11	0.46	
NSVL	60	5.70	1.40	0.35	2.80	
NSVL	140	3.00	0.10	0.03	0.01	
NSVL	167	1.53	0.60	0.25	0.23	
GC	-451	0.37	0.34	0.20	0.02	
GC	-360	1.80	1.00	0.06	0.11	
GC	-105	0.50	0.30	0.05	0.01	
GC	165	0.50	0.50	0.25	0.06	
GC	245	0.40	0.40	0.40	0.06	
GC	285	0.50	0.40	0.02	0.00	
NSVC	2	0.85	0.80	0.17	0.12	
NSVC	325	0.50	0.30	0.05	0.01	
SFP	20	1.40	0.80	0.03	0.03	
SFP	40	0.50	0.30	0.25	0.04	
SFP	150	0.75	0.50	0.04	0.02	
SFP	176	0.80	0.55	0.03	0.01	
SFP	210	0.30	2.00	0.03	0.02	
SFP	325	0.25	0.25	0.04	0.00	
SFP	450	1.00	0.50	0.25	0.13	
SFP	500	0.50	0.50	0.10	0.03	
SFP	750	1.00	1.00	0.05	0.05	
NSVU					0.20	
NSVU					1.26	
NSVU					0.16	
NSVU					0.83	
NSVU					1.10	
NSVU					0.13	
NSVU					0.47	
NSVU					0.28	
NSVU					0.55	
NSVU					0.51	
NSVU					0.22	
NSVU					0.90	

Reach	Meter	OM length (m)	OM width (m)	OM depth (m)	OM vol. (m^3)	Notes
NSVU					0.27	
NSVU					0.09	
NSVU					1.12	
NSVU					1.04	
NSVU					0.41	
NSVU					0.97	
NSVU					0.72	
NSVU	*For OM sed in 500-400m, RIVER LEFT, one channel evaluated; multiply all following data by 2 (for 2 channels) then normalize by the 500m				0.02	500-400m
NSVU					0.02	500-400m
NSVU					0.05	500-400m
NSVU					0.04	500-400m
NSVU					0.03	500-400m
NSVU					0.01	500-400m
NSVU					0.01	500-400m
NSVU					0.03	500-400m
NSVU					0.00	500-400m
NSVU					0.05	500-400m
NSVU					0.01	500-400m
NSVU					0.08	500-400m
NSVU					0.02	500-400m
NSVU					0.03	500-400m
NSVU					0.01	500-400m
NSVU					0.05	500-400m
NSVU					0.02	500-400m
NSVU					0.01	500-400m
NSVU					0.12	500-400m
NSVU					0.08	500-400m
NSVU					0.02	500-400m
NSVU					0.08	500-400m
NSVU	*For OM sed in 100-0m, RIVER LEFT, one channel evaluated; multiply all following data by 2 (for 2 channels) then normalize by the 500m				0.23	100-0m
NSVU					1.25	100-0m
NSVU					0.10	100-0m
NSVU					0.30	100-0m
NSVU					0.25	100-0m
NSVU					0.20	100-0m
NSVU					0.20	100-0m
NSVU					0.10	100-0m
NSVU					1.00	100-0m
NSVU					0.20	100-0m
NSVU					0.20	100-0m

5.2 Appendix B: Selected field photographs

Figure 5.1 Selected photographs of old-growth, unmanaged sites.

Figure 5.2 Selected photographs of younger-growth, unmanaged sites.

Figure 5.3 Selected photographs of younger-growth, managed sites.

Figure 5.4 Selected photographs of jams (left) and multithread channels (right).




Figure 5.5 Selected photographs of pool with POM (top left), ramp pieces in backwater pool (bottom left), and POM (top right).

5.3 Appendix C: Reach data used in wood and complexity analyses

Table 5.5 Summary of data used in wood and complexity analyses by reach.

Control variables							Cross section variables				
Reach	Treatm.	Conf. (cat.)	Conf. (ind. width) (m/m)	Conf. (total width) (m/m)	Mean forest cover (basal area, m^2/ha)	DA (km^2)	Mean gradient (m/m)	Mean valley width (m)	Mean ind. channel width (m)	Mean total channel width (m)	Mean depth (m)
CONYc	OU	C	2.3	2.3	48.2	13.86	0.12	22	9.5	9.5	0.62
CONYu	OU[b]	P	3.1	3.1	50.5	12.48	0.01	24	7.7	7.7	0.50
HUNTc	OU[b]	P	3.8	3.1	43.6	9.66	0.11	25	6.5	8.1	0.68
HUNTu	OU[b]	P	5.5	4.6	52.8	10.00	0.04	25	4.6	5.5	0.64
NSVC	OU[a]	C	1.7	1.4		17.59	0.07	10	7.4	7.4	0.60
NSVH	OU[b]	U	12.4	5.1	43.6	9.32	0.08	47	3.8	9.2	0.45
NSVL	OU[ab]	U	10.3	5.8		18.21	0.03	76	6.1	13.1	0.55
NSVU	OU[ab]	U	9.0	1.9		14.61	0.06	61	6.8	32.3	0.55
OUZELu	OU[b]	P	4.5	3.2	45.9	10.08	0.05	39	8.6	12.3	0.49
GC	YU[a]	P	3.5	3.5		31.08	0.03	32	9.1	9.1	0.70
GLACc	YU	P	4.9	4.9	27.5	19.66	0.03	22	4.5	4.5	0.55
GLACu	YU[b]	U	15.0	11.5	36.7	19.48	0.05	100	6.7	8.7	0.57
MILLc	YU	C	2.2	2.2	32.1	6.81	0.11	11	5.0	5.0	0.44
MILLu	YU	P	5.7	5.7	34.4	6.40	0.01	21	3.7	3.7	0.44
NSVpc	YU	C	2.7	2.7	34.4	33.67	0.07	23	8.4	8.4	0.71
OUZELa	YU	P	5.9	5.9	16.1	12.43	0.05	54	9.2	9.2	0.71
OUZELb	YU[b]	U	9.7	5.8	27.5	11.19	0.05	57	5.9	9.8	0.66
OUZELc	YU	C	2.4	2.4	18.4	12.92	0.07	19	7.8	7.8	0.66
CLP	YM[b]	U	9.0	9.0	13.8	145.04	0.01	155	17.3	17.3	0.53
MULL	YM[b]	P	4.7	3.3	25.3	22.77	0.03	24	5.1	7.4	0.46
ROCK	YM[b]	U	13.7	12.2	11.5	36.05	0.02	89	6.5	7.3	0.47
SFP	YM[a]	P	4.2	4.2		168.35	0.02	51	12.0	12.0	0.90
SFREN1	YM	P	6.7	6.7	25.3	65.57	0.02	88	13.2	13.2	0.50
SFREN2	YM	C	3.0	3.0	16.1	86.93	0.03	42	14.2	14.2	0.64

[a]Intensive sites; [b]Multithread planform

	Planform variables				Wood piece variables					Jam variables			
Reach	Total channel length (main + secondary ; m)	Valley length (m)	Valley area (m^2)	Total channel area (main + sec.; m^2)	Jams/ 100m valley (#)	Wood vol/ 100m valley (m^3)	Pieces/ 100m valley (#)	Prop. bridges & ramps	bridges & ramps/ 100m valley (#)	Backwater pool vol/ 100m valley (m^3)	Jam OM vol/100m valley (m^3)	Pool OM vol/100m valley (m^3)	Avg jam height/ jam freq (m/#)
CONYc	500	470	11000	4760	1.5	9.40	79	0.35	27.23	8.27	0.47	0.00	0.49
CONYu	515	420	12000	3986	1.4	16.22	77	0.30	23.10	7.63	0.99	0.32	0.39
HUNTc	270	200	5500	1755	2.0	13.39	44	0.32	14.00	8.44	1.03	0.00	0.57
HUNTu	550	403	12500	2512	1.7	9.57	40	0.34	13.65	26.96	1.06	0.12	0.52
NSVC	485	435	4850	2895	1.6	6.02	30	0.22	6.67	0.91	0.13	0.02	0.35
NSVH	1575	230	10810	5610	12.6	102.90	272	0.29	80.00	64.16	16.24	6.19	0.07
NSVL	650	210	15960	3791	16.2	36.22	139	0.28	38.57	36.32	5.31	6.45	0.04
NSVU	2330	465	28365	12225	5.6	70.05	226	0.35	79.14	84.78	22.83	5.75	0.22
OUZELu	1780	500	24900	7160	1.2	26.69	112	0.31	34.40	25.43	2.34	1.33	0.65
GC	900	700	28800	8196	2.1	2.31	19	0.28	5.14	5.30	1.44	0.71	0.48
GLACc	150	150	3300	671	0.0	0.74	11	0.81	8.67	0.00	0.00	0.00	1.00
GLACu	1140	435	125000	7000	3.0	24.69	203	0.20	41.61	22.24	1.75	1.71	0.21
MILLc	260	260	2860	1300	2.3	5.99	119	0.31	37.31	4.77	1.22	0.20	0.31
MILLu	380	350	7980	1398	0.9	5.87	81	0.21	16.57	6.55	0.21	0.53	0.51
NSVpc	400	310	9200	3360	1.6	12.89	52	0.33	17.10	8.22	0.62	0.05	0.31
OUZELa	500	500	27000	4610	1.0	19.80	84	0.27	22.80	14.54	4.17	1.06	0.96
OUZELb	747	445	28500	4377	2.2	27.18	101	0.31	31.46	18.86	1.72	0.12	0.25
OUZELc	250	225	4750	1956	1.8	17.02	107	0.25	26.67	2.46	1.46	1.13	0.52
CLP	500	455	77500	8650	0.0	0.13	1	0.75	0.66	0.00	0.00	0.00	1.00
MULL	620	490	12000	3181	0.8	10.31	58	0.32	18.37	1.84	1.39	0.06	1.13
ROCK	605	400	44500	3933	0.0	0.59	4	0.38	1.50	0.00	0.00	0.00	1.00
SFP	1000	880	51000	12022	0.8	2.97	13	0.45	4.77	0.39	0.66	0.01	0.90
SFREN1	500	450	44000	6580	0.0	3.26	20	0.52	10.22	0.00	0.00	0.00	1.00
SFREN2	500	450	21000	7088	0.4	8.02	37	0.34	12.67	0.93	0.61	0.02	1.80

[a]Intensive sites; [b]Multithread planform

5.4 Appendix D: Distribution of values of variables by treatment

Table 5.6 Mean, Range, and Standard Deviation for Variables in ANOVA Analyses.

		Conf. (ind. width) (m/m)	Conf. (total width) (m/m)	Forest cover (basal area, m^2/ha)	DA (km^2)	Gradient (m/m)	Valley width (m)	Mean ind. channel width (m)	Mean total channel width (m)	Jams/ 100m valley (#)	Wood vol/ 100m valley (m^3)	Pieces/ 100m valley (#)	Prop. bridges & ramps	bridges & ramps/ 100m valley (#)
OU	Mean	5.8	3.4	47.40	12.9	0.06	36.6	6.8	11.7	4.9	32.27	113.2	0.31	35.2
	Min.	1.7	1.4	43.60	9.3	0.01	10.0	3.8	5.5	1.2	6.02	30.1	0.22	6.7
	Max.	12.4	5.8	52.80	18.2	0.12	76.0	9.5	32.3	16.2	102.90	272.2	0.35	80.0
	St. Dev.	3.6	1.4	3.10	3.2	0.03	20.0	1.7	7.6	5.3	31.28	80.4	0.04	25.6
YU	Mean	5.8	5.0	28.30	17.1	0.05	37.7	6.7	7.4	1.7	12.94	86.2	0.33	23.0
	Min.	2.2	2.2	16.10	6.4	0.01	11.0	3.7	3.7	0.0	0.74	10.7	0.20	5.1
	Max.	15.0	11.5	36.70	33.7	0.11	100.0	9.2	9.8	3.0	27.18	203.0	0.81	41.6
	St. Dev.	3.9	2.7	7.10	9.3	0.03	26.6	1.9	2.2	0.9	9.22	54.6	0.18	11.7
YM	Mean	6.9	6.4	18.90	87.4	0.02	74.8	11.4	11.9	0.3	4.21	22.0	0.46	8.0
	Min.	3.0	3.0	11.50	22.8	0.01	24.0	5.1	7.3	0.0	0.13	0.9	0.32	0.7
	Max.	13.7	12.2	25.30	168.3	0.03	155.0	17.3	17.3	0.8	10.31	57.6	0.75	18.4
	St. Dev.	3.6	3.3	5.80	53.5	0.01	42.9	4.3	3.6	0.4	3.74	19.8	0.15	6.3

Planform variables	Cross section variables	Jam variables

		Area ratio (m^2/m^2)	Length ratio (m/m)	Depth SD	Width SD	Width CV	Gradient SD	Pool vol/ 100m valley (m^3)	Jam OM vol/ 100m valley (m^3)	Pool OM vol/ 100m valley (m^3)	Avg jam height/ jam frequency (m/#)
OU	Mean	0.373	273.8	0.18	2.73	0.44	0.021	29.21	5.60	2.24	0.37
	Min.	0.201	106.4	0.09	0.77	0.17	0.001	0.91	0.13	0.00	0.04
	Max.	0.597	685.0	0.41	5.38	1.05	0.046	84.78	22.83	6.45	0.65
	St. Dev.	0.124	195.5	0.11	1.63	0.28	0.013	26.91	7.74	2.78	0.21
YU	Mean	0.253	134.1	0.16	1.95	0.29	0.025	9.22	1.40	0.61	0.50
	Min.	0.056	100.0	0.07	0.72	0.15	0.005	0.00	0.00	0.00	0.21
	Max.	0.455	262.0	0.24	5.81	0.63	0.047	22.24	4.17	1.71	1.00
	St. Dev.	0.126	49.7	0.05	1.46	0.15	0.012	7.19	1.15	0.56	0.28
YM	Mean	0.198	120.6	0.13	2.10	0.21	0.006	0.53	0.44	0.02	1.14
	Min.	0.088	109.9	0.10	1.20	0.09	0.002	0.00	0.00	0.00	0.90
	Max.	0.338	151.3	0.17	4.61	0.36	0.012	1.84	1.39	0.06	1.80
	St. Dev.	0.089	14.8	0.02	1.18	0.11	0.003	0.67	0.51	0.02	0.30

5.5 Appendix E: Correlation results between variables

Table 5.7 Correlation Between Variables and Their Significance[a].

Variables	Conf. (ind. Width) (m/m)	Conf. (total width) (m/m)	Forest cover (basal area, m^2/ha)	DA (km^2)	Gradient (m/m)	Valley width (m)	Mean ind. chan. width (m)	Mean total chan. width (m)	Jams/ 100m valley (#)	Wood vol/ 100m valley (m^3)	Pieces/ 100m valley (#)	Prop. bridges & ramps
Conf. (ind. width) (m/m)	1.00	**0.82**	-0.09	0.00	-0.26	**0.71**	-0.18	0.23	**0.42**	**0.46**	**0.47**	0.03
Conf. (total width) (m/m)		1.00	*-0.40*	0.22	**-0.45**	**0.77**	0.08	-0.08	-0.01	-0.09	0.04	0.21
Forest cover (basal area, m^2/ha)			1.00	**-0.55**	*0.38*	*-0.38*	**-0.49**	0.02	**0.42**	*0.40*	**0.43**	*-0.35*
Drainage area (km^2)				1.00	**-0.43**	**0.52**	**0.79**	0.29	-0.25	-0.31	**-0.44**	**0.52**
Gradient (m/m)					1.00	**-0.42**	-0.26	-0.08	0.16	0.26	0.31	-0.31
Valley width (m)						1.00	**0.50**	**0.45**	0.10	0.06	0.05	*0.40*
Mean ind. channel width (m)							1.00	*0.39*	-0.32	*-0.37*	**-0.48**	0.42
Mean total channel width (m)								1.00	0.22	**0.42**	0.14	0.15
Jams/100mvalley (#)									1.00	**0.73**	**0.81**	-0.28
Wood vol/100mvalley (m^3)										1.00	**0.81**	-0.27
Pieces/100mvalley (#)											1.00	**-0.47**
Prop. bridges & ramps												1.00
bridges & ramps/ 100m valley (#)												
Area ratio (m^2/m^2)												
Length ratio (m/m)												
Depth SD												
Width SD												
Width CV												
Gradient SD												
Pool vol/100mvalley (m^3)												
Jam OM vol/100mvalley (m^3)												
Pool OM vol/100mvalley (m^3)												
Avg jam height/jam freq. (m/#)												

[a]R-square values listed, bold values are statistically significant at α=0.05, italic values are statistically significant at α=0.10.

Variables	bridges & ramps/ 100m valley (#)	Area ratio (m^2/m^2)	Length ratio (m/m)	Depth SD	Width SD	Width CV	Gradient SD	Pool vol/ 100m valley (m^3)	Jam OM vol/ 100m valley (m^3)	Pool OM vol/ 100m valley (m^3)	Avg jam height/jam frequency (m/#)
Conf. (ind. width) (m/m)	*0.38*	**-0.50**	**0.54**	-0.19	0.05	0.26	-0.03	**0.46**	0.38	0.50	-0.21
Conf. (total width) (m/m)	-0.15	**-0.79**	0.02	*-0.35*	-0.05	0.00	-0.13	-0.09	-0.16	0.00	0.12
Forest cover (basal area, m^2/ha)	**0.46**	**0.44**	*0.40*	0.11	0.04	0.30	0.30	**0.50**	0.31	0.37	-0.66
Drainage area (km^2)	**-0.43**	-0.27	-0.23	-0.09	-0.05	*-0.35*	**-0.48**	-0.32	-0.21	-0.24	0.52
Gradient (m/m)	*0.39*	**0.63**	0.17	0.34	0.13	0.18	**0.83**	0.20	0.19	0.09	-0.40
Valley width (m)	-0.02	**-0.60**	0.16	-0.12	0.15	0.07	-0.29	0.10	0.09	0.18	0.15
Mean ind. channel width (m)	**-0.43**	-0.15	*-0.36*	0.13	0.19	-0.29	*-0.40*	*-0.36*	-0.24	-0.29	0.54
Mean total channel width (m)	**0.44**	0.09	**0.46**	*0.39*	**0.45**	0.32	-0.29	**0.60**	0.68	0.50	0.00
Jams/100mvalley (#)	**0.66**	0.26	**0.71**	-0.05	0.16	*0.38*	0.02	**0.67**	0.59	0.90	-0.59
Wood vol/100mvalley (m^3)	**0.92**	*0.38*	**0.95**	0.09	0.22	**0.46**	0.19	**0.90**	0.89	0.86	-0.51
Pieces/100mvalley (#)	**0.86**	0.24	**0.76**	-0.09	0.26	**0.54**	0.31	**0.71**	0.60	0.82	-0.64
Prop. bridges & ramps	-0.34	-0.31	-0.19	-0.23	-0.21	-0.32	-0.21	-0.23	-0.15	-0.23	0.44
bridges & ramps/100m valley (#)	1.00	*0.40*	**0.87**	0.10	0.29	**0.54**	0.33	**0.89**	0.87	0.82	-0.58
Area ratio (m^2/m^2)		1.00	0.29	**0.50**	0.02	0.04	0.30	0.26	0.36	0.25	-0.31
Length ratio (m/m)			1.00	0.02	0.22	**0.53**	0.09	**0.90**	0.86	0.86	-0.46
Depth SD				1.00	0.10	-0.04	0.16	0.17	0.26	0.06	-0.20
Width SD					1.00	**0.82**	-0.14	0.30	0.26	0.30	0.14
Width CV						1.00	0.01	**0.52**	0.40	0.50	-0.20
Gradient SD							1.00	0.11	0.05	-0.06	-0.44
Pool vol/100mvalley (m^3)								1.00	0.94	0.87	-0.53
Jam OM vol/100mvalley (m^3)									1.00	0.84	-0.39
Pool OM vol/100mvalley (m^3)										1.00	-0.52
Avg jam height/jam freq. (m/#)											1.00

[a]R-square values listed, bold values are statistically significant at α=0.05, italic values are statistically significant at α=0.10.

5.6 Appendix F: Wood and jam variable differences by stream length

Table 5.8 Results of differences of wood and jam variables by stream length between treatments and confinement. A) All sites; B) no confined sites.

A

		By Treatment				By Confinement			
			Pairwise Comparison				Pairwise Comparison		
Group of Variables	Variable	ANOVA/ KW p-value	OU-YU	OU-YM	YU-YM	ANOVA / KW p-value	P-C	U-C	U-P
Wood piece variables	Jams/100 m stream (#)	**<0.01**	0.65	**<0.01**	**0.02**	0.39	0.39	0.90	0.65
	Wood volume/100 m stream (m^3)	**0.04**	0.92	**0.04**	0.08	0.66	0.84	0.97	0.66
	Pieces/100 m stream (#)	**0.01**	0.22	0.20	**<0.01**	0.18	0.19	0.27	1.00
	Bridges & ramps/100 m stream (#)	**0.04**	0.44	0.25	**0.03**	0.11	0.14	0.14	0.98
Jam variables	Pool volume/100m stream (m^3)	**<<0.01**	0.35	**<<0.01**	**0.01**	0.45	0.82	0.43	0.70
	Jam OM volume/100 m stream (m^3)	0.18	0.88	0.17	0.33	**0.02**	0.05	**0.02**	0.77
	Pool OM volume/100 m stream (m^3)	**0.05**	1.00	0.05	**0.03**	0.09	0.04	0.33	0.55

B

			Pairwise Comparison		
Group of Variables	Variable	ANOVA/ KW p-value	OU-YU	OU-YM	YU-YM
Wood piece variables	Jams/100 m stream (#)	**0.02**	0.44	**<0.01**	0.11
	Wood volume/100 m stream (m^3)	**0.04**	0.71	**0.04**	0.16
	Pieces/100 m stream (#)	**0.04**	0.58	0.16	**0.03**
	Bridges & ramps/100 m stream (#)	0.05	0.87	0.12	0.06
Jam variables	Pool volume/100m stream (m^3)	**<0.01**	0.35	**<0.01**	0.05
	Jam OM volume/100 m stream (m^3)	0.18	0.55	0.16	0.65
	Pool OM volume/100 m stream (m^3)	0.16	1.00	0.15	0.12

5.7 Appendix G: Survey and modeled bed and bank profiles for intensive sites

Figure 5.6 NSVL subreach 1 surveys; survey data in black, modeled fit in red.

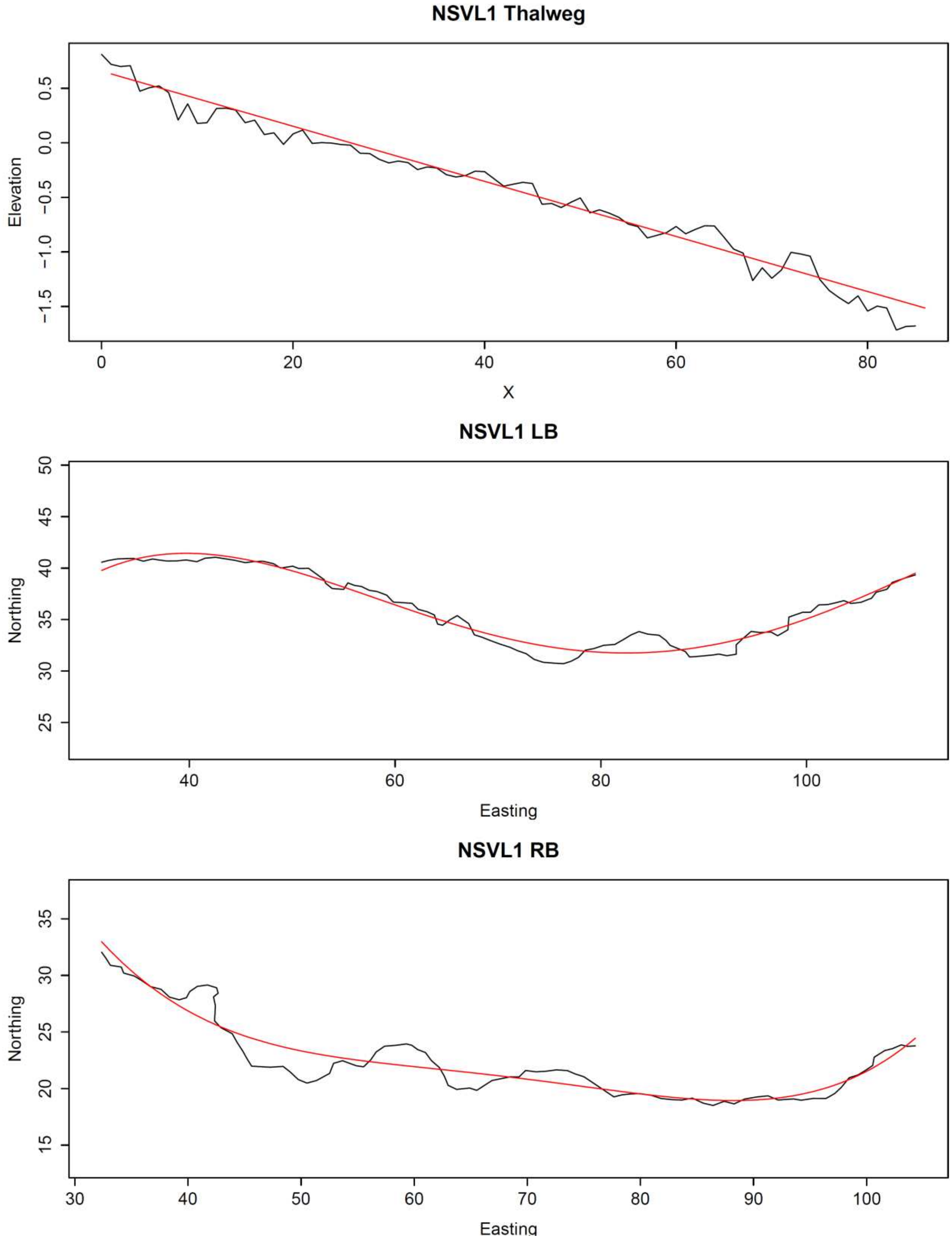


Figure 5.7 NSVL subreach 3 surveys; survey data in black, modeled fit in red.

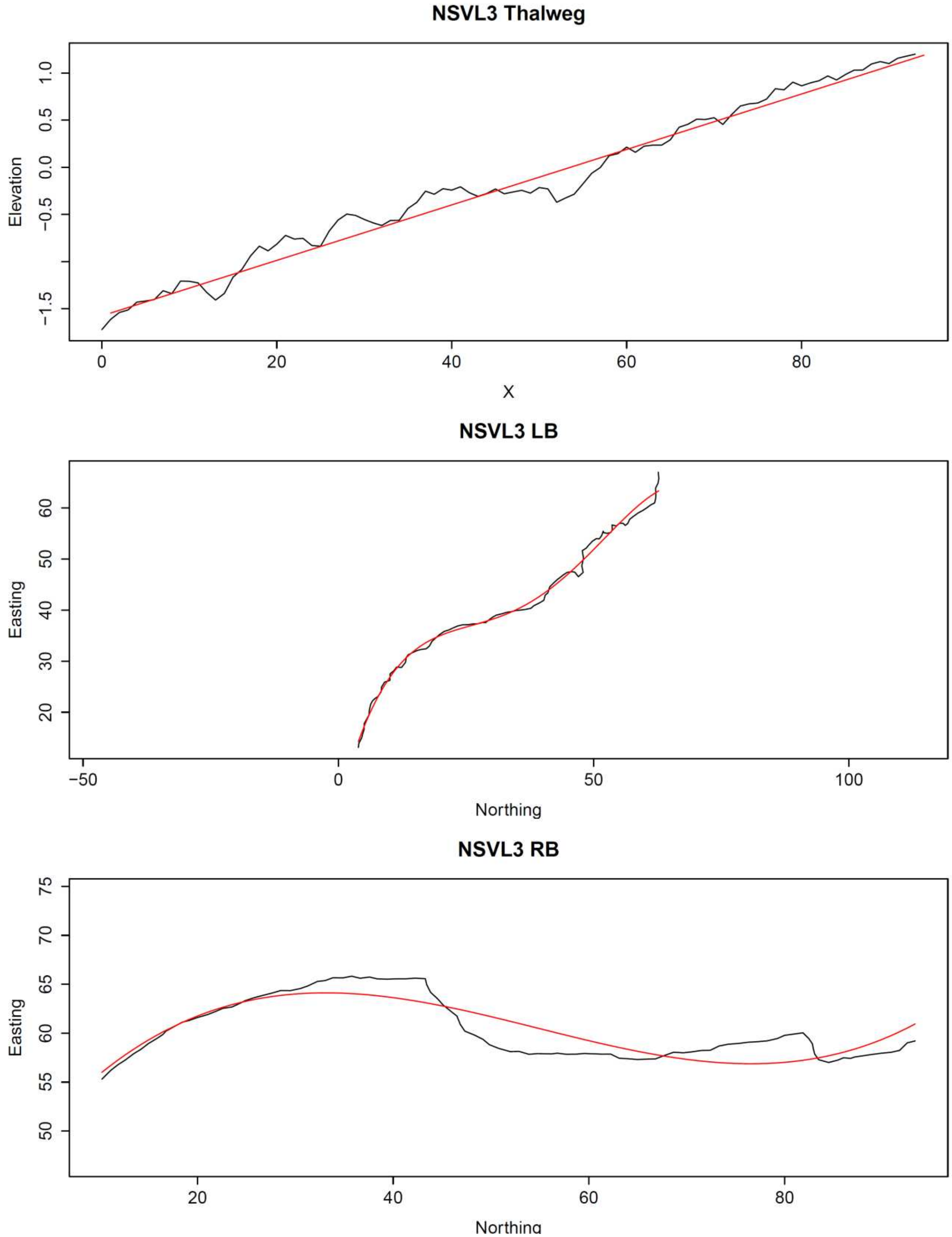


Figure 5.8 NSVC subreach 1 surveys; survey data in black, modeled fit in red.

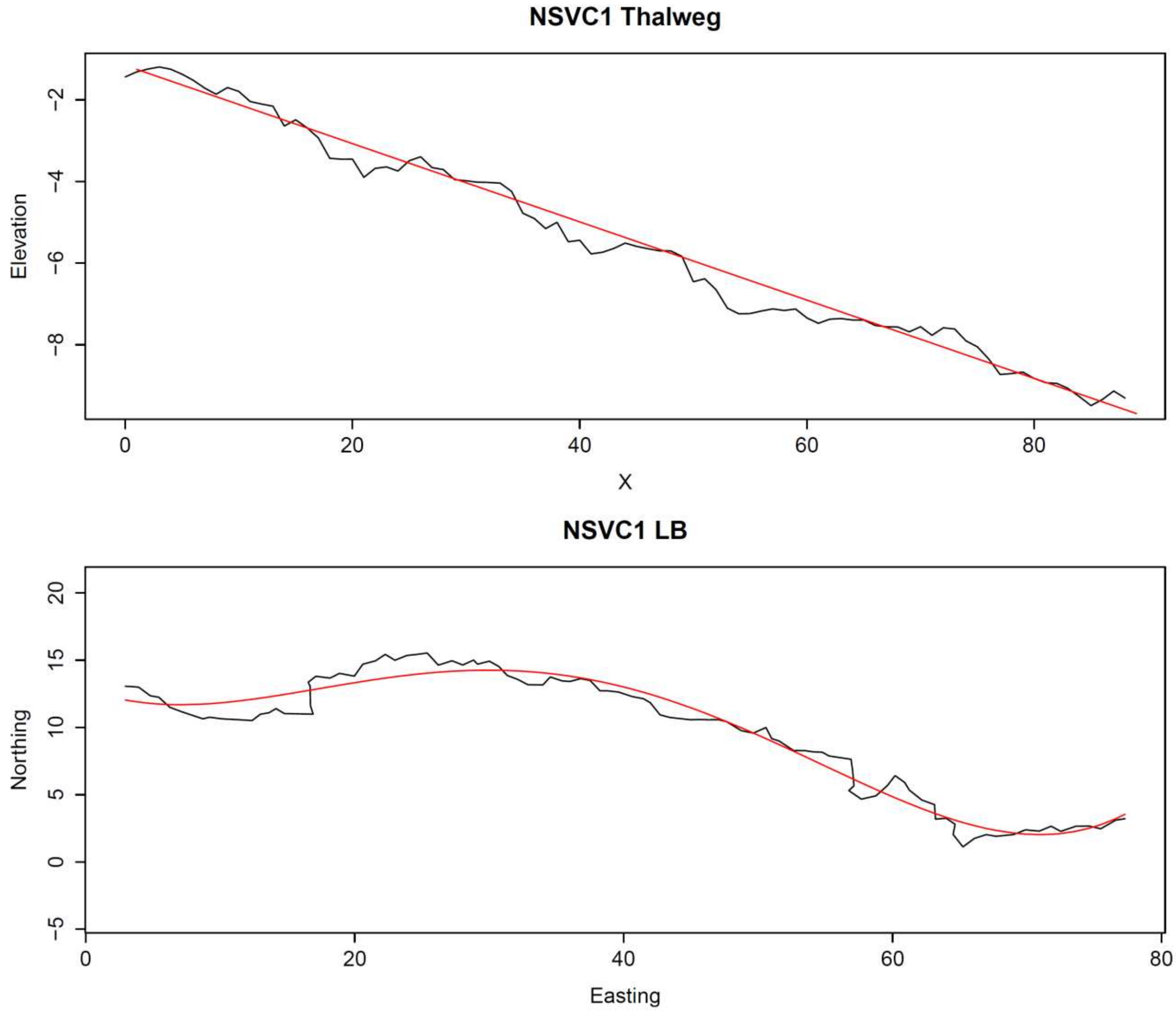
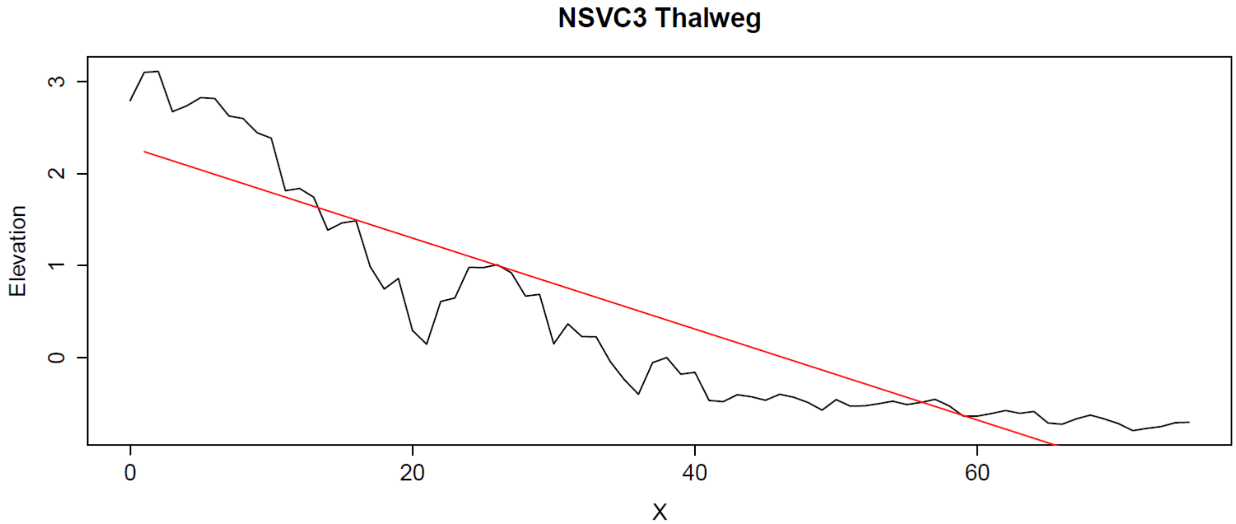


Figure 5.9 NSVC subreach 3 surveys; survey data in black, modeled fit in red.



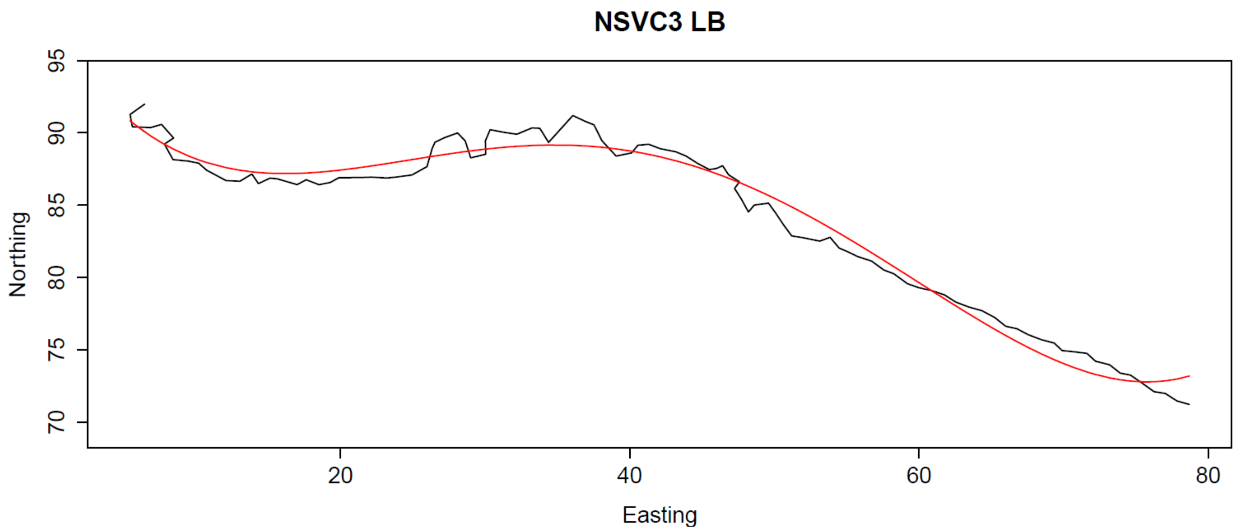


Figure 5.10 GC subreach 0 surveys; survey data in black, modeled fit in red.

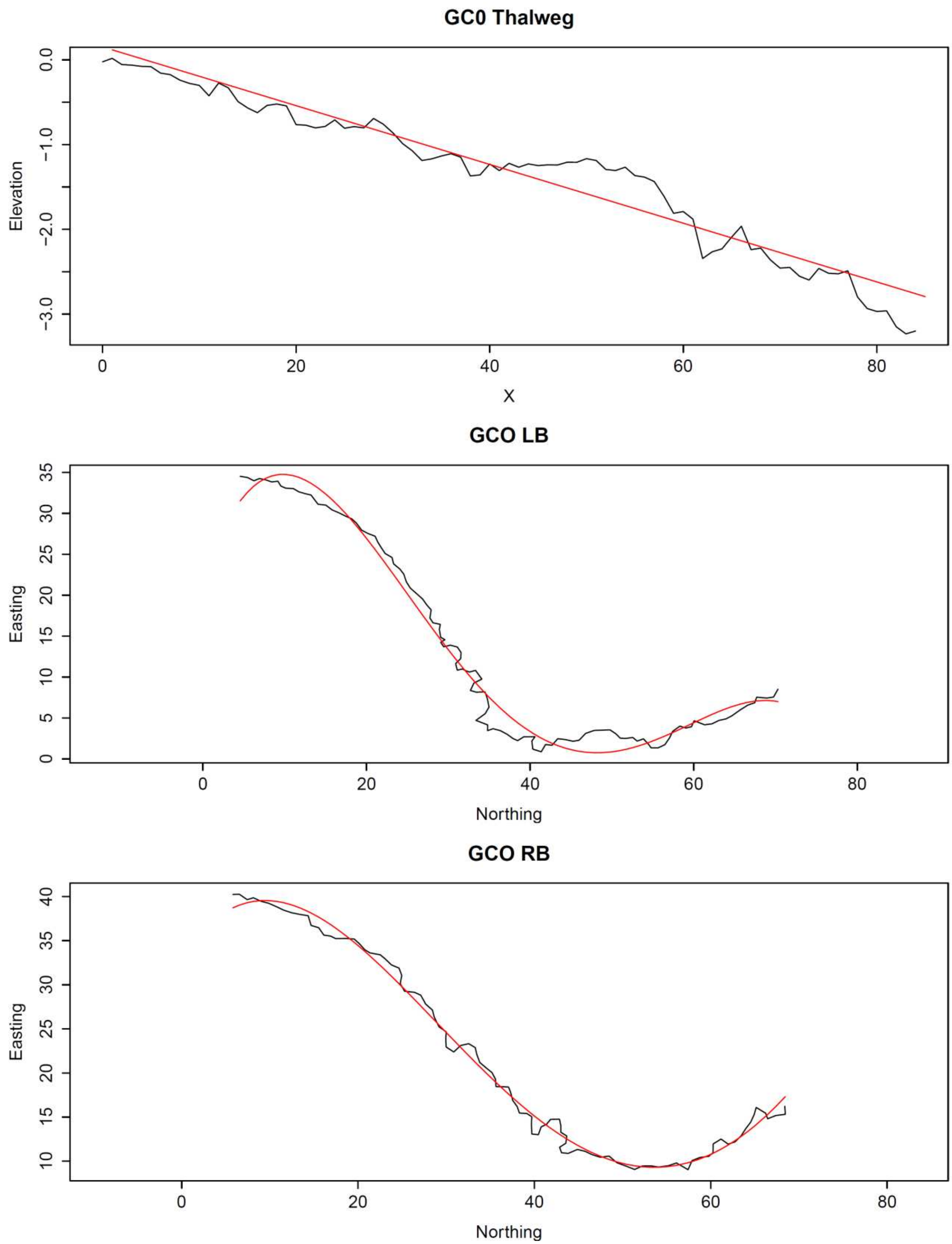


Figure 5.11 GC subreach 1 surveys; survey data in black, modeled fit in red.

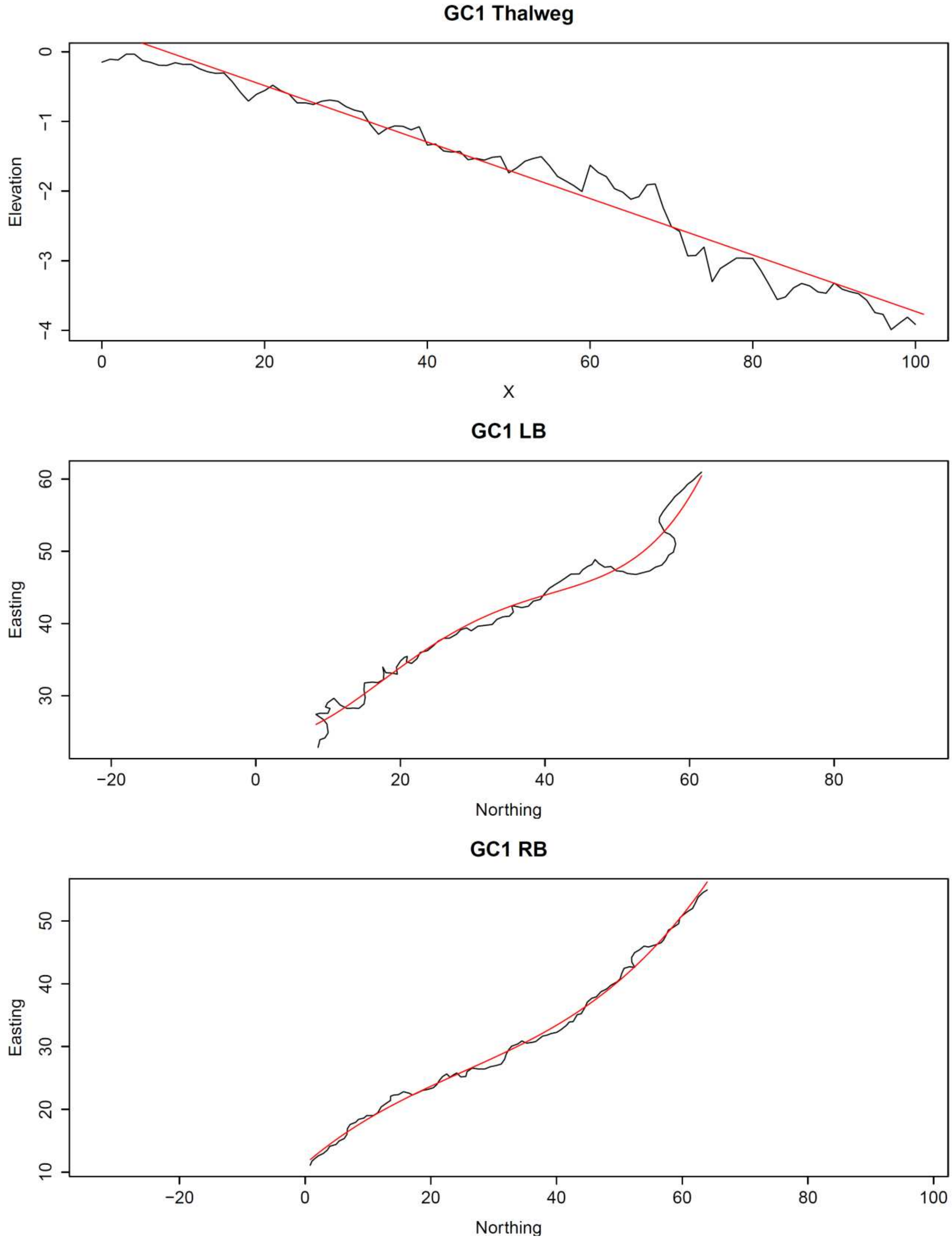


Figure 5.12 GC subreach 3 surveys; survey data in black, modeled fit in red.

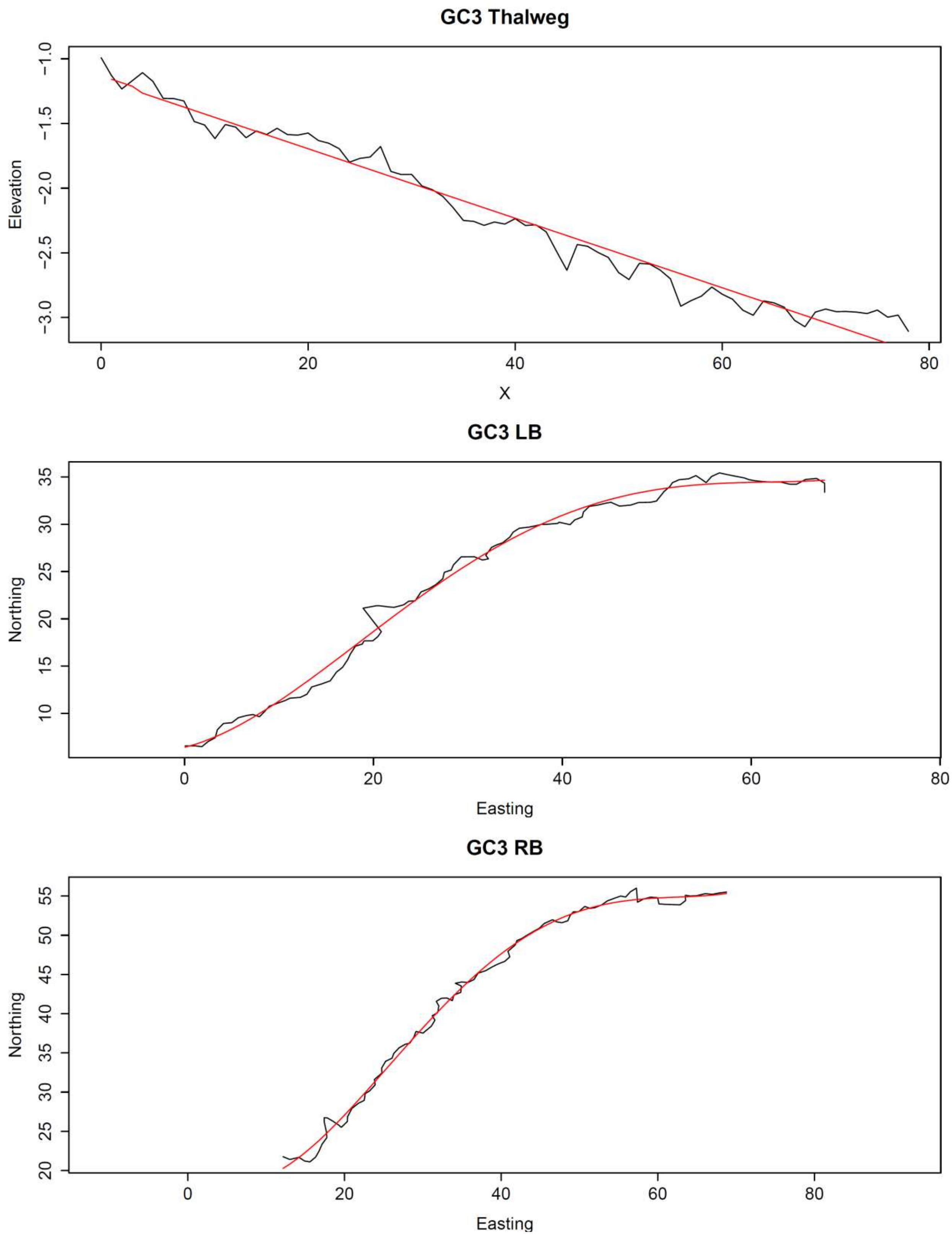


Figure 5.13 SFP subreach 1 surveys; survey data in black, modeled fit in red.

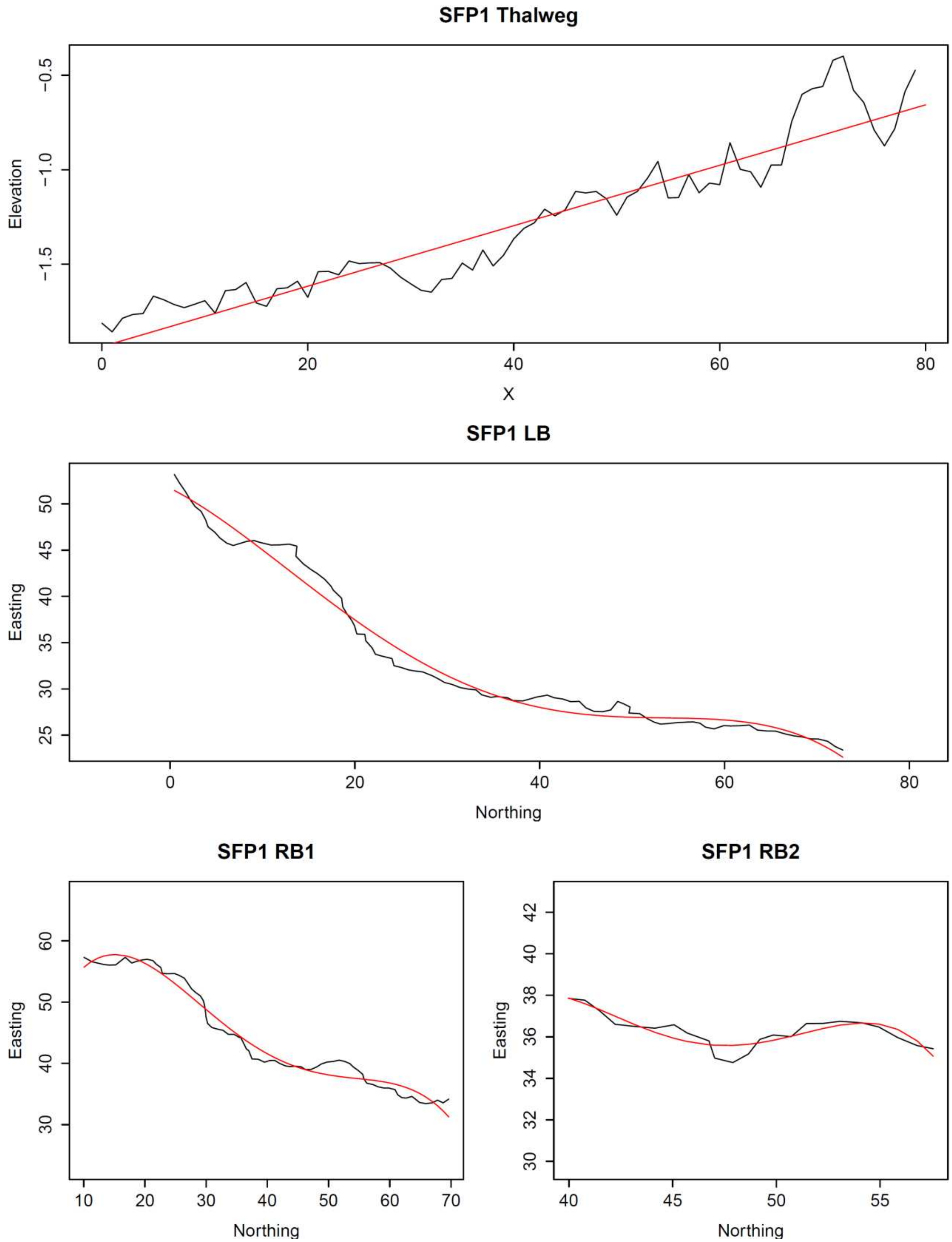


Figure 5.14 SFP subreach 2 surveys; survey data in black, modeled fit in red.

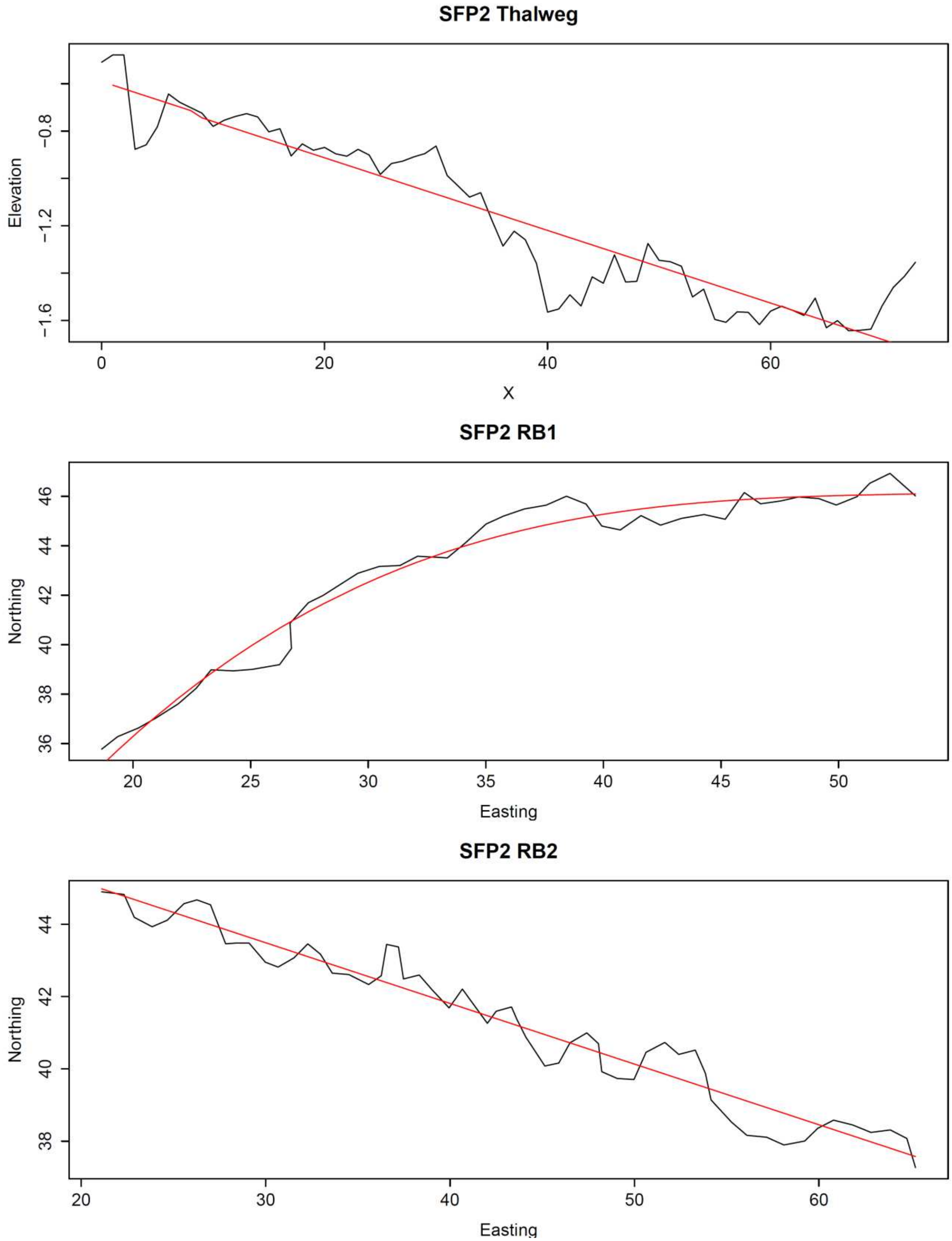
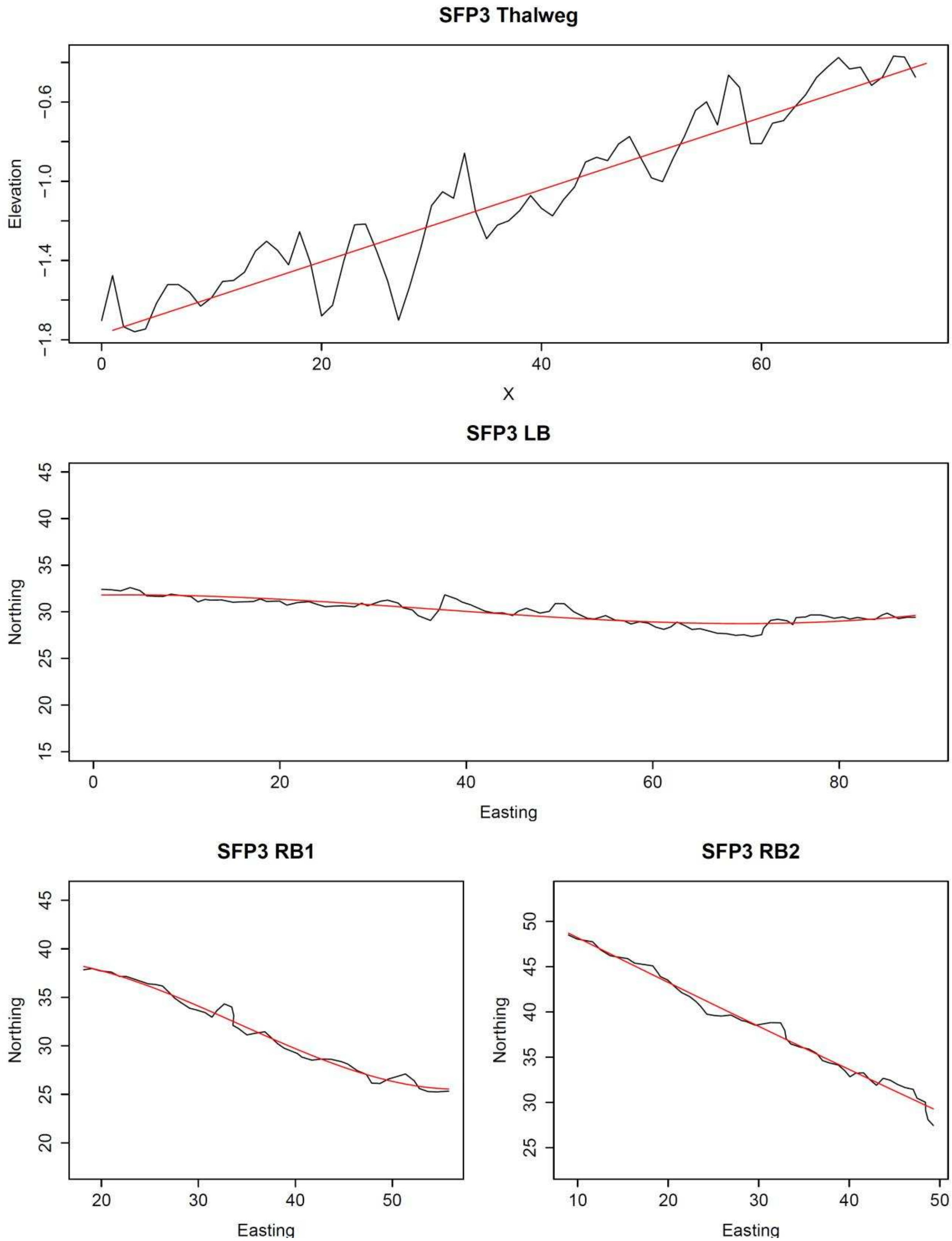


Figure 5.15 SFP subreach 3 surveys; survey data in black, modeled fit in red.



5.8 Appendix H: Managed montane sites data

Table 5.9 Field data summary from managed montane sites[a].

Site	DA (km^2)	S (m/m)	BA (m^2/ha)	Valley length (m)	Valley width (m)	Valley area (ha)	BF width (m)	BF depth (m)	Channel length (m)	Channel area (ha)	GPS coordinates
Elkhorn Cr 1	29.2	0.024	20.66	100	39	0.39	4.7	0.7	119	0.06	40.74747,105.54137
Manhattan Cr	3.6	0.049	22.96	100	34	0.34	2.9	0.5	154	0.04	40.73359,105.59118
Elkhorn Cr 2	11.5	0.028	13.77	100	56	0.56	3	0.5	170	0.05	40.75728,105.61433
Elkhorn Cr 3	21.1	0.033	13.77	100	68	0.68	4.1	0.6	165	0.07	40.75922,105.58099
Lone Pine Cr	48.9	0.015	11.48	100	118	1.18	6.6	1.1	187	0.12	40.78646,105.53867
Sevenmile Cr	24	0.026	13.77	100	55	0.55	4.8	0.7	135	0.06	40.70229,105.58439
Dadd Gulch	7.6	0.043	16.07	100	38	0.38	2	0.5	130	0.03	40.69551,105.54181
Bennett Cr	24.7	0.019	20.66	100	58	0.58	3.1	0.6	135	0.04	40.65659,105.53728

Site	Channel LW (m^3)	Channel LW (m^3/ha)	FP LW (m^3)	FP LW (m^3/ha)	Jams (#)	Jam vol. (m^3)	Porosity (%)	BW pool vol. (m^3)	OM vol. (m^3)	Avg ch. piece size L (cm)	Avg ch. piece size d (cm)	Avg FP piece size L (cm)	Avg FP piece size d (cm)
Elkhorn Cr 1	1.08	18	1.6	4.1	1	3.56	35	8.2	0.12	416	14	382	18
Manhattan Cr	1.18	29.5	3.76	11.06	1	0.38	10	0.7	0.02	304	15	452	19
Elkhorn Cr 2	0.34	6.8	1	1.79	2	1.48	40	14	0.18	237	12	473	15
Elkhorn Cr 3	1.04	14.9	2.62	3.85	2	4.28	40	10.4	0.02	425	19	662	23
Lone Pine Cr	0.48	4	1.46	1.24	0					377	14	482	15
Sevenmile Cr	1.47	24.5	2.34	4.25	1	2.37	30	6.4	0.65	328	18	530	20
Dadd Gulch	0.3	10	3.64	9.58	2	1.42	55	1.5	0.18	220	13	482	25
Bennett Cr	1.68	42	3.36	5.79	1	6.91	20	5.6	0.44	316	25	688	26

[a]All sites in mixed conifer (pine, spruce, fir) in montane zone on state or US Forest Service lands.