

INFLUENCES OF TIMBER MANAGEMENT AND NATURAL LANDSCAPE FACTORS
ON ANADROMOUS STREAMS OF SOUTHEASTERN ALASKA: RELATING LOCAL
AND CATCHMENT FACTORS TO AQUATIC HABITAT

By

Jared A. Ross

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ABSTRACT

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Timber harvest is the primary disturbance to streams of Southeast Alaska. Timber management pre-1980 occurred with few rules restricting harvest near streams, leading to degraded habitat in streams near harvested areas. In response, regulations were established in the late 1970's to protect both terrestrial and aquatic resources. Initial best management practices (BMPs) restricted use of heavy equipment and regulated harvest practices, though did not define how close harvest could occur near streams. Trees would be taken directly up to banks, potentially decreasing future sources of large wood and increasing bank erosion. Further, both historical and current harvest through watersheds can have additional effects on streams, including altering catchment hydrology and increasing streambed sedimentation. Understanding how current and historical timber harvest may affect the region's streams is critical for their successful management. In this study, I characterize current condition of streams harvested under the initial BMPs and explore relationships between natural and timber harvest-related landscape factors at local and catchment scales, with results indicating relationships between landscape factors and stream habitat at both scales. Local channel morphology and riparian characteristics were strongly associated with habitat, with smaller median particle sizes detected in streams with harvested vs. unharvested riparian zones. At the catchment scale, timber harvest factors explained more variation than natural landscape factors in measures of large wood abundance and distribution. Results from this work will aid managers of both timber and fisheries industries in protecting and restoring streams and forests of the region.

To all my human and non-human friends and family.

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TABLE OF CONTENTS

LIST OF TABLES	viii
LIST OF FIGURES	x
INTRODUCTION	1
LITERATURE CITED	6
CHAPTER 1	
THE INFLUENCE OF GEOMORPHIC, RIPARIAN, AND TIMBER HARVEST FACTORS ON AQUATIC HABITAT IN ANADROMOUS STREAMS OF SOUTHEAST ALASKA	
Abstract	8
Introduction	9
Methods	
Study region	13
Site selection	14
Field data collection	16
Geomorphic and riparian factors	17
Channel morphology	17
Riparian condition	18
Aquatic habitat factors	18
Habitat complexity	18
Substrate	19
Large wood	19
Data analyses	20
Data reduction	20
Principal components analysis	21
Understanding influences of geomorphic and riparian factors on aquatic habitat	22
Understanding influences of timber harvest on aquatic habitat	23
Results	
Geomorphic, riparian, and timber harvest characteristics	23
Regional trends in timber harvest	24
Geomorphic factors	24
Riparian factors	24
Aquatic habitat characteristics	25
Habitat complexity, substrate, and large wood	25
Understanding influences of natural factors on aquatic habitat	27
Principal components analysis	27
Stepwise multiple regressions	28
Understanding influences of timber harvest on aquatic habitat	28
Cumulative frequencies	28
Discriminant function analysis	29
Analysis of Covariance (ANCOVA)	29
Discussion	

Geomorphic influences on aquatic habitat.....	31
Pool characteristics	31
Substrate characteristics.....	32
Large wood characteristics	32
Riparian influences on aquatic habitat.....	33
Timber harvest influences on aquatic habitat	34
Management implications	
Stream size and channel type constraints.....	37
Legacy of actions on the landscape	38
Riparian stand composition.....	38
Stream substrate composition	39
Silviculture as a tool to manage for future large wood	39
APPENDIX.....	41
LITERATURE CITED	79

CHAPTER 2

EFFECTS OF LANDSCAPE FACTORS ON LARGE WOOD IN STREAMS DRAINING SECOND GROWTH WATERSHEDS OF SOUTHEAST ALASKA: COMPARING NATURAL AND TIMBER HARVEST-RELATED INFLUENCES

Abstract	88
Introduction.....	89
Methods	
Study area, catchment creation, and landscape data	93
Study site description.....	94
Timber harvest data.....	94
Large wood data.....	95
Statistical methods	96
Data preparation.....	96
Best subsets multiple regression	98
Constrained ordination analysis.....	98
Results	
Regional trends of natural landscape factors in Southeast Alaska watersheds.....	99
Trends in natural landscape factors of study streams	100
Trends in timber harvest-related factors of study streams	100
Explaining variation in large wood habitat factors using natural and timber harvest related landscape factors	101
Average large wood length	101
Large wood recruits located within the active channel vs. above the channel	102
Medium-sized large wood density	102
Large and extra-large-sized large wood density	103
Assessing the relative importance of natural vs. harvest-related landscape factors in explaining variation in large wood habitat factors.....	103
Discussion	
Natural landscape factors	105
Catchment area.....	105

Catchment slope.....	106
Deciduous forests.....	107
Forested wetlands.....	108
Timber harvest-related factors	109
Historical timber harvest (1980-1990).....	109
Current timber harvest (post-1990).....	113
Logging road and stream crossings.....	114
Comparing landscape influences on large wood habitat factors.....	115
Management implications	
Landscape considerations in managing the region's streams	116
Future research.....	117
APPENDIX.....	119
LITERATURE CITED	131

CHAPTER 3

CONCLUSIONS: TIMBER HARVEST, NATURAL LANDSCAPE FACTORS, AND RELATIONSHIPS WITH FLUVIAL HABITAT; FROM REACHES TO WATERSHEDS OF SOUTHEASTERN ALASKA – SUMMARY OF FINDINGS, MANAGEMENT IMPLICATIONS, AND STUDY LIMITATIONS

Principal findings	
Chapter 1: Aquatic habitat and influences from reach scale geomorphic, riparian, and timber harvest factors of Chichagof and Prince of Wales Islands, Alaska, U.S.A.....	139
Chapter 2: Large wood and influences from the landscape – natural and timber harvest factors	141
Management implications	
Natural landscape considerations.....	144
Timber harvest considerations	146
Study limitations	148
LITERATURE CITED	152

LIST OF TABLES

Table 1.1	Pearson's correlations among geomorphic, riparian, and aquatic habitat variables used in analyses. An asterisk next to correlation coefficient indicates significance at a 0.05 level while two asterisks indicate significance at a 0.01 level. Bold variable codes indicate a transformed variable (See Methods for specific transformations and Table 1.2 for variable codes).....	42
Table 1.2	Mean, minimum, maximum, and standard deviation (SD) of calculated variables used to describe the current aquatic and riparian habitat condition of study sites.....	45
Table 1.3	Pearson's correlations between key response variables used in comparison between harvested and unharvested streams. An asterisk next to a correlation coefficient indicates significance at the 0.05 level and two asterisks indicates significance at 0.01 level. Width to depth ratio (WD) is the ratio between bankfull width and bankfull depth, average pool area (APA) was in m ² , pool spacing (SPACE) is measured in # channel widths per pool, and pool length (RPL) is the proportion of reach length classified as pool. All other variable codes can be found in Table 1.2	46
Table 1.4	Total area harvested and percent of total land area harvested for all of Sealaska owned land organized for three time periods. Time periods correspond to changes to Alaska's forest resource regulations	47
Table 1.5	Mean and standard deviation (SD) of study reaches draining land owned by Sealaska Corporation. Sites are grouped by gradient as either low (< 2%) or moderate gradient (2-6 %).....	48
Table 1.6	Results of multiple linear regressions predicting each aquatic habitat variable for 28 streams on Sealaska timberlands. Independent variables are listed in order of their influence on the model, based on standardized coefficients, which are located in parentheses. Sig. indicates the p-value for each hypothesis test on the coefficient of the corresponding term in the linear model. Proportion of variance explained is indicated by R ² for one variable models and R ² adj for two variable models. A variance inflation factor value of 4 (VIF< 4) was used to ensure little multicollinearity	49
Table 1.7	Classification results organized by count and percent correctly classified from the discriminant function analysis for both known (Original) and unknown membership (Cross-validated).....	50
Table 1.8	ANCOVA adjusted means and standard errors of variables reported for both low and moderate gradient reaches. Differences are significant (P < 0.05) when the 95% confidence intervals do not include 0 and an asterisk denotes variables with significant differences.....	51
Table 1.9	ANCOVA adjusted means and standard errors of variables reported for both unharvested and harvested reaches. Differences are significant (P < 0.05) when the 95% confidence intervals do not include 0 and an asterisk denotes variables with significant differences.....	52

Table 1.10	Large wood density (pieces/km) in streams of Southeast Alaska organized by channel type.....	53
Table 1.11	Data characterizing aquatic and riparian habitat in and along 28 study sites on Sealaska-owned land.....	54
Table 1.12	Data characterizing habitat in streams of the Tongass National Forest having unharvested riparian zones.....	58
Table 2.1	Mean, min, max, and standard deviation (SD) of natural landscape variables for 28 sampled stream reaches draining second growth watersheds	120
Table 2.2	Mean, min, max, and standard deviation (SD) of timber harvest-related variables for 28 sampled stream reaches draining second growth watersheds	121
Table 2.3	Pearson's correlations between timber harvest-related and other landscape factors used in analyses. An asterisk indicates significance at a 0.05 level	122
Table 2.4	Natural landscape factors for streams in Southeast Alaska summarized for local and network catchments.....	123
Table 2.5	Results from best subsets regression for LW length. Models are in order of most variance explained, predictor variables are ordered by their influence on the model based on standardized beta coefficients, and Δ AIC represents the difference when compared to catchment area alone.....	124
Table 2.6	Results from best subsets regression for the ratio of LW recruits that are in:above the channel. Models are in order of most variance explained, predictor variables are ordered by their influence on the model based on standardized beta coefficients, and Δ AIC represents the difference when compared to catchment area alone	125
Table 2.7	Results from best subsets regression for medium sized LW density. Models are in order of most variance explained, predictor variables are ordered by their influence on the model based on standardized beta coefficients, and Δ AIC represents the difference when compared to catchment area alone	126
Table 2.8	Results from best subsets regression for large and extra-large sized LW density. Models are in order of most variance explained, predictor variables are ordered by their influence on the model based on standardized beta coefficients, and Δ AIC represents the difference when compared to catchment area alone	127

LIST OF FIGURES

Figure 1.1. Maps of (A) Chichagof Island and (B) Prince of Wales Island showing locations of stream reaches sampled (n=28) on timberlands owned by Sealaska Corporation during the summer of 2011	61
Figure 1.2 Cumulative frequencies of earliest Sealaska Corporation harvest year organized by number of banks that experienced riparian timber harvest	62
Figure 1.3 Frequency of 876 riparian trees organized by size class and vegetation type. Black bars represent coniferous trees, light gray bars represent deciduous trees, and dark gray bars represent standing snags.....	63
Figure 1.4 Relative amount (%) of riparian trees organized by low vs. moderate gradient streams. Black bars represent small (10-30 cm dbh), light gray bars represent medium (30-60 cm dbh), and dark gray bars represent large and extra-large (60-90 & > 90 cm dbh) riparian trees...	64
Figure 1.5 Relative amount (%) of riparian trees organized by number of banks harvested. Black bars represent small (10-30 cm dbh), light gray bars represent medium (30-60 cm dbh), and dark gray bars represent large and extra-large (60-90 & > 90 cm dbh) riparian trees.....	65
Figure 1.6 Relative amount (%) of riparian trees organized by low vs. moderate gradient. Black bars represent conifers, light gray bars represent deciduous, and dark gray bars represent snags.....	66
Figure 1.7 Relative amount (%) of riparian trees organized by number of banks harvested. Black bars represent conifers, light gray bars represent deciduous, and dark gray bars represent snags.....	67
Figure 1.8 Percent distribution frequencies of (a) diameter and (b) length of 2237 LW pieces measured across all 28 Sealaska stream reaches (minimum diameter ≥ 10 cm and ≥ 2 m length). X-axis values equal to minimum length requirement for 3 m length classes	68
Figure 1.9 Relative amount (%) of large wood pieces organized by low vs. moderate gradient streams. Black bars represent small (10-30 cm dbh), light gray bars represent medium (30-60 cm dbh), and dark gray bars represent large and extra-large (60-90 & > 90 cm dbh) pieces of wood	69
Figure 1.10. Relative amount (%) of large wood pieces organized by number of banks harvested. Black bars represent small (10-30 cm dbh), light gray bars represent medium (30-60 cm dbh), and dark gray bars represent large and extra-large (60-90 & > 90 cm dbh) pieces of wood.....	70
Figure 1.11. Box plots showing decay class of LW recruits organized by size class. See Methods for decay class and size class descriptions.....	71
Figure 1.12. Frequency of LW recruits organized by decay class. Darker bars represent recruits that functioned while lighter bars represent recruits that did not function	72

Figure 1.13. Frequency of LW recruits organized by size class. Darker bars represent recruits that function while lighter bars represent recruits that did not function	73
Figure 1.14. Results of the PCA of 17 habitat measures. The four components explained 72.93% of the variation in the habitat data. Axis 1 explained 30.48%, Axis 2, 16.60%, Axis 3, 13.44%, and Axis 4, 12.42%. The y-axes show the weights on each variable for the individual components. Black bars indicate variables with weights with an absolute value greater than 0.55. Variable descriptions are included in Table 1.2.....	74
Figure 1.15. Cumulative percent distributions of (a) D50, (b) RPD, (c) POOLKM, and (d) RPA. Black triangles represent unharvested streams and white boxes represent harvested streams.....	77
Figure 2.1. National Land Cover Database (2001) for Southeast Alaska. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis	128
Figure 2.2. Results of variance partitioning from the CCA. A total of 44% of variation in LW habitat factors is partitioned into timber harvest-related factors in gray, natural factors in black, and the interaction in white.....	129
Figure 2.3 Graph of CCA axis one vs. CCA axis 2. Black arrows are natural landscape factors, red arrows are timber harvest-related factors, and black squares are LW habitat factors. LWLENGTH is average LW length, MEDLWKM and LXLWKM are densities of medium sized and large and extra-large sized LW, while INABOVE is the ratio of LW recruits that are located within vs. positioned above the active channel.....	130

INTRODUCTION

In the harsh, rugged, and remote landscape of Southeast Alaska, anadromous salmonids and old growth forests have supported human populations for thousands of years. Abundant wood resources allowed for houses to be built and for people to settle in permanent villages. A seemingly inexhaustible supply of fish, wildlife, berries, mushrooms, and other wild edibles also supported this subsistence way of life for the earliest Alaskans, and rural populations today still rely on subsistence living. The economic base in Southeast Alaska has also historically revolved around natural resources, including the commercial fishing and timber industries. Currently, it is estimated that salmon provide nearly \$1B annually and are linked to 10% of the jobs in the region, while the timber industry is responsible for another 2% of jobs (TCW Economics 2010).

Salmon and timber, while crucial for humans in the region, also share a mutually beneficial relationship with one another. For longer than humans have been in North America, the coastal temperate rainforests of Southeast Alaska have relied upon marine subsidies as mass migrations of anadromous fishes move into freshwater to spawn and die annually, leaving gametes, excrements, and carcasses to be transported, used, and cycled throughout the regions' forest ecosystems. Streams and the fishes they support in turn are influenced by the forested landscapes within river basins of natal streams as they regulate stream flow by intercepting precipitation and supporting increases in shallow groundwater, slowing delivery of precipitation to streams and encouraging stable stream flows. Natural vegetation also functions to stabilize steep slopes and reduces the risk of landslides and mass wasting events which can lead to excess sediment being delivered to stream channels. Forested riparian zones also provide allochthonous inputs in the form of leaf litter and terrestrial insects to streams. Riparian vegetation in particular

helps to stabilize stream banks and regulate light input and temperature fluctuations through shading.

The immediate riparian zone and the vegetation it supports is the source of the majority of large wood to streams, and this input is of particular importance to salmonids for multiple reasons. First, large wood in stream channels serves as habitat in the form of cover. This is important for numerous life stages of salmon; young fishes will hide from predators within the structure provided by large wood, and feeding fish of many ages use cover to search for drifting invertebrates. Large wood can create low velocity habitats utilized by adult salmonids for resting purposes, as thousands of miles may be traveled before spawning occurs. Aside from directly providing physical cover, large wood also creates cover by influencing channel morphology and forming pools. Scour pools are common and formed when water is forced over and/or under wood structures, scouring the streambed and creating deep, low velocity habitats. Dam pools can also form when a log or accumulation of logs act to hold water back, creating habitats similar to those formed behind a beaver dam. In terms of sediment, large wood retains coarse substrates important for spawning, and it also stabilizes banks and reduces erosion.

While large wood is clearly an important resource to the region's streams and salmonids, it is also vulnerable to conflicting management strategies from the fisheries and timber industries in Southeast Alaska. This is evident as initial best management practices occurring from 1978-1990 for timber harvest activities in the region did not require the retention of any trees directly on the stream bank, even though a one-tree buffer was suggested as part of management practices. It was instead more common to harvest anything of significant economic value directly up to stream banks (Douglas Martin, personal communication).

Alaska's Forest Resources and Practices Act (FRPA) was established in 1978 and is the governing document on how access, harvest, and reforestation can occur on state, private, and municipal land, while federal standards must meet or exceed those of the state. The Act is intended to provide for commercial harvest by both fishing and timber operations while protecting fish habitat, water quality, and productive forests to ensure sustainable use of forest and aquatic resources into the future. With no standards regarding harvest in the riparian zone before 1990, certain streams that salmon depended on for spawning may have been deprived of wood inputs, and research from Alaska and the Pacific Northwest have documented reductions in production of stream fishes, and most notably of Pacific salmon, in watersheds extensively harvested for timber prior to statewide implementation of ecosystem management programs. Amendments to the 1990 FRPA were intended to address that potential challenge by requiring 20 m wide riparian buffers be left along anadromous streams on private timberlands in Southeast Alaska. While effectiveness monitoring of the regulations has occurred since the early 1990's, little research has occurred to empirically describe current condition of streams in the region, and much is assumed about current habitat in streams harvested under the BMP's in place in Southeast Alaska from 1978-1990.

The goal of this research was to determine the current condition of streams harvested under the initial BMPs and explore relationships between natural and timber harvest related landscape factors at local and catchment scales. A better understanding of streams with second growth riparian stands will inform managers in the region regarding if and how habitat is degraded in stands and streams after being harvested under the early BMP's. We also wish to understand whether or not second growth stands are currently providing woody material so we can better understand the amount of time needed after harvest before managed riparian zones

will support large enough trees to provide ecologically-functioning large wood to streams. Addressing these knowledge gaps is crucial as decision makers and resource managers will be tasked with prioritizing restoration efforts or transitioning to second growth timber harvest in Southeast Alaska, and characterization of natural and anthropogenic factors influence on habitat in such streams will support decision making in the region.

To understand the effects of early BMPs on habitat requires knowledge of both natural and anthropogenic factors operating at the local reach as well as additional spatial scales including watersheds (Allan 2004; Wang et al. 2006). Also, stemming from a historically terrestrial focus, the field of landscape ecology has recently been taken “into the water” (Wiens 2002), and rather than characterizing aquatic systems as separate bodies of water, this evolution in thinking considers them as a connected piece of the landscape, affecting and being affected by a myriad of other factors operating across landscapes.

It is currently a challenge in Alaska to examine streams in a landscape context as consistent data representing fluvial resources and their watersheds over large spatial extents are limited. As part of a project supported by the National Fish Habitat Partnership (NFHP), local catchments, defined as the land area draining to a single stream reach, were created for every stream reach in Southeast Alaska. This allows for landscape characteristics occurring within this land area to be summarized and their influence on stream reaches to be assessed. Additionally, a tool was developed that allowed for summarizing landscape factors occurring in the entire upstream network catchment draining to any stream reach of interest. In support of the following research, this spatial framework was constructed for Southeast Alaska, and landscape-scale factors including forested land cover and human influences including timber management history were summarized within local and network catchments of my study streams of the region. I have

associated these landscape scale factors to metrics characterizing large wood abundance and distribution in coastal streams of Southeast Alaska, adding to our general understanding of landscape influences summarized over different spatial extents on large wood, providing a richer understanding of influences of the landscape on the region's streams.

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CHAPTER 1

THE INFLUENCE OF GEOMORPHIC, RIPARIAN, AND TIMBER HARVEST FACTORS ON AQUATIC HABITAT IN ANADROMOUS STREAMS OF SOUTHEAST ALASKA

Abstract

Early logging is known to have negatively affected stream habitat and biota in the Pacific Northwest and Alaska. Large-scale harvest was historically done with no consideration for stream systems. Altered hydrology and connectivity, unstable banks, increased erosion, sedimentation of stream beds, and simplified channels have resulted from logging. As timber management is widely accepted as having the potential to alter stream habitat, understanding the influence of natural controls is also critical to define habitat potential for streams in a given region. The goal of this study is to compare geomorphic, riparian, and timber harvest-related influences on aquatic habitat in streams of Southeast Alaska with riparian zones harvested between 1980 and 1990 to better account for natural controls vs. the legacy of human impacts to the region's streams. Results show that aquatic habitat in sampled streams is tightly linked to both natural and anthropogenic land uses, and that geomorphic and riparian characteristics were associated with many aspects of stream habitat. Pool, substrate, and large wood characteristics were related with geomorphic factors including bankfull width, channel gradient, and channel confinement, while pools formed by wood and large wood density were also related to riparian composition. In this study, size of substrates was found to be related to historical timber management practices; harvested streams were found to have smaller median particle sizes than substrate in unharvested streams. These findings suggest that riparian and geomorphic factors strongly influence fluvial habitat at the reach scale and reinforce the importance of understanding natural controls on aquatic habitat to effectively manage streams in Southeast Alaska.

Introduction

Stream characteristics are influenced by properties of the landscapes they drain (e.g., Hynes 1975, Frissell et al. 1986, Wiley et al. 1997, Allan 2004), and physical and biological conditions within streams are in part created and constrained by hydrologic and geomorphic processes operating within their watersheds (Wang et al 2006). Stream habitats and their biology have also been shown to be differentially affected by landscape factors operating over different spatial scales including riparian zones and catchments (Frissell et al. 1986, Townsend et al. 2003, Cohen and Brown 2007), with that differential influence resulting from specific mechanisms by which landscape factors influence stream conditions (Allan 2004). For example, whole-catchment land cover may be more important for controlling hydrologic factors and delivery of nutrients through river networks (Boyer et al. 2002, Allan 2004). Riparian condition, on the other hand, including deforested riparian zones, may be associated with inputs of fine sediment (Jones et al. 1999, Sutherland et al. 2002), large wood (LW) (Murphy and Koski 1989), and organic litter (Hetrick et al. 1998, Allan et al. 2003). Stream temperature is also influenced by riparian vegetation (e.g., Imholt et al. 2013). The ability to discern between landscape influences and the scale at which they most strongly affect stream characteristics is critical for protecting and managing stream systems from human impacts.

In Southeast Alaska, interrelationships between streams and landscape characteristics of their watersheds are acknowledged as important in supporting anadromous fishes that migrate from the ocean into streams annually. Forested landscapes within river basins of Alaska and the Pacific Northwest regulate flow by intercepting precipitation and encouraging increases in shallow groundwater, slowing delivery of precipitation to streams and providing flood protection (Hicks et al. 1991, Jones and Grant 1996). Natural vegetation also stabilizes steep slopes and

reduces the risk of landslides and mass wasting events that can lead to excess sediment being delivered to stream channels (Wu et al. 1978, Swanson and Marion 1991). Forests provide allochthonous inputs to streams in the form of leaf litter and terrestrial insects, a benefit that is especially pronounced in forested riparian zones of stream channels (Allan et. al 2003). Riparian vegetation also helps to stabilize stream banks (Gregory et al. 1991) and regulate light input and temperature fluctuations through shading (Feller 1981, Johnson and Jones 2000), along with providing the majority of LW to streams in Southeast Alaska (Murphy and Koski 1989, Martin and Grotefendt 2007).

Multiple factors within streams interact to create complex habitats including variation in flow, substrate, and LW. Salmonids rely on complex stream habitats, such as deep pools with LW (Bisson et al., 1982, Quinn and Peterson 1996), to provide cover from predators and refuge during extremes in flow conditions (Dolloff et al. 2003). Spawning salmonids also need clean gravel-size substrate that is free of fine sediments. Fine sediments can inhibit embryo survival by filling interstitial spaces and reducing oxygen supply (Chapman 1988). The input of LW to streams is critical to salmonids for multiple reasons and can have profound influences on the availability of complex habitat and stream substrates. Large wood in stream channels serves as habitat in the form of cover. This helps to support several life stages of salmon. Young fishes will hide from predators within the structure provided by LW, and feeding fish of many ages use cover to search for drifting invertebrates (Rosenfeld et al. 2000, Roni and Quinn 2001, Bryant and Woodsmith 2009). Large wood can create low velocity habitats utilized by adult salmonids for resting purposes, as they may travel thousands of miles before spawning. Aside from directly acting as physical cover, LW also creates cover by influencing channel morphology and forming pools (Bisson et al. 1987, Martin 2001). Scour pools are common and formed when water is

forced over and/or under wood structures, scouring the streambed and creating deep, low velocity habitats. Pools can also form when a log or accumulation of logs act to hold water back, creating habitats similar to those formed behind beaver dams. In terms of sediment, LW retains coarse substrates important for spawning, and it also stabilizes banks and reduces erosion (Montgomery et al. 1996, Gomi et al. 2001).

Geomorphic and riparian factors are known to have a major influence in observed variation in habitat factors of streams in Southeast Alaska and the Pacific Northwest. Large wood input, for example has been shown to be greater in alluvial channels than confined channels (Murphy and Koski 1989, Martin 2001). Additionally the size, abundance, and ability for LW to function in a stream is associated with the density and type of riparian vegetation (Bilby and Wasserman 1989, Gomi et al. 2006). Stream size also influences the density, size, and residence time of log jams in Southeast Alaska (Martin and Benda 2001). Also, pool size and density are known to vary by stream size (Buffington et al. 2002), while other catchment factors such as depth to bedrock or frequency of debris flows may limit the potential of pool formation (Benda 1990).

The earliest best management practices applied by the timber industry in the region initially failed to provide protection to streams, despite the importance of complex habitat, substrates, and LW to salmonids of Southeast Alaska. Alaska's Forest Resources and Practices Act (FRPA) was established in 1978 and dictates how access, harvest, and reforestation can occur on state, private, and municipal land. The Act is intended to allow commercial harvest of timber and fisheries while still protecting fish habitat, water quality, and productive forests into the future. Prior to 1990, the FRPA recommended that low-value timber be left along streams, but the Act did not require the retention of any trees directly on the stream bank. Under these

initial best management practices (BMP's), it was typically common to harvest anything of significant economic value directly up to stream banks (Douglas Martin, personal communication). Amendments to the 1990 FRPA acknowledged the importance of forested stream banks by requiring that 20 m wide riparian buffers be left along anadromous streams on private timberlands in Southeast Alaska.

Timber harvest in the riparian zone before 1990 may have reduced wood inputs and degraded habitat conditions in the region's anadromous streams. Research in Alaska and the Pacific Northwest have documented reduced production of stream fishes in watersheds extensively harvested for timber prior to statewide implementation of ecosystem management programs. Reductions in fish production can be attributed to negative changes to physical habitat that can result from timber harvest including sedimentation (Scrivener and Brownlee 1982), loss of large wood (Bisson and Sedell 1984), and water temperature increases (Moring and Lantz 1975). While effectiveness monitoring of intact stream buffers has occurred since the early 1990's, little research has occurred to empirically describe current condition of streams in the region, and much is assumed about current habitat in streams harvested under the BMP's in place in Southeast Alaska from 1978-1990.

The goal of this study is to characterize geomorphic, riparian, and timber-related influences on aquatic habitat in anadromous streams of Southeast Alaska with riparian zones harvested between 1980 and 1990. To address this goal, my objectives were: a) to document channel geomorphic characteristics, riparian stand composition, and aquatic habitat conditions including habitat heterogeneity, substrates, and LW in streams with harvested riparian zones, b) to characterize associations between geomorphic factors and riparian stand composition with specific aquatic habitat factors, and c) to compare aquatic habitat factors in harvested streams to

similar streams in the Tongass National Forest having no riparian harvest to explore potential differences that may be associated with differences in riparian management. By understanding influences of geomorphic, riparian, and timber-related management actions on aquatic habitat, we can better understand how historical timber harvest practices in the riparian zone may have affected aquatic habitat in the region. Addressing these knowledge gaps is crucial as decision makers and resource managers will be tasked with prioritizing restoration efforts or transitioning to second growth timber harvest in Southeast Alaska, and results of this work can be used to support decision making in the region.

Methods

Study region

Southeast Alaska is part of the Alexander Archipelago which contains approximately 1,100 islands, ranging from islands too small to support stands of harvestable trees to those large enough to support multiple communities (e.g., Chichagof Island). Some of the largest islands in North America occur in this region, including the 4th largest in the United States; Prince of Wales Island. The region is considered part of the largest temperate rainforest in the world, as defined by the World Wildlife Fund's Ecoregion classification (Olson et al. 2001). The North Pacific Coastal Forests contain over 25% of the world's coastal temperate rainforests, many of which have been generally unaltered by human activity. The region also encompasses the Tongass National Forest which is the largest national forest in the United States.

Annual precipitation often exceeds 2000 mm, and a maritime climate produces mild temperatures in the summer and winter. Many of the larger islands of the region are characterized by mountainous terrain with steep slopes and glacially carved U-shaped valleys

(Harris and Farr 1974). Western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), and western red-cedar (*Thuja plicata*) primarily make up the old growth conifer forests of the region, and deciduous alder (*Alnus spp.*) commonly establishes after disturbances. The variable topography and long periods of constant precipitation lead to occasional natural disturbance like mass wasting and large windthrow events. Heterogeneous landscapes and aquatic habitats result in part from such disturbances and support diverse populations of anadromous salmonids. Native salmonids to Southeast Alaska include chinook (*Oncorhynchus tshawytscha*), coho (*Oncorhynchus kisutch*), sockeye (*Oncorhynchus nerka*), dog (*Oncorhynchus keta*), pink (*Oncorhynchus gorbuscha*), steelhead (*Oncorhynchus mykiss*), dolly varden (*Salvelinus malma*), and cutthroat trout (*Oncorhynchus clarki*), all of which can or specifically do exhibit an anadromous lifecycle.

Site selection

This study evaluated streams on Prince of Wales Island and Chichagof Island on Sealaska Corporation timberlands in Southeast Alaska (Figure 1.1). While nine different stream types occur in the region due to broad differences in geology, topology and hydrology (Paustian et al. 1992), we primarily evaluated streams classed as two types for this study: floodplain (FP) and moderate gradient-mixed control (MM). These stream types were selected in part due to their potential sensitivity to disturbances resulting from timber harvest (Paustian et al. 1992, Woodsmith et al. 2005). FP streams are those with low gradients (i.e., < 2%) and are usually sediment-storing stream segments located in low valley bottoms toward the mouths of watersheds. Large wood is abundant and important in creating pools in the region, with a predictable pool-riffle sequence commonly observed in FP channels. MM channels have

moderate gradients (i.e., 2-6%) with plane bed and LW forced pool-riffle sequences that can contribute to sediment retention.

Three different stream coverages for the region were used to identify potential sites for sampling. They are managed by 1) Alaska Department of Fish and Game (ADF&G), 2) Sealaska Timber Corporation (STC), and 3) the United States Forest Service (USFS). Although all three datasets are represented at the same scale of 1:63,360, each stream coverage provides a unique set of attributes that were important in identifying potential study reaches. Streams in the ADF&G and STC coverages are classified by their ability to support anadromous fishes, while streams in the USFS coverage are classified by fish use where a classification of I indicates “Streams with anadromous or adfluvial fish or fish habitat; or high quality resident fish waters or habitat above fish migration barriers known to provide reasonable enhancement opportunities for anadromous fish.” Furthermore, the USFS incorporates Paustian’s stream channel type classification referenced above (1992) which was used to assist in locating unconfined and moderately confined streams having low to moderate gradients. To be considered for site selection, reaches had to be classified as anadromous by either ADF&G or STC or had to be classed as Type I by USFS. Once all anadromous waters of Sealaska lands were identified, reaches were further assigned a channel type from the USFS coverage.

Data on historical timber management practices adjacent to anadromous streams on Sealaska lands were also used to further identify potential study sites. Data on history of the timberlands were obtained from managers at Sealaska Timber Corporation, and possible sample sites were further narrowed using a geographic information system and ortho-photography to identify only reaches in which at least 100 m of at least one of the stream banks had riparian timber harvest prior to the 1990 streamside buffer amendments to Alaska’s FRPA (1978). We

only considered anadromous streams that experienced conventional timber harvest (i.e., clear-cut) in the riparian zone adjacent to the stream between 1980 and 1990. This process led us to identify 326 potential study sites (i.e., target population) that qualified under the anadromous, channel type, and timber management criteria described above. These sites were entered into a generalized random-tessellation stratified design (GRTS, Stevens and Olsen 2004) to randomly select a sample of sites from the target population that were spatially distributed across Sealaska timberlands.

A global positioning system (GPS) and paper maps were used to navigate to potential study sites that were identified by the random sample. The GRTS process resulted in a random sequence of sites which were examined in order. Final selection occurred in the field and after a site was located it would either be sampled or rejected, and exclusion occurred for various reasons including the stream having: a palustrine channel, a confined channel, a dry channel, or no channel present. Other rational for excluding a potential site includes that it was not wadeable or not feasible to sample based on access. In addition, visual confirmation of historic riparian timber harvest was assessed and confirmed prior to selecting a site for sampling. In total, 44 sites were visited and after field verification, 28 sites were selected for sampling that satisfied the selection criteria. The sample size of 28 sites was determined by field time, labor, and funding. Study reaches were identified within sites, and the beginning and end points of all reaches were at least 20 m away from any bridge crossing or major tributary. Average channel width was estimated before each survey, and 20 x the average channel width was used as a minimum reach length (Harrelson et al. 1994), while 40 x the estimated channel width was used as a maximum length.

Field data collection

Geomorphic and riparian factors

Channel morphology

Measures of stream channel morphology were taken at three cross sections along each study reach including bankfull width and depth and channel bed width. While these measurements were taken at the stream reach scale, we evaluated relationships between these factors and stream habitat in subsequent analyses for a number of reasons. First, channel dimensions are known to be strongly influenced by drainage area of river systems (e.g., Schumm 1977, Ralph et al. 1994, Knighton 1998), and they have been treated as surrogates for stream size in previous studies within the region (e.g., Bilby and Ward 1989). Second, using bankfull dimensions as a surrogate for stream size was preferred by managers of the region to provide consistent comparisons with other previously collected data. As bankfull width and drainage area were highly correlated in our sample sites with an r -value of 0.92 we felt that it would adequately represent stream size for subsequent analyses. Morphology measurements were typically taken in straight riffle units that were free of obstructions. When physical obstructions were present (e.g., boulder, woody debris) in or near cross sections, the type of obstruction and degree of influence was recorded prior to making measurements. Bankfull was indicated visually as the point at which flow would begin to enter the depositional floodplain adjacent to low-gradient study reaches. In confined channels, bankfull width was identified by evaluating vegetation changes, substrate changes, slope breaks along the bank, undercuts, stain lines, and the height of depositional features (Harrelson et al. 1994). A visual ranking of stream confinement was performed at all channel cross sections. Unconfined channels were ranked a 1, while totally confined channels were ranked a 3. Channels that were moderately confined or had

mixed confinement (e.g., one bank confined, one unconfined) were ranked a 2. The average was taken across all channel cross sections for a given study reach.

Riparian condition

On each bank and beginning at the edge of bankfull, data collected from three 30 x 3 m rectangular plots that were oriented perpendicular to the stream were used to characterize timber stand and landform characteristics. The upstream valley direction was estimated using a compass, and 90 degrees was added to orient all transects perpendicular to the stream valley. Landform slope in percent was recorded every 5 m along each transect. Additionally, the vegetation type (deciduous vs. conifer), number, and size (dbh) of each tree along each transect were observed and recorded. Size (dbh) for riparian trees was measured and assigned to one of four size categories: small (10-30 cm), medium (30-60 cm), large (60-90 cm) and very large (> 90 cm). The proportion of type and size of trees were calculated to broadly characterize the LW potential available along each study reach.

Aquatic habitat factors

Habitat complexity

Descriptions by Bisson et al. (1982) were used to define geomorphic habitat units (i.e., pool, riffle, glide). Length and width were measured to the nearest half meter for each unit encountered in the channel throughout the study reach. Additional data were collected for pools including the tail crest and maximum depths to the nearest 1 cm. The residual depth of each pool was then calculated as the difference between the maximum and pool crest depths (Lisle 1987). Identification of pools was confirmed by those that with a residual depth equal to or greater than the value determined by the equation: minimum residual depth = $(0.01 * \text{mean bed width (m)}) +$

0.15 m with a length or width at least 10% of the mean bed width (U.S. Forest Service 2001). Pool units were further classed as to whether they occurred in the main channel or in regions of the stream adjacent to the main channel. Main channel units were identified if the thalweg flowed through them at the time of sampling, while associated units were located adjacent to a main channel unit, including those located within the floodplain as long as it had a surface connection to the main channel. A hip chain was used to record the distance from the beginning point of the reach survey to the beginning of each habitat unit. Length and one width measurement was taken to the nearest 0.5 m for units that were approximately 1 m or less in length or had a consistent width. Two width measurements were taken for units that were longer than 1 m or were proportionally heterogeneous. Unit area was estimated as the product of unit length and mean unit width. Relative pool area was determined as the percentage of pool area relative to the total wetted area of the study reach.

Substrate

Estimates of dominant and sub-dominant substrate types were performed visually in each geomorphic unit. Substrate types were classified as sand and fines (smooth to gritty to ladybug size), gravel (pea to baseball size), cobble (baseball to basketball size), boulder (basketball to car size), and bedrock (solid rock or bigger than car size) (Krumbein 1934, U.S. Environmental Protection Agency 1992). At all locations where channel morphology measurements were taken, a pebble count (Wolman 1954) was also performed to characterize bed material. A total of 100 substrate samples were taken along five channel-spanning cross-sections which were centered at the channel morphology cross section.

Large wood

For this study, LW is defined as any log at least 10 cm in diameter and 2 m in length within the bankfull channel following Robison and Beschta (1990) and Martin (2001). All LW pieces were counted and measured within each 10 m long segment in smaller streams (< 10 m average width) and every 20 m long segment in larger streams (> 10 m average width). The diameter of the center of each log was measured and assigned to one of four size categories: small (10-30 cm), medium (30-60 cm), large (60-90 cm) and very large (> 90 cm). The length of each log within the bankfull channel was measured to the nearest 3 m.

All logs in which the source could be identified would be considered a LW recruit and classified by its recruitment process. The woody debris recruitment processes include: bank erosion, windthrow, broke stem (i.e., assumed windthrow), mortality, landslide, cut, beaver, or unknown. Information on whether a LW recruit was in or above the active channel, and whether it was a functioning recruit was also recorded. To be considered functioning, a recruit must do any or all of the following: cause channel scour or flow deflection, create a sediment retention zone, dam water, create an eddy, or catch and hold other woody debris in place.

Large wood recruits were also placed into a visual decay class, modified from Martin and Benda (2001). Classes were determined for the part of the log that was least disturbed by flow (e.g., the portion on the bank). Five decay classes were defined as: green leaves or needles present (green), twigs present (twig), secondary and/or primary branches present (branch), no branches and some nubs present (nub), and moss and saplings present (old).

Data analyses

Data reduction

Distributional properties (i.e., mean, range, standard deviation) of over 200 habitat variables were calculated and used to select those that would adequately describe a range of factors across the five categories of aquatic and riparian habitat variables listed above. For example, variables with many zero values were not selected. Normality and linearity of variables was also assessed by use of histograms and p-p plots. Non-linear variables were transformed as follows: continuous data were transformed using natural log, count data were transformed using square root, and proportions were transformed using arcsin square root. Bankfull width, bankfull depth, and the proportion of fine substrates (i.e., from pebble counts) were transformed to meet the statistical assumptions described above. Next, a Pearson's correlation analysis (Table 1.1) was performed on variables within geomorphic, riparian, and aquatic habitat categories to further limit the number and reduce redundancy in variables used to describe the current condition of stream reaches sampled. If a pair of variables were highly correlated within categories (i.e., $r = \text{absolute value} > 0.8$), one would be retained based on its ecological interpretability. This process led to the selection of twelve aquatic habitat variables including four measures of habitat complexity, two measures of substrate, and six measures of LW. Four variables representing channel morphology and two riparian stand variables were also selected to be included in further analyses (Table 1.2).

Principal components analysis

Principal components analysis (PCA) was performed on the correlation matrix of the 18 chosen aquatic habitat, morphological, and riparian stand variables as an initial step to investigate broad relationships by identifying which geomorphic, riparian, and aquatic habitat factors contribute to explaining the most variation across the sampled study reaches. PCA can be used to simplify large multivariate datasets into a smaller, more interpretable set of variables. It

assigns weights to individual variables to characterize axes of variance within multidimensional space. Only principal components with eigenvalues greater than 1 were retained (Kaiser 1960), and variables weighting individual axes with an absolute value of 0.55 or greater were used to interpret axes. To simplify interpretation of resulting factors, Varimax rotation was applied to the resulting axes.

Understanding influences of geomorphic and riparian factors on aquatic habitat

To relate patterns in aquatic habitat with geomorphic factors and riparian stand composition, multiple regression models were conducted using geomorphic and riparian variables. Eleven aquatic habitat variables were selected in the data reduction process and those investigated include D50, proportion of fine substrates, pool density, residual pool depth, relative pool area, the number of pools formed by wood, large wood density, the mean length of functioning recruits, the percent of functioning recruits, the proportion of recruits entering the stream by erosion, and the proportion of recruits entering the stream by wind. A stepwise multiple regression approach was used to examine associations between geomorphic and riparian factors on each aquatic habitat variable with the significance of the F statistic ($P = 0.05$) used as the model entry criterion. If no significant models were produced for a particular response variable a $P = 0.10$ would be used as the entry criterion. After independent variables were selected, collinearity was assessed based on a variance inflation factor threshold of three ($VIF < 3$). If variables exceeded this threshold they were removed, and the stepwise method would be rerun. I only considered models containing four or fewer independent variables to avoid overfitting and selected the model with the lowest Akaike Information Criterion (AIC) as the best model from the group. The proportion of variance explained is reported as R^2 for models with one variable and as R^2_{adj} for models with more than one variable.

Understanding influences of timber harvest on aquatic habitat

Data characterizing 25 stream reaches within unharvested watersheds in the Tongass National Forest were obtained from the U.S. Forest Service to determine whether differences in stream habitat factors could also be attributed to differing management types (U.S. Forest Service 2001). The dataset represents streams of similar size and channel types to the sampled streams on Sealaska timberlands, and aquatic habitat variables characterizing pools and stream substrates that were collected using comparable methods were pooled from both datasets for further analyses. Pooled data were tested for linearity and normality using steps described previously, and Pearson's correlation analysis was performed on pooled variables. If two variables were moderately correlated with an absolute value > 0.45 , one would be retained for further analysis based on ecologic interpretability and frequency of use in the literature (Table 1.3). This led to the selection of four key aquatic habitat variables that were used to consider the influence of timber harvest on aquatic habitat including: median particle size, mean residual pool depth, relative pool area, and pool density.

Discriminant function analysis (DFA) was performed on the selected variables to test whether streams with harvested riparian zones are different from streams from unharvested watersheds, using the four aquatic habitat variables chosen above. Finally, an analysis of covariance (ANCOVA) was performed on each of the key response variables to test for relationships between channel type and harvest type on the four key response variables while controlling for stream size (i.e., bankfull width) as a covariate.

Results

Geomorphic, riparian, and timber harvest characteristics

Regional trends in timber harvest

Sealaska Corporation owns approximately 1180 km² of land with just over 835 km² (70.76%) either planned for harvest, or having already been harvested for timber using conventional (i.e., clearcut) or helicopter methods (Table 1.4). Of this, over 58% has or is planned to occur after 1990, resulting in less than 13% of their total land area having been harvested without being required to leave a streamside buffer. The majority of sampled reaches (i.e., 20/28) experienced harvest by Sealaska Corporation during or after 1985 (Figure 1.2). Riparian harvest occurred on both banks more often than one bank when considering all reaches (54 vs. 46%, respectively; Table 1.5).

Geomorphic factors

Geomorphic characteristics varied considerably across all reaches ranging from 1 m to over 25 m in bankfull width (Table 1.5). Gradient also varied from 0.5% to about 6% but averaged just over 3% across all reaches. Confinement was less variable and on average, all streams were identified somewhere between unconfined and moderately confined based on visual assessment. Noticeable differences across the two channel types were also observed. Low gradient channels were on average wider (10.8 vs. 3.8 m), which resulted in longer sampled reach lengths for these streams (345 vs. 152 m). The moderate gradient sites were relatively steeper compared to low gradient channels (3.8 vs. 1.5%).

Riparian factors

Data on riparian stand composition were collected for 876 trees across all study reaches. Results suggest that riparian zones consisted of mostly small and medium sized trees as the percentage of large and extra-large trees ranged from 0 to 30%, but on average, less than 10% of

all trees were classed as large or extra-large (Figure 1.3). Little difference in riparian tree size was observed when comparing low gradient to moderate gradient streams (Figure 1.4), but a slightly higher percentage of medium sized trees were found along streams having two banks harvested compared to having just one (Figure 1.5). Riparian tree type was also variable as the percentage of recorded trees that were deciduous ranged from 0 to over 70%, although on average most riparian zones were comprised of coniferous trees (Figure 1.3). When comparing across different stream types there was a slightly higher percentage of deciduous trees along low gradient streams (Figure 1.6), although results suggest that streams having both banks harvested also had relatively more deciduous trees when compared to those only having one side harvested (Figure 1.7).

Aquatic habitat characteristics

Habitat complexity, substrate, and large wood

Substantial variation in aquatic habitat was observed across the study reaches (Table 1.2). Pool density ranged from under 10 to over 125 pools per km. Relative pool area in percent was highly variable with a minimum value of 13.2 and a max of 95.1%. Residual pool depth averages also varied, ranging from 20 to 90 cm. Across all sites, wood was the dominant pool forming element as most pools were formed by wood (i.e., 62%). Rock also accounted for a substantial amount of pool formation (i.e., 14%). Active beaver ponds were observed in 7% (i.e., 2/28) of the reaches, in which they were the dominant pool forming element for 12% and 90% of all pools at these locations. Substrate particle measurements ranged from sand to bedrock (<4 mm - >512 mm), with the majority of measured substrates from pebble counts consisting of gravel (i.e., 71%).

A total of 2237 logs were measured, with 53.2% classed in the small category (i.e., diameter 0.1 – 0.3 cm) and 30.5% classed as medium (i.e., diameter 0.3-0.6 cm). Large logs were less common as 14.8% and just 1.5% of all logs were classed as large and extra-large respectively (i.e., diameter 0.6 – 0.9 and > 0.9 cm). In channel length of logs varied in a similar fashion as 57.3% of logs were between 2 and 5 m long, 34.8% fell between 5 and 11 m in length, while the final 7.9% of LW pieces were greater than 11 m long (Figure 1.8). Large wood density varied from less than 110 to just under 890 pieces per km. Large wood density was relatively higher in low gradient streams compared to moderate gradient streams as an average of 381 pieces/km of wood were measured in 9 low gradient streams, while an average of 356 pieces/km were measured in 19 moderate gradient streams. Little noticeable difference was observed across the two types of channels when comparing size distributions (Figure 1.9). Overall a higher density of wood was found in the 15 streams having two sides harvested (i.e., 378 pieces/km) when compared to the 13 streams only experiencing harvest on one bank (i.e., 348 pieces/km), and in general the wood was relatively larger (Figure 1.10).

The average in stream length of functioning recruits ranged from 3 m to just over 11 m with an average of approximately 6.8 m. On average, recent LW recruits were present with less than two green and twig recruits per 100 m across all reaches (Table 1.2). Only 4 out of 28 reaches had more than three recent recruits per 100 m, two of which exceeded eleven recent recruits in each reach. The decay class (see Methods) of small and medium-size recruits was between the branch and nub stage, while large and extra-large recruits were on average older and fell between the nub and old decay class (Figure 1.11). Recruits were functioning about half the time when averaged across all reaches (i.e., 48%), although this varied widely from 13% to 88% at the individual reach level. New recruits in these reaches were shown to have the capability to

function, although relative to nub and old recruits, green and twig recruits functioned much less often (i.e., 56% vs. 24%; Figure 1.12). A similar pattern was observed for recruits based on their size where larger recruits were less common but functioned more often (Figure 1.13). The recruitment process bringing LW into the stream was dominated by erosion and wind with 59% and 30% respectively, of all recruits entering the stream by these mechanisms. A small percentage (i.e., 4%) of recruits showed signs of entering the stream by harvest, while the remaining 7% were recruited through natural mortality, beaver, or unknown processes.

Understanding influences of natural factors on aquatic habitat

Principal components analysis

The principal components analysis identified five axes that explained a majority of variation across sampled reaches (77.57%) (Figure 1.14). The first component, explaining 27.01% of the variation, was weighted by measures related to stream size, riparian trees, and functioning recruits. Variables positively weighting this axis included bankfull width, residual pool depth, the average length of functioning recruits, bankfull depth, and the proportion of deciduous riparian trees, while confinement was negatively weighted on this axis. The second axis, explaining 16.86% of the variation in aquatic and riparian habitat across reaches, was weighted by measures of stream power having negative weights for both the proportion of fine substrates and the number of pools formed by wood, while this axis had positive weights on D50 grain size and gradient. The third axis was weighted by measures of LW recruitment by both wind and erosion, explaining 13.21% of the variation. The fourth axis explained 12.23% of the variation and was positively weighted on measures of LW and pool density. The fifth and final

axis explained 8.27% of the variation and included both large riparian trees and the proportion of functioning recruits.

Stepwise multiple regressions

By performing stepwise multiple linear regression models, measures of aquatic habitat were related to riparian and geomorphic factors including bankfull width, gradient, confinement, and the proportion of deciduous riparian trees (Table 1.6). Most notably, bankfull width was shown to have a significant relationship with seven out of eleven aquatic habitat variables. Bankfull width was the only significant predictor of six variables including pool density ($R^2 = 0.21$), residual pool depth ($R^2 = 0.68$), the length of functioning recruits ($R^2 = 0.41$), the proportion of functioning recruits ($R^2 = 0.26$), LW recruited by erosion ($R^2 = 0.36$), and LW recruited by wind ($R^2 = 0.14$). For D50 ($R^2_{\text{adj}} = 0.52$), both bankfull width and gradient were significant predictors. Additionally gradient was shown to have a significant relationship with the proportion of fine substrates ($R^2 = 0.28$) and relative pool area ($R^2 = 0.36$) and was the only significant predictor included in those models. The proportion of wood formed pools ($R^2_{\text{adj}} = 0.30$) was significantly related to both confinement and the proportion of deciduous riparian trees. Large wood density was not significantly related to any riparian or geomorphic factors at $P < 0.05$, but did show a negative relationship with the proportion of large and extra-large trees ($R^2 = 0.11$) when the stepwise entry criterion was less conservative at $P < 0.10$.

Understanding influences of timber harvest on aquatic habitat

Cumulative frequencies

A sequence of cumulative frequency distributions comparing logged and unlogged streams showed the potential for differences in the four variables (Figure 1.15). Frequency plots were created for a) D50, b) residual pool depth, c) pool density, and d) relative pool area. Little difference is apparent between harvested and unharvested streams for residual pool depth, pool density, or relative pool area while D50 grain size may be lower in harvested streams.

Discriminant function analysis

The results from the DFA showed moderate success in discriminating between harvested and unharvested stream reaches when developing a linear combination of D50, RPD, RPA, and POOLKM to summarize between-management class variation. The resulting original classification had a 76.0% and 78.6% correct classification for unharvested and harvested streams respectively (Table 1.7). Overall 77.4% of these original grouped cases were correctly classified. Successful classification dropped slightly when cross-validating grouped cases as 76.0% and 71.4% of harvested and unharvested streams were correctly classed with 73.6% of all cases correctly classified in the cross-validation procedure. While this analysis does support some influence of management on the aquatic habitat factors tested, it does not suggest that there are widespread differences in aquatic habitat between harvest and unharvested streams.

Analysis of Covariance (ANCOVA)

All four key response habitat variables were evaluated by an ANCOVA to test for associations with channel type and timber management as factors. The results from the multiple regressions show the importance of stream size in influencing aquatic habitat characteristics, and BFWD was entered into each of the models as a single covariate to control for this factor.

The mean RPD was lower in harvested vs. unharvested streams and in moderate vs. low gradient streams respectively, but neither difference was statistically significant (Table 1.8, Table 1.9). RPA was lower in unharvested vs. harvested streams and higher in FP vs. MM streams, although only significant for the channel type. The POOLKM was lower in harvested than unharvested streams and higher in FP than MM streams, although no statistical differences were observed. D50 showed statistical differences by both management type and channel type with harvested and FP streams having lower values than unharvested and MM streams respectively. No significant interactions were observed between management type (i.e., harvested vs. unharvested) or channel type (i.e., low vs. moderate gradient) for any of the aquatic habitat variables tested.

Discussion

This study describes the current condition of stream geomorphology, riparian stand composition, and aquatic habitat in and along anadromous streams of Southeast Alaska that had experienced riparian timber harvest between 1980 and 1990. In support of our first objective, we described geomorphic, riparian stand, and aquatic habitat conditions in streams draining second growth forests on Sealaska-owned land, and addressed our second objective by comparing key habitat factors to these landscape-scale influences. Geomorphic controls were strongly associated with multiple measures of aquatic habitat such as pool characteristics, substrates, functioning LW, and LW recruitment, while riparian stand composition was related to measures of wood-formed pools and LW density. To understand influence of management on aquatic habitat measures, pool and substrate characteristics of study streams were compared to a set of streams having unharvested watersheds. Differences in size of substrates were noted, with harvested streams having smaller median particle size. These findings suggest that riparian and

geomorphic factors influence aquatic habitat in streams and reinforces the importance of understanding natural controls on aquatic habitat while managing for these characteristics in southeastern Alaska.

Geomorphic influences on aquatic habitat

Pool characteristics

Channel geomorphology was related to multiple measures of aquatic habitat, including measures characterizing pools. Bankfull width was the only significant predictor of pool density, functioning recruit length, proportion of functioning recruits, and residual pool depth, which was the variable most strongly predicted by bankfull width. This relationship follows similar results from coastal Alaska streams; Martin (2001) found pool depths to generally increase with increasing stream size. The importance of pools to the region's salmonids is well established (Heifetz et al. 1986), especially during low flow periods when drying can occur (May and Lee 2004). Besides being a sig predictor of pool dimensions, Pool density was also significantly predicted by bankfull width with fewer and longer pools in larger streams. Similar results from Montgomery et al. (1995) showed a strong influence of stream size on pool spacing (i.e., distance between pools) in forested channels of Southeast Alaska and Washington having similar loads of LW. The proportion of wood-formed pools was significantly related to channel confinement, with a lower proportion of pools formed by wood in streams that were more confined, while relative pool area was strongly associated with stream gradient as fewer pools were observed in steeper streams. Additionally, results from the ANCOVA confirmed a statistical difference in relative pool area between FP and MM channels. More pools were formed by wood in less confined channels, and more pool area was observed in FP channels.

These patterns concur with other observations in the region, as Martin (2001) found higher proportions of pools and more wood formed pools in FP streams of coastal Alaska when compared to MM and contained channels.

Substrate characteristics

Measures of stream substrate were additionally influenced by geomorphic factors. Gradient was the only significant predictor included in the model for the proportion of fine substrates, while both gradient and bankfull width were strongly associated with D50 grain size. The ANCOVA confirmed this relationship as D50 was statistically lower in FP than MM channels. More powerful streams are able to transport larger substrates, resulting in larger median particle sizes. However, as channels become wider, gradients tend to be less steep, so although a higher volume of water is present, the ability to move coarse substrates diminishes (Buffington et al. 2002). Other natural factors can additionally influence substrate characteristics including catchment geology, landslide frequency, and proximity to tributaries (Montgomery 1999, Benda et al. 2004), as well as elements that can increase bed roughness (e.g., LW) which can limit transport of sediment in channels, effectively reducing particle sizes in streams (Buffington and Montgomery 1999). These landscape factors were not accounted for in this study potentially leading to relatively low amounts of variation in substrate measurements explained by the regression models.

Large wood characteristics

Numerous large wood characteristics varied with bankfull width including longer and proportionately more functioning recruits occurring in larger vs. smaller channels. When a recruit falls toward a wider stream, it is less likely to span the entire channel. This allows the

new recruit to function sooner than if it were spanning the riparian zones on both banks. These results concur with Bilby and Ward (1989) who found the strongest relationship between LW volume and sediment storage in the widest streams of Western Washington. The proportion of large wood recruited by erosion increased with increasing channel width, while recruitment by wind was more prevalent in smaller channels. These findings are consistent with Martin and Benda (2001) who found more recruitment through erosion in streams having larger drainages, and more recruitment by mortality (including windthrow) in smaller drainages. While previous studies have related LW densities to stream size in unharvested streams of the Pacific Northwest (Bilby and Ward 1989, Robison and Beschta 1990), this relationship was not found in this study. My results do agree with Ralph et al. (1994) who similarly did not see this relationship and suggested that the high variation observed in LW requires sampling longer stretches of water (i.e., 1-2 km) to achieve proper confidence in the measured frequencies rather than extrapolating a LW density based off shorter surveys.

Riparian influences on aquatic habitat

Riparian stand composition was significantly related to aquatic habitat based on results of this study. Relative composition of sampled riparian stands that were deciduous was inversely related to the proportion of pools formed by wood. The results suggest that a lower proportion of pools are formed by wood in streams having a higher proportion of deciduous trees in the riparian zone. This result may partially be an artifact of relationships between pool density and stream size as the relative amount of deciduous riparian trees was significantly correlated with stream size (Table 1.1). Nevertheless, deciduous species do not have the same size potential as conifers in old growth forests, leading to a lower volume of LW to streams with deciduous zones dominated by deciduous vs. conifer species, and our results suggest that larger wood (i.e.,

typically conifers) more readily influences channel morphology. In addition, deciduous trees are shorter-lived and decay faster than conifers (Deal et al. 2004), but may influence size potential of surrounding conifers in the same stand. In fact, previous research found slightly larger (i.e., dbh) dead conifers as the percentage of red alder increased in 13 second-growth headwater riparian stands of Southeast Alaska (Orlikowska et al. 2004). Large wood density was additionally negatively related to the proportion of large and extra-large riparian trees. A greater proportion of large trees in the riparian zone may be the result of other smaller trees being outcompeted for space and resources over time. Large wood in streams is dictated partially by what is available in the riparian zone and in streams draining old-growth forests of western Washington, LW diameter was equal or larger than the average riparian tree diameter while younger forests showed less association between diameter of riparian trees and in-stream LW (Rot et al. 2000). In northeastern Oregon little difference was observed in amounts of LW or pools formed by wood when comparing 11 streams having undisturbed riparian forests with 5 streams having riparian zones harvested for timber up to 17 years prior (Carlson et al. 1990).

Timber harvest influences on aquatic habitat

Previous studies on the influence of timber harvest on stream habitats in Southeast Alaska and the Pacific Northwest have documented numerous effects including habitat simplification (Ralph et al. 1993, McIntosh et al. 2000), increased erosion and sedimentation (Grant and Wolff 1991), and a long term reduction in pools and LW over time (Murphy et al. 1986, Murphy and Koski 1989). While many of these influences were not evident in this study, there is evidence to support a shift to a smaller median particle size as a result of historical timber management. The results from the DFA suggest moderate differences in aquatic habitat between harvested and unharvested sites given our available habitat data, although similar

research comparing 13 pristine streams and 10 streams harvested in Southeast Alaska before 1980 had substantially more success discriminating streams based on timber management as 92% and 90% of pristine and disturbed sites were classified correctly in their study (Woodsmith and Buffington 1996). The ANCOVA showed no significant differences in residual pool depth, pool density, or relative pool area in regards to timber harvest, which concurs with Carlson et al. (1990), but not with Heifetz et al. (1986) who found lower amounts of woody debris and pool area in clearcut streams when compared to unlogged and streams with riparian buffers. My results do suggest that median particle size was significantly lower in streams having had riparian harvest compared to unharvested streams after controlling for stream size, a result that contradicts Carlson et al. (1990) who did not find this relationship. This association is plausible, and common effects documented from the absence of riparian vegetation, loss of LW, the presence of roads, and cumulative watershed disturbances include increased erosion and decreased bank stability leading to increased sedimentation (Murphy 1995), although in Southeast Alaska the majority of non-federal, closed and decommissioned logging roads comply with BMP's issued by the State and are likely not a significant source of sediment to streams (ADNR 2010). Additionally as LW was abundant in many of the sampled reaches, and LW for example increases bed roughness which can reduce particle sizes in streams by limiting transport of suspended sediments down channels (Buffington and Montgomery 1999).

The effects of timber harvest on LW was untested by this study, and timber harvest related influences on LW dynamics may be occurring in streams having riparian zones harvested for timber between 1980 and 1990. These factors were not tested due to inconsistencies in defining LW between the harvested and unharvested aquatic habitat datasets, although general conclusions can be inferred based on our data and previously published research on streams

draining old growth forests in the region. Most LW in Southeast Alaska is recruited within the first 20-30 m of the stream bank (Murphy and Koski 1989, Martin and Grotefendt 2007), making the riparian zone the main source of wood for streams in the region. Our results suggest that the majority of riparian trees were of the smallest size class which has implications for new wood recruited to streams, most notably that input of LW to such streams will be small pieces. It has been estimated that on productive valley floors of Southeast Alaska, second growth trees will reach a dbh of 60 cm (i.e., smallest size of large LW) after 75 years, and the quantity of trees this size doesn't equal old-growth forests until 130 years (Taylor 1934). Additionally, new recruitment of LW is generally low in the region (Martin and Benda 2001), a result supported by our findings as nearly 30% of the sampled sites had no green or twig recruits. While recruitment of wood is low in the region, 20-30 years have passed since harvest and LW loads are not substantially different when compared to streams having unharvested riparian stands (Table 1.10).

Perhaps more notably are the implications for the size distribution of LW in the future as opposed to LW density. As the largest pieces of wood decay or are transported, the harvested riparian zones will not be able to provide replacement large logs for potentially hundreds of years (Murphy and Koski 1989), skewing future distributions towards smaller pieces of wood. Our results also suggest that those largest pieces have more ability to function in streams compared to smaller recruits, while the functioning capability also increases with log age (Figures 1.12 and 1.13). Remnant wood was still prevalent throughout the study reaches, a characteristic that may mitigate the loss of future recruitment of the largest LW pieces. Results suggest that recruitment of LW since harvest has been mostly small and medium sized LW, while some medium sized wood was additionally decayed enough to be recruited before harvest,

and the largest pieces of wood are almost all decayed enough to be recruited prior to harvest (Figures 1.11 and 1.12). This follows similar research as Martin and Benda (2001) found that logs in the later stages of decay were typically at least 18 years old and recruited before harvest.

Historical effects of timber harvest on streams often focus on catchments experiencing more anthropogenic disturbance than timber harvest alone so teasing out mechanisms can be difficult (McIntosh et al. 2000). Moreover, the earliest logging in Alaska and the Pacific Northwest occurring near streams had little to no regulations requiring that aquatic resources be taken into account while harvesting timber (Bryant 1983), so the legacy of historic riparian management practices may still be affecting streams and may continue to do into the future (Benda et al. 2002).

Management implications

Stream size and channel type constraints

The results of this study suggest that geomorphic factors largely control many aquatic habitat factors in streams of Southeast Alaska, and they must be accounted for when assessing the potential of a stream to exhibit desired pool, substrate, and LW characteristics. We found relatively more wood in low gradient streams when compared to moderate gradient streams. Higher gradients have more power to transport wood out of those reaches, but low gradient floodplain streams often meander which allows more wood to be recruited to these streams through bank erosion. More bank erosion also encourages relatively more deciduous vegetation to colonize because of increased light reaching the forest floor as established conifers are removed, and we did find more deciduous vegetation in low gradient streams. These natural controls are consistent with previous findings in forested catchments of Wisconsin and Michigan

where natural controls explained more variation in aquatic habitat than anthropogenic landscape factors (Wang et al. 2003). This study concurs with previous research in streams of Southeast Alaska, suggesting that size and channel type will dictate how aquatic habitat will be distributed throughout a given reach (Paustian et al. 1992). Larger streams will have deeper pools and fewer, but longer pools than smaller streams. Wood will be more capable of forming pools in less confined reaches (e.g., FP channels), and a lower proportion of pools will be found in steeper reaches (e.g., MM channels). Efforts aimed at increasing pool habitat by adding LW should focus on streams most suited for LW formed pools. Additionally, wood placement projects must consider that the functioning capability of wood in Southeast Alaska streams depends on the size of the stream in which it resides as larger streams will allow for longer, and proportionately more pieces of LW to function.

Legacy of actions on the landscape

Riparian stand composition

While riparian stand composition can vary by landscape factors (Villarin et al. 2009), harvesting timber influences both the type and size structure of riparian vegetation. The findings of this study support this, and relatively few riparian trees measured were larger than 60 cm dbh. We also found that streams having two banks harvested also had relatively more deciduous riparian trees. This influence has implications for aquatic habitat as opened canopies and abandoned logging roads provide patches of light following timber harvest and encourage thick stands of deciduous trees to colonize and out-compete young-growth conifers (Deal et al. 2004). Large wood of deciduous origin has a smaller size potential and decays faster than conifers, so managers tasked with conserving or creating pool habitat in streams having second growth

riparian zones will have to consider the ability and time frame in which potentially new LW may function in streams. In contrast, Deal et al. (2004) states that deciduous trees can enhance productivity through changes in light penetration and the input of leaf litter. Moreover, red alder and other deciduous tree species can also influence nutrient levels by fixing nitrogen in soils, and hyporheic activity can transport these nutrients into nearby streams. Based on the different types of benefits associated with differing riparian stand composition, decision makers directing stream enhancement projects need to have explicitly defined goals and objectives as management efforts are being planned.

Stream substrate composition

The results of this study show a potential decrease in median particle size influenced by timber management in the riparian zone. These conclusions are limited as other factors affecting sediment were not accounted for, including geology and landslide frequency in the catchment, and while an abundance of gravel was observed in the study reaches sampled (only 2/28 sites had less than 50% gravel from pebble count summaries (Table 1.2) embeddedness by fine substrates can drastically reduce the quality of gravel and even LW for stream biota (Richards and Host 1994). Managers must also consider natural controls on sediment by knowing floodplain streams are likely to include smaller substrates, and future research and stream enhancement projects should take into account geology and historic landslide information as mass wasting events can input large volumes of not only fine, but coarse sediment.

Silviculture as a tool to manage for future large wood

Silviculture, and more specifically thinning has historically been used by foresters to increase productivity of second growth forests with the goal of having more timber resources in a

shorter time frame than would occur naturally, although this can also be employed to enhance future sources of LW to streams. Research has found that thinning is effective in dense young stands, and it can accelerate the production of large trees by up to 20 years (Spies et al. 2013). While tree growth may be enhanced, conventional thinning could actually result in less dead trees over the lifetime of a stand (Garman et al. 2003, Dodson et al. 2012), potentially limiting input of LW to streams. Non-conventional methods may supplement this loss if thinning efforts directly added trees to streams at the time of thinning. Additionally thinning will be most effective near streams as most LW input comes from sources closest to the stream. Stream type and location also matter as small headwater streams may not be capable of delivering wood to larger streams that support anadromous fishes without debris flows, which only occur in mountainous regions, so thinning may not be beneficial in these locations.

APPENDIX

Table 1.1: Pearson's correlations among geomorphic, riparian, and aquatic habitat variables used in analyses. An asterisk next to correlation coefficient indicates significance at a 0.05 level while two asterisks indicate significance at a 0.01 level. Bold variable codes indicate a transformed variable (See Methods for specific transformations and Table 1.2 for variable codes).

		Geomorphic				Riparian	
		BFWD	BFDP	GRAD	CONF	DCRT	PLXL
Geomorphic	BFWD	1.00					
	BFDP	0.76 **	1.00				
	GRAD	-0.50 **	-0.24	1.00			
	CONF	-0.55 **	-0.23	0.65 **	1.00		
Riparian	DCRT	0.62 **	0.57 **	-0.10	-0.39 *	1.00	
	PLXL	0.24	0.20	-0.25	-0.13	0.21	1.00
Aquatic habitat	LWKM	0.11	0.10	-0.15	-0.17	-0.18	-0.34
	FNRL	0.64 **	0.42 *	-0.57 **	-0.48 **	0.31	0.20
	PFNR	0.51 **	0.27	-0.33	-0.35	0.21	0.33
	EROSLW	0.60 **	0.52 **	-0.23	-0.32	0.48 *	0.29
	WINDLW	-0.38 *	-0.27	0.34	0.38 *	-0.24	-0.15
	POOLKM	-0.45 *	-0.34	0.13	0.22	-0.38 *	-0.19
	RPD	0.82 **	0.65 **	-0.56 **	-0.37	0.36	0.20
	RPA	0.42 *	0.27	-0.60 **	-0.30	0.03	0.03
	WOOD	0.07	-0.16	-0.26	-0.40 *	-0.25	-0.12
	D50	0.25	0.20	0.48 **	0.16	0.42 *	-0.05
	FINE	-0.01	0.02	-0.53 **	-0.29	-0.24	0.09

Table 1.1: (cont'd).

		Aquatic habitat					
		LWKM	FNRL	PFNR	EROS	WIND	POOLKM
Geomorphic	BFWD						
	BFDP						
	GRAD						
	CONF						
Riparian	DCRT						
	PLXL						
Aquatic habitat	LWKM	1.00					
	FNRL	0.03	1.00				
	PFNR	0.00	0.31	1.00			
	EROSLW	-0.08	0.22	0.12	1.00		
	WINDLW	-0.14	0.02	-0.17	-0.78 **	1.00	
	POOLKM	0.43 *	-0.34	0.07	-0.42 *	0.22	1.00
	RPD	0.15	0.70 **	0.37	0.48 **	-0.35	-0.42 *
	RPA	0.60 **	0.46 *	0.39 *	0.16	-0.34	0.23
	WOOD	-0.04	0.37	0.18	-0.19	0.25	-0.10
	D50	-0.11	-0.01	-0.05	0.22	0.02	-0.23
	FINE	0.21	0.15	0.02	-0.08	-0.08	0.17

Table 1.1: (cont'd).

		Aquatic habitat				
		RPD	RPA	WOOD	D50	FINE
Geomorphic	BFWD					
	BFDP					
	GRAD					
	CONF					
Riparian	DCRT					
	PLXL					
	LWKM					
	FNRL					
Aquatic habitat	PFNR					
	EROSLW					
	WINDLW					
	POOLKM					
	RPD	1.00				
	RPA	0.61 **	1.00			
	WOOD	0.01	-0.07	1.00		
	D50	0.07	-0.32	-0.37	1.00	
	FINE	0.05	0.33	0.33	-0.75 **	1.00

Table 1.2: Mean, minimum, maximum, and standard deviation (SD) of calculated variables used to describe the current aquatic and riparian habitat condition of study sites.

Category	Variable name	Code	Mean	Min	Max	SD
Channel morphology						
	Mean gradient (%)	GRAD	3.03	0.50	6.17	1.52
	Visual confinement*	CONF	1.61	1.00	2.00	0.44
	Bankfull depth (m)	BFDP	0.19	0.06	0.43	0.10
	Bankfull width (m)	BFWD	6.06	1.00	25.13	5.95
Riparian						
	Deciduous riparian trees (proportion)	DCRT	0.27	0.00	0.73	0.24
	Large and extra-large trees (proportion)	PLXL	0.06	0.00	0.30	0.06
Habitat complexity						
	Relative pool area (%)**	RPA	45.89	13.18	95.05	21.54
	Pool density (#/km)**	POOLKM	61.26	9.86	125.87	24.11
	Mean residual pool depth (m)**	RPD	0.44	0.20	0.90	0.20
	Pools formed by wood (proportion)	WOOD	0.61	0.06	1.00	0.25
Substrate						
	Fine (proportion ≤ 4 mm)	FINE	0.11	0.01	0.46	0.11
	D50**	D50	28.80	4.76	76.11	17.13
Large wood (LW)						
	LW pieces/km (#)	LWKM	363.73	109.89	887.85	187.58
	Green & twig recruits (#/100 m)	GTREC	1.94	0.00	11.75	2.91
	Mean length of functioning recruits (m)	FNRL	6.72	3.00	11.19	2.52
	Proportion functioning recruits	PFNR	0.48	0.13	0.88	0.17
	LW recruitment by erosion (%)	EROSLW	58.48	12.50	100.00	23.29
	LW recruitment by wind (%)	WINDLW	29.98	0.00	87.50	21.84
* 1 = unconfined, 2 = moderately confined, 3 = totally confined						
** Used in comparison to 25 unharvested stream reaches						

Table 1.3: Pearson's correlations between key response variables used in comparison between harvested and unharvested streams. An asterisk next to a correlation coefficient indicates significance at the 0.05 level and two asterisks indicates significance at 0.01 level. Width to depth ratio (WD) is the ratio between bankfull width and bankfull depth, average pool area (APA) was in m², pool spacing (SPACE) is measured in # channel widths per pool, and pool length (RPL) is the proportion of reach length classified as pool. All other variable codes can be found in Table 1.2.

	RPD	RPA	POOLKM	D50	APA	SPACE	RPL	WD	D84
RPD	1.00								
RPA	0.40 **	1.00							
POOLKM	-0.41 **	0.21	1.00						
D50	0.19	-0.41 **	-0.24	1.00					
APA	0.83 **	0.37 **	-0.50 **	0.03	1.00				
SPACE	-0.48 **	-0.39 **	-0.23	-0.19	-0.31 *	1.00			
RPL	0.49 **	0.82 **	0.27 *	-0.16	0.34 *	-0.58 **	1.00		
WD	0.61 **	0.22	-0.41 **	0.01	0.59 **	-0.33 *	0.14	1.00	
D84	0.12	-0.49 **	-0.26	0.92 **	-0.01	-0.13	-0.29 *	0.00	1.00

Table 1.4: Total area harvested and percent of total land area harvested for all of Sealaska owned land organized for three time periods. Time periods correspond to changes to Alaska's forest resource regulations.

	Area harvested (km ²)			Percent of total land area (%)		
Harvest method and time period	Conventional	Helicopter	Total	Conventional	Helicopter	Total
Pre 1980	53.21	0.04	53.25	4.50	0.00	4.50
1980-1990	93.80	0.31	94.11	7.93	0.03	7.95
Post 1990	278.61	411.44	690.06	23.54	34.77	58.31
Total	425.63	411.79	837.42	35.97	34.80	70.76

Table 1.5: Mean and standard deviation (SD) of study reaches draining land owned by Sealaska Corporation. Sites are grouped by gradient as either low (< 2%) or moderate gradient (2-6 %).

Variable	Low (n=9)		Moderate (n=19)		All reaches (N=28)	
	Mean	SD	Mean	SD	Mean	SD
Average reach length (m)	345.11	129.62	152.08	92.83	214.13	138.39
Average bankfull width (m)	10.78	7.44	3.83	3.49	6.06	5.95
Gradient (%)	1.46	0.61	3.77	1.23	3.03	1.52
Visual confinement *	1.29	0.42	1.75	0.38	1.61	0.45
One bank harvest (% of sites)	14.29		32.14		46.43	
Two bank harvest (% of sites)	17.86		35.71		53.57	

* 1 = unconfined, 2 = moderately confined, 3 = totally confined

Table 1.6: Results of multiple linear regressions predicting each aquatic habitat variable for 28 streams on Sealaska timberlands. Independent variables are listed in order of their influence on the model, based on standardized coefficients, which are located in parentheses. Sig. indicates the p-value for each hypothesis test on the coefficient of the corresponding term in the linear model. Proportion of variance explained is indicated by R^2 for one variable models and R^2_{adj} for two variable models. A variance inflation factor value of 4 ($VIF < 4$) was used to ensure little multicollinearity.

Aquatic habitat variable	Independent variable(s)	Model F	Sig.	R^2 (R^2_{adj})	VIF
D50	GRAD (0.81)	15.86	< 0.0001	0.52	1.34
	BFWD* (0.66)		< 0.001		
FINE*	GRAD (-0.53)	10.04	0.00	0.28	1.00
POOLKM	BFWD* (-0.45)	6.70	0.02	0.21	1.00
RPD	BFWD* (0.82)	54.15	< 0.0000001	0.68	1.00
RPA	GRAD (-0.60)	14.29	< 0.001	0.36	1.00
WOOD	CONF (-0.59)	6.82	0.00	0.30	1.18
	DCRT (-0.48)		0.01		
LWKM**	PLXL (-0.34)	3.28	0.08	0.11	1.00
FNRL	BFWD* (0.64)	17.69	< 0.001	0.41	1.00
PFNR	BFWD* (0.51)	9.00	0.01	0.26	1.00
EROSLW	BFWD* (0.60)	14.63	< 0.001	0.36	1.00
WINDLW	BFWD* (-0.38)	4.33	0.05	0.14	1.00
* Indicates transformed variables					
** Significance of the F statistic ($P = 0.10$) used as entry criterion					

Table 1.7: Classification results organized by count and percent correctly classified from the discriminant function analysis for both known (Original) and unknown membership (Cross-validated).

Original				Cross-validated			
Classified membership				Predicted membership			
	Unharvested	Harvested	Total		Unharvested	Harvested	Total
Unharvested (#)	19.00	6.00	25.00	Unharvested (#)	19.00	6.00	25.00
Harvested (#)	6.00	22.00	28.00	Harvested (#)	8.00	20.00	28.00
Unharvested (%)	76.00	24.00	100.00	Unharvested (%)	76.00	24.00	100.00
Harvested (%)	21.43	78.57	100.00	Harvested (%)	28.57	71.43	100.00
* 77.4% of original grouped cases correctly classified							
** 73.6% of cross-validated grouped cases correctly classified							

Table 1.8: ANCOVA adjusted means and standard errors of variables reported for both low and moderate gradient reaches. Differences are significant ($P < 0.05$) when the 95% confidence intervals do not include 0 and an asterisk denotes variables with significant differences.

Variable	Low gradient channels		Moderate gradient channels		Difference	95% CI
	Mean	SE	Mean	SE		
RPD	0.46	0.03	0.41	0.02	0.05	-0.01 - 0.12
RPA*	0.60	0.06	0.37	0.04	0.23	0.09 - 0.37
POOLKM	67.51	5.80	66.61	3.83	0.91	-13.74-15.56
D50*	25.15	3.94	41.95	2.60	-16.80	-26.77--6.84

Table 1.9: ANCOVA adjusted means and standard errors of variables reported for both unharvested and harvested reaches. Differences are significant ($P < 0.05$) when the 95% confidence intervals do not include 0 and an asterisk denotes variables with significant differences.

Variable	Unharvested		Harvested		Difference	95% CI
	Mean	SE	Mean	SE		
RPD	0.45	0.02	0.43	0.02	0.01	-0.04-0.07
RPA	0.46	0.05	0.50	0.04	-0.05	-0.17-0.08
POOLKM	73.09	4.72	61.03	4.56	12.06	-1.08-25.19
D50*	42.03	3.21	25.06	3.10	16.97	8.04-25.90

Table 1.10: Large wood density (pieces/km) in streams of Southeast Alaska organized by channel type.

Previous research	Forest condition	Channel type	
		FP	MM
Murphy and Koski 1989	Old growth	399	311
Robison and Beschta 1990	Undisturbed	337	330
Bryant et al. 2004	Nonharvested	350-450	350-450
Martin 2001	Some harvest	390	355
Ross 2013	At least 1 bank harvested	381	356

Table 1.11: Data characterizing aquatic and riparian habitat in and along 28 study sites on Sealaska-owned land sampled in 2011.

Site code	9	34	52	68	69	74	77	83	102
Creek name	Perry	Unnamed	Unnamed	Unnamed	Unnamed	Unnamed	Unnamed	Unnamed	Unnamed
Latitude	-132.67	-133.11	-132.93	-133.18	-133.11	-133.03	-133.02	-132.94	-133.22
Longitude	55.28	55.62	55.61	55.62	55.64	55.64	55.63	55.66	55.6
Year	2011	2011	2011	2011	2011	2011	2011	2011	2011
Channel type	MM	MM	MM	FP	MM	MM	MM	MM	MM
Variable name									
Bankfull width (m)	3.53	1.57	1.70	2.17	2.53	6.23	1.93	4.92	2.60
Bankfull depth (m)	0.17	0.12	0.14	0.17	0.14	0.22	0.06	0.34	0.11
Mean gradient (%)	3.17	3.33	2.17	2.00	4.83	2.50	2.50	4.17	2.50
Visual confinement*	2.00	2.00	2.00	2.00	2.00	1.00	1.00	2.00	2.00
Relative pool area (%)***	57.58	45.23	37.26	95.05	34.17	49.68	60.57	57.21	38.98
Pool density (#/km)***	94.53	125.87	74.77	68.32	78.26	60.24	98.77	73.47	47.30
Mean residual pool depth (m)***	0.50	0.26	0.29	0.57	0.28	0.46	0.25	0.61	0.35
Pools formed by wood (proportion)	0.45	0.60	0.29	0.00	0.56	0.79	1.00	0.67	0.73
Fine (proportion ≤ 4 mm)	0.02	0.31	0.11	0.24	0.02	0.04	0.35	0.01	0.09
D50***	39.40	9.19	13.00	13.93	43.71	43.71	5.46	27.86	20.39
LW pieces/km (#)	452.74	319.44	292.45	676.83	380.53	572.29	790.12	608.16	317.57
Mean length of functioning recruits (m)	10.13	5.50	3.00	5.63	4.00	9.28	4.36	7.00	5.67
Proportion functioning recruits	0.46	0.46	0.21	0.33	0.63	0.48	0.34	0.50	0.39
LW recruitment by erosion (proportion)	0.43	0.46	0.29	0.50	0.37	0.73	0.31	0.33	0.48
LW recruitment by wind (proportion)	0.57	0.46	0.50	0.00	0.63	0.20	0.25	0.50	0.30
Deciduous riparian trees (proportion)	0.20	0.00	0.06	0.00	0.03	0.11	0.00	0.19	0.00
Large and extra-large trees (proportion)	0.00	0.10	0.09	0.00	0.06	0.05	0.00	0.00	0.03

Table 1.11: (cont'd).

Site code	112	123	126	174	176	183	187	189	374
Creek name	Unnamed	Lime	Unnamed	Unnamed	Dog Salmon	Unnamed	Steelhead	Unnamed	Unnamed
Latitude	-133.1	-133.02	-133.01	-132.97	-132.99	-133.09	-132.94	-132.94	-132.7
Longitude	55.62	55.63	55.64	55.62	55.62	55.62	55.65	55.65	55.24
Year	2011	2011	2011	2011	2011	2011	2011	2011	2011
Channel type	FP	FP	FP	MM	MM	MM	FP	MM	MM
Variable name									
Bankfull width (m)	3.30	10.67	5.30	4.33	6.73	2.20	25.13	16.40	2.50
Bankfull depth (m)	0.08	0.13	0.09	0.28	0.23	0.12	0.36	0.31	0.09
Mean gradient (%)	1.83	1.17	1.50	6.17	2.17	4.67	1.83	3.33	3.00
Visual confinement*	1.00	1.00	2.00	2.00	1.00	2.00	1.33	1.67	1.33
Relative pool area (%)***	32.23	70.94	77.11	24.81	74.89	17.69	22.87	75.54	36.27
Pool density (#/km)***	58.82	59.88	63.43	45.11	75.76	53.76	9.86	42.55	54.95
Mean residual pool depth (m)***	0.38	0.59	0.60	0.32	0.61	0.26	0.84	0.90	0.26
Pools formed by wood (proportion)	0.68	0.81	0.71	0.20	0.38	0.62	0.60	0.54	0.45
Fine (proportion ≤ 4 mm)	0.17	0.10	0.12	0.03	0.02	0.08	0.04	0.04	0.03
D50***	17.75	17.75	16.56	43.71	27.86	19.03	59.71	43.71	29.86
LW pieces/km (#)	310.16	447.11	392.86	417.91	376.74	302.08	239.60	330.32	197.67
Mean length of functioning recruits (m)	6.69	10.17	8.90	3.00	6.60	4.80	7.29	9.25	5.25
Proportion functioning recruits	0.52	0.72	0.58	0.33	0.45	0.29	0.44	0.73	0.50
LW recruitment by erosion (proportion)	0.62	0.48	0.64	1.00	0.91	0.53	0.88	0.94	0.63
LW recruitment by wind (proportion)	0.23	0.48	0.26	0.00	0.00	0.41	0.12	0.03	0.00
Deciduous riparian trees (proportion)	0.07	0.58	0.00	0.49	0.61	0.00	0.51	0.46	0.41
Large and extra-large trees (proportion)	0.02	0.06	0.08	0.04	0.01	0.04	0.02	0.08	0.03

Table 1.11: (cont'd).

Site code	376	379	414	507	511	519	599	601
Creek name	Unnamed	Deer	Unnamed	Unnamed	Unnamed	Unnamed	Unnamed	Unnamed
Latitude	-132.71	-132.71	-135.56	-135.67	-135.67	-135.56	-132.77	-132.83
Longitude	55.24	55.24	58.17	58.11	58.13	58.15	55.29	55.27
Year	2011	2011	2011	2011	2011	2011	2011	2011
Channel type	MM	FP	MM	MM	MM	MM	FP	MM
Variable name								
Bankfull width (m)	2.07	8.33	2.50	2.43	1.00	1.63	10.40	5.90
Bankfull depth (m)	0.10	0.21	0.12	0.17	0.10	0.11	0.24	0.20
Mean gradient (%)	5.17	2.00	3.00	4.00	4.33	5.17	1.83	5.50
Visual confinement*	1.67	1.00	1.67	2.00	2.00	2.00	1.33	2.00
Relative pool area (%)***	25.72	43.30	35.85	20.29	16.04	13.18	49.71	40.83
Pool density (#/km)***	52.63	46.43	87.72	58.82	50.00	32.97	36.90	87.25
Mean residual pool depth (m)***	0.20	0.48	0.26	0.22	0.26	0.31	0.49	0.29
Pools formed by wood (proportion)	0.82	0.50	0.58	0.33	0.80	0.67	0.73	0.05
Fine (proportion ≤ 4 mm)	0.07	0.03	0.04	0.06	0.10	0.05	0.10	0.01
D50***	22.63	46.85	27.86	25.99	23.43	48.50	28.84	76.11
LW pieces/km (#)	265.96	421.99	201.75	245.10	125.00	114.94	270.37	457.52
Mean length of functioning recruits (m)	5.14	9.20	4.29	3.00	6.00	9.00	9.00	4.67
Proportion functioning recruits	0.58	0.41	0.88	0.43	0.25	0.13	0.52	0.53
LW recruitment by erosion (proportion)	0.17	0.76	0.33	0.71	0.75	0.13	0.88	0.59
LW recruitment by wind (proportion)	0.58	0.19	0.22	0.29	0.25	0.88	0.12	0.35
Deciduous riparian trees (proportion)	0.11	0.73	0.23	0.58	0.09	0.44	0.26	0.59
Large and extra-large trees (proportion)	0.00	0.10	0.10	0.09	0.09	0.00	0.16	0.11

Table 1.11: (cont'd).

Site code	605	608
Creek name	Natzuhini	Natzuhini
Latitude	-132.79	-132.82
Longitude	55.29	55.29
Year	2011	2011
Channel type	FP	FP
Variable name		
Bankfull width (m)	12.77	18.93
Bankfull depth (m)	0.39	0.81
Mean gradient (%)	0.50	0.50
Visual confinement*	1.00	1.00
Relative pool area (%)***	63.76	68.11
Pool density (#/km)***	26.19	58.69
Mean residual pool depth (m)***	0.82	0.60
Pools formed by wood (proportion)	0.55	0.88
Fine (proportion ≤ 4 mm)	0.24	0.46
D50***	8.88	4.76
LW pieces/km (#)	240.20	431.46
Mean length of functioning recruits (m)	11.20	10.50
Proportion functioning recruits	0.71	0.65
LW recruitment by erosion (proportion)	0.71	0.71
LW recruitment by wind (proportion)	0.24	0.25
Deciduous riparian trees (proportion)	0.50	0.59
Large and extra-large trees (proportion)	0.30	0.00

Table 1.12: Data provided by John McDonell, 2013, U.S. Forest Service, characterizing streams in the Tongass National Forest having unharvested riparian zones.

Site code	CHAN	CORN	DRINK	DBAYL	DBAYU	EMER	FARR	FRESH
Creek name	Chanterelle	Corner Bay	Drinkingwater	Dry Bay Lower	Dry Bay Upper	Emerald	Farragut	Freshwater
Latitude	-132.79	-135.11	-132.25	-133.6	-133.58	-132.01	-133.27	-135.3
Longitude	55.65	57.68	55.26	57.63	57.63	55.88	57.19	57.92
Year	2008	2006	2008	2006	2006	2008	2008	2008
Channel type	MM	MM	MM	FP	FP	MM	FP	MM
Variable name								
Bankfull width (m)	4.85	2.70	4.80	5.50	5.40	4.00	5.25	3.85
Bankfull depth (m)	0.26	0.21	0.47	0.43	0.36	0.45	0.22	0.40
Relative pool area (%)	28.79	38.26	29.12	62.68	38.39	69.79	60.01	11.72
Pool density (#/km)	40.98	95.63	52.63	84.81	77.52	104.76	79.44	81.97
Mean residual pool depth (m)	0.41	0.30	0.38	0.36	0.34	0.36	0.56	0.36
D50	49.39	40.11	60.21	34.68	21.23	41.93	30.00	24.35

Table 1.12: (cont'd).

Site code	GUNS	GYPM	HOYA	JENK	KEG	MIRK	MONT	OHMER	OXBOW	PACK
Creek name	Gunsight	Gypsy Main	Hoya	Jenkins	Keg	Mirkwood	Montana	Ohmer	Oxbow	Packer
Latitude	-131.37	-132.19	-131.71	-132.18	-133.13	NA	-131.18	-132.71	-132.59	-131.37
Longitude	55.49	56.45	56.18	56.43	55.3	NA	55.35	56.58	55.6	55.43
Year	2008	2008	2006	2008	2008	2008	2008	2008	2008	2008
Channel type	MM	MM	FP	FP	FP	MM	MM	FP	MM	MM
Variable name										
Bankfull width (m)	9.65	11.60	7.60	5.00	15.05	3.30	3.18	8.80	2.50	7.40
Bankfull depth (m)	0.27	0.39	0.50	0.47	0.52	0.21	0.36	0.47	0.25	0.32
Relative pool area (%)	75.19	29.68	89.75	82.13	27.83	17.19	28.34	42.70	33.32	23.01
Pool density (#/km)	64.52	49.65	48.19	74.38	70.42	82.73	56.00	59.60	86.67	31.91
Mean residual pool depth (m)	0.64	0.69	0.48	0.51	0.67	0.24	0.24	0.56	0.28	0.41
D50	33.76	81.73	27.00	38.36	48.29	37.42	55.91	67.80	45.30	65.77

Table 1.12: (cont'd).

Site code	PERK	SALT	SFMONT	TUNE	VIAL
Creek name	Perkins	Salty	SF Montana	Tunehean	Vial
Latitude	-132.17	-131.56	NA	-133.46	-132.8
Longitude	54.95	55.53	NA	56.62	56.28
Year	2008	2008	2009	2008	2008
Channel type	MM	MM	MM	MM	MM
Variable name					
Bankfull width (m)	1.30	2.20	4.00	5.80	11.25
Bankfull depth (m)	0.28	0.16	0.41	0.22	0.23
Relative pool area (%)	68.32	46.21	5.43	18.41	18.94
Pool density (#/km)	135.80	51.28	82.53	70.51	26.14
Mean residual pool depth (m)	0.29	0.35	0.36	0.46	0.72
D50	18.65	25.24	55.42	51.57	71.20

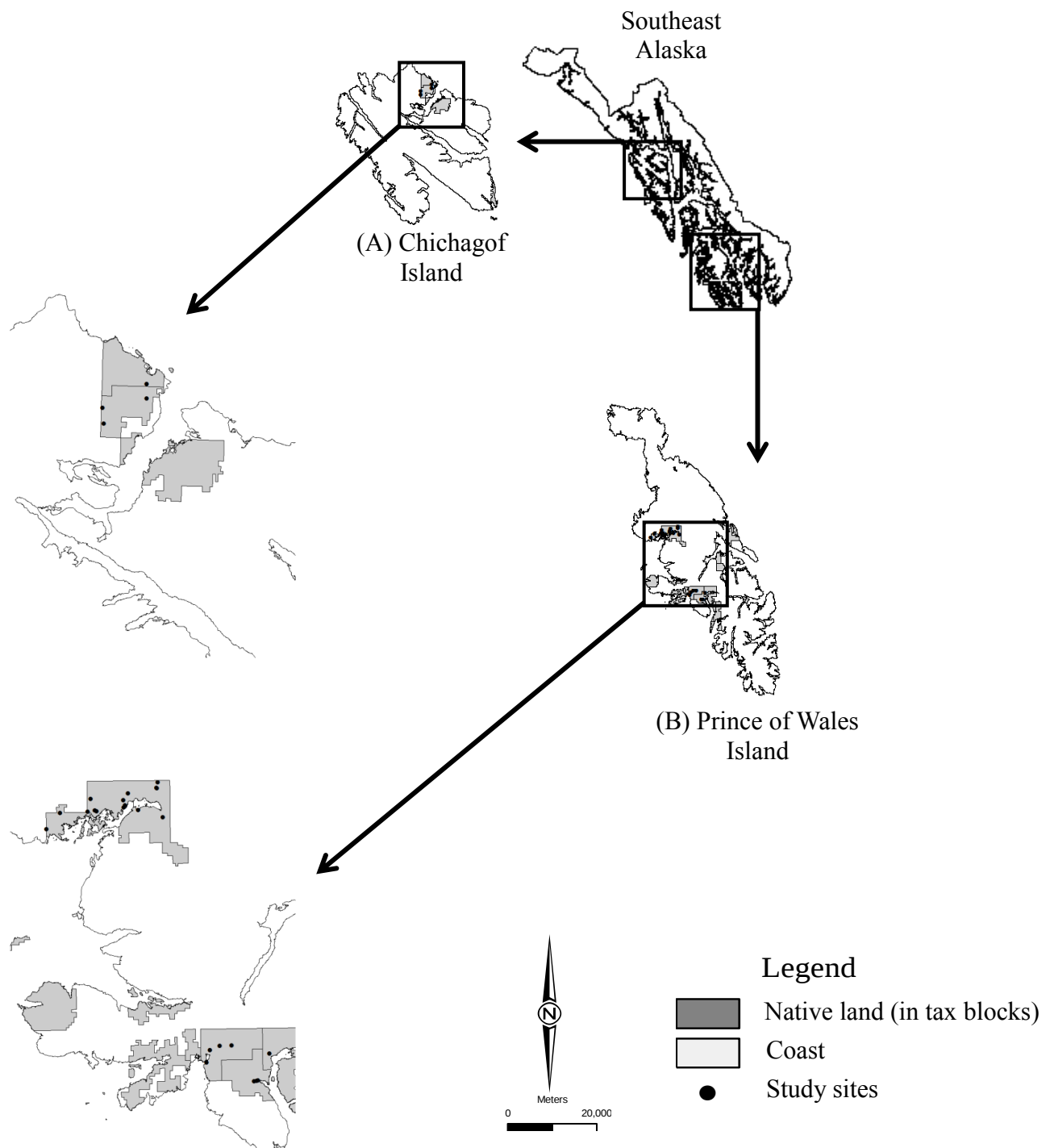


Figure 1.1: Maps of (A) Chichagof Island and (B) Prince of Wales Island showing locations of stream reaches sampled ($n=28$) on timberlands owned by Sealaska Corporation during the summer of 2011.

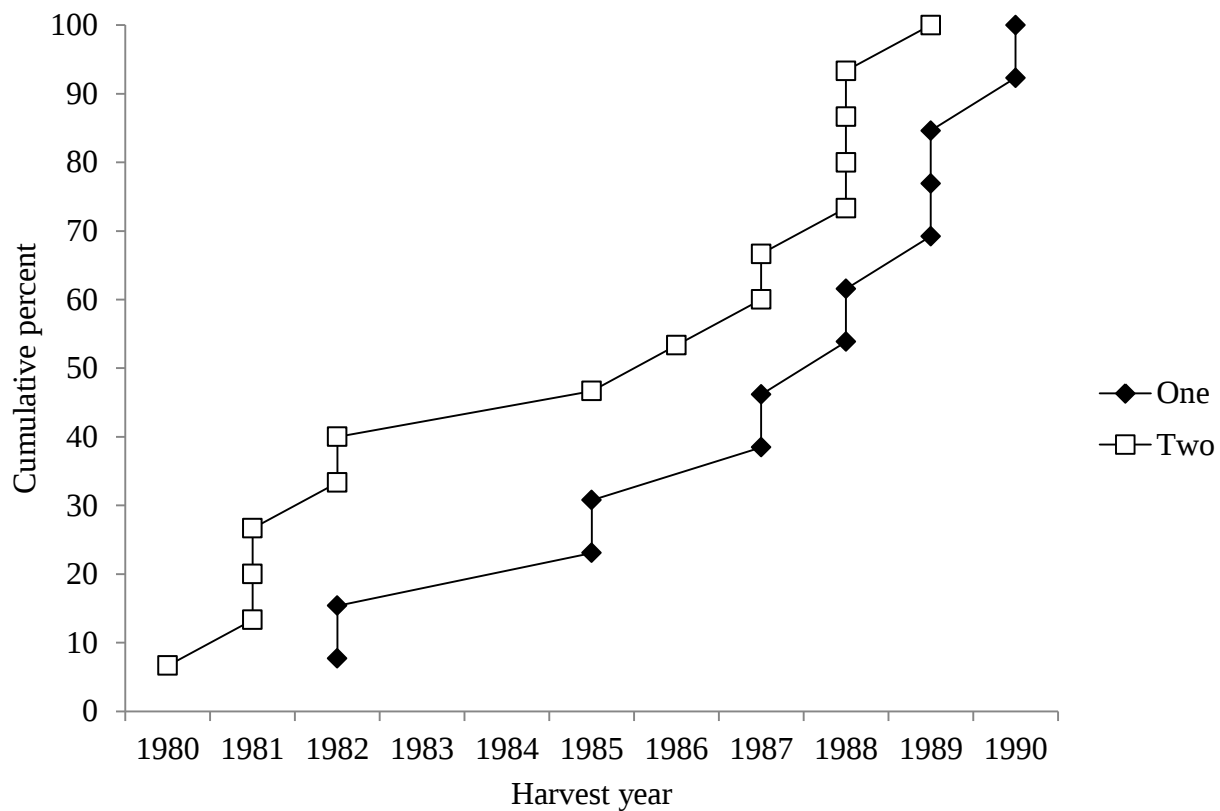


Figure 1.2: Cumulative frequencies of earliest Sealaska Corporation harvest year organized by number of banks that experienced riparian timber harvest.

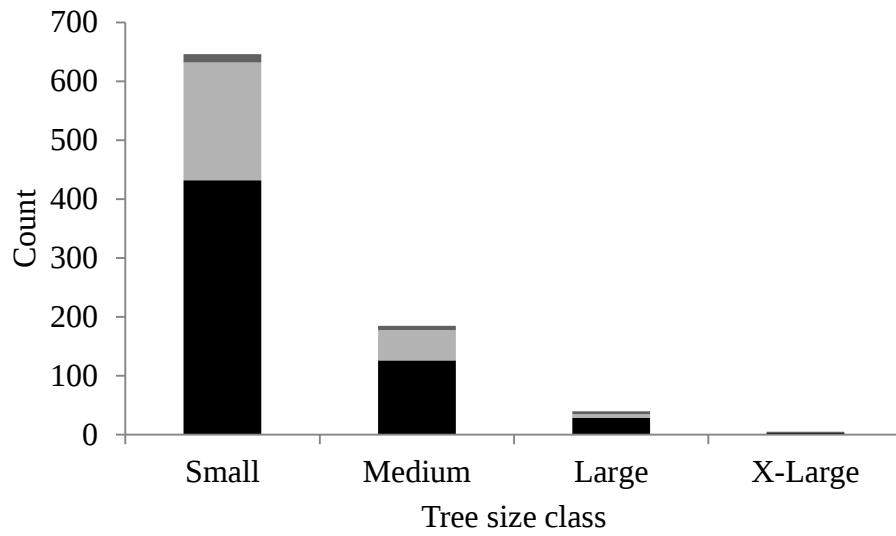


Figure 1.3: Frequency of 876 riparian trees organized by size class and vegetation type. Black bars represent coniferous trees, light gray bars represent deciduous trees, and dark gray bars represent standing snags.

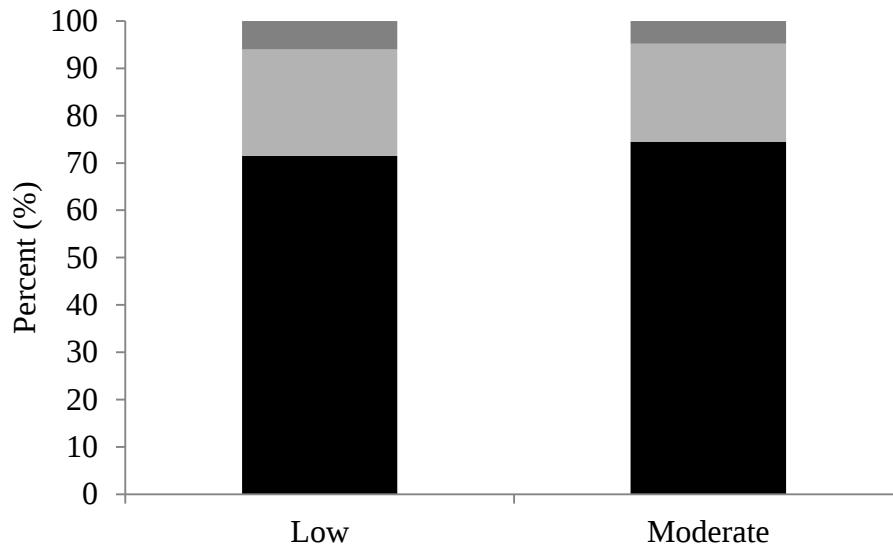


Figure 1.4: Relative amount (%) of riparian trees organized by low vs. moderate gradient streams. Black bars represent small (10-30 cm dbh), light gray bars represent medium (30-60 cm dbh), and dark gray bars represent large and extra-large (60-90 & > 90 cm dbh) riparian trees.

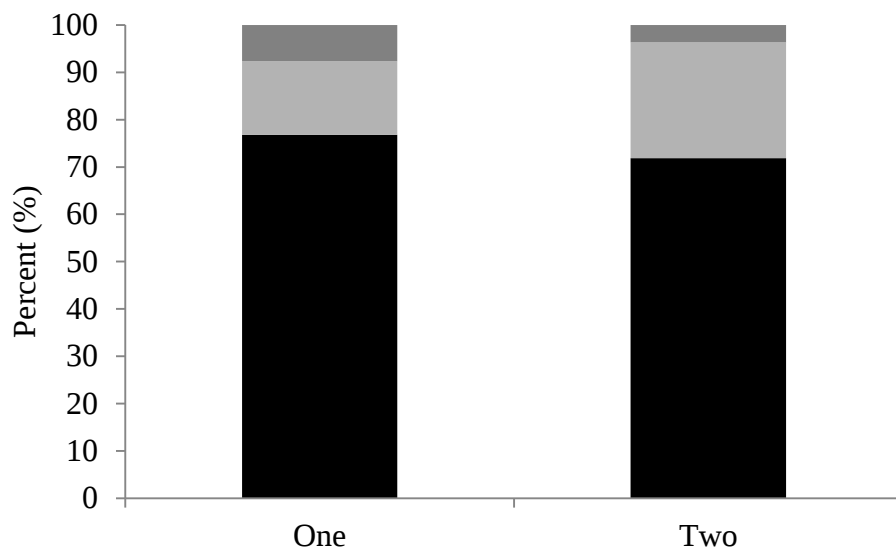


Figure 1.5: Relative amount (%) of riparian trees organized by number of banks harvested. Black bars represent small (10-30 cm dbh), light gray bars represent medium (30-60 cm dbh), and dark gray bars represent large and extra-large (60-90 & > 90 cm dbh) riparian trees.

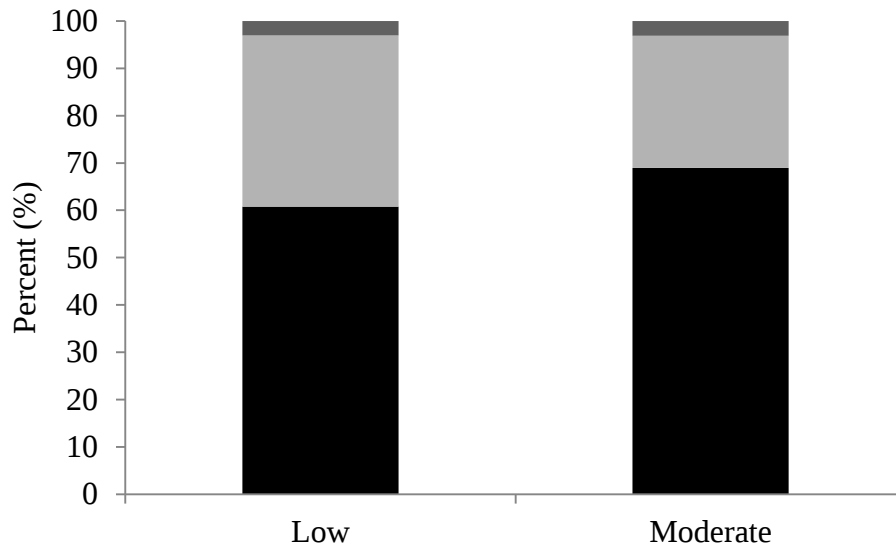


Figure 1.6: Relative amount (%) of riparian trees organized by low vs. moderate gradient. Black bars represent conifers, light gray bars represent deciduous, and dark gray bars represent snags.

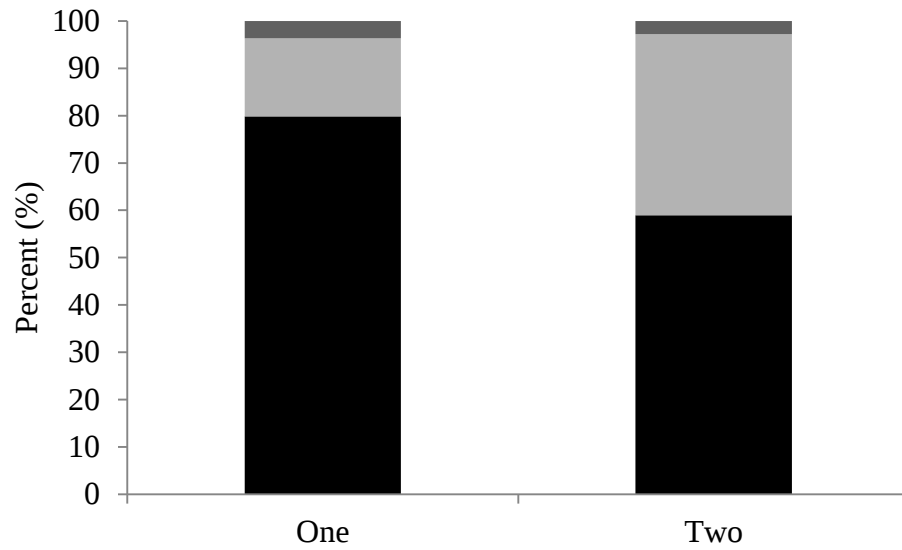


Figure 1.7: Relative amount (%) of riparian trees organized by number of banks harvested. Black bars represent conifers, light gray bars represent deciduous, and dark gray bars represent snags.

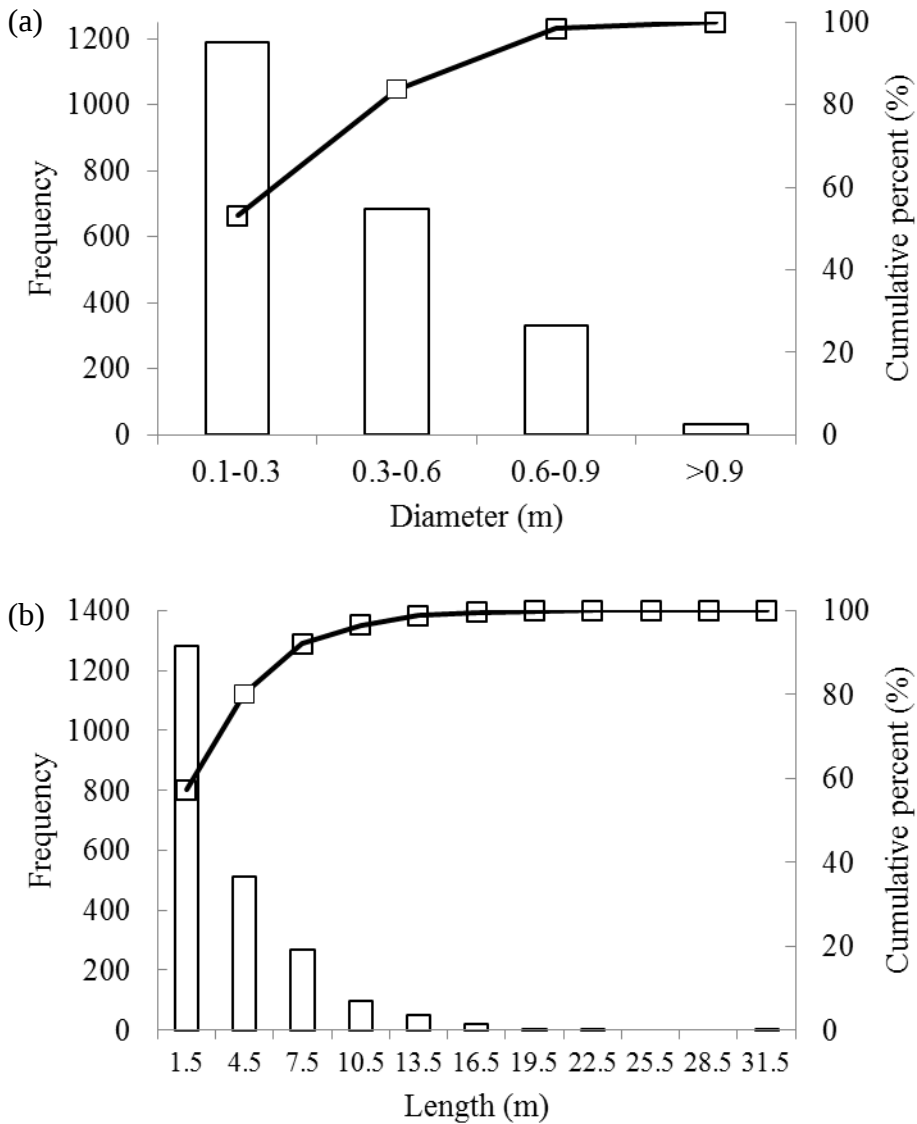


Figure 1.8: Percent distribution frequencies of (a) diameter and (b) length of 2237 LW pieces measured across all 28 Sealaska stream reaches (minimum diameter ≥ 10 cm and ≥ 2 m length). X-axis values equal to minimum length requirement for 3 m length classes.

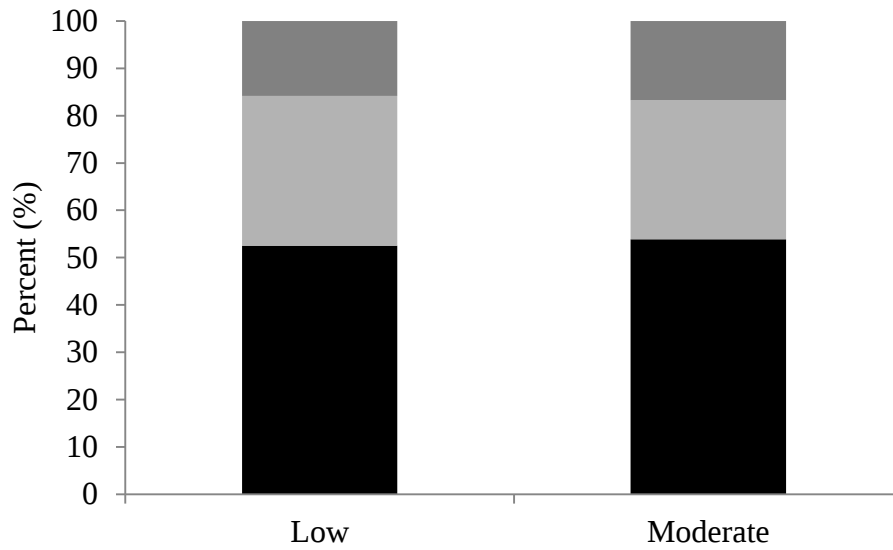


Figure 1.9: Relative amount (%) of large wood pieces organized by low vs. moderate gradient streams. Black bars represent small (10-30 cm dbh), light gray bars represent medium (30-60 cm dbh), and dark gray bars represent large and extra-large (60-90 & > 90 cm dbh) pieces of wood.

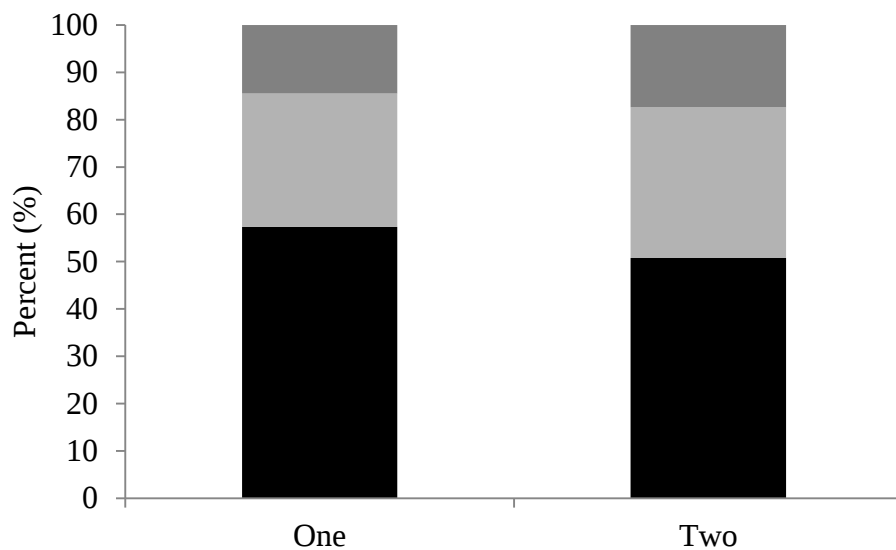


Figure 1.10: Relative amount (%) of large wood pieces organized by number of banks harvested. Black bars represent small (10-30 cm dbh), light gray bars represent medium (30-60 cm dbh), and dark gray bars represent large and extra-large (60-90 & > 90 cm dbh) pieces of wood.

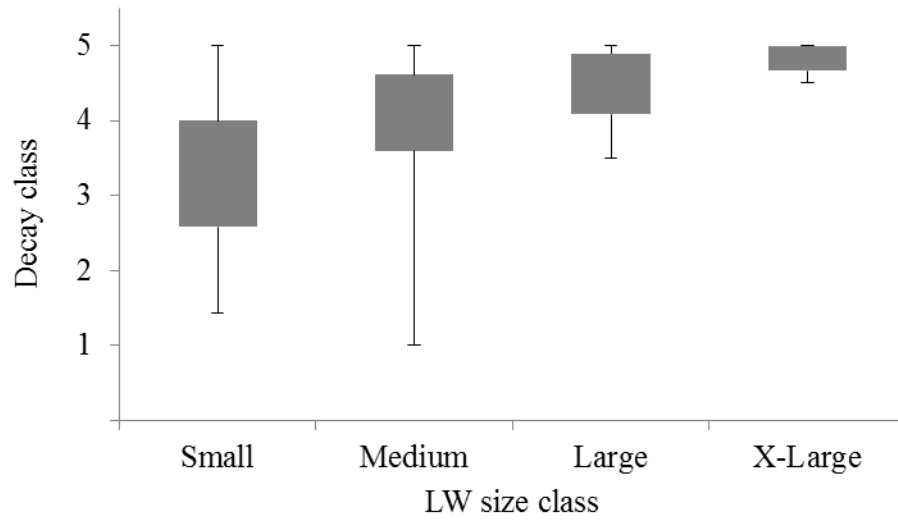


Figure 1.11: Box plots showing decay class of LW recruits organized by size class. See Methods for decay class and size class descriptions.

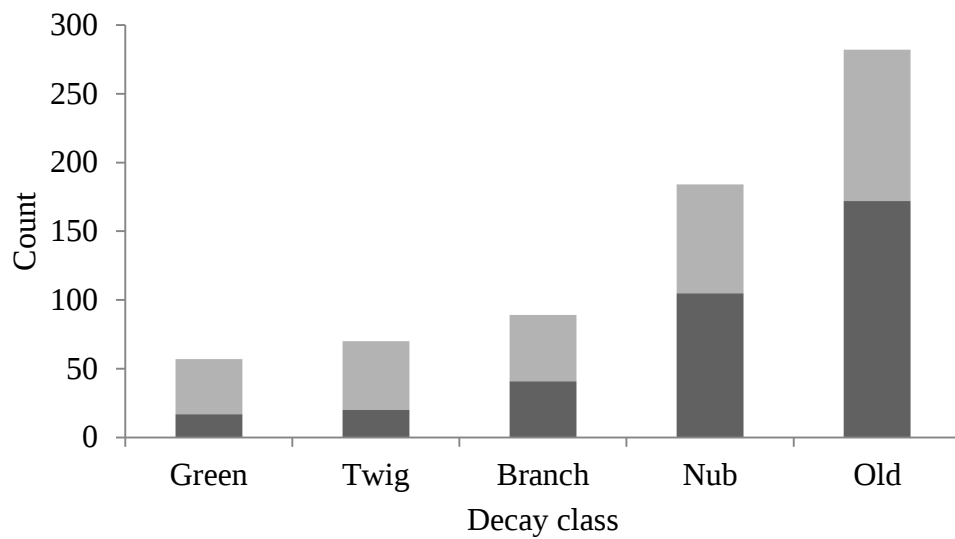


Figure 1.12: Frequency of LW recruits organized by decay class. Darker bars represent recruits that functioned while lighter bars represent recruits that did not function.

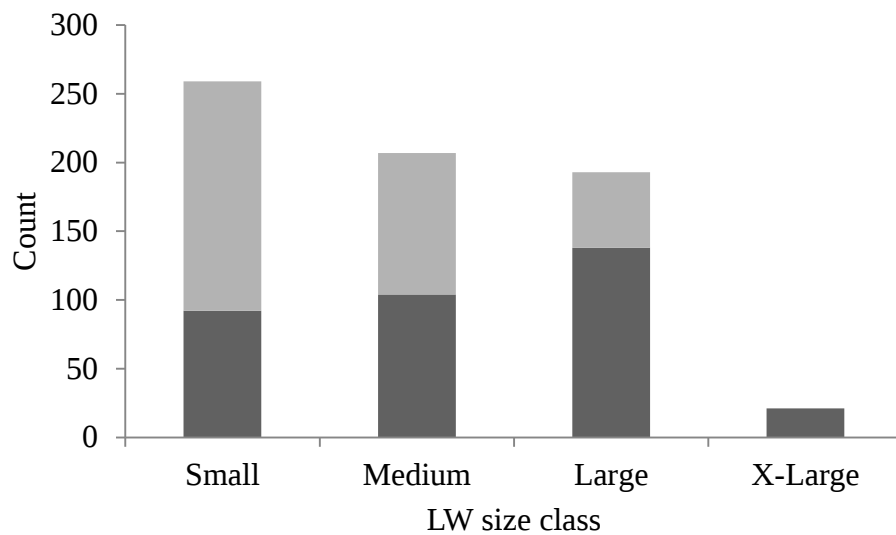


Figure 1.13: Frequency of LW recruits organized by size class. Darker bars represent recruits that function while lighter bars represent recruits that did not function.

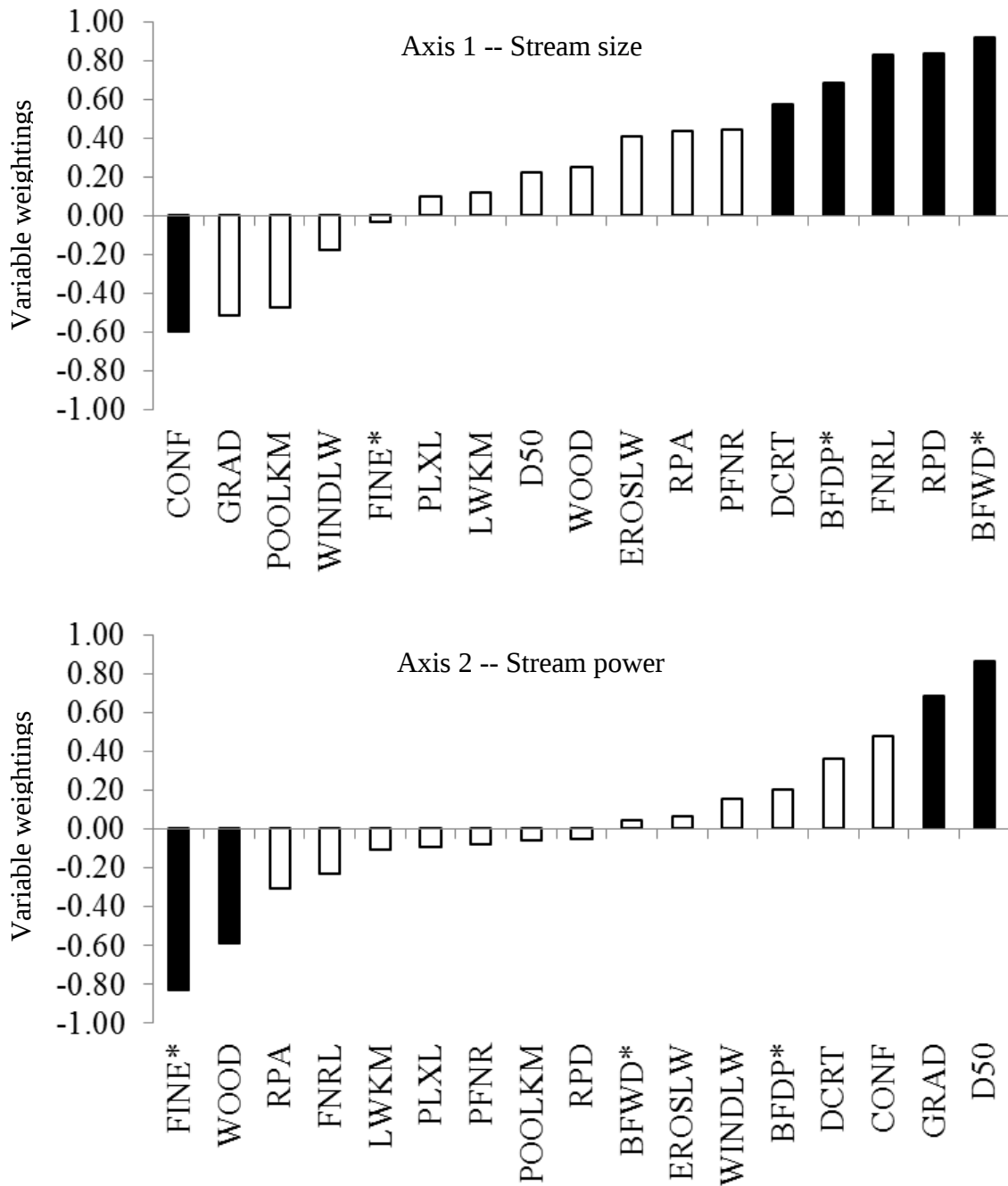


Figure 1.14: Results of the PCA of 17 habitat measures. The four components explained 72.93% of the variation in the habitat data. Axis 1 explained 30.48%, Axis 2, 16.60%, Axis 3, 13.44%, and Axis 4, 12.42%. The y-axes show the weights on each variable for the individual components. Black bars indicate variables with weights with an absolute value greater than 0.55. Variable descriptions are included in Table 1.2.

Figure 1.14 (cont'd):

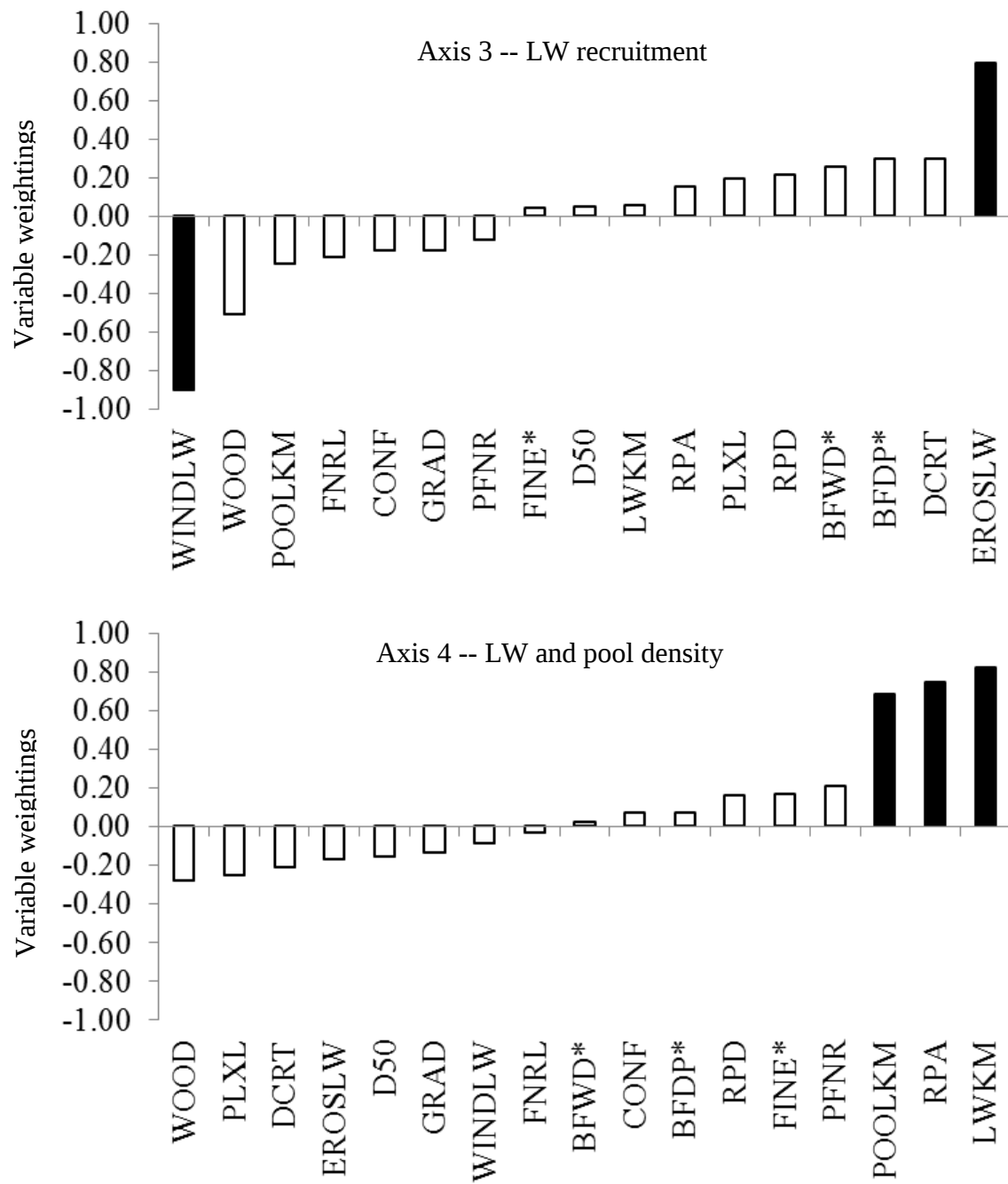
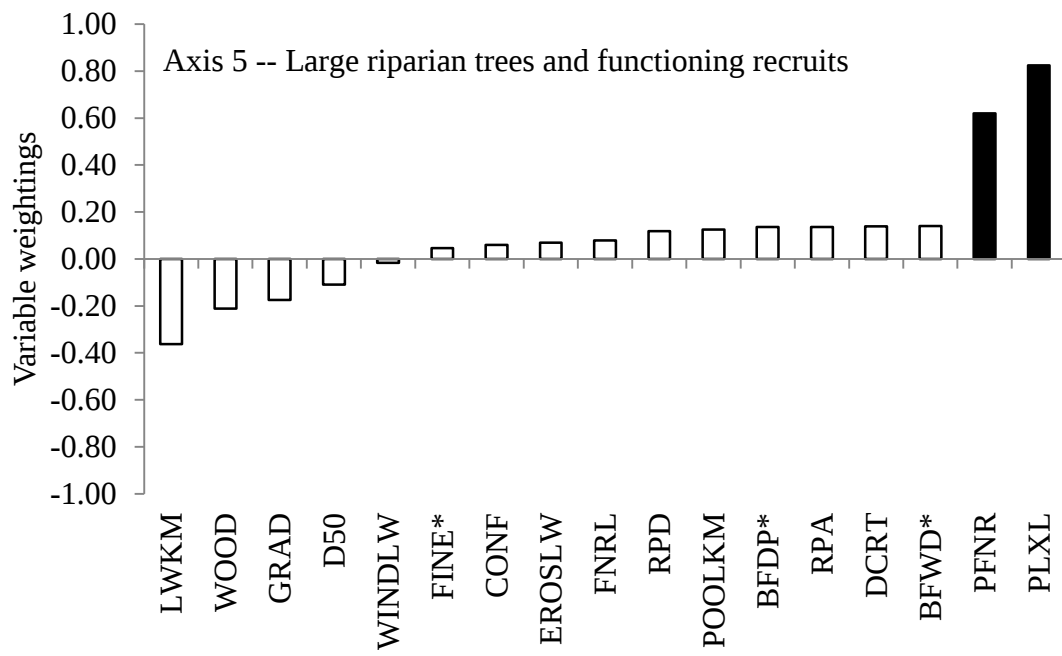


Figure 1.14 (cont'd)



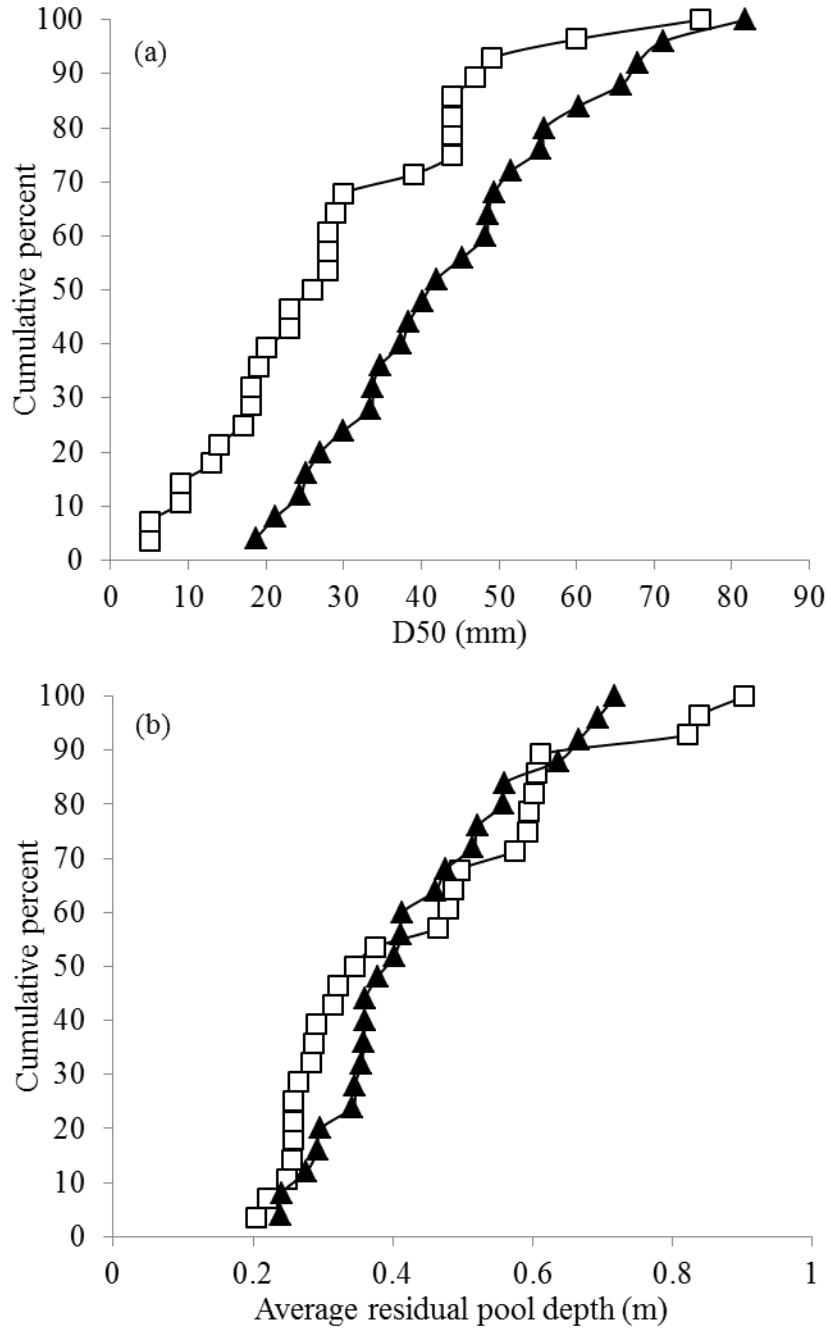
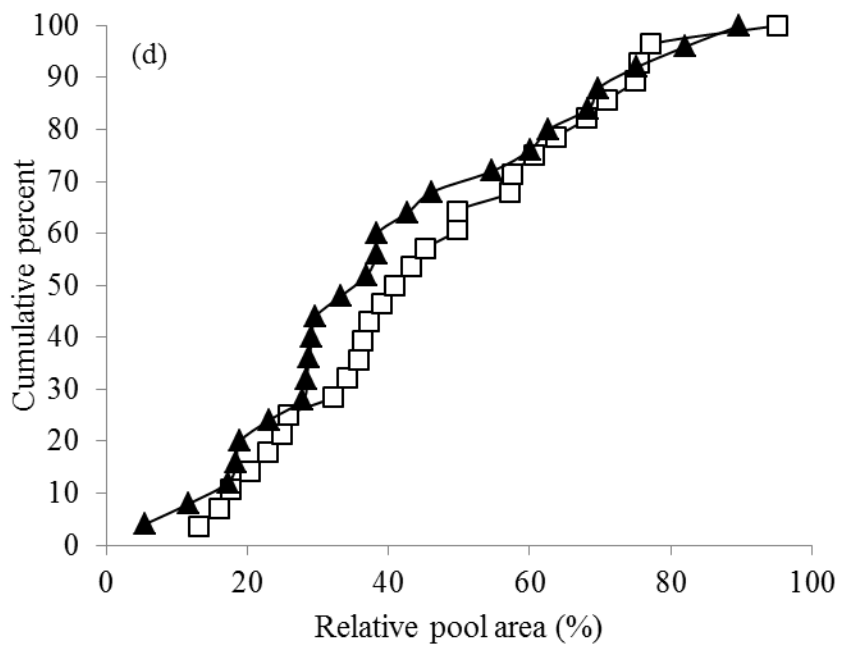
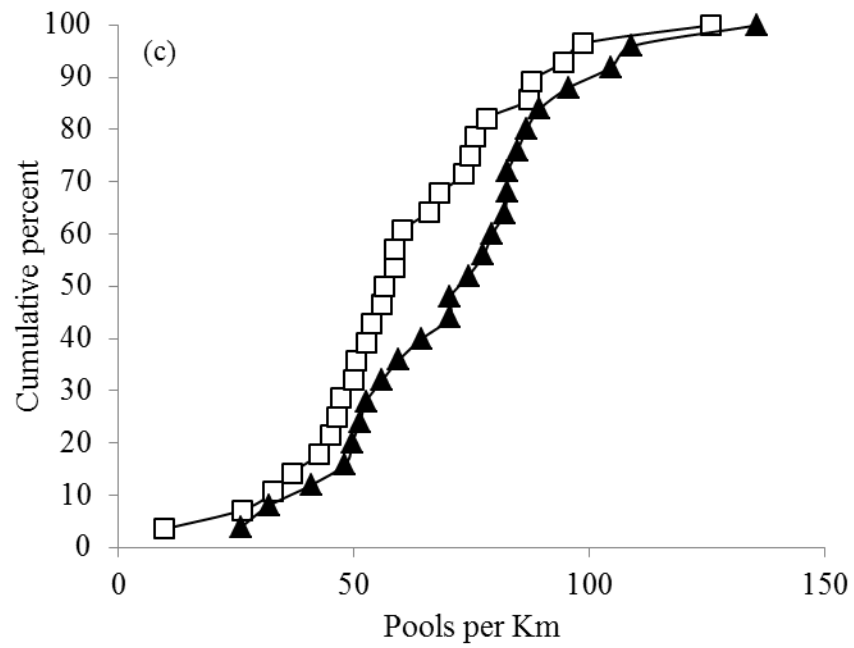


Figure 1.15: Cumulative percent distributions of (a) D50, (b) RPD, (c) POOLKM, and (d) RPA. Black triangles represent unharvested streams and white boxes represent harvested streams.

Figure 1.15 (cont'd):



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LITERATURE CITED

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CHAPTER 2
EFFECTS OF LANDSCAPE FACTORS ON LARGE WOOD IN STREAMS DRAINING
SECOND GROWTH WATERSHEDS OF SOUTHEAST ALASKA: COMPARING
NATURAL AND TIMBER HARVEST-RELATED INFLUENCES

Abstract

Large wood is an important resource to fishes and streams in Southeast Alaska, and currently, much is known about influences of landscape factors in riparian zones, including timber harvest activities, on large wood dynamics. However, comparatively less is known about influences of landscape factors within catchments on streams of Alaska, due in part to a historical lack of consistent catchment-scale data available for the region. This study addresses these limitations by characterizing catchment-scale influences on large wood in streams of Southeast Alaska. We first summarized multiple measures of landscape factors including natural and anthropogenic variables in catchments of streams throughout the region. Next, we predicted multiple measures of large wood habitat factors from a subset of streams using both natural and timber harvest-related landscape factors summarized within catchments to identify those that may be most influential to large wood. Natural factors including catchment area, deciduous forests, wetlands, and stream slope all had significant influences on measures of large wood, as did various measures of current and historical timber harvest in the region. Finally, we compared relative amounts of variation in a group of large wood habitat factors explained by natural vs. harvest-related landscape factors as a way to broadly compare types of influences on the region's streams. Results indicate that in our study streams, timber harvest explained more variation in large wood factors, underscoring its importance to stream habitat and the importance of considering catchment landscape factors in efforts to manage streams of Southeast Alaska.

Introduction

Large wood (LW) is acknowledged as an important component of habitat in stream systems. Large wood can directly act as habitat for aquatic organisms, and it can influence numerous other physical and chemical factors important for supporting aquatic communities such as channel morphology and habitat heterogeneity; size and distribution of sediment; and nutrient cycling (Bisson et al. 1987, Gomi et al. 2001, Brookshire and Dwire 2003). For example, LW in stream channels can serve as cover for both fishes and aquatic macroinvertebrates (McMahon and Hartman 1989, Bryant and Woodsmith 2009), and macroinvertebrates are also known to rely on LW as a food source (Sweeney 1993). LW can slow water velocities, and young fishes will hide from predators within the structure provided by LW. Feeding adult and juvenile fishes use cover to search for drifting invertebrates (Rosenfeld et al. 2000, Roni and Quinn 2001), and large wood can also create cover by influencing channel morphology and forming pools (Fausch and Northcote 1992).

In streams of Southeast Alaska, LW is acknowledged as especially important for supporting salmonids, a group of native fishes that are critical to the economy and a major focus of management actions in the region. Large wood in streams of Southeast Alaska benefits salmonids in a number of ways, including promoting channel complexity, forming pools, and retaining coarse substrate. Robison and Beschta (1990) found LW loadings to be positively related to heterogeneous channel characteristics in five low-gradient streams of Southeast Alaska. Pools are acknowledged as being critical habitat for resident trout and juvenile salmon (Bryant et al. 2005, Bryant et al. 2007). Scour pools are most commonly associated with LW in low and moderate gradient streams of Southeast Alaska (Martin 2001) and form when water is forced over and/or under wood structures, scouring the streambed and creating deep, low

velocity habitats which can be utilized by adult salmonids for resting purposes during migration, as well as providing refuge for young and resident fishes during periods of flooding and droughts (Lisle 1986). Pools can also form when a log or accumulation of logs acts to hold water back, creating habitats similar to those formed behind beaver dams. Deposition and transport of organic matter and fine sediment are influenced by the presence of LW (Gomi et al. 2001). Large wood also retains coarse substrates important for lithophilic spawners (including salmonids), and it stabilizes banks and reduces erosion (Montgomery et al. 1996, Gomi et al. 2001).

Just as large wood influences stream habitats and organisms, the amount, type, and movement of LW to and through stream channels is influenced by properties of the landscapes drained by streams (e.g., Hynes 1975, Frissell et al. 1986, Wiley et al. 1997, Allan 2004). Further, the influence of landscape factors on physical characteristics of streams have been shown to be differentially affected by landscape factors operating over different spatial scales including riparian zones vs. watersheds (e.g., Frissell et al. 1986, Townsend et al. 2003, Cohen and Brown 2007). That differential influence results from specific mechanisms by which landscape factors influence stream conditions (Allan 2004), and teasing apart the scale at which landscape factors affect different components of stream habitat, including LW, is critical for identifying restoration opportunities when habitat factors are found to be limiting.

Currently, much is known about influences of landscape factors in riparian zones on LW in streams of Southeast Alaska. For example, forested riparian zones provide a majority of LW to streams in the region (Murphy and Koski 1989, Martin and Grotefendt 2007). Bank erosion, driven by climatic factors, geology, flooding frequency, and position within river networks (Martin and Benda 2001), is acknowledged as an important LW input process. Landslides and

mass wasting events can deliver large quantities of LW to streams locally, and river valley characteristics, such as slope, can also influence the potential for material to reach stream channels (Benda 1990, Paustian et al. 1992, May and Gresswell 2004). Riparian tree composition, including type and size of trees, also influences LW habitat factors such as the relative amount of pools formed by wood and the size of LW functioning within stream channels (Ross Chapter 1 *this volume*).

Compared to influences of landscape factors in riparian zones, less is known about influences of landscape factors within watersheds on LW throughout Southeast Alaska. One study, however, found catchment area to be related to aspects of LW storage and transport in streams of the region. Longevity of debris jams decreased with stream size, and large streams were found to move logs farther and more frequently than smaller streams (Martin and Benda 2001). This relationship likely results at least in part from hydrologic controls within a catchment, as streams having greater catchment areas will deliver more water to and through stream channels (Knighton 1998). In a similar manner, other natural and anthropogenic landscape factors that influence catchment water routing are also likely influential in controlling LW in streams of Southeast Alaska including amount of forest and wetland cover within catchments (e.g., Roth et al. 1996, Cohen and Brown 2007). Further, anthropogenic disturbances that alter these natural catchment influences may also have detectable effects on LW in stream channels. In Southeast Alaska, large-scale timber harvest represents the greatest potential anthropogenic landscape disturbance to streams, yet we are aware of no studies that relate logging efforts throughout stream catchments to amount and type of LW in stream channels of the region. Such understanding could provide critical information for managing the region's

streams and ultimately provide insights for improvement of salmonid habitats in previously and currently-logged watersheds.

To meet those needs, the goal of this study is to characterize influences of catchment landscape factors, including both current and historical timber harvest activities, on LW in streams of Southeast Alaska. One factor potentially contributing to the absence of research characterizing catchment landscape influences on streams of the region may be the absence of comparable landscape data summarized in stream catchments throughout Southeast Alaska. Consequently, our first objective will be to summarize landscape factors for catchments throughout Southeast Alaska using a geographic information system (GIS) and region-wide data characterizing various catchment features. This summarization will provide insights into the range of natural and anthropogenic landscape conditions across stream catchments of the region, and it will inform our second objective, which will be to predict multiple measures of LW habitat factors in a subset of the region's streams from natural and timber harvest-related landscape factors summarized within catchments to identify those that may be most influential to LW. Finally, we will compare relative amounts of variation in a group of LW habitat factors explained by natural vs. harvest-related landscape factors as a way to broadly compare types of influences on the region's streams. By addressing these objectives, we expect to gain a broader understanding of influences on LW habitat in streams of Southeast Alaska. Our results can ultimately be used to support the region's fisheries by providing a framework capable of summarizing landscape factors that are biologically and socio-culturally important as decision makers are tasked with administering actions in a holistic manner, considering a myriad of factors required for management.

Methods

Study area, catchment creation, and landscape data

Landscape data were summarized for this study from the entire region of Southeast Alaska (Figure 1) in two spatial extents, local and network stream catchments. Streams throughout this area were identified from the 1:63,360 scale National Hydrography Dataset (NHD) with reaches defined as confluence to confluence stretches of water. For all stream reaches of the region, local catchment boundaries were delineated from a 60 m digital elevation model (DEM) to encompass the land area draining to the downstream end of a particular reach. Additionally, network catchments were also delineated and defined as the entire upstream area draining to the downstream end of any given reach; these steps were performed using a geographic information system (GIS).

Various natural landscape variables were calculated and attributed to the local catchment of each study reach. Data for network catchments were then created by aggregating data from all upstream local catchments for each particular study reach. Natural landscape variables associated with each reach include catchment area and catchment slope, derived from the 60 m DEM and used to create catchment boundaries. The center of each cell in the DEM was used to derive slope by taking the maximum rate of change in value from a single cell with all neighboring cells. Topologically Integrated Geographic Encoding and Referencing (TIGER) roads data were obtained from the U.S. Census Bureau and summarized as density within local and network catchments. The National Wetlands Inventory was acquired for Alaska and summarized in local and network catchments for the entire region. The National Land Cover Database for Alaska (NLCD 2001) was also acquired, and variables used from this database include measures of urban land use and forest type which were summarized as percentages of total land cover in local and network catchments (Table 2.1).

Study site description

Measurements were taken in 2011 at twenty-eight sample reaches that drain second growth watersheds for multiple LW characteristics on Prince of Wales and Chichagof Islands following methods described in Ross (Chapter 1 *this volume*). Sampled reaches ranged from 72 to 507 m in length. All reaches sampled were identified as supporting anadromous fisheries based on multiple datasets for the region (Paustian et al. 1992, Alaska Department of Fish and Game 2011). Sampled reaches were additionally classified as either floodplain or moderate gradient, mixed control stream channels following Paustian et al. (1992). These stream types were selected in part due to their ability to retain abundant and functioning LW, as well as their potential sensitivity to disturbances resulting from timber harvest (Paustian et al. 1992, Woodsmith et al. 2005).

Timber harvest data

Timber harvest and logging road data were obtained from managers at Sealaska Timber Corporation and from the U.S. Forest Service (USFS). All data were in a GIS format and polygons represented harvested areas for timberlands. Network catchments of study streams occasionally extended beyond Sealaska-owned land, so additional comparable timber harvest and logging road data were obtained from the USFS for the Tongass National Forest to ensure that all harvest-related activities could be accounted for. Due to changes in regulations regarding timber harvest in Southeast Alaska over time, harvest data were summarized into three time periods. The first time period includes harvest that occurred before 1980. The initial Forest Resources and Practices Act (FRPA) for Alaska was adopted in 1978, and prior to the FRPA, there were no standards regarding how timber could be harvested, felled, and transported in

proximity to anadromous streams in the region. While the initial FRPA required more stringent guidelines for how timber activities could occur, there were no standards regarding timber harvest within the riparian zone, and trees would regularly be harvested directly up to the stream bank if valuable timber was present. In 1990, amendments to the FRPA required that 20 m uncut riparian buffers be left along all streams on private timberlands that support anadromous fishes. To match these regulations, the second period for which harvest data were summarized occurred between 1980 and 1990, while the third included any harvest occurring after 1990. Additionally there are two types of harvest summarized which include conventional clear-cut harvest and selective helicopter harvest. Harvest data were summarized for the three time periods for both local and network catchments in all 28 sampled reaches (Table 2.2). Logging road density (m/km^2) and logging road/stream crossing density ($\#/\text{km}^2$) were also calculated and summarized for local and network catchments.

Large wood data

For this study, large wood (LW) is defined as any log at least 10 cm in diameter and 2 m in length within the bankfull channel following Robison and Beschta (1990) and Martin (2001). In the 28 study streams, all LW pieces were counted and measured within each 10 m long segment in smaller streams (< 10 m average width) and every 20 m long segment in larger streams (> 10 m average width). The diameter of each log was measured and assigned to one of four size categories: small (10-30 cm), medium (30-60 cm), large (60-90 cm) and very large (> 90 cm). The length of each log was measured to the nearest 3 m. The number of wood-formed pools was additionally counted to calculate the density ($\#/\text{km}$) of wood formed pools for each study reach.

All logs in which the source could be identified would be considered a LW recruit and classified by its recruitment process. Woody debris recruitment processes include: bank erosion, windthrow, broke stem (i.e., assumed windthrow), mortality, landslide, cut, beaver, or unknown. Information on whether a LW recruit was in or above the active channel and whether it was a functioning recruit was also recorded. Recruits in the channel were often interacting with the active channel bed, while recruits above the channel were often at or near bankfull, spanning across the channel but not typically associated with physical stream characteristics at lower flows. To be considered functioning, a recruit must do any or all of the following: cause channel scour or flow deflection, create a sediment retention zone, dam water, create an eddy, or catch and hold other woody debris in place (Martin 2001).

Statistical methods

Data preparation

Distributional properties including the mean, range, and standard deviation of all LW habitat, natural landscape, and harvest-related landscape variables were calculated and assessed to remove those variables having very few records or that failed to characterize a range in conditions across study sites. Normality and linearity of variables was also assessed by use of histograms and p-p plots to identify those that would be suitable for analyses to identifying relationships between LW habitat factors and landscape factors. All variables were transformed to maximize linearity, and transformations occurred as follows: continuous data were transformed using natural log, count data were transformed using square root, and proportions were transformed using arcsin square root.

Selection of LW variables for analyses occurred based on their ecological relevance and data distribution across study sites. Selected variables included average LW length in reaches, large and extra-large sized LW density, medium sized LW density, and the ratio of the number of recruits found in channel to those found above channel. The length of LW is important as longer vs. smaller pieces have a greater ability to function within the stream channel. Similarly, the size (i.e., dbh) of LW is important, as bigger pieces proportionately function more vs. small pieces, so density of the largest pieces was also selected. Additionally, medium sized LW density was selected for a number of reasons. It is functionally important to streams in a manner similar to larger wood (Ross Chapter 1 *this volume*), the medium size class encompasses the average size that deciduous alder tends to achieve (Worthington et al. 1962), and the maximum diameter at breast height for this class (i.e., 60 cm) is about the largest that Sitka spruce will grow in 80 years in Oregon where trees are on average larger than in Southeast Alaska (Smith et al. 1984). These facts make it a relevant size to evaluate landscape influences in the second growth watersheds targeted for this study. Finally, the ratio of LW recruits that are located within the stream channel as opposed to positioned above the channel was selected as a measure of how often recruits are actually functioning along a sampled reach in relation to the number of recruits identified in the reach.

Landscape influences on LW habitat factors used in analysis included natural and timber harvest-related landscape factors summarized in both local and network catchments. Natural factors included: network catchment area (km²), network catchment forested wetlands (%), local catchment max slope (%), and local catchment deciduous forest (%). Timber-harvest related landscape variables included local catchment conventional harvest between 1980 and 1990, local catchment other harvest post-1990, network catchment logging road/stream crossing density

(#/km²), and network catchment conventional harvest post-1990. These landscape variables were selected based on 1) variable distributions throughout the study streams and 2) theorized influences on LW habitat factors. Pearson's correlation analysis on pairs of transformed landscape variables was performed to ensure that measures were minimally redundant ($R < \text{absolute value of } 0.50$, Table 2.3).

Best subsets multiple regression

Two sets of regression models were developed to relate LW habitat factors to timber harvest and natural landscape factors. Due to catchment area's known influence on LW (Martin and Benda 2001, Ross *this volume*), each LW variable was initially regressed with only catchment area to better compare the performance of subsequent models with additional variables (Burnett et al. 2006). Models having an AIC near or lower than the model with catchment area alone indicate that they perform as well or better than that model. Next, I performed a best subsets regression (R leaps package) on each LW variable with the suite of landscape and timber harvest factors to identify the five best models, characterized by those having the largest R^2_{adj} value. I considered only significant models that contained no more than four explanatory variables to avoid model overfitting (Johnston et al. 1990) and only those within 2 AIC units of the "best" model. Collinearity was assessed based on a variance inflation factor threshold of three ($\text{VIF} < 3$).

Constrained ordination analysis

A constrained ordination analysis was run in the program CANOCO to assess the relative importance of timber harvest vs. natural landscape factors on LW in the study reaches. To determine whether a canonical correspondence analysis (CCA) or redundancy analysis (RDA)

was more appropriate given the data distribution, a detrended correspondence analysis (DCA) was first performed to assess the gradient lengths in the response dataset. This analysis suggested that the data follow a linear distribution, making RDA a more appropriate technique (ter Braak and Prentice 1988). RDA is a direct gradient analysis and can be used to quantify variation in a set of response variables (in this case, LW variables) by constraining their ordination to a linear combination of independent predictors (i.e., landscape variables) (ter Braak and Prentice 1988). An equal number of harvest-related and other landscape variables were chosen so as not to over or underestimate variance explained due to difference in numbers of predictor variables.

Results

Regional trends of natural landscape factors in Southeast Alaska watersheds

Conditions of network catchments in Southeast Alaska showed considerable variation in natural factors occurring across the landscape (Table 2.4). Catchment area ranged from less than 1 km² up to as large as 2168 km² across the entire region. Deciduous forests average 2.5%, but ranged from 0-100% across all catchments. Evergreen forests were more prominent in the region and network catchments averaged about 50%, while mixed forests were on average about 13% of catchment area. Percent of forested wetlands in network catchments ranged from 0-100% but averaged 17% across all catchments in the region. Very little human influence is present in Southeast Alaska catchments as low, medium, and high intensity urban land use all averaged less than 0.25% in network catchments across the region with no agricultural land use present in any catchments according to the 2001 NLCD. Timber harvest data were only

available for the Tongass National Forest so we were unable to summarize these factors for the entire Southeast Alaska region.

Trends in natural landscape factors of study streams

Considerable variation was observed in natural landscape factors of catchments in the sampled study streams. The maximum slope ranged from 1.21% to 7.13% and averaged 3.52% locally (Table 2.1). Deciduous forests comprised on average about 7% of local catchment area. Network catchment area averaged 4.24 km², and ranged from less than 1 km² to just below 20 km². The percent of network catchment area comprised of forested wetlands ranged from none to a maximum of over 90%, but averaged slightly more than 25% across all study catchments. Non-harvest related human influences were not evident in the study catchments as low-intensity urban land use occurred in network catchments of only 5 sites and averaged 0.25% across all sites, while only 4 sites had roads in their network catchments.

Trends in timber harvest-related factors of study streams

Conventional timber harvest occurring from 1980-1990 in local catchments was the most pervasive timber harvest practice across study sites; it averaged over 40% across study site catchments and exceeded 80% in one site's local catchment (Table 2.2). Other harvest after 1990 averaged 10% of local catchment area and ranged from 0 to slightly more than 30% of local catchments for sampled reaches. Conventional harvest occurring in network catchments after 1990 averaged about 14% across sites with a max of 49%. Logging roads were present in all network catchments, and logging road/stream crossing density averaged 3/km² across all sites with a maximum of about 9/km². Conventional harvest before 1980 was relatively uncommon

within network catchments and ranged from 0 to more than 6% but averaged less than 1% across all study sites.

Explaining variation in large wood habitat factors using natural and timber harvest-related landscape factors

A substantial amount of variation (Adj. $r^2 = 0.16-0.59$) was explained by using a best subsets regression approach that derived multiple significant linear models predicting average LW length, the ratio of recruits that are located within the channel vs. recruits positioned above the channel, and medium-sized LW density by using both natural and harvest-related landscape variables. The procedure only derived one significant model predicting large and extra-large LW density, and this included only timber harvest related variables.

Average large wood length

The average length of LW was significantly related to natural and harvest-related landscape factors in 5 linear regression models. A substantial amount of variation (Adj. r^2 ranging from 0.57 to 0.59, Table 2.5) was explained by models, and all 5 included network catchment area, local catchment deciduous forest, and network catchment conventional harvest occurring after 1990, with the “best” model containing only these three variables. In all models, average length of LW in the study reaches was positively associated with these landscape factors. Subsequent models included network catchment logging road density, network catchment forested wetlands, local catchment conventional harvest from 1980-1990, and local catchment other harvest after 1990. Network catchment area had the greatest contribution in all models predicting LW length, followed by local deciduous forest, and network catchment conventional harvest after 1990 based on standardized beta coefficients.

Large wood recruits located within the active channel vs. above the channel

The ratio of recruits that are in vs. above the active channel was best predicted by a model incorporating three natural and one harvest-related landscape factors; it explained a moderate amount of variation in this wood habitat factor (Adj. $r^2 = 0.34$, Table 2.6).

Conventional harvest occurring from 1980-1990 in the local catchment explained the most variation and was positively associated with this habitat factor in all models. Local deciduous forest, local max slope, and finally network catchment area were additionally included in this model, with max slope having the only negative relationship with the habitat factor. Four subsequent models that included both local catchment conventional harvest occurring from 1980-1990 and local max slope, also included local deciduous forest as having a positive association in two of the remaining four models. Local other harvest after 1990 and network catchment density of logging road/stream crossings were negatively related to the LW habitat factor, and included in two of the five models.

Medium-sized large wood density

A moderate amount of variation (Adj. $r^2 = 0.37$, Table 2.7) was explained in medium-sized LW by two measures of timber harvest and two natural landscape factors. Variables included in this model – network catchment conventional harvest after 1990, local deciduous forest, network catchment forested wetlands, and local conventional harvest occurring from 1980-1990 – all had positive relationships with medium-sized large wood density. Three subsequent models significantly explained variation (Adj. $r^2 = 0.32 - 0.33$) in this LW habitat factor, and all of these included network catchment conventional harvest after 1990 and network catchment forested wetlands, while local catchment deciduous and local catchment other harvest

after 1990 were included in two of the remaining three models. Local catchment other harvest after 1990 had the only negative association with medium-sized LW density in any models. Network catchment area was related to medium-size LW density in only one of the four regression models and was the weakest contributing landscape factor included for that model.

Large and extra-large-sized large wood density

Large and extra-large-sized LW density was significantly related to only timber harvest landscape factors. The amount of variation explained for this model was relatively low (Adj. $r^2 = 0.16$, Table 2.8). Harvest-related landscape variables explaining this LW habitat factor include local catchment conventional harvest occurring from 1980-1990, which had a positive association, while a negative association existed between this habitat factor and local other harvest after 1990.

Assessing the relative importance of natural vs. harvest-related landscape factors in explaining variation in large wood habitat factors

CCA variance partitions indicated that the four natural and four harvest-related landscape factors evaluated in this study explained 44% of the variation in the set of LW habitat factors tested (Figure 2.2). Of the explained variation, timber harvest-related factors explained about 54% and natural factors explained about 28%, while about 18% was explained by the interactions among harvest-related and natural landscape factors.

Plots of landscape and habitat factors based on CCA axes scored supported some findings shown by best subsets regression models (Figure 2.3). Catchment area, local deciduous forest, and local catchment conventional harvest occurring from 1980-1990 were positively associated with all four habitat factors along Axis 1, while local other harvest after 1990 was negatively

associated with these factors. Along Axis 2, conventional harvest occurring after 1990 was positively associated with length of wood and medium-sized LW density. While interpretation of CCA axes plots is in part subjective, corroboration of our findings using multiple techniques lends confidence to our results.

Discussion

Results from best subsets regressions predicting LW habitat factors from landscape variables indicate that LW is significantly associated with multiple factors summarized in catchments of study streams, including both natural and timber harvest-related landscape variables. CCA results further support association of specific LW habitat variables with major landscape drivers and also show that unique amounts of variation in a set of four LW habitat factors can be attributed to both natural and anthropogenic landscape factors. Timber harvest activities occurring within current and historical time periods were found to explain the most variation in the set of LW habitat variables investigated in this study, underscoring the complexities associated with understanding factors that influence stream conditions in the region given the natural and human context of the landscapes they drain. The legacy of timber harvest practices may have influenced changes associated with LW abundance and distribution in the region's streams, increased proportions of deciduous trees following harvest for example, may increase the average length of large wood as deciduous trees have rapid growth early after colonization, providing more woody debris to streams than early-successional conifer stands. To our knowledge, this is the first study comparing relationships between multiple catchment factors and LW in Southeast Alaska. It establishes the importance of considering watershed-level landscape summaries to support decision making in the region and may ultimately contribute to more effective management of the region's streams.

Natural landscape factors

Catchment area

Catchment area was included in all five models produced for average LW length, and over half of the variance in this variable was explained. An increase in LW length with increasing catchment area follows previous research from the Pacific Northwest. Pieces of wood are on average longer in wider channels as LW is generally stored when wood length is longer than the stream width, with wider channels holding longer pieces (Martin and Benda 2001). Therefore, larger streams have on average, longer pieces of wood. This relationship occurs up to a point as wood is more easily transported when the channel becomes wider than the tallest tree (Benda et al. 2002). My results also concur with Bilby and Ward (1989) who explained over 75% of variance in LW diameter, length, and volume through 22 sampled reaches of Western Washington using stream size alone. Catchment area was also included as a predictor in two other LW factors (i.e., the ratio of recruits located in the channel vs. positioned above the channel and medium LW density), but only did so in a single model each, suggesting that area has relatively less influence on these factors.

Catchment area predicted medium-sized LW density in the third best model for that variable, and its influence was positive. While its inclusion into only a single model suggests that catchment area is not the strongest landscape variable influencing LW density, the positive relationship does not follow Bilby and Ward (1989) who found decreasing wood density with increasing stream size. This may be due to the fact that they did not analyze LW by separate size classes, and they also sampled streams having a wider range of stream slopes (i.e., up to 18%), with slope acknowledged as an important factor influencing stream power and transporting

capability of streams (Knighton 1998), potentially leading to less wood in streams with higher slopes. As bank erosion generally accounts for a majority of identifiable wood in streams of the Pacific Northwest and Alaska (Martin and Benda 2001, Benda et al. 2002), steep confined headwater channels are less susceptible to bank erosion than low to moderate gradient streams having active floodplains, additionally accounting for contradicting results between the two studies regarding LW density. Furthermore, regional differences in geology and climate, not accounted for in this study, as well as regional land use differences, have the potential to affect relationships with LW density and stream size. While Bilby and Ward (1989) sampled streams draining old-growth forests, all reaches sampled for this study drained mixed old-growth and second-growth catchments.

Catchment slope

Maximum slope in the local catchment was included in the prediction of one LW habitat factor, the ratio of recruits located within vs. positioned above the active channel. It was included in all five models predicting this habitat factor, although it was never the most influential landscape factor as indicated by standardized coefficients. Results show that with increasing gradient there are fewer recruits located within the channel than spanning above the channel. Stream power, and consequently a stream's capability to move LW and other materials, increases with increasing slope, so wood that falls into a stream channel with a relatively higher slope may not remain in the channel as long due to increased power associated with increasing gradient (Knighton 1998). Steep headwater streams are typically narrower and more confined than low to moderate gradient streams, and this characteristic may restrict the capacity for LW to intersect stream channels (Liquori et al. 2008). May and Greswell (2004) found 33 % of locally recruited wood pieces were spanning the full width or suspended over the channel of headwater

streams in a coastal Oregon watershed. Furthermore, steep channels are less prone to bank erosion, resulting in overall low LW recruitment in the absence of wood delivering landslides. When tree-fall occurs due to windthrow or mortality, for example, tree roots often remain positioned on the bank, whereas recruitment by erosion generally occurs as undercut banks begin to slump over time, and rootwads have a better probability of slipping down the bank with at least one end in the channel.

Deciduous forests

Deciduous forest was associated with average LW length in all five models predicting this factor, although its influence was always second to that of catchment area. These models indicate that with more deciduous forests in local catchments, streams will contain longer pieces of LW. Floodplain streams are typically lower in the stream network having larger catchments and wider channels which allows for longer pieces of wood to be located in the channel. Floodplain streams also have migrating channels, providing more disturbances for deciduous trees to colonize (Villarin et al. 2009), although my data showed almost no correlation between catchment area and proportion of local deciduous forest in catchments (Table 3). Another potential factor may be due to growth rates as red alder in Southeast Alaska grow rapidly during early stages of succession (Deal et al. 2004). Higher densities and death rates occur for alder than conifers in similar young growth stands of the Pacific Northwest (Minore and Weatherly 1994, Hibbs and Giordano 1996), initially providing more pieces of deciduous wood than conifer stands due to quickly-growing deciduous juvenile trees (Andrus et al. 1988, Gomi et al. 2006). Hanley and Hoel (1996) also found that 40 years after timber harvest in Southeast Alaska, riparian stands became dominated by red alder trees large enough to be considered LW (i.e., 15-25 cm dbh). They also found old growth floodplains of a 4th-order stream to produce higher

densities of large spruce trees, while old growth upland stands were characterized by higher frequencies of smaller conifers. The red alder dominated riparian zones were additionally on a trajectory towards conifer dominated stands as the youngest trees were spruce. This may change size distributions and functioning capability of LW in streams over time as deciduous trees are smaller and decompose faster than conifers in streams (Bilby et al. 1999). While some evidence exists that high deciduous productivity early after disturbances may provide short term mitigation in LW production, Gomi et al. (2006), studying woody debris in headwater streams of Southeast Alaska, found little contribution of second growth trees larger than 10 cm dbh from second growth stands. However, they did find more deciduous pieces of wood in streams having greater amounts of deciduous forests. In addition to length, a positive relationship was also suggested between deciduous forest and medium-sized LW in streams having more deciduous forest, a finding also supported by previous research that found alder in second growth stands of Southeast Alaska grow to sizes near the medium class (i.e., 30 cm dbh) used in my study (Hanley and Hoel 1996, Deal et al. 2004).

Forested wetlands

Wetlands have a significant influence on the hydrologic cycle, and while there are many examples of wetlands reducing stream flooding by storing large amounts of precipitation (e.g., Maltby 1991, Hey and Philippi 1995), wetlands can also function to increase floods and high flows (Bullock and Acreman 2003). Wetlands can store large quantities of water, potentially restricting LW transport out of stream reaches draining catchments with wetlands having very high water storing capacity, and holding smaller pieces of wood due to lack of transport. In contrast, when wetlands are full and become saturated, they can act like an impervious surface, routing essentially any new hydrologic input in catchments to stream channels, contributing to

high flows, potentially increasing fluvial transport of LW previously stored in upstream channels. The amount of forested wetlands located within the network catchment was positively related to medium-sized LW density in all four regression models produced in this study. As described above, wetlands are a critical aspect regulating water routing within watersheds, and in a small headwater temperate rainforest catchment of British Columbia, 30-99% of stream discharge was regulated by a headwater wetland, depending on preceding conditions (Fitzgerald et al. 2003), so substantial amounts of wetland in a catchment combined with large, or long-lasting or intense precipitation events may increase transport of wood from upstream channels. Poor stand productivity in wetlands may contribute to this result if medium-sized wood is the largest these stands can produce and recruit to streams.

Forested wetlands of Southeast Alaska also have the potential to produce trees large enough to be considered LW, and models estimate that forested wetlands can produce wood volumes nearly twice the U.S. Forest Service minimum standard to be considered productive forestland (Julin and D'Amore 2003). Wetlands are known to influence stream physical, chemical, and biological processes in Alaska (King et al. 2012, Walker et al. 2012), but more research is needed to determine specific mechanisms in which wetland land cover influences LW dynamics in streams. Only forested wetlands were included in this analysis, and the National Wetlands Inventory defined forested wetlands as being those dominated by woody vegetation at least 20 feet tall, but differing wetland types in conjunction with spatial positioning throughout watersheds will likely influence LW in streams differentially.

Timber harvest-related landscape factors

Historic timber harvest (1980-1990)

Timber harvest efforts occurring from 1980-1990 in Southeast Alaska were not required to leave riparian buffers along anadromous streams, but rules in place during this time regulated heavy equipment use near streams and removal of LW from streams. Timber harvest occurring as a land use during this time period was summarized in local catchments of the study streams, and it was related to all four key LW habitat factors tested, though it was most strongly associated with LW recruit position. This suggests that with more conventional harvest from 1980-1990 in local catchments of study streams, more LW recruits may have been made available to stream channels in relation to being positioned above the channel. While this may be due to LW being left within streams after harvest (Gomi et al. 2001, Benda et al. 2002), only 4% of LW in which the source could be identified was attributed to timber harvest in my study. As LW ages and decays over time, it breaks down and will be located within the channel more often than more recently-recruited LW (Powell et al. 2009, Ross Chapter 1 *this volume*). Harvest from 1980-1990 near streams removed the main source of LW from riparian zones. Because of this, a more plausible explanation may be that the higher proportion of LW recruits positioned within these streams are remnant and were recruited before timber harvest occurred, while the lower proportion of LW located above the channel in these streams was recruited more recently and may originate from second growth stands. Consequently, stream catchments having more of this type of harvest may consist of relatively more LW recruits located within the stream channel as the loss of riparian trees would eliminate new LW recruitment for a period of time skewing the ratio toward relatively more in-stream recruits as remnant pieces decay and are repositioned from above the channel into the channel (Powell et al. 2009).

Harvest occurring from 1980-1990 was also positively, associated with the density of medium-sized LW. In Southeast Alaska, local disturbances to riparian zones such as timber

harvest, landslides, and bank erosion can remove patches of old-growth conifers which invite quickly-growing deciduous species like red-alder to colonize. As deciduous tree types grow more rapidly than conifers (Deal et al. 2004), they also die more quickly and potentially enter the stream as LW, and the medium size-class is the largest these trees tend to grow (Worthington et al. 1962). For this study, only LW recruits were determined to be deciduous or conifer, so I lacked sufficient data to determine the type of all logs measured making the above explanation plausible. Deciduous recruits were as high as 56% at one reach, although across all reaches they averaged 12%, and 46% of reaches had no deciduous recruits identified. The association contradicts Gomi et al. (2006) who found little contribution of trees large enough to be considered LW (i.e., 10 cm dbh) from second growth stands of previously logged headwater streams in Southeast Alaska. Differences may be due to their focus on headwater streams having relatively narrow bankfull widths and some stream slopes > 10%. Also, their catchments included logging that occurred as early as the 1950's.

More medium sized large wood with increasing harvest from 1980-1990 may also be a result of altered hydrology in extensively harvested catchments. Increased timber activity within a watershed removes vegetation that intercepts precipitation. Heavy equipment can compact soils and decrease infiltration, essentially increasing soil water moisture and the rate of water movement from upland areas into stream channels (Chamberlin et al. 1991), although evidence from a small California watershed with more than 15% of the watershed compacted by roads suggest that only the smallest storm volumes were affected by logging road construction while no differences were observed in water volumes following large storms (Wright et al. 1990). Clearcuts can acquire more snow resulting in higher peaks in flows occurring in the spring (Harr 1986) which may have increased transporting capacity of catchments having more harvest during

this time period. Keppeler and Ziemer (1990) studying harvest effects on stream flow in northwestern California suggest an average 15% increase in annual water yield should be expected following intensive logging based on their results. Cumulative percent of area logged and percent area covered by roads, landings, and skid trails were the most significant variables associated with six flow-related dependent variables, although both watersheds were second growth forests previously logged in the 1800's. Harr et al. (1979) suggests similar effects of harvest with increased peak and summer low flows, although they studied small headwater basins which may be more responsive to flow alterations following harvest. Reduced evapotranspiration in heavily logged watersheds can lead to higher soil moisture content at the beginning of the wet season, providing more precipitation to streams as less water is needed to recharge soils (Douglas and Swank 1975, Ziemer 1981).

While increases in flow following the removal of watershed vegetation have been suggested for quite some time (Hibbert 1967, Ponce and Meiman 1983, Surfleet and Skaugset 2013), this effect is strongest immediately following harvest (Keppeler and Ziemer 1990), and diminishes over time as rapidly growing understories and second growth stands take advantage of increased light and have higher evapotranspiration rates than old growth forests which may ultimately reduce stream flow as succession proceeds (Harr 1983, Jarvis 1985, Greenwood et al. 1985). Few studies have documented these hydrologic effects following harvest in the temperate rainforests of Southeast Alaska, although greater flow increases are suggested to occur in wetter years (Harr et al. 1979, Ponce and Meiman 1983) and wetter climates (Hewlett 1982). In-stream processing of wood such as transport from upstream sources, for example, is not well understood and has historically been ignored or assumed to be equal to the output of a stream reach (Murphy

and Koski 1989, Van Sickle and Gregory 1990, Liquori et al. 2008), and transport is typically limited in low order stream reaches.

Another plausible influence of harvest on increased LW density could be due to altered rates of landslides and slope failure following harvest. Logging roads and loss of hillside vegetation from harvest often increase the rate of landslides and mass wasting events (Amaranthus et al. 1985, Wu and Sidle 1995, Tang et al 1997). These soil movements have the potential to deliver large amounts of wood and other materials from upland areas into stream channels, and debris flows down channels have been documented to contribute large amounts of wood from upstream sources into high-order streams (Benda et al. 2002, Reeves et al. 1993), although attributing LW transport by debris flows is difficult because of complexities in aging these deposits (Liquori et al. 2008). Data on the occurrence of landslides and mass wasting events within catchments sampled for this study were not acquired and would need to be investigated to further support such timber harvest influences.

Current timber harvest (post-1990)

Two types of timber harvest were summarized post-1990 including conventional in the network catchment, and other types, including selective and helicopter harvest in the local catchment. Harvest after 1990 required that forested streamside buffers be left along anadromous streams, while selective harvest within riparian buffers could occur under certain circumstances. Conventional harvest after 1990 was positively related to average LW length in all models predicting this factor, although it was typically less influential compared to natural factors in the models (i.e., catchment area and deciduous forest). Nevertheless riparian buffers were required to be left after 1990, so these catchments should have more intact riparian zones

compared to catchments harvested previously, providing taller trees as longer LW to streams. A similar relationship is present between this landscape factor and medium-sized LW density. More medium-sized LW was observed in stream catchments with greater amounts of conventional harvest after 1990. Timber harvest can increase LW input in Southeast Alaska, not only from harvest related debris being left over (Gomi et al. 2001), but also from increased windthrow of standing riparian buffers (Martin and Grotefendt 2007), and medium-sized trees may be more vulnerable to this effect due to potentially shallower rooting depths than larger trees. In contrast, other types of harvest after 1990 in local catchments are negatively related to the density of large and extra-large LW. There was only one model significantly predicting the largest wood in streams, and it included two measures of harvest. While it was a comparatively weaker model and explained little variation, and these largest pieces of wood are typically rare even in streams having old growth riparian stands, the negative relationship between other harvest after 1990 and the density of the largest pieces of LW may be a product of selective harvest methods targeting very large trees from the riparian zone.

Logging road and stream crossings

The density of logging road/stream crossings within network catchments was present in three models predicting the ratio of recruits located within vs. above the channel (although it was less influential than other predictors). The recruit ratio decreased as logging road/stream crossings increased within catchments. This result may be due to the fact that logging road/stream crossings typically occur at locations where the channel is confined and has less opportunity to meander. The lack of channel migration and bank erosion in confined channels additionally results in low overall LW recruitment and narrow, confined channels restrict wood from intersecting the stream (Liquori et al. 2008), although we lacked data to fully evaluate this

relationship. Furthermore, confined channels are more powerful and may additionally be capable of moving LW out of those reaches. An alternate explanation may simply be a reflection of streamside buffering as streams harvested after 1990 required riparian buffers be retained and increased windthrow in riparian buffers shortly after harvest can increase wood loading (Martin 2001).

Comparing landscape influences on large wood habitat factors

CCA results indicate that a substantial amount of variation (i.e., 44%) in average LW length, LW recruit position in relation to the active channel, medium LW density, and large and extra-large LW density can be explained using natural and timber harvest-related landscape factors. While managers and scientists have typically assessed and documented effects of timber management on the region's streams at local scales, these findings suggest that landscape scale associations are also important in understanding LW dynamics in streams.

The findings of this study additionally suggest that timber harvest factors at a landscape scale have significant influences on LW habitat factors in streams of Southeast Alaska, and its interaction with natural landscape factors accounts for a comparatively low amount of variation in LW habitat factors which is not surprising as little covariation exists within the set of landscape variables selected. More compelling is that timber harvest factors across the landscape account for more variation than natural landscape factors in the second-growth study catchments. Our results contradict similar approaches investigating human impacts on streams. Wang et al. (2003) found substantial amounts of variation can be explained using natural landscape factors, and in relatively undisturbed regions these influences were strongest locally. As my study did not investigate the influence of scale, local and network factors characterizing natural land cover

and timber harvest activities were successful in explaining variation in LW habitat factors, and while links between the riparian zone and in-stream LW have been well studied, the findings of this research enforce the idea that influences on LW characteristics occur at scales larger than the riparian zone alone. Windthrow within streamside buffers, for example, may increase as large areas outside the riparian zone are harvested. Peak flows can increase after extensive timber harvest, especially in small catchments during wet years and wet climates, and while this effect is typically not long-lived, future research may investigate if short term increases effectively increase transport of wood from channels that would otherwise be characterized as LW storage locations. While source distances of LW recruitment from landscapes are typically confined to riparian zones, altered hillsides can increase landslide rates and essentially increase this source distance in steep catchments. The most important scales of influence and specific mechanisms affecting LW in streams is currently unknown and likely varies regionally. Johnson et al. (2006) found that both natural and anthropogenic factors occurring in stream catchments influenced LW habitat factors differentially across two Midwestern states. This study concurs with their findings and demonstrates that the legacy of actions on the landscape affect LW in Southeast Alaska and are important considerations when managing for natural resources in the region.

Management implications

Landscape considerations in managing the region's streams

The results of this study suggest that landscape factors are important for describing characteristics of LW abundance and distribution in streams of Southeast Alaska. Natural conditions, current and historic land use, and LW habitat factors differ throughout catchments of Southeast Alaska, so understanding these factors and how they are distributed across multiple

scales is important in characterizing the current condition and developing management prescriptions to restore and protect streams of the region. Forested wetlands in watersheds may influence water routing and LW production, although small streams generally do not transport LW in the absence of debris flows so a better understanding of land cover and disturbance history of watersheds is needed provide insight into the potential for a stream to store and transport LW. Increased timber harvest in catchments might affect peak flows in the short term (Harr et al. 1979) and the spatial location of harvested areas influences the risk of slope failures (Tang et al. 1997) that can have major effects on LW recruitment and transport throughout watersheds, so a thorough investigation of landscapes in relation to streams is important when identifying factors limiting LW production. The landscape approach can also assist in locating those streams most vulnerable to the effects of timber harvest, or most likely to benefit from restoration efforts.

Future research

Numerous landscape factors known to affect habitat factors within streams were untested in this study including underlying geology and silviculture efforts like thinning and pruning, for example, which can accelerate the production of trees and increase the rate of succession from early to old forests. Various geologic differences exist across Southeast Alaska and geology is known to influence LW availability. Confined bedrock channels, for example, have low rates of bank erosion and more power to transport materials resulting in low wood storage. Steep slopes in headwater catchments may additionally be prone to landslides and debris flows capable of delivering LW into higher order channels, and timber harvest in these catchments can increase the rate of hillslope failures. Much of the region contains previously glaciated landscapes, and coarse deposits of surficial materials are known to contribute to groundwater delivery in streams

systems (Wiley et al. 1997). Also, streams draining karst landscapes (found, for example, on Prince of Wales Island) have higher alkalinities, and higher fish production than non-karst streams (Bryant et al. 1998), while differences in salmonid densities between northern and southern Southeast Alaska watersheds have additionally been attributed to differences in geology (Bryant and Woodsmith 2009). The potential of landscapes to produce large trees is also mainly controlled by catchment topology, local landforms, as well as soil moisture and structure (Hanley and Hoel 1996, Villarin et al. 2009). Silviculture practices like thinning and pruning are intended to maximize forest productivity and can be employed to enhance the quality of potential LW available to streams which affects numerous aquatic habitat factors important for fish (e.g., pool formation). Thinning dense stands can increase primary production in streams during the summer through increased light and deciduous benefits, while still maintaining inputs of LW (Sedell and Swanston 1984). Thinning dense second growth vegetation in streams of Wisconsin has been shown to enhance trout production compared to similar, unmanaged second growth streams (Hunt 1979). Inclusion of these factors may improve the predicting capability in future efforts to relate landscape factors to LW habitat factors in streams of Southeast Alaska.

APPENDIX

Table 2.1: Mean, min, max, and standard deviation (SD) of natural landscape variables for 28 sampled stream reaches draining second growth watersheds.

Scale	Variable name	Code	Mean	Min	Max	SD
Local						
	Area (km ²)	T1areasqkm	0.71	0.02	2.83	0.75
	Ave slope (%)	T1slpAVE	1.16	0.43	2.95	0.62
	Max slope (%)*	T1slpMAX	3.52	1.21	7.13	1.97
	Open water (%)	T1open	NA	NA	NA	NA
	Deciduous forest (%)*	T1decid	6.59	0.00	37.93	9.02
	Evergreen forest (%)	T1evgrn	36.64	0.00	65.62	16.91
	Mixed forest (%)	T1mixd	27.40	2.74	57.14	15.29
	All forest (%)	T1allFOR	70.62	23.59	99.99	19.54
	Dwarf scrub (%)	T1dwfscrub	0.02	0.00	0.35	0.08
	Scrub/shrub (%)	T1shrbscrub	25.91	0.00	76.40	20.67
	Forested wetlands (%)	T1WETfor	33.17	0.00	100.00	30.77
	Developed-low intensity (%)	T1dvlLOW	0.76	0.00	9.37	2.01
	Road density (m/km ²)	T1rDens	58.80	0.00	680.81	181.91
Network						
	Area (km ²)*	T2areasqkm	4.24	0.12	19.75	5.63
	Slope (%)	T2slpAVE	1.38	0.50	2.48	0.50
	Max slope (%)	T2slpMAX	3.82	1.47	6.54	1.38
	No Harvest/No data (%)	T2noHVST	40.76	0.00	87.05	27.71
	Open water (%)	T2open	0.02	0.00	0.24	0.05
	Deciduous forest (%)	T2decid	3.95	0.00	37.93	7.01
	Evergreen forest (%)	T2evgrn	42.03	0.00	66.98	19.77
	Mixed forest (%)	T2mixd	19.17	2.75	44.63	12.65
	All forest (%)	T2allFOR	65.16	23.59	100.00	19.92
	Dwarf scrub (%)	T2dwfscrub	0.09	0.00	0.68	0.20
	Scrub/shrub (%)	T2shrbscrub	32.47	0.00	76.41	21.53
	Forested wetlands (%)*	T2WETfor	25.69	0.00	93.16	22.65
	Developed-low intensity (%)	T2dvlLOW	0.25	0.00	2.97	0.67
	Road density (m/km ²)	T2rDens	1425.75	0.00	24972.66	4978.11

Table 2.2: Mean, min, max, and standard deviation (SD) of timber harvest-related variables for 28 sampled stream reaches draining second growth watersheds.

Scale	Variable name	Code	Mean	Min	Max	SD
Local						
	Conventional pre 1980 (%)	T1CONpre80	1.76	0.00	27.27	6.49
	Conventional 1980-1990 (%)*	T1CON8090	41.58	5.78	80.23	21.03
	Conventional post 1990 (%)	T1CONpo90	10.30	0.00	37.81	11.88
	Other pre 1980 (%)	T1OTpre80	0.00	0.00	0.00	0.00
	Other 1980-1990 (%)	T1OT8090	0.25	0.00	3.46	0.79
	Other post 1990 (%)*	T1OTpo90	10.34	0.00	31.61	9.81
	Logging rd density	T1LogXDens	2.79	0.00	6.49	1.67
	Logging rd/stream crossing density (#/km ²)	T1LogRDens	5.58	0.00	75.73	14.41
Network						
	Conventional pre 1980 (%)	T2CONpre80	0.46	0.00	6.43	1.44
	Conventional 1980-1990 (%)	T2CON8090	30.29	3.64	77.55	22.43
	Conventional post 1990 (%)*	T2CONpo90	14.24	0.00	49.10	12.69
	Other pre 1980 (%)	T2OTpre80	0.00	0.00	0.00	0.00
	Other 1980-1990 (%)	T2OT8090	0.18	0.00	2.12	0.55
	Other post 1990 (%)	T2OTpo90	14.07	0.00	41.91	11.93
	Logging rd density (m/km ²)	T2LogXDens	37.88	0.27	244.29	62.18
	Logging rd/stream crossing density (#/km ²)*	T2LogRDens	3.00	0.00	8.92	2.53

Table 2.3: Pearson's correlations between timber harvest-related and other landscape factors used in analyses. An asterisk indicates significance at a 0.05 level.

	T2areasqkm	T2WETfor	T1slpMAX	T1decid	T1OTpo90	T2LogXDens	T2CONpo90	T1CON8090
T2areasqkm	1.00							
T2WETfor	-0.24	1.00						
T1slpMAX	0.01	-0.27	1.00					
T1decid	-0.07	-0.24	-0.09	1.00				
T1OTpo90	-0.21	-0.03	0.15	-0.20	1.00			
T2LogXDens	-0.13	0.10	-0.42 *	-0.17	0.14	1.00		
T2CONpo90	0.13	-0.11	0.06	-0.03	-0.07	-0.06	1.00	
T1CON8090	0.14	-0.26	0.01	0.26	-0.08	0.20	-0.21	1.00

Table 2.4: Landscape factors for streams in Southeast Alaska summarized for local and network catchments.

Scale		Mean	Min	Max
Local	Area (km ²)	0.47	0.00	1833.10
	Ave slope (%)	1.57	0.00	10.78
	Max slope (%)*	3.95	0.00	43.55
	Open water (%)	0.01		40.00
	Deciduous forest (%)*	3.58	0.00	100.00
	Evergreen forest (%)	53.17	0.00	100.00
	Mixed forest (%)	14.04	0.00	100.00
	Dwarf scrub (%)	1.19	0.00	100.00
	Scrub/shrub (%)	17.94	0.00	100.00
	Forested wetlands (%)	0.00	0.00	100.00
	Developed-low intensity (%)	0.22	0.00	100.00
	Developed-medium intensity (%)	0.01	0.00	100.00
	Developed-high intensity (%)	0.00	0.00	37.50
Network				
	Area (km ²)*	0.51	0.00	2168.90
	Ave slope (%)	1.70	0.00	10.68
	Max slope (%)	4.82	0.00	43.55
	Open water (%)	0.79	0.00	100.00
	Deciduous forest (%)	2.55	0.00	100.00
	Evergreen forest (%)	48.18	0.00	100.00
	Mixed forest (%)	12.87	0.00	100.00
	Dwarf scrub (%)	1.82	0.00	100.00
	Scrub/shrub (%)	20.60	0.00	100.00
	Forested wetlands (%)*	0.00	0.00	100.00
	Developed-low intensity (%)	0.13	0.00	100.00
	Developed-medium intensity (%)	0.00	0.00	23.08
	Developed-high intensity (%)	0.00	0.00	32.24

Table 2.5: Results from best subsets regression for LW length. Models are in order of most variance explained, predictor variables are ordered by their influence on the model based on standardized beta coefficients. Variance inflation factor value of four ($VIF < 4$) was used to ensure low multicollinearity between landscape variables, and ΔAIC represents the difference when compared to catchment area alone.

Model	Landscape variables	Adj r^2	Standard beta	F	Model sig	VIF	ΔAIC
1	T2areasqkm	0.59	0.66	13.70	0.000021	1.02	-6.89
	T1decid		0.32			1.01	
	T2CONpo90		0.28			1.02	
2	T2areasqkm	0.58	0.68	10.36	0.00006	1.04	-5.79
	T1decid		0.34			1.04	
	T2CONpo90		0.28			1.02	
	T2LogXDens		0.11			1.05	
3	T2areasqkm	0.57	0.68	10.03	0.000075	1.09	-5.22
	T1decid		0.34			1.08	
	T2CONpo90		0.28			1.03	
	T2WETfor		0.07			1.15	
4	T2areasqkm	0.57	0.65	9.89	0.000083	1.07	-4.96
	T1decid		0.31			1.09	
	T2CONpo90		0.28			1.08	
	T1CON8090		0.03			1.17	
5	T2areasqkm	0.57	0.66	9.86	0.000085	1.07	-4.92
	T1decid		0.32			1.05	
	T2CONpo90		0.28			1.02	
	T1OTpo90		-0.02			1.10	

Table 2.6: Results from best subsets regression for the ratio of LW recruits that are in:above the channel. Models are in order of most variance explained, predictor variables are ordered by their influence on the model based on standardized beta coefficients. Variance inflation factor value of four ($VIF < 4$) was used to ensure low multicollinearity between landscape variables, and ΔAIC represents the difference when compared to catchment area alone.

Model	Landscape variables	Adj r^2	Standard Beta	F	Model sig	VIF	ΔAIC
1	T1CON8090	0.34	0.40	4.50	0.008	1.11	-8.20
	T1decid		0.28			1.10	
	T1slpMAX		-0.26			1.01	
	T2areasqkm		0.23			1.03	
2	T1CON8090	0.33	0.43	4.38	0.009	1.08	-7.88
	T1slpMAX		-0.24			1.03	
	T1decid		0.21			1.12	
	T1OTpo90		-0.21			1.06	
3	T1CON8090	0.33	0.53	4.33	0.009	1.07	-7.74
	T1slpMAX		-0.36			1.31	
	T2LogXDens		-0.23			1.37	
	T1OTpo90		-0.20			1.10	
4	T1CON8090	0.32	0.50	4.23	0.01	1.18	-7.47
	T1slpMAX		-0.36			1.30	
	T2LogXDens		-0.22			1.42	
	T1decid		0.19			1.20	
5	T1CON8090	0.32	0.56	5.22	0.006	1.05	-8.08
	T1slpMAX		-0.41			1.23	
	T2LogXDens		-0.28			1.28	

Table 2.7: Results from best subsets regression for medium sized LW density. Models are in order of most variance explained, predictor variables are ordered by their influence on the model based on standardized beta coefficients. Variance inflation factor value of four ($VIF < 4$) was used to ensure low multicollinearity between landscape variables, and ΔAIC represents the difference when compared to catchment area alone.

Model	Landscape variables	Adj r^2	Standard beta	F	Model sig	VIF	ΔAIC
1	T2CONpo90	0.37	0.50	4.96	0.005	1.08	-10.37
	T1decid		0.39			1.11	
	T2WETfor		0.37			1.15	
	T1CON8090		0.34			1.20	
2	T1decid	0.33	0.40	4.37	0.009	1.11	-8.79
	T2CONpo90		0.40			1.02	
	T1OTpo90		-0.26			1.05	
	T2WETfor		0.26			1.08	
3	T1decid	0.32	0.49	4.24	0.010	1.08	-8.44
	T2CONpo90		0.39			1.03	
	T2WETfor		0.35			1.15	
	T2areasqkm		0.25			1.09	
4	T2CONpo90	0.32	0.47	4.15	0.011	1.09	-8.19
	T2CON8090		0.39			1.16	
	T1OTpo90		-0.31			1.02	
	T2WETfor		0.28			1.11	

Table 2.8: Results from best subsets regression for large and extra-large sized LW density. Models are in order of most variance explained, predictor variables are ordered by their influence on the model based on standardized beta coefficients. Variance inflation factor value of four ($VIF < 4$) was used to ensure low multicollinearity between landscape variables, and Δ AIC represents the difference when compared to catchment area alone.

Model	Landscape variables	Adj r^2	Standard beta	F	Model sig	VIF	Δ AIC
1	T1CON8090	0.16	0.36	3.50	0.046	1.01	-4.11
	T1OTpo90		-0.28				

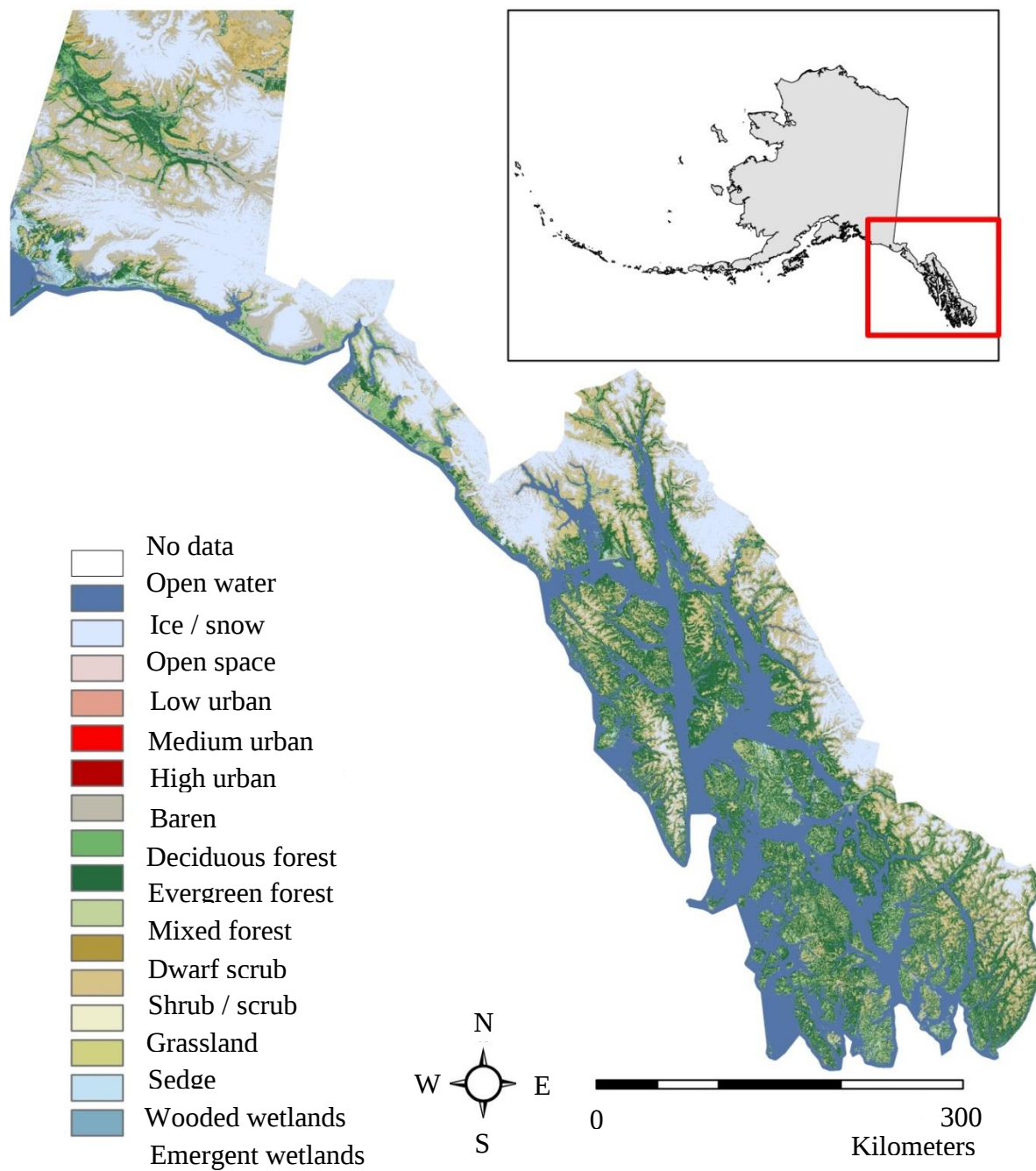


Figure 2.1: National Land Cover Database (2001) for Southeast Alaska. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.

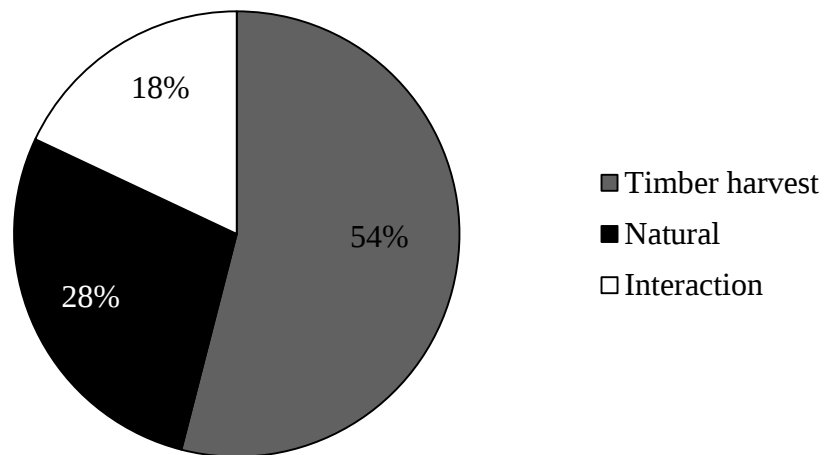


Figure 2.2: Results of variance partitioning from the CCA. A total of 44% of variation in LW habitat factors is partitioned into timber harvest-related factors in gray, natural factors in black, and the interaction in white.

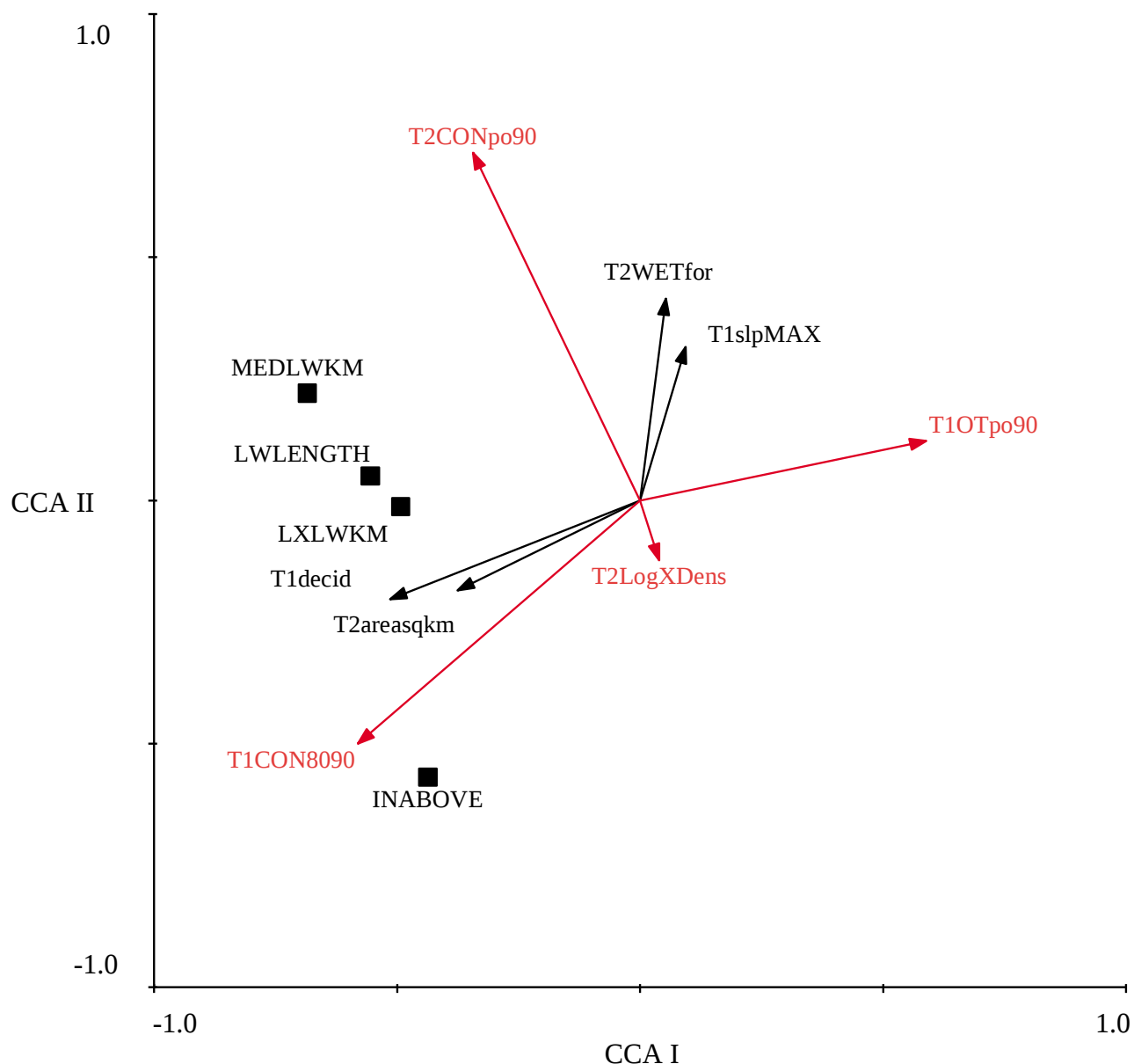


Figure 2.3: Graph of CCA axis one vs. CCA axis 2. Black arrows are natural landscape factors, red arrows are timber harvest-related factors, and black squares are LW habitat factors. LWLENGTH is average LW length, MEDLWKM and LXLWKM are densities of medium sized and large and extra-large sized LW, while INABOVE is the ratio of LW recruits that are located within vs. positioned above the active channel.

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CHAPTER 3

CONCLUSIONS: TIMBER HARVEST, NATURAL LANDSCAPE FACTORS, AND RELATIONSHIPS WITH FLUVIAL HABITAT; FROM REACHES TO WATERSHEDS OF SOUTHEASTERN ALASKA – SUMMARY OF FINDINGS, MANAGEMENT IMPLICATIONS, AND STUDY LIMITATIONS

This chapter provides a brief overview of the main findings of my MS thesis. I will present a suite of ideas supported by the results and provide managers of timber and aquatic resources in Southeast Alaska and the Pacific Northwest with the implications that have been suggested by this work. These include management considerations related to natural landscape factors such as stream size or the amount and type of forest within a streams catchment. Timber harvest related influences on stream habitat were also considered and included harvest type and intensity at reach and watershed scales. Principal findings include that a potential reduction in median particle size has been detected in streams with riparian zones harvested during initial best management practices (i.e., 1978-1990) for the timber industry in the region. Associations between landscape factors and large wood were additionally made, including timber harvest efforts occasionally showing stronger relationships with woody debris than natural landscape factors. The importance of natural factors in controlling aquatic habitat in streams is also shown, and associations supported in the literature from multiple regions have also been detected in my study area. Study limitations will also be presented to guide and improve future research on topics related to stream ecology and management in regions with streams that depend on woody debris and/or support anadromous fishes.

Principal findings

Chapter 1: Aquatic habitat and influences from reach scale geomorphic, riparian, and timber harvest factors of Chichagof, and Prince of Wales Islands, Alaska, U.S.A.

While studies have documented the importance of riparian zones to stream habitats in Southeast Alaska and across the world (e.g., Murphy and Koski 1989, Allan et al. 2003, Pusey and Arthington 2003), this study builds from previously-conducted work to explore linkages occurring at the transition zone between streams and the landscapes they drain. Additionally, timber harvest in Southeast Alaska is a major human land use, and regulations in the state did not initially restrict harvesting trees from the riparian zone, potentially altering processes occurring between aquatic and terrestrial habitats. Streams and riparian zones are complex ecosystems, and their connections are not fully understood, so it is challenging to identify the most sensitive and meaningful descriptors that still adequately describe variation observed across a particular set of study streams. For this study, stream habitat was characterized at the reach-level using both quantitative and visual measures of channel morphology, substrate, and large wood (LW) characteristics, while reach-level landform and tree measurements characterized riparian zones, resulting in over 200 variables being calculated. Redundancy in aquatic and riparian habitat variables was reduced initially by investigating correlation values between related variables. Next, a principal components analysis (PCA) was run on 17 minimally-redundant measures of stream and riparian habitat to identify main gradients in habitat across the 28 study sites. Five axes explaining 77.6% of the variation were interpreted as gradients in stream size, power, LW recruitment, density of LW and pools, and large-sized riparian trees and functioning LW recruits. Further exploration of reach-level relationships between channel morphology and riparian zones with aquatic habitat characteristics in the study streams was based on these PCA results.

To further associate geomorphic and riparian factors with aquatic habitat in streams, eleven variables characterizing channel substrate, LW, and pool habitat were selected based on the initial data reduction. Geomorphic variables deemed important included bankfull width,

gradient, and channel confinement. Riparian variables selected include the proportion of riparian trees that are deciduous and the proportion of riparian trees that are large and extra-large. Multiple regression models were run using the independent (i.e., geomorphology and riparian) variables to predict the suite of aquatic habitat variables selected. To determine how timber harvest may have influenced aquatic habitat in streams, unpublished data from the U.S. Forest Service were obtained, and select measures were compared to data from the study sites by using analysis of covariance (ANCOVA) and also a discriminant function analysis (DFA), while controlling for known natural controls on aquatic habitat. The results of these analyses suggest that stream size (i.e., bankfull width) was associated with multiple aquatic habitat measures including substrate, LW, and complex habitat, while stream power (represented by gradient and confinement) was related to measures of substrate and wood-formed pools. Riparian factors (e.g., tree type and size) were less influential, but still associated with wood formed pools and density of LW in stream reaches. ANCOVA results showed little difference in aquatic habitat when considering habitat complexity, but a significantly lower median particle size was observed in streams having experienced riparian zone harvest compared to unharvested streams. Classification results from the DFA had moderate success discriminating between harvested and unharvested streams and correctly classified 73.6% of grouped cases after cross-validation. These results emphasize the importance of considering natural controls on stream habitat before attributing differences to human land use. While timber harvest may have the potential to reduce median particle sizes in streams similar to those sampled for this study, the abundance of wood and presence of beavers will also influence this habitat factor.

Chapter 2: Large wood and influences from the landscape – natural and timber harvest factors

Large wood influences stream habitats, and likewise, landscapes influence LW. For example, LW is increasingly recruited to streams through bank erosion as catchment size increases, and most LW recruitment comes from the immediate riparian zone. As much is known about landscape influences in riparian zones on LW, less is known about larger catchment influences on wood in streams of Southeast Alaska, partially due to limited availability of landscape data for the region. This study was intended to fill this gap in knowledge by associating landscape factors at catchment scales, both natural and timber harvest related to LW in stream channels. Catchment scale data are limited in much of Alaska, so the first step was to delineate catchment boundaries for stream reaches of the southeastern region of the state and attribute landscape data to those spatial units. Natural factors calculated for catchments include watershed area and slope, forest type, and wetland cover. Timber harvest data were obtained and additionally attributed to study catchments including percent of area harvested. Logging type, as well as when logging occurred, were summarized and grouped separately due to potential differences in methods used to harvest trees as regulations over time became more restrictive in how operations could occur near streams. Logging road and logging road/stream crossing densities were additionally calculated and summarized for stream catchments. Study catchments showed considerable variation in landscape factors as catchment area ranged from 1 to about 20 km² and maximum slope ranged from 1.2 to 7.1%. The average amount of deciduous forest in local catchments was about 7% while average amount of forested wetlands in catchments was slightly more than 25%. Timber harvest was also highly variable, and conventional logging occurring from 1980-1990 was the most pervasive type of practice across study catchments, averaging over 40% in local catchments, while conventional harvest after 1990 averaged 14% in study catchments.

To determine how influential natural vs. timber harvest related landscape factors were in explaining variation in measures of LW, two analyses were performed; a best subsets regression, and a canonical correspondence analysis (CCA). Response variables included LW length, LW size (i.e., two categories; medium and large and extra-large), as well as LW position in relation to the active stream channel. Results indicate that LW length was most strongly associated with catchment size and deciduous forests. Large wood position showed a moderately strong relationship with conventional harvest from 1980-1990 as well as with slope, while moderate associations were made between medium-sized LW density and conventional harvest after 1990, along with deciduous forests. Large and extra-large sized LW density was poorly predicted, but had a significant relationship with conventional harvest from 1980-1990 as well as selective harvest after 1990. Variance partitioning results from the CCA suggest that at a catchment scale, timber harvest factors were more influential in explaining variation in the four LW response variables as 44% of the total variance was explained; timber harvest accounted for 54% of this while natural factors accounted for 28%, and their interaction was responsible for the remaining 18%.

Together the results of these two chapters suggest that influences of natural and timber harvest-related factors on stream habitat vary depending on the scale at which they are investigated. At a reach-level, natural factors (i.e., channel morphology and riparian tree size and type) were more important than timber harvest in influencing aquatic habitat measures, while at a catchment scale, timber harvest explained more variation in LW measures than the natural factors investigated. These results support the notion that physical characteristics of streams are differentially affected by landscape factors operating over different spatial scales (Wiens 2002),

and these influences result from specific mechanisms by which landscape factors influence stream conditions.

Management implications

Natural landscape considerations

Natural landscape factors have long been known to influence fluvial systems, and classifications based on natural landscape conditions are useful to more appropriately manage for streams that behave in similar ways (e.g., Strahler 1957, Paustian et al. 1984, Montgomery and Buffington 1997). The results from both chapters of this study concur with previous research and reinforce the notion that natural factors such as stream size, channel type, and surrounding vegetative cover can largely dictate how aquatic habitat will be distributed throughout a given stream reach (Paustian et al. 1992).

This study found catchment size to be greatly important in driving physical stream characteristics in the study streams, and this is a known control on physical and biological characteristics of streams around the world (Frissell et al. 1986, Bilby and Ward 1989, Hughes et al. 1986, Robison and Beschta 1990). While watersheds of the region are generally quite small, results from multiple regressions in Chapter 1 and Chapter 2 indicate the importance of catchment size in determining the potential of a stream, whether it be substrate size and distribution, LW, or habitat complexity. Larger catchments will have more water routed to and through the channel while slope tends to decrease with increasing basin area (Schumm 1977, Leopold 1994, Knighton 1998). Longer pieces of wood will be found in larger catchments, and these streams will have more ability to transport sediment and wood more efficiently down channels (Benda et al. 2002). Bilby and Ward (1989) also found stream size to be a strong

predictor for wood size in Washington. Additionally recruitment of wood is affected by catchment size and more erosion is found along streams that are larger (Martin and Benda 2001, Ross Chapter 1 *this volume*). Managers tasked with prioritizing restoration efforts must acknowledge how stream size will affect those efforts. Streams that are adequately wide, and powerful enough to transport large amounts of wood might not benefit as much from wood placement projects compared to moderately-sized streams that transport less large pieces of wood. Gravel-poor streams that are moderate in size may benefit from wood placement projects to increase retention of coarse substrates important for lithophilic spawners, and to act as pool forming elements. Channels having larger catchments will also be more dynamic in terms of meandering and bank erosion so they may not need supplemental wood placement, given the riparian zones have adequate sources and sizes of trees to be recruited in the future.

Deciduous and forested wetlands were additionally important in the density of medium-sized LW, both having a positive relationship. Channel migration can promote colonization of deciduous trees which grow and die faster than conifers (Minore and Weatherly 1994, Hibbs and Giordano 1996), and more deciduous pieces have been found in streams with riparian zones that consist of deciduous vegetation (Andrus et al. 1988, Gomi et al. 2006). Second growth forests have also been documented to produce LW sized deciduous trees, and increasing proportions of deciduous trees may promote larger conifers in the long term (Hanley and Hoel 1996, Orlikowska et al. 2004). Forested wetlands additionally can regulate water routing and increase transport capacity of small headwater streams after long periods of precipitation that fill wetlands (Fitzgerald et al. 2003), and this may play a role in moving wood out of fishless headwater streams into larger fish bearing streams, although LW loads 25 years after harvest were similar to unlogged streams in the region. Further, forested wetlands of Southeast Alaska have the

potential to produce trees large enough to be considered LW, and models estimate that forested wetlands can produce wood volumes nearly twice the U.S. Forest Service minimum standard to be considered productive forestland (Julin and D'Amore 2003), while forested wetlands may also limit the size of LW available to streams. Managers concerned with improving wood dynamics in streams must consider forest type in the catchment and how it may play a role in producing, or transporting LW to and through channels.

We also found channel slope to be influential to LW position in relation to the active stream channel. Steep headwater streams are typically narrower and more confined than low to moderate gradient streams and this characteristic restricts the capacity for LW to intersect stream channels (Liquori et al. 2008). May and Greswell (2003) found 33 % of locally recruited wood pieces were spanning the full width or suspended over the channel of headwater streams in a coastal Oregon watershed. Furthermore, steep channels are less prone to bank erosion, resulting in overall low LW recruitment in the absence of wood delivering landslides. Management efforts regarding wood in these channels will need to balance whether a stream may be too narrow for LW to function with whether or not sufficient power exists to transport wood out of the channel; a natural characteristic that can negate efforts intended to increase more woody debris. Streams having moderate gradients that lack sufficient woody debris may also transport gravel and other spawning substrates out of these reaches, so increased LW can increase bed roughness which has been shown to lower particle size distributions by holding substrate and reducing channel slopes locally (Buffington and Montgomery 1999).

Timber harvest considerations

Results of this study suggest the importance of scale when considering effects of timber harvest on streams in Southeast Alaska. Chapter 1 suggests a potential reduction in median particle size when considering streams that have had riparian zones harvested for timber, although the effect may be minimal as most substrates measured were still gravel; the ideal spawning substrate for salmonids, and the presence of beavers (a factor untested in this study) can also influence stream substrate sizes. While ample gravel still exists in the study streams, fine sediment can fill interstitial spaces and reduce spawning success while remaining undetected by pebble counts until larger substrates are mostly embedded, as pebble counts are known to be biased toward sampling larger particles. Increased erosion during harvest and increased landslide rates post-harvest may have contributed to a reduction in particle size by increasing sedimentation (Murphy 1995). While roads in catchments can also increase sedimentation, pilot data suggest most non-federal, decommissioned logging roads in Southeast Alaska are in good shape and likely do not contribute much sediment to streams (ADNR 2010). Managers tasked with increasing spawning habitat will want to investigate history of timber harvest near streams, and additionally explore methods used and the time period in which trees were harvested. A gradient of protection exists through time in regards to timber harvest near streams and while little difference was observed in aquatic habitat characteristics when timber harvest occurred at the reach-scale between 1980 and 1990, harvest efforts occurring prior to 1980 will potentially have more pronounced effects. These include less large wood and reduced particle sizes due to LW removal and use of heavy equipment in and near stream channels, while timber harvested post-1990 were required to leave riparian buffers and may not be different than their old-growth counterparts when considering aquatic habitat characteristics.

Results from Chapter 2 indicate that at a catchment scale, patterns in timber harvest explained more variation in measures of LW than natural factors (e.g., catchment area, deciduous forest). In general, study streams with more harvest from 1980-1990 also had more medium-sized pieces of LW. Some pieces measured had signs that they entered the stream through timber harvest (e.g., one end cut), and streams having both riparian zones harvested also had relatively more medium and large sized pieces of LW when compared to only one side harvested. Additionally timber harvest encourages deciduous vegetation to colonize, and they can reach a size large enough to be considered a medium piece of LW. Streams having more deciduous forest in the riparian zone will also have more deciduous pieces of LW in the channel. Chapter one results indicate that streams having both banks harvested for timber typically had more deciduous trees in the riparian zone as well. While deciduous trees provide a lower quality of wood to streams in terms of physical functionality to create pools or armor banks for example, they do provide a better food source for macroinvertebrates, are nitrogen fixers for streams as well as other riparian vegetation (e.g., conifers), and this may enhance growth of very large conifers in the future. Balancing how much deciduous vegetation is beneficial to streams will depend on clearly defined goals and objectives. Enhancing productivity in streams may require more light penetration and more nutritious leaf litter that comes from deciduous trees, while wood-poor streams may benefit more from the long-term channel shaping and substrate holding characteristics that come with input of coniferous trees. Selectively thinning out either conifers or deciduous trees can assist in reaching these goals although little research empirically tests for theoretical benefits provided to streams that can be provided by thinning.

Study limitations

Aquatic landscape ecology is an increasingly useful focus of study that investigates relationships between landscapes and stream conditions, reinforcing the notion that the valley rules the stream (Hynes 1975). Landscapes influence stream conditions, and humans alter landscapes, resulting in potential for altered stream conditions, and while research continues to find associations between landscapes and streams, mechanistic drivers behind these relationships continue to be unclear. Mechanisms driving linkages between landscapes and streams remain unknown and hard to test, a point that Allan (2004) acknowledges. This paper also identifies four main challenges to riverscape-based studies including: covariation of natural and anthropogenic gradients, multiple interacting stressors, scale of measurement and influence, and possible legacy effects from historical disturbance.

This study shares all these limitations and more. Multiple factors known to be important to fishes were unavailable or untested in this study including: geology, landslide history and frequency, as well as silviculture efforts (e.g., selective thinning) in second-growth riparian stands, although the spatial location and human influence present in the study region limits some of the challenges identified by Allan (2004) in riverscape research. Some covariation between natural and anthropogenic landscape factors do exist in the study catchments. For example more harvest surely occurred in areas having the most productive soils and largest trees, but landscape variables used in Chapter 2 analyses showed very little covariation or collinearity with each other, as indicated by results from the multiple regressions which had low variance inflation factor values. Additionally the CCA results showed the interaction between natural and timber harvest related factors explained the least amount of variation in measures of woody debris.

This study did not specifically test for the effect of scale, or the most appropriate scale to test the effects of timber harvest on streams, but it did investigate multiple scales from reach to

watershed-level and found varying associations between stream habitat and timber harvest factors, depending on the scale investigated. This research still lacks the ability to elucidate mechanisms that underlie the relationships presented or how scale affects these patterns, which continues to be a major challenge in ecological studies (Levin 1992). It is important that future research considers scales that are relevant to the questions being asked, or the resource being managed.

Southeast Alaska has very few urban areas and virtually no agriculture, so timber harvest is the most pervasive human land use, making the problem of multiple interacting stressors rare for watersheds in the region. Legacy effects from historical disturbances are mostly limited to activities occurring after 1950 because most large-scale timber exploitation occurred much later in Alaska than in the conterminous U.S., but there are localized areas that have historic and current mining operations. Because of the remoteness and lack of historical human influence, in addition to the sociocultural and economic importance of salmonids in Alaska, it may be possible to identify the closest thing to “true” reference conditions. This would allow us to link mechanisms to associations as legacy effects are currently limited and there is not a suite of stressors acting in conjunction to influence aquatic habitat in the state. This certainly differs from most watersheds in North America as much of the continent has been altered from its “pre-colonial” condition. It is important for future researchers and natural resource managers and decision makers to remember to use the term reference condition, even in Alaska or other remote regions, in an appropriate context as likely no watershed on earth is void of human influence. The earliest North Americans quite possibly entered the continent through Alaska so some of the earliest exploitation of resources occurred here. Native Alaskans established relatively large, permanent communities and cultures that revolved around wood resources, so timber harvest has

occurred here for thousands of years, and even the most remote watersheds on earth have certainly not escaped exposure to deposition of atmospheric pollutants, so terms like minimally disturbed, or least disturbed (Stoddard et al. 2006) may be more appropriate as physical and biological assessments of stream condition continues into the future.

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