INFLUENCE OF STREAM CORRIDOR GEOMORPHOLOGY ON LARGE WOOD JAMS AND ASSOCIATED FISH ASSEMBLAGES IN MIXED DECIDUOUS-CONIFER FOREST IN UPPER MICHIGAN

DISSERTATION

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ABSTRACT

Wood structure and spatial arrangement in rivers reflect hierarchical processes of the stream corridor and valley. Large wood jams (aggregations of 2 or more pieces of wood greater than 10 cm diameter and longer than 1 m; LWJ) often form the focus of stream restoration projects that require knowledge about factors controlling LWJ characteristics and stability. Because geomorphic structure at the stream corridor scale controls stream channel geomorphology and riparian forest structure and dynamics, which have also been shown to control LWJ characteristics, we hypothesized that patches of relatively long sections of similar valley geomorphology create unique LWJ signatures or combinations of LWJ characteristics, and that these signatures should exist in all similar geomorphic patches. We studied characteristics of LWJ in first through third-order streams in the hemlock-hardwood forests of the Porcupine Mountains Wilderness State Park, one of the largest old-growth forest landscapes in the midwestern United States. These rivers showed little change in channel size, but local topography created discontinuous segments of stream corridor and valley geomorphology. We identified four distinct types of valley geomorphology along river corridors in the study area, and designated a section (1 km) for study in each geomorphic setting. In the first part of the study we evaluated characteristics of loose large wood (LW) and LWJ compared to riparian forest composition and imminent recruits (dead, leaning, or undercut trees within
10 m of the bankfull channel) in 300 m reaches encompassed by each geomorphic section in one river in old-growth and matching sections in two second-growth streams. We quantified specific relationships between structural characteristics of large wood and 10 geomorphic factors in an effort to develop reference conditions for large wood restoration for streams of the region. We also developed simple predictive models relating environmental variables to large wood characteristics. Using redundancy analysis, we determined that geomorphic factors alone explained 38.5% of the variance in large wood (pieces greater than 10 cm diameter and longer than 1 m; LW) and LWJ characteristics, riparian forests 18.4%, and the intersection of geomorphic and riparian forest factors (the redundant portion) explained 29.8% of the variance in LW and LWJ characteristics. Variability in LW and LWJ measures were high among reaches (e.g., the mean number of pieces of wood per LWJ varied by more than 20 pieces among reaches within the some geomorphic settings). Similar to studies in other regions, however, we found that increased channel width corresponded with increasingly large LW, and LWJ with larger and more pieces of LW. We also found that pieces of LW corresponded in abundance and size primarily with sinuosity, gradient, and channel wet width, while LWJ abundance, volume, the number of pieces, and channel-spanning corresponded primarily with channel confinement, rock-plane bedding, and distance from the headwaters. The number of riparian trees that were undercut, leaning more than 45 degrees toward the river or were dead within 10 m of the channel related poorly with LW or LWJ abundance, indicating that current inputs of individual trees do not represent the standing stock of LW in the stream. In the second part of this study we used linear K-function analysis to quantitatively evaluate spatial patterns of LWJ in repetitions of the four
geomorphic settings within 6 rivers (4 in old-growth, two in second-growth). Most LWJ (in 12 of 17 geomorphic sections) and large wood dams (LWJ that spanned more than half of the channel; random in 11 of 14 cases) showed random distribution patterns within geomorphic sections regardless of the scale of evaluation within a geomorphic setting. However, when several contiguous geomorphic sections were considered together, clumping of LWJ in some sections always led to aggregated patterns (at scales from 50 m to 8 km), and segregated patterns in two of four cases (at 5 m and more than 1 km), indicating that patterns of LWJ spatial distribution occurred at relatively large scales of stream landscapes that encompass patches of geomorphic elements.

During the third part of this study we compared LWJ characteristics (measured at the scale of about 1 km) among geomorphic sections in the same 6 rivers as in part two of the study. The abundance of LWJ, the proportion of LWJ spanning 100% of the channel, and proportion of LWJ with 2 pieces to 5 pieces related significantly with geomorphic setting: more LWJ and a higher proportion spanning 100% of the channel, but fewer small LWJ, in low-gradient geomorphic sections where sinuosity was relatively high, channels were narrow, and channel confinement was low. The proportion of LWJ with pieces contacting the active channel and the number of LWJ of more than 20 pieces did not, however, significantly correlate with geomorphic setting. We also found that the number of pieces in LWJ could only be significantly predicted by multiple regression when factors representing riparian forest were included in the model.

Finally, we surveyed brook trout (Salvelinus fontinalis) and other fish associated with LWJ in October of 2003 and again in June and October of 2004. We did not find a significantly greater abundance of resident brook trout or other fish species at LWJ or in
pools with LWJ compared to reference pools without LWJ. Resident brook trout in pools with LWJ were significantly longer than individuals in reference pools without LWJ, but the relative length of resident brook trout associated with LWJ compared to pools without LWJ did not change with geomorphic setting. The geomorphic context of LWJ, therefore, does not determine the abundance or size of resident brook trout or other fish associated with LWJ in the old-growth conditions of the Little Carp River. Further study could evaluate the association of fish with LWJ during the early spring or winter, the consequences of longer brook trout in pools with large wood on fish abundance in those pools, and the consequences of the arrangement of geomorphic segments (metastructure) on LWJ structure and function.
Dedicated to old growth
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CHAPTER 1

INTRODUCTION

Wood in rivers often functions as a major factor in the dynamic interrelationships between aquatic and terrestrial systems (Zimmerman et al. 1967, Keller and Swanson 1979, Bilby and Ward 1989, Naiman et al. 2002). The presence of wood in rivers has been shown to develop stream geomorphologic structure (Montgomery et al. 1995, Wallerstein et al. 2001) and influence hydrologic processes, including connectivity with floodplains (Ward et al. 2002). Wood provides habitat elements for both aquatic and terrestrial organisms including fish of many species (Robinson et al. 2002, Dolloff and Warren 2003), and may function to increase both aquatic and terrestrial biodiversity (Wondzell and Bisson 2003).

Larger pieces of wood (relative to channel size) control stream structures more often than small pieces (Gurnell et al. 2002) so current research often focuses on large wood (LW) or pieces above an arbitrary threshold of 10 cm diameter and 1 m length. In addition, large wood jams (LWJ) form where wood has been recruited to the stream, and stream conditions facilitate the movement of some pieces of wood and trapping structures exist (Swanson 2003). Large wood jams often exert very strong influences on hydrologic processes because of their size, complexity, and relative stability (Wallerstein et al. 1997, Abbe 2000).
Because of the strong influence of LWJ on stream structures and organisms, LWJ often form the focus of stream restoration (e.g., Reich et al. 2003). Yet much remains unknown about physical processes that arrange and stabilize LW or LWJ, particularly in deciduous and mixed deciduous-conifer forests. Most evaluations of large wood structure have occurred in areas of the Pacific Northwest characterized by steep headwater streams and coniferous forests (Gregory 2003, Swanson 2003, Wildman and Neuman 2005), providing information of sometimes uncertain application for restoration of wood to streams in other areas. Gregory (2003) identified communication of LW research to inform ecological restoration, and the development of principles and guidelines for restoration as important goals for current research. In order to evaluate the use of research in restoration of LW to streams, and to provide insight into effective practices for communicating research with restoration practitioners, we began a survey and review study in 2002. In addition to reviewing available literature, we questioned stream restoration professionals about sources of information they used to guide their restoration practices, and contrasted responses from the Lakes States and the Pacific Northwest (Chapter 2).

In addition to the need for development of knowledge about LW and LWJ in environments of deciduous and mixed conifer-deciduous forests, there is a need for research on LWJ in patchy riverine landscapes. Abbe (2000) and others (e.g., Zimmerman et al. 1967, Keller and Swanson 1979, Rot et al. 2000, Wing and Skaugset 2002) have characterized wood accumulations in streams according to stream and valley characteristics, with an emphasis on characteristics associated with wood accumulations in different stream orders. Little has been done to investigate and characterize the
variability of wood structural characteristics in small streams where changes in stream
corridor geomorphology do not correspond primarily with stream order.

Evaluating LWJ in discontinuous geomorphic riverine patches is important for
several reasons. First, riverine landscapes have been historically modeled as continua
(Vannote et al. 1980), but are increasingly being understood as dynamically patchy
Few studies have examined the distribution and characteristics of large wood in relation
to patch dynamics. Second, evaluating LWJ in riverine patches increases understanding
how the physical structure of the environment relates to LWJ structure, which influences
the ecological function(s) of LWJ. Third, evaluating LWJ in geomorphic riverine patches
helps to inform and guide stream and forest management, particularly restoration of LWJ
to streams. Current restoration trends emphasize soft engineering and passive restoration
techniques that rely on understanding hierarchical and patchy natural processes to
stabilize LWJ in streams (Abbe et al. 2003, Bisson et al. 2003). In addition, further
evaluation of LWJ characteristics in discontinuous geomorphologies of rivers in old-
growth deciduous or mixed conifer-deciduous forest will complement pioneering work
on LWJ from the Pacific Northwest (Abbe 2000, Abbe et al. 2003, Swanson 2003) and
provide valuable baseline reference information for ecological restoration of streams in
the eastern and northeastern United States.

We began a three-part study to elucidate relationships among characteristics of
stream corridor geomorphology with LWJ characteristics. This study differs from
previous studies by evaluating LW and LWJ characteristics in streams where channel size
differences were not large, but where geomorphic discontinuities along the course of the
river gave rise to large changes in stream channel gradient and other factors of channel valley shape. Based on previous studies, we predict that patches of relatively long sections of similar valley geomorphology create unique LWJ signatures or combinations of LWJ characteristics, and that these signatures should exist in all similar geomorphic patches. In addition, this study takes place in one of the largest old growth ecosystems remaining in the northeastern United States: the hemlock-hardwood forest of the Porcupine Mountains Wilderness State Park in Upper Michigan. We focused our study primarily on streams in old-growth forest because reference information from old-growth systems to guide stream and forest management and restoration in the Eastern United States is needed but lacking. We also contrasted, however, LW and LWJ characteristics in old-growth streams with nearby second-growth streams to evaluate both the consequences of forest age and geomorphology on characteristics of wood in rivers.

The first part of this three part study was to compare in detail the characteristics of individual pieces of LW, LWJ, and riparian forests with geomorphology at the scale of 300 m reaches encompassed in four sections of distinct stream-corridor geomorphology along the Little Carp River in old-growth forest and two other rivers in second-growth forest (Chapter 3). The second part of the study was to quantitatively evaluate linear spatial distributions of LWJ at various spatial dimensions in 6 streams (Chapter 4). And the third part of this study was to compare LWJ characteristics at a relatively large scale, using data only for stream-corridor geomorphic patches of approximately 1-km each to compare LWJ characteristics among 6 streams (Chapter 5). As part of our evaluation of the structural variability of LWJ associated with stream corridor geomorphology we also investigated associations among LWJ and the abundance and length of brook trout
(Salvelinus fontinalis) and other fish because these relationships may be important, but have not been clear in the literature (Berg et al. 1998, Ford and Lonzarich 2000).

Large wood jams have been shown to act as important wildlife habitat in some cases (Dolloff and Warren 2003), although the effects of LWJ do not appear to be consistent between all environments. For example, while some studies have suggested that young salmonids preferentially use large wood habitat, especially when several pieces have aggregated to form LWJ (Bilby and Bisson, 1998; Sundbaum and Näslund, 1998; Flebbe 1999), other studies have found that large wood habitat in streams has a variable or negligible effect on the distribution of juvenile salmonids (e.g., Cederholm et al., 1997; Berg et al., 1998, Ford and Lonzarich 2000, DuBois et al. 2001, Warren and Kraft 2003). Richmond and Fausch (1995), Warren and Kraft (2003), and Wondzell and Bisson (2003), have suggested that the effects of wood on stream organisms depends on the environmental context, with LW forming particularly attractive habitat in some settings but not in others. We studied the relationship between LWJ and fish assemblages using two different study designs. First, in October of 2003 we surveyed fish in reaches centered on LWJ in each of four geomorphic settings on the Little Carp River to determine whether the numbers and sizes of brook trout and other fish at LWJ corresponded with geomorphic setting, and to determine which geomorphic factors corresponded best with fish occurrence and size at LWJ (Chapter 6). Second, in June and October of 2004 we surveyed fish in matched pools with and without LWJ, in the same four geomorphic sections of the Little Carp River (Chapter 7). Evaluation of fish associations with LWJ in different geomorphic contexts provides knowledge about the functional relationships of LWJ with aspects of larger-scale geomorphology.
In each chapter we make explicit suggestions for application of the research to restoration of large wood to streams. This research addresses, however, more than just the practical need for information about stream corridor patterns that have not yet been identified. We believe, as stated by Levin (1992), that the identification of pattern at different scales is the fundamental issue of ecology. Willson and Halupka (1995) wrote that studies are needed to work out the details, especially to quantify, the linkages between aquatic and terrestrial systems. Our objective with this research on large wood jams is to work out and quantify when possible a bit more of the linkage between forests and streams, identifying patterns at scales of practical and conceptual value.

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CHAPTER 2

CURRENT PERSPECTIVES ON RESTORING LARGE WOOD IN STREAMS OF THE GREAT LAKES STATES

Introduction

The perception of wood in North American streams has changed over the last 100 years. Around the turn of the 20th century, flash dams were often used to flush felled timber and obstructions were removed from streams to allow water and logs to pass unimpeded. Wood in streams presented an economic resource or was perceived simply as a hazard to navigation or transport, so it was removed (Maser and Sidell 1994, DuBois et al. 2001). As the consequences of removing wood became apparent, protection and replacement of wood in streams began. We now know that wood in streams shapes stream channels, increases the diversity of habitat for fish and wildlife within and near streams, and influences stream and riparian hydrology (Domínguez and Cederholm 2000, Gurnell et al. 2002). Large wood (wood pieces greater than 1 m long and more than 10 cm in diameter) in streams provides habitat preferred by trout, young salmon, and other fish species (Weigel and Sorensen 2001, Wildman and Neumann 2003). Large wood in streams particularly affects stream flow dynamics, flood levels, flood timing, and groundwater (Bilby and Bisson 1998, Gurnell et al. 2002). As research and experience revealed desirable functions of large wood in streams, government regulations were
emplaced in many areas to control logging near streams and modifications to stream channels, in part to promote habitat in the form of large wood in streams. Ongoing research has continued to clarify interactions between wood and streams and adjacent riparian forests. While information to guide large wood management or restoration in streams is available now more than ever before, research is geographically skewed, possibly affecting the ability of stream and forest managers to implement research findings to restore and manage large wood in streams.

Most of the published literature on large wood in streams originates from the Pacific Northwest, where the plight of salmon, forests, and the fishing and timber industries focused attention on forest and stream interactions. According to Lassettre’s (1999) bibliography of large wood in stream ecosystems, 128 publications have been derived from British Columbia, Washington, Oregon, and Alaska. This was more than the number of publications about large wood in streams from all other locations combined worldwide. The Great Lakes region was the best represented area from eastern North America, with 16 of 39 publications. One consequence of the disproportionate amount of large wood research in the Pacific Northwest is that most information about wood in rivers pertains to conifer forests with steep headwaters. Less is known about forest-stream interactions and how they influence large wood characteristics in streams of the Great Lakes and eastern U.S. forests, even though stream enhancement projects are occurring rapidly in both regions. For instance, the Wisconsin Division of Wildlife spent approximately $100,000 of inland waters trout stamp revenue each year from 1998 to 2001 to maintain and develop trout stream habitat in more than 80 degraded streams. Over half of those projects included maintenance or addition of wood to improve trout
habitat. Usually the wood was constructed into specific arrangements (e.g. lunker structures) and anchored in place (Wisconsin DNR 2001).

Restoring wood in streams provides opportunity for the stream and forest manager to transform stream structure and dynamics, as well as to restore critical linkages between the riparian forest and the stream. However, wood is not desirable everywhere in a stream and reversing the effects of channel degradation is more difficult than just adding large wood (Dominguez and Cederholm 2000, Gurnell et al. 2002). Because restoring wood to streams involves many variables as well as potential ecological and human risk, decisions about where and how to place large wood in streams must be made as accurately and completely as possible. Obtaining information for stream restoration planning may involve consulting a variety of sources such as government regulations, guidelines and research published in scientific journals. However, in many instances the desired information may not be available (Hilborn and Ludwig 1993, Costanza 1993). Further, information that is available might not be reflected in legislation or valued by field practitioners and incorporated into the stream restoration programs. Considering three important questions will improve our understanding of how scientific information is actually used to inform large wood restoration decisions: 1) Is research information available to affect decisions regarding large wood restoration to streams? 2) To what extent are stream restoration professionals constrained or informed by government regulations? and 3) How do stream restoration professionals perceive the importance and their use of a variety of information sources to restoring large wood to streams? We reviewed current literature and legislation and surveyed targeted stream restoration professionals to answer these questions. We focused our review on information,
legislation, and restoration in the Great Lakes region and northeastern U.S. at approximately the same latitude as forests of the Pacific Northwest, but where geomorphology, climate, and forest communities are very different.

**Restoring large wood in streams**

A distinction must be made between perspectives of placing wood in a stream only as fish habitat, and placing wood in a stream as part of a forest ecosystem (Figure 2.1). In fact, attempting to enhance stream conditions by introducing large wood without an ecosystem perspective may lead to frustrating restoration failures even if the objective is not a complete return to some reference state (Hall and Baker 1982, Schmetterling and Pierce 1999). The term "enhancement" may be a misnomer when management activities are undertaken without an ecosystem perspective, since consequences may be unpredictable or undesirable. In this paper, we use the term restoration as prescribed for ecological restoration by the Society for Ecological Restoration (i.e., “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed”; SER 2002). We concur with other restorationists that for long term effectiveness, restoration of wood must act on a stream so that the stream’s own processes and processes of the surrounding forest perpetuate desired characteristics of wood within the stream.

One way to maintain an ecosystem perspective when introducing wood to streams is to allow natural geomorphic processes or geomorphology (land shape and composition; topography and geology) at multiple scales guide decisions on the quantity and type of wood to restore to streams, as well as where to place the large wood. It is generally
accepted that stream habitat reflects processes occurring at larger spatial and temporal scales (Figure 2.2) (Benda and Sias 1998, Rot et al. 2000). Much recent research has aimed at examining streams within an ecosystem context, which includes considering the influence of landscapes at a large scale on processes at smaller scales (Benda and Sias 1998, F.J. Swanson, personal communication). Although our understanding of large-scale geomorphic controls on large wood requires further elucidation, especially in the Great Lakes region and northeastern U.S., it is clear that landscape-level geomorphology controls forests and hydrology, both of which influence large wood input and retention in streams (Palik et al. 1998, Goebel et al. 2003). In fact, recent research suggests that processes at every level of the landscape hierarchy influence the amount of large wood in streams. Some patterns of interaction between large wood and stream morphology at different scales appear to be typical, and probably apply as well in the Pacific Northwest as in the Great Lakes and northeastern U.S (Figure 2.3).

**Legislation and regulation**

In general, federal and state laws do not provide specific guidelines about how to restore large wood to altered or degraded streams although they do address potential threats of stream manipulations to environmental quality. Regulations exist, and work permits are required in some of the Great Lakes states (Minnesota, Michigan, and Wisconsin) and northeastern states (Maine and New York) for activities that could change the course, condition, location, or capacity of streams, affect water quality, or imperil threatened and endangered wildlife or plants. Restoring large wood to streams
falls within the scope of these regulations, although large wood manipulations are not specifically addressed.

The regulations related to large wood in Maine are a good example of how state regulations are vague when it comes to providing guidelines for restoring large wood to streams. While a person intent on placing (or replacing) large wood in a stream in Maine is required to obtain a permit under the Natural Resources Protection Act (Maine 2002), the applicant only has to demonstrate that placing large wood in the stream will not:

- unreasonably interfere with existing scenic, aesthetic, recreational, or navigational uses;
- cause unreasonable erosion of soil or sediment, or prevent naturally occurring erosion;
- unreasonably harm any significant wildlife, fisheries, or aquatic habitat; unreasonably interfere with the natural flow of any surface or subsurface waters; lower water quality;
- and, cause or increase flooding. The law in Maine allows considerable interpretation by the Maine Department of Environmental Protection personnel who review and issue permits, however, there are no guidelines to help these personnel assess the restoration potential of large wood restoration projects.

Many stream managers of the Great Lakes states also retain the responsibility for designing and implementing specific stream manipulations within broad constraints. In some instances, government-issue information resources provide some technical and/or ecological information that can be of direct use for the local placement of large wood in streams. However, none of the published stream restoration guidebooks or case studies we examined from the eastern U.S. or Canada provides specific recommendations for the use of landscape hierarchies in predicting either the type of wood to restore or where to place wood in streams.
We provided an internet-based survey to experienced stream restoration professionals from across the United States and Canada through targeted direct electronic mailings and the weekly electronic newsletter of the Society of Ecological Restoration (to view survey, see http://www.oarde.ohio-state.edu/survey/stream.asp). We intended the short survey to examine the perceptions of stream restoration professionals on the influence of scientific research and other sources of information to their use of large wood in stream restoration decisions, and how important they considered landscape hierarchies in deciding the type and location of wood to place in streams. We asked them to:

1) rank sources of information (previous experience, guidelines from handbooks, scientific research in journals, guidelines from classes, conferencing, and information from product suppliers) in terms of their relative influence on decisions about the type of wood to place in streams and where to place it;

2) rank these same sources of information, this time in terms of how often they were used in their large wood restoration decisions; and

3) indicate the importance of geomorphology at different scales (stream baseflow, stream bankfull flow, valley, stream corridor, and landscape) to their decisions regarding large wood in stream restoration.

In addition to numerical rankings for the different categories, we provided opportunity for open-ended comments.

Seven targeted stream restoration professionals from the Great Lakes region replied to our survey. Three were affiliated with federal government agencies, one was
affiliated with a state government and three were independent consultants. Twenty more restoration professionals responded to the SER mailing. Most of the additional respondents were allied with federal or state government agencies from across the U.S. Thirteen restoration professionals responded from the Pacific Northwest (Alaska, Washington, Oregon, and British Columbia), three from the western United States (California, Utah, and Texas), two from the midwestern United States (Ohio and Kentucky), and two did not specify their location. We focus our analysis particularly on responses of the seven Great Lakes stream restoration professionals since they consist of experienced practitioners within our primary area of concern. We also considered responses from Pacific Northwest restorationists separately and pooled all responses for comparative purposes. To evaluate selected differences between “importance” and “use” within treatments (sources of information) we used a Mann-Whitney test. We considered rankings for "importance" as a measure of the relative value of different sources of information to decisions about restoring large wood to streams. Rankings for the "use" of the information sources indicated whether they were used more or less than they were valued. Clearly, results from this exploratory survey are not comprehensive because of the small sample size, nor were they intended to be comprehensive. Instead, this survey was undertaken to obtain preliminary insight about the perceptions of stream restoration practitioners as they relate to different sources of information about large wood in ecosystem restoration processes.

Survey responses from the Great Lakes showed that experience was considered the most important source of information for guiding decisions about the type of wood and where to place it during stream restoration (Figure 2.4). On the other end of the
spectrum was information from product suppliers, which ranked lowest overall. The low rank of information from product suppliers probably reflects the fact that large wood restoration does not usually require products specifically created for wood restoration to streams (although some products like ELWd™ may become more widely used and then provide an increased information source). The importance of information from other sources ranked intermediate between experience and information from product suppliers. Published scientific research, guidelines from handbooks, and conferencing ranked about equally in importance, after personal experience.

Rankings for the information sources changed for some categories as Great Lakes stream restoration professionals reported their use of different sources of information rather than the importance they placed on the sources of information. Experience still easily ranked highest, indicating that personal experience is the source of information used most readily by these restorationists (Figure 2.4). In terms of actual use, conferencing ranked second highest, guidelines from handbooks third, and published scientific research fourth. Rankings for actual use suggest that published scientific literature is used less than it is valued although the difference was not significant ($P = 0.29, n = 7$).

Comparing responses from restoration professionals in the Pacific Northwest to those from the Great Lakes shows that respondents from the Pacific Northwest ranked guidelines from handbooks and research from journals higher than conferencing, in contrast to the Great Lakes restorationists’ relatively higher ranking of conferencing and lower ranking of guidebooks and research. Although guidelines from handbooks and research from journals ranked higher among Pacific Northwest restorationists, their
overall response was similar to the Great Lakes restorationists’ in indicating that they used research from journals less in restoration decisions than their perception of its importance would suggest. However, use of information from published research ranked higher among Pacific Northwest (PNW) than Great Lakes (GL) restorationists ($P = 0.08$, PNW $n = 14$, GL $n = 7$).

Survey responses for all respondents pooled indicated the same pattern of rankings as those from the Great Lakes. Experience ranked highest in terms of importance and use in guiding decisions about what type of wood to place in streams and where to place it. Information from product suppliers ranked lowest among all respondents, while other sources of information ranked intermediate. Most sources of information were ranked very similarly with regard to their importance and their actual use in guiding restoration decisions. However, when all responses were pooled, published scientific research again showed the greatest difference between importance and use, ranking lower in use than in importance ($P = 0.25$, $n = 27$).

With regard to considerations of landscape hierarchies, survey responses indicated that stream restoration professionals in the Great Lakes considered stream bankfull channel geomorphology most important to their decisions regarding the type of large wood to place in streams and where to place it (Figure 2.5). Landscape-scale geomorphology received a mean rank of “low importance,” suggesting that large-scale features (such as physiographic systems that reflect surficial geology and topographic features) do not receive the attention that might be warranted in ecosystem-based stream restoration. In contrast, restoration professionals from the Pacific Northwest consistently ranked larger-scale geomorphology as more important than was reported by their peers in
the Great Lakes. Reported consideration of stream corridors by Pacific Northwest restorationists was significantly higher than for Great Lakes restorationists \((P = 0.05, \text{PNW } n = 14, \text{GL } n = 7)\).

We consider results of the survey consistent with the idea that stream restorationists use the most available information resources most often, even if they are not considered the most important resources. The comparatively higher value reported for guidelines from handbooks and research from journals, and a lower value on conferencing in the Pacific Northwest, may reflect the higher relative availability of site-specific research in the Pacific Northwest. Scientific information in the Pacific Northwest appears to be more available and to guide stream restoration decisions more directly than in the Great Lakes region. Conferencing may be more important to restorationists near the Great Lakes because new information to inform stream restoration decisions must be derived from other restorationists in their area. Higher rankings for the importance of larger-scale geomorphology in large wood restoration decisions in the Northwest compared to the Great Lakes may also reflect the higher availability of information linking and emphasizing landscape hierarchies to stream processes in the Pacific Northwest.

**Implications for restoring large wood to streams**

Survey responses from restoration professionals suggest that low use of scientific research in decisions about restoring large wood to streams does not reflect a disregard for scientific information. Actually, information from scientific literature was ranked intermediate in importance relative to other sources of information for restoration
decisions involving large wood in streams. Rather, the comparatively low use compared to reported importance of scientific research in deciding how to restore large wood to streams may reflect some kind of difficulty in obtaining or implementing research findings. We suggest three possible difficulties associated with using scientific research to guide the restoration of large wood to streams (1) scientific research is incomplete, (2) scientific research is inaccessible, and (3) current restoration objectives discourage the use of research.

*Scientific research is incomplete*

One reason research may be unavailable to restoration professionals and practitioners centers on the relative scarcity of research conducted on large wood in streams, specifically in the Great Lakes and northeastern U.S. Current and forthcoming research on large wood in streams is poised to facilitate an increased understanding of the relationships and feedback loops within stream ecosystems of the Great Lakes and northeastern forests. Still, further research is needed to address the effects of large wood in streams within ecosystem settings (even at very large scales). The engineering or physical aspects of wood in streams within large-scale landscape constraints should be considered to provide practical information for placing wood in streams in such a way that the wood and the stream remain or become naturally stable. Ecological relationships at scales that include stream, riparian, and terrestrial organisms should be investigated so that large wood can be placed with consideration for many organisms, including and in addition to fish. Some of this research will be useful to those who wish to design and implement ecosystem-based restoration projects. However, our review of the literature indicates that there are general relationships between large wood and geomorphic
hierarchies that could be used in stream restoration decisions in the Great Lakes just as well as the Northwest. We suggest that there are also other reasons—in addition to the limited amount of information available—why published research may remain relatively untapped by restoration professionals.

**Scientific research is inaccessible**

Scientific research may be inaccessible to stream restoration professionals in several ways. First, published scientific literature can be difficult to read for many restoration professionals or practitioners. Even when research has been conducted and published, it is most available to those who have become familiar with the fairly specialized idioms and structure of written scientific communications. Second, finding pertinent published literature often requires a substantial amount of time, as well as experience with the tools needed for searching and accessing the information. Finally, the application of conclusions from academic research to field manipulations is often not very clear. This may be a fundamental reason why scientific findings are not being incorporated into large wood restoration projects. As one respondent wrote in the open-ended section of the survey, “There is very little applicable research born from applied science, therefore most is of little use in the field where liability is great...As with most elements of stream ecosystem restoration, we have very little understanding of the synergy and complexity of the system and how to put those complexities on plan sheets, justify the costs, provide specifications, understand the implications and get it built. There is no appreciation for actual field experience.”
When information is available from research and practice there ought to be reliable, swift means for knowledge and ideas to flow between the academic and field-application communities. However, technical information often remains inaccessible even when presented to decision-makers. Research shows that decision-makers often tend to rely on experience and “common sense” (i.e., heuristics) rather than new, technical information (Arvai and Gregory 2003).

**Current restoration objectives discourage research use**

Stream restorationists often work under immediate funding and time constraints to meet short-term, localized objectives. Under these conditions, ecological information or theory provides limited utility either in the efficient management of the project, or to meet immediate objectives. In addition, ecosystem perspectives may not be valued as highly as an increase in fish production or a decrease in bank erosion, because ecosystem function is usually not directly measurable (Gregory 1999). Ecological costs are also poorly recognized under any restoration regime. Consequently, ecosystem considerations are perceived to be of lower immediate value and may take low priority status in management decisions (Hall et al. 2000). A case in point is the Ohio General Assembly’s 1999 decision to release five million dollars to soil conservation districts to pay for wood removal from streams in an effort to mitigate flooding. While there are certainly concerns regarding flooding in urban and agricultural areas of the state, this action demonstrates policy that values a decrease in flooding more highly than ecosystem services provided by wood in streams and the connections between streams and riparian forests.
As long as stream managers make choices in an environment that values immediate, local benefits most highly, and ecosystems (as a whole) relatively lower, emphasis may not be placed on one of the most unique contributions of scientific research, which is the elucidation of complex ecological relationships. In a system where experience determines techniques and most experience is obtained on projects with immediate, non-ecosystem objectives, cumulative knowledge will tend to drive the development of stream manipulative techniques further away from whole-ecosystem considerations. Conversely, when the perception of stream managers and regulators embraces the need for techniques to meet long-term, ecosystem restoration or rehabilitation objectives, then the influence of scientific investigation may increase in restoration practice.

Conclusions

Review of the current literature shows that information to guide the use of large wood in stream restoration stems largely from the Pacific Northwest, but that general principles from the literature may be applied in other areas as well. This includes the importance of landscape hierarchies as a major factor regulating the accumulation and retention processes of large wood in streams. A consideration of government regulations and guidelines from the Great Lakes region reveals that legislation only broadly constrains the use of large wood in stream restoration so that most of the technical details of wood choice and placement remain with the restoration professional. Our survey of restoration professionals provides evidence that published scientific research is considered valuable but used less than its value would indicate, and used less overall in
the Great Lakes when compared to the Pacific Northwest. One reason that Great Lakes stream restoration professionals appear to not fully utilize published scientific literature is that the research information is inaccessible. We suggest that the inaccessibility of scientific research to stream restorationists is because of the relative scarcity of region-specific research and also to the inherent difficulty of accessing and implementing ecological research to stream restoration.

To increase the implementation of research to stream restoration decisions, scientists (whether in academia, government agencies, or functioning independently) should recognize and accommodate the need for developing information that can be applied in the field. At the same time, field practitioners should continue to enhance their efforts to implement scientific findings to their work by seeking research information and becoming more familiar with research investigation if necessary. Stream managers should consider implementing systems within their jurisdiction for the efficient assimilation of scientific knowledge to stream manipulations, as appropriate. Recently, social scientists have focused on methods for informing complex decisions so that values and research can be recognized and incorporated into management decisions (Hammond et al. 1999, Gregory et al. 2001). Advances in decision-making practice may be implemented directly in decisions relating to stream restoration, which could serve to inform and direct both scientists and field practitioners. Trained decision analysts may provide a means for linking research scientists and restoration practitioners (Gregory et al. 2001).

As means for the collection and implementation of scientific research become more functional for stream management decisions involving large wood, new research
findings will be more efficiently incorporated in large wood restoration and management. Ideally, stream restoration programs focused on restoring large wood that integrate experience, scientific research, and landscape hierarchies can be expected to enhance the ecological services provided by both streams and forests, and benefit all who utilize these resources.

References


### Definitions and Scope of Common Stream Activities

**Stream manipulation:** Any activity designed to change the stream channel.

**Stream enhancement:** Often used euphemistically to mean stream manipulations that alter a stream in some apparently desirable manner. Placing wood in a stream with little regard for floodplain processes might be considered stream enhancement since it is designed to improve immediate conditions for fish.

**Stream rehabilitation:** Refers to stream enhancement activities that are designed to cause conditions in and around the stream to return to some previous state, as defined by Dominguez and Cederholm (2000). Stream rehabilitation does not indicate an attempt to manually fashion stream conditions to match preexisting conditions, but rather an attempt to act on the stream in such a way that its own processes return conditions in the stream to some previous (or desired) state.

**Stream restoration:** (1) The process of assisting the recovery of a stream ecosystem that has been degraded, damaged, or destroyed, after the definition of ecological restoration used by the Society of Ecological Restoration (SER) (SER 2003). (2) The direct attempt to artificially shape the stream ecosystem to match a desired state, as defined by Dominguez and Cederholm (2000).

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Figure 2.1 Definition and scope of common stream activities
<table>
<thead>
<tr>
<th>Scale</th>
<th>Definition</th>
<th>Spatial Extent</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region</td>
<td>Broad geographical area with a common microclimate</td>
<td>hundreds to thousands of square km</td>
<td>Mixed Deciduous-Coniferous Forests</td>
</tr>
<tr>
<td>Subregion (Landscape)</td>
<td>Geographic area distinguished by a repeated pattern of components, which include communities like forest patches and wetlands.</td>
<td>few to several thousand square km</td>
<td>Northern Great Lakes Section</td>
</tr>
<tr>
<td>Stream Corridor (Valley, Riparian Landform)</td>
<td>Linear spatial element with its own set of structural elements; includes the stream channel, and the plant community on either side of the stream.</td>
<td>few to hundreds of km laterally, few to thousands of km longitudinally</td>
<td>River Valley and Watershed</td>
</tr>
<tr>
<td>Stream Channel</td>
<td>Area which is frequently or always covered by stream water.</td>
<td>generally less than few km laterally, few to thousands of km longitudinally</td>
<td>River Channel</td>
</tr>
<tr>
<td>Stream Reach</td>
<td>Area with similar geomorphic characteristics within the stream channel.</td>
<td>generally less than few km laterally and longitudinally</td>
<td>Reach or Portion of River</td>
</tr>
</tbody>
</table>

Figure 2.2 Definition and examples of hierarchical scales relative to streams.
Structure and Function of Large Wood in Streams

- **Individual pieces**: The least mobile pieces of large wood are longer than channel width, are large diameter, and have root wads or irregular growth forms. Trees may be anchored when they remain attached to the bank after falling.

- **Channel geomorphology**: Wood accumulates most in low-gradient reaches, where stream channels are sinuous, obstructions exist, where wood frequently contacts the bed material and becomes lodged, and where stream flow is moderate. Large wood typically does not remain in entrenched or constrained, straight reaches, especially if the channel is steep with bedrock or rock plate bedding.

- **Large-scale geomorphology**: Factors controlling wood recruitment (regional disturbance, individual mortality, channel incision and lateral migration, and flooding) and factors controlling wood accumulation (wood abundance and form, stream channel form, and hydrology) are all influenced by geomorphology at a scale larger than the stream channel. Sinuous channels (usually low-gradient and depositional) occur in open valleys. Straight channels (often high-gradient, rock bedded, and capable of transporting entrained material) occur in narrow valleys. Landscape hydrology (which reflects climate) determines the quantity of stream flow, and acts as a major factor in slope stability.

- **Uncoupling**: As rivers increase in size or humans alter the landscape, streams overcome some landscape geomorphic limits. Large rivers usually control floodplain forest structure and dynamics. Timber harvest and stream channelization uncouples local morphology and processes from large-scale geomorphology.

Figure 2.3  Structure and function of large wood in streams at different scales.
Figure 2.4 Rankings of potential sources of information on the use of large wood in stream restoration programs from stream restoration professionals in the Great Lakes Region ($n = 7$) and the Pacific Northwest ($n = 14$). Rankings increase numerically (6 is best). Error bars represent standard error.
Figure 2.5  Rankings of the importance and use of geomorphology at different scales in deciding the type and location of large wood by stream restoration professionals in streams of the Great Lakes Region ($n = 7$) and the Pacific Northwest ($n = 14$). Error bars represent standard error.
CHAPTER 3

GEOMORPHIC INFLUENCES ON LARGE WOOD JAMS IN THREE STREAMS IN NORTHERN MICHIGAN

Introduction

Physical and spatial characteristics of large wood in streams (abundance, size, physical composition, accumulation, and orientation) reflect a variety of environmental factors interacting hierarchically (Wallerstein et al. 1997, Abbe 2000, Swanson 2003). At a small scale, the retention and recruitment of wood in streams reflects interactions among individual pieces of wood, localized streamflows and channel characteristics (Abbe et al. 2003, Mutz 2003). At larger scales, streamflows, channel characteristics, and the characteristics of pieces of wood reflect local hydrologic regimes, the physical structure of stream channels, and riparian forests (Benda and Sias 1998, Hyatt and Naiman 2001, Rot 2000, Swanson 2003). At still larger scales, stream structure and riparian forests are influenced by stream-corridor and valley geomorphology (Ward et al. 2002, Nakamura and Swanson 2003, Goebel et al. 2003). Because there are so many interacting factors affecting the structure and function of large wood in streams, reducing the number of variables to consider for management or conceptual purposes is difficult. However, considering large wood characteristics in geomorphic settings at the scale of stream corridors is likely to provide information useful for predicting specific
characteristics of wood in streams (e.g., the number of pieces, the size of pieces, and the arrangement of pieces relative to the stream).

Streams retain wood where large-scale environmental factors create processes and structures that directly influence pieces of wood in streams. Specifically, bedrock geology, valley geomorphology, riparian forests, and hydrology regulate channel bedforms and riparian attributes that interact directly with pieces of wood to control the movement of wood and the manner in which wood is retained in the stream (Nakamura and Swanson 1994, Gurnell et al. 2002, Benda et al. 2003, Swanson 2003). Geomorphic characteristics shown to have the greatest control on LW in streams are: channel and valley width and depth (Lienkamper and Swanson 1987, Bilby and Ward 1989, Braudrick and Grant 2001, Gurnell 2003), bedding (Gurnell et al. 1995), gradient (Richmond and Fausch 1995, Gurnell 2003), and sinuosity (Nakamura and Swanson 1994, Wing and Skaugset 2002).

Abbe (2000) and others (Zimmerman et al. 1967, Keller and Swanson 1979, Rot 2000, Wing and Skaugset 2002) have characterized wood accumulations in streams according to stream and valley characteristics, with an emphasis on characteristics associated with wood accumulations in different stream orders. Few studies have investigated and characterized the variability of wood structural characteristics in small streams where changes in stream corridor geomorphology do not correspond primarily with stream order. In addition, most evaluations of large wood structure have occurred in areas of the Pacific Northwest characterized by steep headwater streams and coniferous forests. Much still remains to be understood about the correspondence of different
structural aspects of large wood accumulations with particular geomorphic factors in different physiographic regions.

The relationships between large wood characteristics and stream corridor geomorphology has particular interest for guiding restoration of wood jams to streams. Current wood restoration practices include trends toward soft engineering techniques and landscape-oriented objectives. Restoration managers attempt to foster the development of aggregated wood structure favored by natural stream processes, in contrast to earlier restoration objectives that focused on adding fixed amounts of wood throughout a stream (Bisson et al. 2003, Gregory 2003). Predicting the characteristics of a particular logjam in a given reach depends on understanding the relationship between geomorphic factors at appropriate scales (Abbe et al. 2003). Channel characteristics like gradient and sinuosity that have been shown to influence wood structure in streams can be measured relatively easily from aerial photographs or topographic maps and thus hold potential for being particularly useful for guiding wood restoration to streams where relationships between geomorphic conditions and specific characteristics of large wood in the channels can be determined. As restoration progresses in the eastern United States and other areas where large old-growth forested landscapes are rare, information on the correlations between stream corridor geomorphology and large wood characteristics in old-growth deciduous and mixed conifer-deciduous forests is particularly needed, but lacking.

Since 2002, we have been studying the physical characteristics of large wood in reaches of different geomorphic settings along a small (first and second-order) old-growth river and comparable geomorphic sections in two second-growth rivers in Michigan’s western Upper Peninsula. Our objectives were to (1) quantify specific
relationships between individual large wood and geomorphic variables in an effort to begin to develop reference conditions for large wood restoration to streams of the region, and (2) develop simple predictive models relating environmental variables to large wood characteristics. We hypothesized that large wood (LW) and large wood jams (LWJ) characteristics reflect physiographic characteristics of the stream valley or channel at a level higher than the proximate conditions of the reach where the LWJ occurred, and that old-growth conditions lead to maximum variability in LWJ characteristics.

Methods

Study sites

We studied wood in rivers in old-growth and second-growth forests in the Porcupine Mountains Wilderness State Park (PMWSP) in Upper Michigan. The Porcupine Mountains are located along the south shore of Lake Superior and rise at 3 km to 5 km inland to about 120 m above Lake Superior. Between the mountains and Lake Superior lies a lake plain with deep loam and silt loam soils on gentle (1-10%) slopes. Inland from the lake-plain, slopes increase to around 30% and are generally covered with soil to a depth of 1 m or more (Figure 3.1). The Porcupine Mountains form a curved ridgeline between a relatively flat upland and the clay-lake plain. The streams we studied formed in low-gradient areas in the flat inland areas of the Porcupine Mountains, descended steeply as they flowed across lava inclusions that comprise the Porcupine Mountains, and then flowed through moderate to low-gradient, clay-lake plains before entering Lake Superior.

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The PMWSP contains 13,000 hectares of uncut forest—the largest virgin old-growth hardwood-hemlock forest in the Lake States (Frelich 2002). We focused our sampling efforts within this large uncut forest in the Little Carp River. Eastern hemlock (*Tsuga canadensis*, (L.) Carr.), northern white cedar (*Thuja occidentalis*, L.), yellow birch (*Betula alleghaniensis*, Britt.), and sugar maple (*Acer saccharum*, Hook) dominate riparian forests along the Little Carp River. Maximum tree height is approximately 40 m, with mean height of the tallest trees in the study area roughly 25 m and mean dbh about 60 cm. Most of the river is forested to the edge of the bankfull channel. There is little evidence of anthropogenic disturbance along the Little Carp River, with the most consistent human activities consisting of recreational hiking, camping, and fishing. Beaver activity was apparent in the Little Carp River during our study, although all beaver dams from 2002 were removed by spring flooding in 2003.

The substrate of the Little Carp River generally consists of loose cobble and gravel with rock-plane bedding in a high-gradient section and the clay-lake plain. Floodplain extent varies, with the least floodplain development in the central, high gradient section that crosses the lava inclusions. Few records of streamflow exist for the Little Carp River. Goebel et al. (2003) reported discharge during annual floods ranging from 4.7 m$^3$ sec$^{-1}$ in the low gradient sections of the river to 9.4 m$^3$ sec$^{-1}$ in the lower, high gradient portions of the River.

In contrast to large areas of old-growth forest, the northern portions of the PMWSP and adjacent forests along the eastern side of the PMWSP have been logged within the last century, with logging currently ongoing in some areas. We examined portions of the Union River and the Little Iron River in these second-growth forests,
Second-growth forest composition is similar to that of the old-growth in the PMWSP except with a higher proportion of hardwood species and smaller trees overall, especially maple (*Acer* spp), birch (*Betula* spp.), and ash (*Fraxinus* spp.). Dense patches of small balsam fir (*Abies balsamea* (L.) Mill.) also occur more frequently in riparian areas of second-growth forest. Most of the Union River and Little Iron River forests extend to the edge of the river channels in segments we studied, and narrow strips (<10m) of uncut trees remained along the channel in the clay-lake plain of the Little Iron River where timber harvest has occurred most recently (within the last five years).

The substrate of the Union and Little Iron Rivers consists of loose cobble and gravel except for rock plane bedding where valley gradient is highest in the Union River and in the clay-lake plain of the Little Iron River. Along the upper portion of the Little Iron River, approximately 2 cm to 3 cm of sedimentation occurs along the stream bed. No records of stream flow exist for rivers in the second-growth forest, but the size of stream flows in the Union and Little Iron Rivers are believed to be similar to those of the Little Carp River. The Little Iron River in the clay-lake plain is the only third order stream site that we included in this study, but it was the best available second-growth counterpart to the clay-lake plain of the Little Carp River (old-growth). Although timber harvesting is the dominant human influence along the Union and Little Iron Rivers, localized camping areas exist, as well as trail and road crossings. Beaver activity is evident in the upstream portions of Little Iron River that we studied with dams in various states of repair, although no active, channel-spanning dams occurred in the study area during our study. Many beaver dams on the Little Iron River have been washed out, but the thatching of wood from old dams is visible under current vegetated banks.
The major sources of riparian tree mass mortality along study rivers in both old-growth and second-growth forests are bank slope failure and windthrow (Frelich, personal communication), with aerial photographs revealing large bank slope failures areas along the streams in the clay lake plain. Windstorms frequently result in the felling of individual trees, and in some areas is evidence of large blowdowns covering 100 to 100 m². Seasonal precipitation can be heavy (800-900 mm precipitation, up to 7 m snowfall; McNab and Avers 1994) but the topography is not conducive to avalanches, landslides, or other forms of mass wasting, and fire is infrequent in these northern forests.

**Study Design**

We identified four different geomorphic segments of the Little Carp River (3.1), and then identified sites in streams flowing through nearby second-growth forests with similar geomorphic characteristics. These geomorphic sites included: a clay-lake plain (CLP); moderate-gradient, bedrock control flowing transverse to the lava inclusions (MRT); relatively high-gradient, bedrock control, flowing transverse to the lava inclusions (HRT); and a low-gradient, bedrock-controlled section (LRP). Study sites located in each geomorphic segments are hereafter referred to as geomorphic sections. Along the Little Carp River, the CLP section occurred approximately 5 km downstream from the end of the MRT section, and the LRP section was approximately 5 km upstream from the top of the HRT section. In the Little Iron River the LRP section occurred approximately 10 km upstream from the CLP section. Valley geomorphology in the study area generally remained similar for at least 1 km in each type of geomorphic setting. However, we only studied 980 m of LRP section in the Little Carp River to
avoid sampling in an area of beaver meadows dominated by tag alder (*Alnus incana* (L.) Moench), grasses (*Leersia* spp.), and sedges (*Carex* spp.). Additionally, the HRT section of the Union River was intersected by two large culverts through which the entire Union River flowed under a paved road crossing. As these culverts presented an artificial control on stream and LW dynamics, we focused our efforts on the 480 m of HRT upstream from the culverts.

Within each geomorphic section we delineated three non-overlapping reaches 300 m in length. We chose 300- m reaches so that each reach was long enough to contain a few LWJ and short enough for three reaches to occur in each study section. In sections at least 1200 m in length (containing at least 4 possible study reaches) we randomly designated which three reaches to study. In the old-growth LRP and second-growth HRT where study sections were less than 1 km, we designated long enough reaches for three to fit in each section (Table 3.1).

**Large wood measurements**

We measured all pieces of LW and LWJ in the bankfull channel of each study reach using a modified TFW protocol for monitoring large wood jams in streams (Schuett-Hames et al. 1999). We determined the distance of each piece of wood and the approximate centers of each LWJ from end of section along the course of the channel. Large wood jams consisted of at least two pieces of large wood contacting each other and extending into the bankfull channel. For each piece of loose large wood we identified species when possible, and noted approximate midpoint diameter and length of the piece. We also counted the number of pieces in each jam, classified them by size, and estimated
percent of the wetted channel spanned by the jam in increments of 10% (See Table 3.2 for a list of the variables we measured to describe loose LW and LWJ).

**Geomorphology measurements**

We used a Pentax® 24 total station for topographic surveying of the stream thalweg of each study reach, as well as several stream valley cross-sections. We based surveyed lines on benchmarks for which we obtained latitude and longitude with an Eagle Explorer® handheld global positioning system (GPS) unit. Changes in elevations were calculated relative to the downstream end of each study section. Coordinates were converted to state plane coordinates, and northing, easting, and elevation changes were computed. Points were then projected onto orthophotoquads of the Porcupine Mountains using ARCGIS (v. 9.0, ESRI, Redlands, CA). We drew polylines for stream channels by manually connecting surveyed points while tracing channels as they appeared in satellite images in each geomorphic section. These polylines were used to compute a sinuosity index, defined as the length of the studied channel divided by the straight line between endpoints of that channel segment (Allan 1995; hereafter referred to as sinuosity). We averaged wet width and bankfull channel width from at least five points (endpoints and three randomly selected internal points) at each reach. We computed stream gradient from surveyed points (regression line fitting elevation to distance along the channel) except for second-growth CLP where we computed gradient using reach endpoint elevations determined from digital elevation models (Michigan 2005). We also measured the distance to each reach from the headwaters using ARCGIS maps showing perennial
streams. We considered headwaters to be the furthest upstream end of the perennial portion of the stream.

We estimated channel confinement using data from digital elevation models by dividing the channel width at twice the bankfull depth by the bankfull channel width (as Rosgen 1996). Using Goebel et al. (2003) as a guide, we determined that bankfull depth was approximately 1 m for most of the Little Carp River except for the LRP section (the furthest upstream section of the Little Carp River) where bankfull depth is 0.75 m. Based on visual observations, we estimated that bankfull depth for Little Iron River is similar to the lower portions of the Little Carp River (1 m) and 0.67 m for the Union River. Using spatial data from a 1:24,000, 30 m DEM, we measured confinement for at least three points (top, middle, and bottom) of each geomorphic section. We used direct observations and our topographic surveys to verify the DEM data. We then divided the mean width at twice bankfull depth by mean bankfull channel width by reach. Any confinement metric less than 6.1 m m⁻¹ we classified as high confinement, greater than 12 m m⁻¹ was low confinement, and in between (6.1 m m⁻¹ ≤ x ≤ 12 m m⁻¹) was medium confinement.

We also characterized valley constraint of the main channels based on the valley width (bottom of escarpment slope) divided by the bankfull channel width (Fetherstone et al. 1995) then we visually characterized constraint of second growth sections relative to Little Carp River designations. Predominant channel bedding material was visually classified as rock-plane bedding or other (boulder, cobble, gravel, sand, or sediment). We noted bedrock geology, particularly the presence of lava inclusions, for each section.
using a bedrock geology map from Reed (1987). We also noted quaternary geology for each section from a 1982 glacial geology map of Michigan (Farrand 1982).

**Riparian Forest Measurements**

We used point quarter transects to describe forest overstory composition and structure (Fitzpatrick et al. 1995). Transects were established 10 m from the bankfull channel edge for 300-500 m on both sides of the rivers near the upstream end of each geomorphic section. At points every 20 m along these transects we measured the distance from the transect to the nearest stem in four directions. For each of the nearest stems we identified species, noted whether the stem was alive or dead, and measured the diameter at breast height. Trees that had an especially high chance of falling into the river (e.g., dead trees or trees leaning more than approximately 45 degrees within 10 m of the bank along study sections, or trees (living or dead) for which more than half of the stem was undercut) within the next few years we termed imminent recruits. We measured the location, species, and size (diameter and height; Table 3.3 of each imminent recruit. Because of limited access in the second-growth clay-lake plain section (private land being logged) and an oversight in directions to field personnel we did not note imminent faller characteristics in that section. (See Table 3.4 for a list of variables we measured to describe geomorphic and riparian characteristics.)

**Statistical Analysis**

As LW and LWJ characteristics were not unimodally distributed along the gradients we measured, we used multivariate ordination analyses based on linear
distributions: PCA and RDA. We used the unconstrained gradient analysis, PCA, to evaluate total variability in LW and LWJ characteristics. We then used redundancy analysis (RDA), a form of constrained gradient analysis to evaluate variability of LW characteristics related specifically to the environmental variables we measured. By reiteratively performing RDA, each time with one variable or a combination of variables as the environmental factor(s) and all other variables as covariates, we partitioned the variance so that variability associated with subsets of the factors could be identified (after Miller et al. 2004). Specifically we partitioned variance due to geomorphic factors (sinuosity, gradient, width, etc.), riparian forest factors (riparian forest and imminent recruit measures), and the intersection of those two categories. Within geomorphic or riparian forest categories we also partitioned the variance uniquely associated with each factor and the intersection of those factors, by category (geomorphic or riparian forest). The proportion of the total variance explained by an individual variable or subset is simply the sum of all canonical eigenvalues (trace) as the total variance is always equal to one (1.0). We calculated the variance associated with an intersection of variables by subtracting the summed traces associated with the target variables from the trace of the full model (i.e., the full model includes both geomorphic and riparian forest categories). In the case of geomorphic or riparian variable subsets, the variance explained by the intersection of factors within each subset was computed by subtracting the variance uniquely associated with all individual factors from variance explained by the subset (geomorphic or riparian factors). Unexplained variance was computed by subtracting the trace of the model including all measured factors (total variance explained) from the total variance (1.0). We also performed RDA with each independent variable as the only
environmental factor with no covariates, to determine the proportion of variability in LW characteristics corresponding only with variability of each factor. Response variables (LW characteristics) were measured in different units, so they were centered and standardized before analysis, thus ordinations were performed with correlation matrices. The statistical significance of RDA gradients along the first axis and for the sum of all axes was determined by 199 permutations of the association between environmental data sets and response variable data sets. Principal component analyses, RDA, and permutation tests were performed with CANOCO (v. 4.02 for Windows, Centre for Biometry Wageningen, Wageningen, The Netherlands). Broken-stick eigenvalues were obtained by running the identical PCA in PC-ORD (for Windows, MjM Software, Gleneden Beach, Oregon).

To evaluate the contribution of environmental variables and the interactions of those variables on individual LW characteristics, we used regression tree analysis, with CART software (v. 5.0, Salford Systems, San Diego, CA). Regression tree analysis using CART methods consist of using hierarchical arrangements of single environmental variables to split collections of a particular response variable (e.g. number of logjams per 100 m) into groups on a decision-tree. Optimal decision-trees represented the number and arrangement of groups with the lowest possible variance (measured by least squares) within the groups relative to any other possible grouping. Such a CART analysis quickly identifies strong interactions between explanatory variables and provides a relatively direct measure of the hierarchical level at which environmental variables correspond with response variables. For these regression tree analyses, we used untransformed values of the variables. We found the optimum tree regardless of size, with a minimum of two
cases in the parent node and one in any terminal node. The maximum number of nodes was 24, and learn and test sample sizes were also set to 24 (default in CART reflecting number of reaches). No penalties or weightings were used for any variable. The importance of a particular explanatory variable was calculated from its effect both as a primary splitter and as a surrogate or substitute for the reported primary splitter(s). All surrogates counted equally when calculating variable importance. The predictive ability of a tree is represented by the relative error, or the change in variance of groups after splitting.

One disadvantage to regression tree analysis is that it is not probabilistic, so the likelihood that an arrangement of variables arose from random chance cannot be represented by a traditional P-value. The performance of a regression tree model is, however, represented by the relative decrease in the variability (sum of squares) within groups after being divided by the model (this is termed the relative error). The accuracy of the model is determined by considering its relative error as data sets not used to create the model are processed. Because we had a limited dataset, we used 10-fold cross validation (Lewis 2000). In 10-fold cross validation, the data is split into 10 parts, and models are created 10 times, each time with a different 9 parts and using the remaining one part to test the model. The average size of the models--number of nodes on the trees--with the lowest relative error is used as the size of the optimal tree. Consequently, trees with different numbers of terminal nodes have different relative errors. A tree with relative error of 1.0 indicates that variability within the divided groups is no different from variability of the original group, and therefore the tree does not provide any increased predictive ability. Conversely, the closer the relative error is to zero, the better
the model allows predictability or separation of groups (i.e., variance within groups is minimal compared to variance between groups).

**Results**

**Variable selection**

We evaluated ten response variables, which were characteristics of LW and LWJ (Table 3.5) measured at 24 sites (reaches). We initially considered 18 environmental variables (Table 3.6), but eliminated 6 of them from ordination analysis. We retained wet width for ordination analysis rather than bankfull channel (BFC) width because it could be measured more exactly than BFC width. Wet width and estimated BFC width correlated strongly with each other (BFC width = 1.1994 (wet width) + 1.9991, $r^2 = 0.70$). The presence of lava inclusions in bedrock geology of the study sections was a linear combination of other variables so this variable was also excluded from the ordination analysis. We did not include quaternary geology in the ordination analysis because it remained the same for most reaches and so had little potential for differentiating patterns among reaches. We finally retained 12 environmental variables for ordination analysis: five representing riparian forests (the number of imminent recruits per 100m, the mean diameter of imminent recruits, the percent conifer of imminent recruits, the percent conifer of riparian trees in general, and old-growth classification), and 7 variables representing stream channel and valley geomorphology (reach gradient, reach sinuosity, reach wet width, reach channel confinement, distance from the reach to the headwaters, valley constraint, and section rock-plane bedding). We evaluated reach-level gradient, sinuosity, and width because differences between reaches
could potentially correspond with differences in LW and LWJ characteristics, but if attributes were similar within sections then reaches would still group together in ordinate space by section. Several of the environmental variables that we did include in our ordination analyses correlated strongly with each other, but these variables were included in the RDA to determine the relative strength of their correspondence with LW and LWJ characteristics. Initial exploratory analyses showed that the data from the second-growth CLP section formed a group of extreme outliers with disproportionate influence on ordination results, thus they were excluded from the final analysis.

For regression tree analysis we used only the geomorphic variables and stand age (old-growth or second-growth). We also included in regression tree analysis the variable representing bankfull channel width, lava inclusions, and a variable representing quaternary geology (Table 3.6). All riparian forest variables were excluded from regression tree analysis, because our primary interest was evaluating how geomorphic factors corresponded with LW characteristics.

**Large wood characteristics**

Variability in the data set corresponded with more than one trend in ordination space. Broken-stick eigenvalues exceeded one (1.0) for the first four PCA eigenvalues, indicating significant gradients for those axes (Table 3.7). The first two axes captured 65.2% of the variability in the characteristics of loose and aggregated wood we measured in the study. The first axis corresponded with a gradient of increasingly large pieces of wood and more pieces of wood in LWJ, and it is along this gradient that reaches from forests of different age seemed to vary (Figure 3.2). Reaches from old-growth forest
appeared to have larger diameter and larger volume pieces of wood and to have more pieces of wood in LWJ than did reaches in second-growth forests. Notable exceptions were two reaches from the old-growth LRP that appeared to have smaller pieces and fewer pieces per LWJ, similar to reaches of second-growth forests. The second axis corresponded with the number of LWJ and pieces of loose wood and with the amount of channel spanned by LWJ, and it is along the second axis that geomorphic sections appeared to separate. Reaches from high-gradient (HRT) and clay-lake plain (CLP) geomorphic sections appeared to contain the most pieces of loose large wood with few LWJ and LWJ spanning the least amount of the channel. In contrast, reaches from low-gradient (LRP) sections appeared to contain fewer pieces of wood, but more LWJ and LWJ that spanned more of the channel.

Redundancy analysis (RDA) explained 86.7% of the variability we measured in LW characteristics (Table 3.8). Patterns of reach separation and grouping in the RDA are essentially identical to patterns in the PCA (Figure 3.3.a). Scores representing reaches generally grouped together by section, indicating less variability in the set of LW characteristics within geomorphic sections than between geomorphic sections. Again, reaches from the old-growth LRP section grouped closely together with reaches from the second-growth LRP section, while reaches from other old-growth geomorphic sections did not group closely with their counterparts from second-growth forest. An RDA biplot (Figure 3.3.b) represents two factors controlling LWJ and LW characteristics: The first is related primarily to stand age, the amount of conifer in riparian forests, and the distance from the headwaters (axis 1), and the second is related to rock-plane bedding, channel confinement, and sinuosity (axis 2). All reaches from the old-growth forest except for
reaches from the LRP section occur on the positive side of axis 1, indicating that in this study old-growth forests with relatively high proportions of riparian conifers, medium channel constraint, and far from headwaters contained larger pieces of LW (both loose and in LWJ), and had LWJ containing the most pieces of LW. However, reaches without rock-plane bedding, with low channel confinement, and relatively high sinuosity contained the most abundant LWJ that spanned the largest proportion of the channel.

Several environmental factors that we measured correlated strongly with each other as can be seen by their similar associations with ordination axes. Along axis 1, the proportion of conifers in riparian forests and imminent fallers was positively correlated ($r = 0.85$, $P < 0.01$), and stand age as represented by the binary old-growth variable correlated strongly with the proportion of conifers (overall riparian forest: $r = 0.90$, $P < 0.01$; only imminent recruits: $r = 0.78$, $P < 0.01$). Also corresponding with axis 1, reach wet width correlated with distance to headwaters ($r = 0.93$, $P < 0.01$). Reach wet width also correlated strongly with the abundance of imminent recruits ($r = -0.70$, $P < 0.01$), although the abundance of imminent recruits was not a major factor ordering the gradient along axis 1. For factors primarily associated with axis 2, channel gradient varied inversely with valley constraint ($r = -0.89$, $P < 0.01$). Reach-level gradient was not correlated with reach sinuosity, the presence of rock-plane bedding, or reach wet width ($|r| < 0.32$ for all).

Correlation between variables resulted in redundancy, so that substantial variability in LW characteristics could be explained by more than one environmental factor. With regard to geomorphic environmental factors compared to riparian forest factors, geomorphic factors alone or in combination explained 38.5% of the variability in
LW characteristics, riparian forest factors uniquely explained 18.4% of the variance, and the intersection of the two categories of environmental factors (i.e., the redundant portion) was 29.8% (Figure 3.4). Correlation among variables was high enough that no single variable uniquely explained a significant proportion of variance in LW characteristics when all other variables were treated as covariates ($P > 0.05$, permutation test for each model in variance partitioning). When considered alone (without accounting for covariance of other environmental factors), however, several individual variables corresponded with significant amounts of variability in LW characteristics (Table 3.9). When we performed single-factor RDA (only one explanatory variable and no covariates), the following variables each significantly explained about 30% of the variability in LW characteristics: channel confinement, distance to the headwaters, percent conifer in the riparian forest, percent conifer in imminent recruits, and old-growth classification. Wet width alone significantly explained 17% of the variance, and the presence of rock-plane bedding significantly explained 16% of the variance in LW characteristics.

**Regression tree analysis**

Regression tree analysis computed an optimal decision tree for each LW and LWJ characteristic from which patterns of associations between environmental variables and single LW or LWJ characteristics can be evaluated, and which quantify the thresholds between most similar groupings of values of each characteristic. With regards to trends or general patterns, when optimal regression trees were compared, channel wet width figured as the single most important geomorphic factor in splitting LW characteristics.
(i.e., channel wet width had the highest average importance when considered across all response variables; Table 3.10). Bankfull channel width and distance from headwaters, which were both strongly correlated with channel wet-width, also had high importance rankings, although bankfull channel width ranked higher for correspondence with LWJ while distance from headwaters ranked higher on corresponding with characteristics of loose pieces of LW.

Channel gradient and sinuosity also received fairly high importance ratings for their roles splitting groups of both loose LW and LWJ. Valley constraint, the presence of lava inclusions, and quaternary geology apparently did not correspond strongly with variability of individual LW or LWJ characteristics and remained relatively unimportant in regression tree model predictions. Stand age (old-growth classification) only figured as a primary splitter in the percent of channel spanned by LWJ, and received very low importance ratings for other LW characteristics.

Multi-level, optimal trees were created for six response variables (PCJJ, JD, PSPAN, VPCLW, and LD), revealing simple interactions of geomorphic factors that improve predictability of those characteristics. Trends apparent from regression tree models indicated that different environmental factors related most strongly with different LW and LWJ characteristics, which was in agreement with ordination analyses that showed multiple trends organizing LW and LWJ (Table 3.11, 3.12). Large wood jams occurred about twice as frequently in sections without rock-plane bedding (4.0 ± 1.4 LWJ 100m⁻¹, n = 12) compared to sections with rock-plane bedding (1.6 ± 1.1 LWJ 100m⁻¹, n = 12). In reaches where rock-plane bedding was absent, LWJ also spanned more of the channel, with the greatest proportion of the channel spanned in the narrowest channels.
(60.2 ± 4.0%, n = 2). Where channels were rock-plane bedded, LWJ spanned less of the channel, and the span was less in second-growth reaches (2.2 ± 1.9%, n = 6) than in old-growth reaches (25.5 ± 10.4%, n = 6). Reaches with medium channel confinement and reach gradient less than 0.016 m m⁻¹ contained LWJ with the most pieces (28.9 ± 3.7, n = 2) and highest volume (13.1 ± 2.2 m³, n = 2): averaging at least two times more pieces and higher volume than LWJ in reaches with high or low channel confinement. The smallest diameter pieces occurred in LWJ in the narrowest, steepest reaches (bankfull channel width > 6.4 m and gradient > 0.024 m m⁻¹; 17.6 ± 1.7 cm, n = 4) of the second-growth forest. Sinuosity created four of six terminal nodes relating to the diameter of pieces in LWJ, with smaller pieces in LWJ in more sinuous reaches. In comparison, variability among reaches in the abundance of pieces of large wood prevented an optimal split to be found for most, although 4 reaches with very low gradient contained the fewest pieces of LW (3.8 ± 3.8 pieces/100m, n = 4). All four reaches with gradient less than 0.007 m m⁻¹ and few pieces of loose LW occurred in second growth, with three of the reaches occurring in the CLP section, and one in the LRP section. As with the diameter of pieces of LW LWJ⁻¹ (JD), larger loose pieces occurred where sinuosity was lower (41.3 ± 1.7 cm, n = 2). Both low sinuosity reaches with larger diameter pieces were in the second-growth CLP. Reaches with lower sinuosity also contained pieces of greater volume, presumably because larger pieces were retained in lower sinuosity reaches. Reaches with low confinement contained about 20% lower absolute proportion of loose conifer LW pieces (0.3 ± 0.1%, n = 10) compared to reaches with high or medium confinement. No optimal tree could be generated to split groups of LW volume per LWJ (i.e., relative error was greater than 1.0 for every possible tree). We also discerned no
general threshold values for environmental variables overall. For example, the levels of
sinuosity that split reaches based on the number of pieces of LW in LWJ (sinuosity ≤
1.231 and ≤ 1.129) were different from the values of sinuosity that split reaches based on
the number of pieces of loose LW (sinuosity ≤ 1.667) or volume per piece of loose large
wood (sinuosity ≤ 1.063 and ≤ 1.028).

Discussion

Geomorphic factors

Numerous studies have documented changes in wood characteristics, and
systematic changes in large wood jam characteristics, related to stream order (e.g., Bilby
et al. 2002, Wing and Skaugset 2002). Stream order is, however, a proxy measure for
other stream characteristics that affect large wood, including the width of the stream
(Braudrick and Grant 2001; Gurnell et al. 2003) and physiographic context (Ward and
Stanford 1983, Poole 2002, Swanson 2003), so changes in LW and LWJ characteristics
such as we measured can be expected to occur with more specific environmental factors
than just stream order.

We measured LW and LWJ characteristics in streams where many changes in the
stream channel were not a result of changes in stream order. We found that stream width
related significantly to LW and LWJ characteristics, particularly with the size
(represented by the volume and diameter) of pieces of loose LW and in LWJ (increased
channel width corresponded with increasingly large LW, and LWJ with larger and more
pieces of LW). Regression tree analysis identified channel width in combination with
rock-plane bedding as a primary factor related to the amount of channel spanned by LWJ. Channel width directly influences wood retention because long pieces relative to channel width contact the banks most frequently (Braudrick and Grant 2001). Channel width increased with distance from the headwaters, suggesting that the occurrence of more and larger pieces of wood in wider channels reflected not only recruitment from forests proximate to geomorphic sections but also instream transport of wood pieces, and showed that in this study, stream width corresponded with changes occurring in other rivers as a function of stream order.

Regional variation influences with the effect of stream order on LW characteristics, and has been predicted to change among regions. For example, in Oregon, 1st and 2nd order streams are narrow and occur in steep mountain valleys with very large trees (Keller and Swanson 1979, Nakamura and Swanson 1993, 2003). Our study area presents just one of many possible contrasting regional geomorphologies: headwater streams in low-gradient, relatively broad valleys with high-gradient, narrow valley channels occurring further downstream in discrete segments. Keller and Swanson (1979) proposed that in stream systems where pieces were small relative to the channel size, the typical arrangement of pieces would shift to lower orders, so that channel-spanning LWJ which occurred in 3rd to 5th order streams in western Oregon would occur in lower order streams in other areas where streams were larger compared to pieces in them. We studied 1st and 2nd order streams where variation in stream size was relatively small from headwaters to the mouths in Lake Superior, and trees were generally much smaller than in the Pacific Northwest. We found that in the Little Carp River, LWJ characteristics corresponded with increasing stream width so that changes associated with
stream order in other studies occurred within streams of low order in this study, in keeping with previous predictions (Keller and Swanson 1979, Gurnell et al. 2002). We hypothesize that in systems where wood pieces and streams area small, patterns of LW structure will shift not only to lower orders, but also occur over shorter longitudinal distance as streams widen. Under conditions in which LW forms the primary anchor for LWJ, maximum LWJ abundance and size will occur where some wood pieces are large enough compared to stream size to anchor LWJ but stream size and associated stream flows are not large enough to move many pieces. However, we found that geomorphic factors other than stream width also corresponded consistently enough with LW and LWJ characteristics to form some recognizable patterns.

We found that sinuosity was primarily important in explaining the size of pieces occurring in the channel, and this is probably because higher sinuosity increased the trapping potential of a channel for smaller pieces (Braudrick and Grant 2001). Sinuosity plays a direct role in LW retention by increasing the contact of wood pieces with banks and beds, and by creating variable water flows with slow-flow pockets where wood may rest (Nakamura and Swanson 1994, Braudrick and Grant 2001). Sinuosity also increases stream capacity for actively recruiting wood as meanders cut banks (Nakamura and Swanson 1994).

Wing and Skaugset (2002) found with regression tree analysis that LW abundance in streams of western Oregon related primarily to stream gradient and bankfull width. We found that stream gradient alone (considering no other geomorphic factors) corresponded only poorly with observed changes in combinations of LW features. Channel gradient appeared to vary most directly with the abundance of loose pieces of
LW and inversely with LWJ abundance and percent of the channel spanned by LWJ.
Stream channel gradient relates directly to stream flow, with greater water power in high-gradient compared to low-gradient channels of the same cross sectional dimensions. However, high-gradient streams in mountainous areas are often small headwater streams so that the capacity of the stream to transport large wood pieces is limited by stream size (Nakamura and Swanson 1993). In our study area, the steepest channels occurred relatively far downstream from headwaters so the quantity of stream flow was relatively high in high-gradient geomorphic sections, which probably minimized the number of channel-spanning LWJ. Regression tree analysis identified channel gradient as a primary splitter of the number of pieces of LW, with fewer pieces of LW in lower gradient sections. The presence of few LW in low gradient settings (Table 3.11), however, primarily reflects the very low-gradient reaches in the Little Iron River clay-lake plain, where a large channel, rock-plane bedding, and few recruits discouraged the presence of LW.

Confinement of the channel directly affects LW distributions by controlling water power, affecting incoming wood (Nakamura and Swanson 1993), and increasing the contact of pieces of wood with banks. Regression tree analysis identified channel confinement as the most important factor involved in predicting the number and pieces of wood in LWJ and the abundance of conifer LW pieces. We also found that higher channel confinement corresponded with fewer LWJ that spanned less of the channel. In addition to its direct effects on wood pieces, channel confinement in our study corresponded with factors (rock-plane bedding, reach gradient, and sinuosity) that affected both the transport ability of the channel and its recruitment potential, so that in
channels with higher confinement, transport of wood was probably increased and recruitment diminished.

Valley constraint affects LW in streams by controlling mass recruitment of wood from slope failures (Keller and Swanson 1979) and by controlling lateral (floodplain) connectivity that affects wood recruitment and water power. Channel constraint in general appeared to be relatively unimportant in LW or LWJ abundance or structure in our study reaches, most likely because low and medium constraint only corresponded weakly with LW characteristics. High valley constraint appeared to correspond relatively strongly with LW characteristics, probably because high valley constraint also correlated positively with high channel gradient, high channel confinement, and rock-plane bedding, all factors associated with high wood transport potential.

Rock-plane bedding represents low channel roughness, which both increases water flow and minimizes trapping capacity. Large wood is usually less abundant in reaches with plane-bed structure (Montgomery et al. 1995). When considered as the only environmental factor, rock-plane bedding significantly explained about 15% of the variability we observed in LW characteristics overall, and particularly corresponded inversely with the number of LWJ and percent of channel spanned by LWJ. Rock-plane bedding appeared to influence LWJ characteristics more strongly than it influenced loose LW characteristics, suggesting that pieces of LW loose in rock-plane bedded stream segments are probably transient. We noticed, as did Long (1987), that large LWJ occurred downstream from rock-plane bedded sections, probably because wood that was transported through the smooth rock-plane bedded reaches was trapped when it encountered rougher downstream channel conditions.
Bedrock geology and quaternary geology both influence valley and therefore stream geomorphology. In our study, however, connections between the underlying geologic features and proximate controls on LW in streams were moderated enough by intervening stream channel structure that neither bedrock geology nor quaternary geology figured as primary correlates with variability in LW characteristics.

Large wood pieces and LWJ corresponded differently with stream channel geomorphology, as explained above. To summarize these differences: pieces of LW corresponded in abundance and size primarily to sinuosity, gradient and channel wet width, while LWJ abundance, volume, the number of pieces, and channel-spanning corresponded primarily to channel confinement, rock-plane bedding, and distance from the headwaters. We suggest that loose pieces of large wood were overall more mobile than LWJ and responded directly to their interactions with the channel bed and banks. Channel sinuosity and wet-width correspond especially strongly with increased trapping potential for pieces of LW (Braudrick and Grant 2001). Large wood jams, in contrast, depended on the instream transport of many pieces of LW and trapping sites sufficiently well-developed to provide high resistance to local streamflow. Channel confinement and rock-plane bedding probably inversely related with possibilities for wood to be trapped and aggregated, and distance from the headwaters reflected both greater stream size (capable of moving more pieces of wood into LWJ) and more recruitment possibilities from upstream.
Riparian forest and stand age

Forest management also influences LW characteristics as it influences the types and amounts of wood available to the stream, riparian forest dynamics, and hydrologic processes (Slaymaker 2000, Boyer et al. 2003). Harvesting riparian forests generally results in smaller LW in streams (Baille et al. 1999, Elosegi et al. 1999, Rot 2000, Slaymaker 2000, Collins et al. 2002), and repeated harvesting near streams can lead to decreased amounts of wood in streams (Hering et al. 2000, Diez et al. 2001). While short term effects of timber harvesting vary, some researchers have shown that logging may lead to increased wood in streams over the short term as slash is recruited to streams or as forest dynamics change (e.g., increased windthrow in riparian buffer strips along streams; Grizzel and Wolff 1998, Baille et al. 1999, Gomi et al. 2001). We found that streams in the second-growth forests contained fewer pieces of LW in LWJ, less volume of wood in LWJ, and smaller diameter pieces of loose LW and in LWJ than in old-growth forests. Old-growth forests also contained more abundant conifers and overall larger trees than did second-growth forests, so the source-pool of wood contained larger potential pieces that will decompose more slowly in streams associated with old-growth forests than second-growth forests.

Large wood and LWJ characteristics in the old-growth low-gradient (LRP) section were very similar to LW and LWJ characteristics in streams in second-growth forest, most likely because recruitment processes are similar between those sites. Natural processes led to smaller trees and a higher proportion of deciduous trees in the old-growth low-gradient section than in other old-growth geomorphic sections. The extremely low number of LWJ in the second-growth clay-lake plain (CLP) section likely
resulted from timber harvesting activities that reduced the size of riparian trees along the Little Iron River (especially in the CLP section), which in combination with high stream flows (widest channel measured) and relatively smooth bedding (rock-plane), created conditions where the channel would not retain very much of the available wood. The pieces of wood that remained in the second-growth CLP section are larger on average than pieces that remain in other study sections because smaller pieces were rapidly lost from the second-growth CLP. The combination of timber harvest and channel characteristics have created conditions in the second-growth clay-lake plain (3rd order) where LW is present along channel margins similar to patterns recognized by Keller and Swanson (1979) for 5th order streams.

Imminent recruits represented wood that would enter the stream individually within a few years. The number of imminent recruits related very poorly with any LW characteristics, showing that current individual inputs of LW do not represent the standing stock of LW in the stream, which is not surprising given the potential for mass inputs from slope failures and long retention times of wood in streams (Hyatt and Naiman 2001). Rot et al. (2000) reported that the diameter of LW in streams of old-growth forests in western Washington exceeded the diameter of trees in riparian forests. We found, however, the diameter of riparian snags almost always exceeded the diameter of LW and LW in LWJ in the Little Carp River (Table 3.5, 3.6), and hypothesize that the differences are because of breakage of small pieces when entering the river (leading to high contributions of small diameter pieces to mean values) coupled with fairly high retention of LW in most sections (preventing the loss of smaller pieces).
Pieces of conifer may behave differently than hardwood pieces in streams because of shape and resistance to decomposition (Hyatt and Naiman 2001). Hyatt and Naiman (2001) reported that hardwood pieces were depleted more rapidly from streams than were conifer pieces, leading to a higher proportion of conifers and a lower proportion of hardwoods in LW in the stream than in riparian forests. We found that the percent of conifers in the riparian forest was higher than the percent of conifer in LW in the streams except in second-growth forest, where more conifer occurred in LW in many stream reaches than occurred in the forest. Conifer in LW in second-growth forests probably represents historical inputs.

**Statistical analysis**

Regression tree analysis has several advantages that made it well-suited for creating predictive models of LW in this case: (1) It identifies interactions. Identifying and interpreting interactions is cumbersome in ordination analyses like RDA, but straightforward in regression tree analysis. (2) It is distribution free, so underlying distributions of response and environmental variables need not be known or assumed. We assumed linear distributions for ordination analyses, but this was because we considered linear distributions more likely to approximate LW characteristics than unimodal distributions; actual distributions are of course unknown. (3) It operates with both categorical and continuous predictor variables, both of which we had in the set of environmental factors we measured. Dummy variables are not needed, which improves the ease of interpreting results, (4) Resulting decision trees are simple to interpret, and the software is easy and quick to operate. Restoration managers can use similar regression
tree techniques to rapidly and clearly identify parameters to guide restoration decisions relating to LW characteristics.

The importance of an environmental factor reflects the role of that factor as a primary splitter (evident in the optimal tree) and as a surrogate splitter (not evident in the optimal tree, but which would provide just as optimal or nearly as optimal splits as the factors shown on the final trees). Thus an environmental factor that was consistently a good surrogate for other variables in a model could have a higher importance ranking than a variable that provided the best split once. Although channel wet-width did not figure as a primary splitter in any optimal regression tree, it consistently formed good surrogate splitters for other variables, and so had importance ratings greater than 50% for 9 of the 10 response variables, and consequently the highest average importance rating.

Perhaps the most important concern for regression tree analysis using CART methodology is that optimum trees may change drastically when explanatory variables are added or when settings are changed (e.g., 20-fold rather than 10-fold cross validation leads to different trees) especially with small datasets like ours. The model generated by CART represents the optimum model for that specific set of variables and settings, and is therefore not invariable. Quantitative relationships we report represent some of the only numerical reference information relating old-growth characteristics with LW characteristics in streams of old-growth forests in the Lake States, but because of the limited nature of the study and the sensitivity of predictive models to additional data, reference relationships need to be tested further. The accuracy of the models we present here may be tested and enhanced with independent data sets from other rivers in other
geographic regions or with expanded data sets from the northern Great Lakes region where we performed the study.

**Management implications**

Direct addition of wood to streams during stream restoration projects occurs at small scales (each piece of wood must be added), and engineering wood or logjam introductions must use information at small scales where local conditions will affect forces on individual logs (Abbe et al. 2003). At the same time, ecological restoration necessitates construction of patterns larger than individual wood structures or short stream reaches. One prescription for the amount or type of direct addition of large wood throughout a stream will not suffice for channels where forests and streams show longitudinal discontinuities (Bisson et al. 2003) as they do in the Porcupine Mountains. Recognizing LW and LWJ characteristics that correspond with large-scale geomorphology will allow stream restoration practitioners to plan wood additions that create spatial and temporal variation where it is most favored by natural controlling factors.

Managers should design variability in LW and LWJ abundance, size, and span of the channel to correspond with stream corridor geomorphology if they desire to mimic the Little Carp River, which is an anthropogenically undisturbed river flowing through old-growth forest. Our results suggest that patches of LW and LWJ abundance occur along the stream channel in accordance with geomorphology, suggesting that clusters of LW structure may be placed at intervals along river channels corresponding with geomorphic patches. For instance, we show that high channel confinement and rock-
plane bedding are inversely related to LW and LWJ abundance in both old-growth and second-growth forests, suggesting that it would mimic old-growth conditions to restore fewer LW structures to stream segments with rock-plane bedding and high channel confinement.

The patchy nature of streams with inherent complexity as shown by the Little Carp River, the Union River, and the Little Iron River, indicates some of the difficulty in planning direct manipulations of LW in streams to mimic natural processes. Managing riparian forests to favor natural wood additions (passive restoration) seems to be favored where stream geomorphology remains intact enough to self-regulate LW distribution (Collins and Montgomery 2002, Bisson et al. 2003, Boyer et al. 2003).

References


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<table>
<thead>
<tr>
<th>River</th>
<th>Forest</th>
<th>Geomorphic Section</th>
<th>Reach Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little Carp</td>
<td>old-growth</td>
<td>clay-lake plain (CLP) mid-gradient, bedrock controlled,</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>transverse bedding (MRT) high-gradient, bedrock</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>controlled, transverse bedding (HRT) low-gradient,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>bedrock controlled, parallel bedding (LRP)</td>
<td></td>
</tr>
<tr>
<td>Little Iron</td>
<td>second-growth</td>
<td>clay-lake plain (CLP) mid-gradient, bedrock controlled,</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>transverse bedding (MRT) high-gradient, bedrock</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>controlled, transverse bedding (HRT) low-gradient,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>bedrock controlled, parallel bedding (LRP)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1. Summary of geomorphic study sections in the Porcupine Mountains Wilderness State Park, Northern Michigan.
### Response Variable

#### Large wood jam variables
- Jams/100m: J100M, number/100m
- Number of pieces per jam: PCJJ, number/LWJ
- Volume per jam: VJJ, m³/LWJ
- Mean diameter per piece of LW in jams: JD, cm
- Mean volume per piece of LW in jams: VPCLWJ, m³/piece/LWJ
- Percent of wet channel spanned by the jam: PSPAN, %

#### Loose large wood variables
- Number of pieces/100 m: LW100M, number/100m
- Mean diameter per piece of LW: LD, cm
- Mean volume per piece of LW: VPCLW, m³/piece
- Percent of conifer among LW: PCONLW, %

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>Abbreviation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jams/100m</td>
<td>J100M</td>
<td>number/100m</td>
</tr>
<tr>
<td>Number of pieces per jam</td>
<td>PCJJ</td>
<td>number/LWJ</td>
</tr>
<tr>
<td>Volume per jam</td>
<td>VJJ</td>
<td>m³/LWJ</td>
</tr>
<tr>
<td>Mean diameter per piece of LW in jams</td>
<td>JD</td>
<td>cm</td>
</tr>
<tr>
<td>Mean volume per piece of LW in jams</td>
<td>VPCLWJ</td>
<td>m³/piece/LWJ</td>
</tr>
<tr>
<td>Percent of wet channel spanned by the jam</td>
<td>PSPAN</td>
<td>%</td>
</tr>
<tr>
<td>Number of pieces/100 m</td>
<td>LW100M</td>
<td>number/100m</td>
</tr>
<tr>
<td>Mean diameter per piece of LW</td>
<td>LD</td>
<td>cm</td>
</tr>
<tr>
<td>Mean volume per piece of LW</td>
<td>VPCLW</td>
<td>m³/piece</td>
</tr>
<tr>
<td>Percent of conifer among LW</td>
<td>PCONLW</td>
<td>%</td>
</tr>
</tbody>
</table>

Table 3.2. Variables used to describe large wood jams and loose large wood characteristics in forests in or near the Porcupine Mountains Wilderness State Park, Northern Michigan.
<table>
<thead>
<tr>
<th>Class</th>
<th>Diameter</th>
<th>Length</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-5 m</td>
<td></td>
<td>0.04 m³</td>
</tr>
<tr>
<td>2</td>
<td>10-20 cm</td>
<td>6-10 m</td>
<td>0.13 m³</td>
</tr>
<tr>
<td>3</td>
<td>&gt;10 m</td>
<td></td>
<td>0.19 m³</td>
</tr>
<tr>
<td>4</td>
<td>21-50 cm</td>
<td>6-10 m</td>
<td>0.72 m³</td>
</tr>
<tr>
<td>5</td>
<td>&gt;50 cm</td>
<td>6-10 m</td>
<td>1.53 m³</td>
</tr>
<tr>
<td>6</td>
<td>1-5 m</td>
<td>&gt;10 m</td>
<td>0.51 m³</td>
</tr>
<tr>
<td>7</td>
<td>21-50 cm</td>
<td>&gt;10 m</td>
<td>2.25 m³</td>
</tr>
<tr>
<td>8</td>
<td>&gt;50 cm</td>
<td>6-10 m</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>&gt;10 m</td>
<td>&gt;10 m</td>
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Table 3.3. Classification of size and volume used to characterize LW pieces in study streams.
<table>
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<tr>
<th>Environmental Variable</th>
<th>Abbreviation</th>
<th>Units</th>
</tr>
</thead>
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<tr>
<td><strong>Imminent recruit (IR) variables</strong></td>
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<td></td>
</tr>
<tr>
<td>Number IR/100m</td>
<td>SF100M</td>
<td>number/100m</td>
</tr>
<tr>
<td>Mean diameter of IR</td>
<td>SD</td>
<td>cm</td>
</tr>
<tr>
<td>Percent conifer among IR</td>
<td>PCONSF</td>
<td>m</td>
</tr>
<tr>
<td><strong>Riparian forest variables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent snags in riparian forest</td>
<td>RIPS</td>
<td>%</td>
</tr>
<tr>
<td>Mean diameter breast height of stems in riparian forest</td>
<td>RIPD</td>
<td>cm</td>
</tr>
<tr>
<td>Percent conifer in riparian forest</td>
<td>PCONRI</td>
<td>%</td>
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<tr>
<td><strong>Reach-level variables</strong></td>
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<tr>
<td>Channel gradient</td>
<td>GRAD</td>
<td>m/100 m</td>
</tr>
<tr>
<td>Channel sinuosity</td>
<td>SINU</td>
<td>m/m</td>
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<tr>
<td>Channel confinement</td>
<td>CONFIN</td>
<td>low, medium, high</td>
</tr>
<tr>
<td>Wet width</td>
<td>WETW</td>
<td>m</td>
</tr>
<tr>
<td>Bankfull channel width</td>
<td>BFCW</td>
<td>m</td>
</tr>
<tr>
<td>Distance from headwaters</td>
<td>DISTHW</td>
<td>m</td>
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<tr>
<td><strong>Section-level variables</strong></td>
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<td></td>
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<tr>
<td>Valley constraint</td>
<td>CONSTR</td>
<td>low, medium, high</td>
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<td>Bedding</td>
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<td>Quaternary geology</td>
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<td>Forest age</td>
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Table 3.4. Variables used to describe site characteristics of forests in or near the Porcupine Mountains Wilderness State Park, Northern Michigan
<table>
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<tr>
<th>SECTION</th>
<th>FOREST CLASS</th>
<th>REACH</th>
<th>Variable</th>
<th>J100M</th>
<th>PCJJ</th>
<th>VJJ</th>
<th>JD</th>
<th>VPCLWJ</th>
<th>PSPAN</th>
<th>LW100M</th>
<th>LD</th>
<th>VPCLW</th>
<th>PCONLW</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Units</td>
<td>no./100m</td>
<td>no./LWJ</td>
<td>m3/LWJ</td>
<td>cm</td>
<td>m3/pc</td>
<td>%</td>
<td>no./100m</td>
<td>cm</td>
<td>m3/pc</td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>CLP</td>
<td></td>
<td>no./LWJ</td>
<td>2.67</td>
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<td>4.62</td>
<td>26.75</td>
<td>0.43</td>
<td>31.88</td>
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<tr>
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<td>19.31</td>
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<tr>
<td>2</td>
<td>MRT</td>
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<td>10.95</td>
<td>27.98</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>no./LWJ</td>
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<td>5.17</td>
<td>1.16</td>
<td>23.34</td>
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</table>

Table 3.5. Large wood and large wood jam (LWJ) characteristics. Note: ¹ PCONLW was not measured for the second-growth CLP section, so percent conifer in riparian forest (PCONRI) was substituted to fill those blanks.
| SECTION | FOREST    | REACH | SF100M | PCONSF | SD | PCONRI | SNU | GRAD | WETW | BFCW | CONFIN | DISTHW | CONSTR | RPBED | LAVAINC | QUA_GEO |
|---------|-----------|-------|--------|--------|----|--------|-----|------|------|------|--------|--------|--------|-------|--------|--------|--------|
| CLP     | OLD-GROWTH| 1     | 7.33   | 45.5   | 26 | 57.7   | 1.31| 1.92 | 8.83 | 18.58| HIGH   | 15.94  | LOW    | YES   | NO     | LSS    |
|         |           | 2     | 10.33  | 71.0   | 35 | 57.7   | 1.08| 2.11 | 6.80 | 13.90| HIGH   | 16.84  | LOW    | YES   | NO     | LSS    |
|         |           | 3     | 7.00   | 81.0   | 29 | 57.7   | 1.47| 0.93 | 6.22 | 12.98| MED    | 17.44  | LOW    | YES   | NO     | LSS    |
| MRT     | OLD-GROWTH| 1     | 8.00   | 66.7   | 30 | 51.5   | 1.15| 1.79 | 4.60 | 6.74 | MED    | 11.33  | MED    | NO    | YES    | LSS    |
|         |           | 2     | 13.00  | 56.4   | 34 | 51.5   | 1.22| 1.47 | 4.48 | 11.00| MED    | 10.43  | MED    | NO    | YES    | LSS    |
|         |           | 3     | 6.00   | 50.0   | 33 | 51.5   | 1.24| 2.31 | 4.75 | 10.91| MED    | 10.73  | MED    | NO    | YES    | LSS    |
| HRT     | OLD-GROWTH| 1     | 3.00   | 77.8   | 33 | 51.4   | 1.04| 4.47 | 7.03 | 11.16| HIGH   | 9.78   | HIGH   | YES   | YES    | TELL   |
|         |           | 2     | 6.00   | 72.2   | 37 | 51.4   | 1.38| 3.73 | 4.69 | 10.30| MED    | 9.18   | HIGH   | YES   | YES    | TELL   |
|         |           | 3     | 4.00   | 66.7   | 39 | 51.4   | 1.11| 3.92 | 6.58 | 9.30 | HIGH   | 9.48   | HIGH   | YES   | YES    | TELL   |
| LRP     | OLD-GROWTH| 1     | 8.21   | 43.5   | 29 | 39.4   | 1.18| 2.20 | 3.63 | 2.60 | LOW    | 1.10   | LOW    | NO    | NO     | TELL   |
|         |           | 2     | 8.93   | 52.0   | 20 | 39.4   | 1.56| 1.63 | 2.63 | 2.35 | LOW    | 1.34   | LOW    | NO    | NO     | TELL   |
|         |           | 3     | 6.43   | 27.8   | 22 | 39.4   | 1.34| 1.11 | 2.62 | 3.92 | LOW    | 1.38   | LOW    | NO    | NO     | TELL   |
| CLP     | SECOND-GROWTH| 1   | 0.04   | 31.0   | 20 | 31.0   | 1.04| 0.12 | 10.67| 11.33| LOW    | 24.65  | LOW    | YES   | NO     | LSS    |
|         |           | 2     | 0.04   | 31.0   | 20 | 31.0   | 1.15| 0.02 | 12.00| 15.00| LOW    | 24.35  | LOW    | YES   | NO     | LSS    |
|         |           | 3     | 0.04   | 31.0   | 20 | 31.0   | 1.02| 0.35 | 12.00| 13.43| LOW    | 24.06  | LOW    | YES   | NO     | LSS    |
| MRT     | SECOND-GROWTH| 1  | 13.33  | 25.0   | 20 | 19.8   | 1.45| 2.34 | 2.07 | 4.81 | LOW    | 3.19   | MED    | NO    | YES    | LSS    |
|         |           | 2     | 8.33   | 28.0   | 26 | 19.8   | 1.28| 1.89 | 3.19 | 5.33 | MED    | 3.49   | MED    | NO    | YES    | LSS    |
|         |           | 3     | 12.33  | 16.2   | 23 | 19.8   | 1.14| 2.40 | 3.10 | 4.11 | MED    | 2.89   | MED    | NO    | YES    | LSS    |
| HRT     | SECOND-GROWTH| 1  | 4.67   | 28.6   | 31 | 25.5   | 1.10| 2.57 | 4.06 | 5.06 | HIGH   | 4.18   | HIGH   | YES   | YES    | TELL   |
|         |           | 2     | 10.00  | 6.7    | 32 | 25.5   | 1.17| 2.53 | 3.84 | 5.06 | HIGH   | 4.03   | HIGH   | YES   | YES    | TELL   |
|         |           | 3     | 4.67   | 42.9   | 28 | 25.5   | 1.08| 5.35 | 4.33 | 6.16 | HIGH   | 3.88   | HIGH   | YES   | YES    | TELL   |
| LRP     | SECOND-GROWTH| 1  | 1.67   | 32.0   | 32 | 30.0   | 1.45| 0.80 | 5.90 | 7.55 | LOW    | 5.59   | LOW    | NO    | NO     | LSS    |

Table 3.6. Values for environmental factors measured at main-channel reaches of rivers in or near Porcupine Mountains Wilderness State Park, Northern Michigan. Note: 1 SF100M, PCONSF, SD were not measured at the reach level for the second-growth CLP, so blanks were filled with section-level data from riparian forests for analyses.
<table>
<thead>
<tr>
<th>Axis</th>
<th>1</th>
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<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
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<td>0.207</td>
<td>0.112</td>
<td>0.097</td>
</tr>
<tr>
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<td>2.929</td>
<td>1.929</td>
<td>1.429</td>
<td>1.096</td>
</tr>
<tr>
<td>Cumulative % total variance</td>
<td>44.4</td>
<td>65.2</td>
<td>76.4</td>
<td>86.1</td>
</tr>
</tbody>
</table>

Table 3.7. Summary of principal components analysis (PCA) with large wood characteristics by 300 m reach. Note: Broken-stick eigenvalues greater than one indicate statistical significance for that axis.
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<tr>
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<th>Axis</th>
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<th>3</th>
<th>4</th>
<th>Total</th>
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</thead>
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<td>0.203</td>
<td>0.096</td>
<td>0.071</td>
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<tr>
<td>Section-environmental factor correlation</td>
<td>0.969</td>
<td>0.991</td>
<td>0.939</td>
<td>0.865</td>
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<td></td>
</tr>
<tr>
<td>Cumulative % total variance</td>
<td>41.5</td>
<td>61.8</td>
<td>71.4</td>
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<td></td>
</tr>
<tr>
<td>Cumulative % variance explained by environmental factors</td>
<td>47.9</td>
<td>71.3</td>
<td>82.4</td>
<td>90.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum of all canonical eigenvalues (trace)</td>
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<td></td>
<td></td>
<td>0.867</td>
<td></td>
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<tr>
<td>P-value</td>
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<td></td>
<td>0.01</td>
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Table 3.8. Summary of redundancy analysis (RDA) comparing large wood characteristics, geomorphology, and riparian factors.
<table>
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<th>Environmental variables</th>
<th>Sum of all canonical eigenvalues (proportion of total variance explained)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geomorphic variables</strong></td>
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<td></td>
</tr>
<tr>
<td>SINU</td>
<td>0.058</td>
<td>0.26</td>
</tr>
<tr>
<td>GRAD</td>
<td>0.087</td>
<td>0.12</td>
</tr>
<tr>
<td>WETW</td>
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<tr>
<td>CONFIN</td>
<td>0.308</td>
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</tr>
<tr>
<td>DISTHW</td>
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<td>CONSTR</td>
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</tr>
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<td>RPBED</td>
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<td><strong>Riparian forest variables</strong></td>
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<td>SF100M</td>
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<td>PCONSF</td>
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<tr>
<td>SD</td>
<td>0.072</td>
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<td>PCONRI</td>
<td>0.337</td>
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<td>OLD-GROWTH</td>
<td>0.279</td>
<td>0.01</td>
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</tbody>
</table>

Table 3.9. Variance explained by individual variables when used alone in redundancy analysis (RDA) with no covariables. Notes: 1 Each sum of canonical eigenvalues represents the proportion of variability corresponding only with the variable or group of the same row. 2 The P-value indicates the probability that the association between an environmental variable or group and response variables (LW characteristics) was random (determined by comparison of actual patterns with 199 random permutations).
Table 3.10. Importance of explanatory variables in splitting groups of LWJ and LW characteristics in regression tree analyses. Optimal trees were created with 10-fold cross validation. Importance is computed relative to the most important environmental variable by row, which is the variable used to make the most splits with least amount of heterogeneity in child nodes compared to parent nodes for that target variable (row). Importance reflects occurrence of a variable as a primary splitter and as a surrogate splitter in the optimum (minimum cost) tree. Notes: 1 No optimal tree found for VPCLWJ. 2 Variable importance for LWJ characteristics and loose LW characteristics was calculated as the proportion of the maximum mean importance comprised of the mean importance for a specific environmental variable. (Maximum mean importance occurred in both cases at wet width; mean wet width importance for LWJ characteristics = 63%, mean wet width importance for loose LW characteristics = 88%).

<table>
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<th>Sinuosity</th>
<th>Gradient</th>
<th>Wet Width</th>
<th>BFC width</th>
<th>Valley Constraint</th>
<th>Channel confinement</th>
<th>Rock-plane Bedding</th>
<th>Distance from headwaters</th>
<th>Forest Age</th>
<th>Lava Inclusion</th>
<th>Quaternary Geology</th>
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<td>17</td>
<td>64</td>
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<td>78</td>
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<td>42</td>
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<tr>
<td>all LWJ variables(^2)</td>
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<td>100</td>
<td>82</td>
<td>11</td>
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<td>19</td>
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<tr>
<td>all LW variables(^2)</td>
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<td>77</td>
<td>100</td>
<td>34</td>
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<td>31</td>
<td>0</td>
<td>94</td>
<td>5</td>
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Table 3.11. Summary of regression tree models relating characteristics of loose large wood pieces (LW) to geomorphic variables.

<table>
<thead>
<tr>
<th>LW variable</th>
<th>Relative error of optimal tree</th>
<th>Branches</th>
<th>Terminal node mean</th>
<th>Terminal node standard deviation</th>
<th>Number of reaches in terminal node</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW/100m (LW100M)</td>
<td>0.685 ± 0.241</td>
<td>GRAD ≤ 0.007</td>
<td>3.8</td>
<td>3.8</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>GRAD &gt; 0.007</td>
<td>18.7</td>
<td>5.4</td>
<td>20</td>
</tr>
<tr>
<td>Diameter cm/p</td>
<td>0.770 ± 0.264</td>
<td>SINU ≤ 1.667</td>
<td>41.3</td>
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</tr>
<tr>
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<td></td>
<td>SINU &gt; 1.667</td>
<td>22.3</td>
<td>3.8</td>
<td>22</td>
</tr>
<tr>
<td>m³/piece LW (VPCLW)</td>
<td>0.626 ± 0.167</td>
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<td>0</td>
<td>1</td>
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<tr>
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<td></td>
<td>SINU ≤ 1.063, SINU &gt; 1.028</td>
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<td>0.1</td>
<td>2</td>
</tr>
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<td></td>
<td></td>
<td>SINU &gt; 1.063, DISTHW ≤ 7.682</td>
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<td>% conifer LW (PCONLW)</td>
<td>0.544 ± 0.095</td>
<td>CONFIN = LOW</td>
<td>31.4</td>
<td>10.5</td>
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<tr>
<td></td>
<td></td>
<td>CONFIN = med, high</td>
<td>54.7</td>
<td>10.6</td>
<td>14</td>
</tr>
<tr>
<td>LWJ characteristic</td>
<td>Relative error of optimal tree</td>
<td>Branches</td>
<td>Terminal node mean</td>
<td>Terminal node standard deviation</td>
<td>Number of reaches in terminal node</td>
</tr>
<tr>
<td>--------------------</td>
<td>-------------------------------</td>
<td>----------</td>
<td>-------------------</td>
<td>-------------------------------</td>
<td>----------------------------------</td>
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<tr>
<td>LWJ/100m</td>
<td>0.936 ± 0.269</td>
<td>RPBED = yes</td>
<td>1.6</td>
<td>1.1</td>
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<td></td>
<td>RPBED = no</td>
<td>4</td>
<td>1.4</td>
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<tr>
<td>Pieces / LWJ</td>
<td>0.442 ± 0.088</td>
<td>CONFIN = high, low</td>
<td>6.7</td>
<td>3</td>
<td>17</td>
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<tr>
<td></td>
<td></td>
<td>CONFIN = med, GRAD ≤ 0.016</td>
<td>28.9</td>
<td>3.7</td>
<td>2</td>
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<td></td>
<td></td>
<td>CONFIN = med, GRAD &gt; 0.016</td>
<td>15.7</td>
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<tr>
<td>m³ / LWJ</td>
<td>0.405 ± 0.160</td>
<td>CONFIN = high, low</td>
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<td>1.3</td>
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<td></td>
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<tr>
<td>Diameter</td>
<td>0.460 ± 0.158</td>
<td>BFCW ≤ 6.447, GRAD ≤ 0.024, SINU ≤ 1.231</td>
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<td>cm / piece in LWJ</td>
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<td>22</td>
<td>1.1</td>
<td>5</td>
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<td></td>
<td></td>
<td>BFCW ≤ 6.447, GRAD &gt; 0.024</td>
<td>17.6</td>
<td>1.7</td>
<td>4</td>
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<td>(VJJ)</td>
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<td>1.2</td>
<td>3</td>
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<td></td>
<td></td>
<td>BFCW &gt; 6.447, DISTHW ≤ 17.141, SINU &gt;1.129</td>
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<td>6</td>
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<td>(JD)</td>
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<td>34.1</td>
<td>0.8</td>
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<td>% channel spanned</td>
<td>0.926 ± 0.221</td>
<td>RPBED = yes, FOREST = second-growth</td>
<td>2.2</td>
<td>1.9</td>
<td>6</td>
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<td>by LWJ</td>
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<td>RPBED = yes, FOREST = old-growth</td>
<td>25.5</td>
<td>10.4</td>
<td>6</td>
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<td>(PSPAN)</td>
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<td>2</td>
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<td></td>
<td>RPBED = no, BFCW &gt; 3.778</td>
<td>31.5</td>
<td>11.7</td>
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Table 3.12. Summary of regression tree models relating characteristics of large wood jams (LWJ) to geomorphic variables.
Figure 3.1. Map of the study area in the Porcupine Mountains. Locations of geomorphic sections are shown with boxes approximating their extent; CLP is the clay-lake plain, MRT is the mid-gradient, HRT is the high-gradient, and LRP is the low-gradient geomorphic section. Dotted lines represent boundaries between old-growth and second-growth forest.
Figure 3.2. Principal components analysis of large wood jam and loose large wood characteristics in 24 reaches of streams in old-growth and second-growth forests in or near the Porcupine Mountains Wilderness State Park, Northern Michigan. Three letter codes in the legend refer to geomorphic sections. Black filled symbols represent sites in old-growth forest. Gray filled symbols represent sites from second-growth forest. Axis 1 significantly represented 44.4% of the variance in LWJ and LW characteristics (broken-stick eigenvalue = 2.929). Axis 2 represented an additional 20.7% of the variance (broken-stick eigenvalue = 1.929). Variable identification codes are explained in Table 3.4.
Figure 3.3. Redundancy analysis comparing LWJ and LW characteristics to geomorphic and riparian variables. Both plots show the same RDA, but are separated for clarity. Solid lines represent LWJ and LW characteristics (response variables). Dashed lines represent continuous environmental variables, and open circles represent categorical environmental variables. Three letter codes in the legend refer to geomorphic sections. Black filled symbols represent reaches from old-growth forest and gray filled circles represent reaches from second-growth forest.
Figure 3.4. Results of variance partitioning based on redundancy analyses of LW and LWJ characteristics and environmental variables in 300 m reaches of streams in the Porcupine Mountains Wilderness State Park, Northern Michigan.
CHAPTER 4

LINEAR SPATIAL PATTERN OF LARGE WOOD JAMS IN STREAMS OF OLD-GROWTH AND SECOND-GROWTH FORESTS IN NORTHERN MICHIGAN

Introduction

Large wood (LW; pieces greater than 10 cm diameter and longer than 1 m) in streams represents an interaction between forests and streams in which hierarchical processes control the structural characteristics of LW (Richmond and Fausch 1995, Abbe 2000, Rot et al. 2000, Gurnell et al. 2002, Swanson 2003; Chapter 2). Pieces of wood distribute along river channels in response to complex, interacting processes of recruitment and transport that reflect stream channel processes, forest processes, and hydrologic processes, all within larger geomorphic settings (Benda and Sias 1998, Gurnell et al. 2002). Events leading to recruitment, trapping, and removal of wood from a stream influence wood at the scale of the wood itself, but exhibit the consequences of processes and limits at other scales, which can lead to patches of different wood abundance at different temporal and spatial scales along streams (Richmond and Fausch 1995, Swanson 2003). Spatially clustered or randomly distributed large wood in streams may result from the relative influence of recruitment that occurs in patches, transport
potential of the stream that varies with landscape setting, and a variable capacity of
stream structure for trapping wood (Swanson 2003).

Kraft and Warren (2003) proposed that naturally occurring wood debris dams in
streams distribute randomly after major riparian disturbances, as long as streamside
forests are relatively homogeneous (in age and species) and have been subject to similar
levels of disturbance. Based on the work of Montgomery et al. (1995) and others who
found regular spacing of pools and other geomorphological features along stream
channels, Kraft and Warren (2003) further predicted that over time fluvial processes
would lead to debris dams distributed at regular intervals along stream reaches. We
propose that the spatial distribution of LW will vary among patches of different stream
corridor geomorphology after a long period of natural redistribution in streams.

My previous work has shown that LW and large wood jam (LWJ) abundance
varies between segments of stream differentiated at the scale of at least a few hundred
meters where stream and valley geomorphology differ (Chapter 2). However, the spatial
arrangement of LW (or LWJ) in and among these different geomorphic patches is
unknown. It is possible that relatively small-scale processes lead to uniform distribution
of LW or LWJ within stream segments of similar geomorphology, as predicted generally
by Kraft and Warren (2003). It is also possible that segments of stream with different
abundance of LWJ associated with larger-scale geomorphology create spatial patterns
other than a uniform distribution when large areas of streams are evaluated that capture
the metastructure of several geomorphic elements (Poole 2002).

Conceptual models and predictions of spatial patterns of wood distribution in
streams require quantitative evaluation. While several studies have evaluated numbers of
large wood as they correlated with geomorphology at larger scales (e.g., Rot et al 2000),
few studies have attempted to evaluate spatial patterns of the distribution of large wood
or jams statistically (Wing et al. 1999, Keim et al. 2000, Kraft and Warren 2003).
Consequently methods for statistical evaluation of spatial patterns are not well developed
and have rarely been applied to large wood in streams. The potential benefits of
quantitative analysis of patterns of large wood distribution include: statistically
analyzable reflections of ecological processes, a means for understanding complex
arrangements, and a means for comparing distributions between stream systems (Kraft
and Warren 2003). Quantifying spatial distributions of jams would also provide a tool
for planning and monitoring projects aimed at restoring ecological processes at scales
greater than the recognized influence of a single jam.

I quantitatively evaluated linear patterns of aggregation, segregation, and/or
random distribution of LWJ in streams at different scales (from 5 m to a few km) among
different geomorphic settings in old-growth and second-growth forests of northern
Michigan. These stream systems provide an excellent setting for testing predictions of
LWJ distribution patterns relating to long periods of LW distribution. Specifically, we
test the prediction LWJ distributes uniformly after a long period of redistribution in
streams surrounded by forests with constant structure and dynamics, based on a similar
prediction for debris dams by Kraft and Warren (2003). We also test whether relatively
large-scale patterns of LWJ distribution differed from smaller-scale patterns within
patches of different stream corridor geomorphology. To evaluate LWJ distribution
patterns we utilize a linear \( K \)-function analysis similar to that used by Kraft and Warren
(2003), which allows for a straightforward analysis of spatial pattern including
segregation of points along streams. We evaluate both the distribution of all LWJ in the bankfull channel, regardless of size or orientation, and the distribution of large wood dams (LWJ spanning 50% or more of the bankfull channel).

Methods

Study Site

I studied portions of six 1st through 3rd order streams in the Porcupine Mountains in Upper Michigan. Elevations in the Porcupine Mountains increase to 120 m above Lake Superior by about 5 km inland. The clay-lake plain along the shore of Lake Superior is covered with deep loam and silt loam soils on gentle (1-10%) north-facing slopes. Further inland, slopes are considerably steeper (30%) and are generally covered with 1 m or more of soil (Frelich 2002). The Porcupine Mountains form a curved ridgeline between a relatively flat upland and the clay-lake plain. Streams in the study area form in low-gradient areas in the flat inland areas of the Porcupine Mountains, descend steeply as they flow across lava inclusions that comprise the Porcupine Mountains, and then flow through moderate to low-gradient, clay-lake plains before entering Lake Superior.

Most of the study area occurred in the Porcupine Mountains Wilderness State Park (PMWSP) which preserves one of the largest (13,000 ha) virgin, old-growth, hardwood-hemlock forest in the Lake States (Frelich 2002). We studied four rivers in virgin old-growth forest in the PMWSP: Little Carp River, Big Carp River, Scott Creek, and Upper Carp River. Logging occurs currently and has occurred continuously for the last century in areas around the PMWSP. We studied segments of two rivers in this
second-growth forest landscape near the northeastern boundary of the PMWSP: Union River (mostly inside the PMWSP) and Little Iron River.

Old-growth forests of the PMWSP are mixed conifer-hardwood forests dominated by eastern hemlock (*Tsuga canadensis*, (L.) Carr.), northern white cedar (*Thuja occidentalis*, L.), yellow birch (*Betula alleghaniensis*, Britt.), and sugar maple (*Acer saccharum*, Hook). The furthest upstream portions of the Big and Little Carp Rivers, and the segments of the Upper Carp River we studied contained a relatively higher proportion of hardwood species than the downstream portions of the Little and Big Carp Rivers. Maximum tree height is approximately 40 m, with mean canopy tree height of 25 m and 60 cm mean diameter at breast height. The segments of these rivers that we studied were forested to the edge of the bankfull channel. Human influences in these old-growth forests is limited, primarily consisting of recreational hiking, camping, and fishing. Beaver activity was apparent in all rivers we studied in old-growth forest. No well-established beaver dams occurred in segments of stream that we studied during the period of data collection, however, because of high flows in the spring of 2003.

Second-growth forests in the study area of the Porcupine Mountains are similar in terms of species composition to the old-growth forests. Second-growth forests contain, however, a high proportion of hardwood species and smaller trees in some areas, especially maple (*Acer* spp), birch (*Betula* spp.), and ash (*Fraxinus* spp.). Dense patches of small balsam fir (*Abies balsamea* (L.) Mill.) also occur in riparian areas. Most of the Union River and Little Iron River forests grew to the edge of the river channels in segments we studied, and narrow strips (<10m) of uncut trees remained in the clay-lake plain of the Little Iron River where timber harvest has occurred within the last five years.
Unlike the old-growth areas studied, second-growth forests have experienced a variety of human-related disturbances including timber harvesting, limited mining, localized camping, and road building. Beaver dams in various states of repair were located in the upstream portions of the Union River and Little Iron River, although no active beaver dams occurred in streams segments we studied. Most beaver dams on the Little Iron River in our study area had been abandoned and washed through, but the thatching of wood from old dams was visible under current vegetation.

Bank slope failures and individual mortality associated with windthrow appear to be the most common sources of LW recruitment to streams in both old-growth and second-growth forests of the Porcupine Mountains. Seasonal precipitation can be heavy with 800-900 mm precipitation, up to 7 m of which occurs as snow (McNab and Avers 1994). The topography is, however, not conducive to avalanches, landslides, or other forms of mass wasting that are significant factors associated with large wood dynamics in the Pacific Northwest. Fires occur infrequently in these forests. Windstorms are common, however, and are responsible for mortality of individual trees and stands. The last major windstorm responsible for mass mortality in the study area occurred in 1953, affecting 1800 ha near the center of the PMWSP, around the northern, upstream end of the Little Carp River.

**Geomorphic Sections**

I identified four major stream valley types distinguished on the basis of stream valley geomorphology, including: a clay-lake plain, mid-gradient, high-gradient, and low-gradient settings (Figure 4.1). We studied sections of river encompassed in each
geomorphic setting. In the Little Carp, Big Carp, Upper Carp, and Union Rivers we surveyed three contiguous geomorphic sections, providing data for analysis of scales that included several units of visually different geomorphology. We also selected another 6 geomorphic sections to study in the other streams, for a total of 4 clay lake plain sections, 4 high-gradient, 4 mid-gradient, and 6 low-gradient sections (Table 4.1).

**LWJ and Stream Measurements**

Large wood jams (LWJ) in this study consisted of two or more pieces of LW in contact with each other and extending into the bankfull channel. We measured the distance along the channel to the approximate midpoint of each LWJ using a nylon tape or hip chain (Fremaco Fieldranger®). We represented one very long (80 m), loose aggregation of LW in the Little Carp River mid-gradient section with 4 points; all other LWJ were shorter and were represented by single points. Geospatial coordinates were obtained for most points using a global positioning system (Satloc SLXg3® backpack; Trimble® and Eagle Explorer® handheld) and entered points into a geographic information system (GIS) to generate distribution maps using ARCGIS (v. 9.0, ESRI, Redlands, CA).

I estimated gradient by measuring elevation at the upstream and downstream ends of each study section from 1:24,000, 30 m digital elevation models (DEM), or topographic maps where DEM data was unavailable, then dividing the change in elevation by the length of the surveyed channel. The sinuosity index was computed from GIS maps as the total channel distance between the furthest upstream and downstream points in a study section divided by the straight line distance between those two points. If
rock-plane bedding comprised a substantial portion of a geomorphic section bedding was noted as rock-plane. Otherwise bedding was noted as the visually most predominant material: boulder, cobble, gravel, or sediment. Mean wet channel width was computed from 5 or more survey points for each section, including the upstream end and downstream end of each section. We also noted the proportion of wetted channel spanned by LWJ as well as the channel feature (rock, live tree, bank, or bed) that appeared most likely to have trapped and anchored large wood at that location. Because LWJ that dammed flow might be most likely to correspond with pools, riffles, and other channel structures with regular spatial arrangement in channels, we also evaluated the distribution of large wood dams (defined as LWJ that spanned more than 50% of the bankfull channel).

Statistical Analysis

To evaluate the distribution of LWJ along the length of the river channels, we represented rivers as one-dimensional lines with LWJ forming points on these lines. We used a linear $K$-function to detect differences in LWJ distribution, similar to the analysis used by Kraft and Warren (2003), but with a different formula for $K$. The linear $K$-function summarizes the number of LWJ occurring within a given distance of every LWJ along a stream reach. Because LWJ near the end of a surveyed stream reach have an unknown number of neighbors beyond the end, we used a variable-width edge correction to remove unknown effects of LWJ near the ends of sections (Cressie 1993). Computations were made using a spatial version of the temporally-linear, edge-corrected equation for $K$ shown by Cressie (1993) using the following equation:
\[ K(d) = \frac{D}{N} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} I(0 < d_j - d_i \leq T, d_i > T) / \sum_{i=1}^{N} I(d_i > T) \]  

(Eq 1)

where \( D \) is the total distance of the surveyed stream reach (m), \( N \) is the number of LWJ in the reach, \( d_i \) is the distance (m) along the channel to the \( i \)th LWJ, \( d_j \) is the distance (m) along the channel to the \( j \)th LWJ, \( T \) is the distance (m) or scale of consideration, and \( d_i \) is the distance from the end of the reach to \( d_i \) (i.e., \( T - d_i \)). The term \( I \) takes a value of one when the conditions in parentheses are met, or 0 if they are violated (e.g., if \( d_j - d_i \leq T \) and positive, and \( d_i > T \), then \( I = 1 \)). All distances are in meters and we defined distances only in one direction. Specifically, the \( j \)th distances were upstream from the \( i \)th distances. We computed \( K \) for a range of \( T \) values corresponding to the length of surveyed stream, in 5-m increments, because aggregation, random distribution, or segregation may vary with the scale of consideration.

For a completely random distribution of many points, \( K \) will equal \( T \). The value of \( K \) will be higher for clustered points than for points from a random distribution (\( K > T \)) because each aggregated point will have many neighbors, or more points within distance \( T \) than would occur randomly. Conversely, segregated points will show a lower \( K \) value than randomly distributed points (\( K < T \)) because each segregated point will have fewer neighbors (points within distance \( T \)) than would occur randomly.

To compare empirical \( K \)-values to those of known random distributions we used Monte Carlo simulations. We generated 1000 random distributions of points to represent LWJ. Distributions represented the number of LWJ over the length of each particular
reach. For example, if a reach actually had 50 LWJ in 1500 m, we generated 1000 distributions of 50 LWJ (i.e., 50 points) within 1500 m (i.e., along lines of 1500 units) each. Each random distribution of LWJ formed the basis for computing $K$ at the same $T$ values as the empirical distribution. For every $T$-value we therefore had 1001 $K$-values: 1000 simulated-$K$ values representing known random distributions, and one empirical-$K$ value representing the actual distribution.

As is standard for Monte Carlo simulations, the statistical significance of the empirical-$K$ can be computed as the proportional rank of the empirical-$K$ relative to the simulated-$K$. For a single $T$ value, a proportional rank greater than 0.975 indicates statistically significant aggregation, and a proportional rank less than 0.025 corresponds to significant segregation ($\alpha = 0.05$, two-tailed). When the proportional rank of the empirical-$K$ is evaluated for many $T$ values for the same set of 1001 distributions, concerns of multiple hypothesis testing arise. Many statistical tests on the same data require an adjustment of the significance cutoff level ($\alpha$) to avoid type I errors (in this case rejecting randomness when the distribution is actually random). Where the empirical-$K$ value is much greater than the largest random-$K$ value (proportional rank of the empirical-$K = 1.00$) or much smaller than the smallest random-$K$ value (PR = 0) then significance is clear, and adjusting the $\alpha$-level is not necessary (it cannot be made smaller than 0.00). In cases where significance was not clear, we chose to avoid issues of multiple hypothesis testing by formally testing significance at only a few $T$ values.

To decide which points to test, we represented the departure of $K$ from the expected random distribution and tested $K$ at the maximum and minimum departures of $K$ from random. We divided $K$ by $T$, then plotted the product ($K:T$) against $T$ (essentially
plotting the rate of change of $K$ in terms of $T$). We also plotted the envelope of $K:T$ values from the Monte Carlo randomizations. For a random distribution the ratio of $K:T$ equals one because $K$ equals $T$. From the plot of $K:T$ versus $T$, scales of aggregation appear where the empirical $K:T$ exceed the envelop of random $K:T$ values. Segregation appears where the empirical $K:T$ fall below the envelop of random $K:T$ values. In cases where the trace of $K:T$ does not clearly exceed or fall below the envelop of random values, we evaluated significance of empirical-$K$ departures from random at no more than two $T$ values at which $K:T$ was maximum (indicating maximum aggregation) and no more than two $T$ values at which $K:T$ was minimum (indicating maximum segregation).

Although the statistical significance of the proportional rank may be difficult to determine when many are calculated together, patterns of the proportional rank (PR) still reveal the relationship of the empirical $K$ value to known random simulated $K$ values. We used plots of PR vs. $T$ to show the relative tendency of empirical distributions to aggregation, segregation, or randomness at various scales. At the largest scales relative to reach length some distributions contain no points that met the edge-correction criteria for inclusion in $K$-function analysis. We therefore only compare empirical and simulated $K$ distributions for scales ($T$) where all 1001 distributions contributed. We performed $K$-function computations and simulations using SAS/STAT (v. 9.1, SAS, Cary, NC). We have also included an illustration of the procedure with a known distribution of uniformly-spaced (segregated) points over a line of the same length as the longest contiguous section we studied in the Little Carp River (Attachment 4.A).
Results

Large wood jam distribution

Only about 8% of the LWJ for which we noted anchors were anchored on large rocks. A large proportion (41%) of the LWJ we observed were anchored by LW pieces trapped by standing riparian trees. Forty four percent of the LWJ anchored by interacting with the bank or bed of the channel itself with no apparent anchoring tree or boulder. In all channels except the Little Iron River clay-lake plain, many of the largest trees that have fallen appeared to have remained in-situ, based on bankside evidence such as rootwad divots or broken stems that match the pieces in the river.

Distributions of LWJ showed visually apparent regions of different point (LWJ) density (Figure 4.2). Linear $K$-function analysis indicated that the Little Carp River LWJ were aggregated at scales ($T$) from 200 m to 2.3 km. In other words, more LWJ occurred near other LWJ at distances between 200 m and 2.3 km than would likely have occurred by random in the Little Carp River. Because more LWJ occurred near other LWJ than occurred in most random distributions, the $K$-values at scales ($T$) from 200 m to 2.3 km ranked higher than $K$-values for all of the simulated random distributions (i.e., the proportional rank, PR $>$ 1.0) at those scales (Figure 4.3). Similar zones of aggregation though at smaller maximum scales were observed in the other rivers in which we surveyed long, contiguous stretches: the Big Carp River (aggregated at about 500 m), the Union River (aggregated at about 300 m) and the Upper Carp River (aggregated at about 50 m to 90 m; Figure 4.3). None of the long, contiguous sections showed significantly segregated LWJ.
Large wood jams almost always occurred in distributions not different from random within single geomorphic sections (Table 4.3). None of the clay lake plain or high-gradient sections showed aggregation or segregation of LWJ. The only LWJ distributions significantly different from random occurred in two low-gradient sections with aggregation, and two mid-gradient and one low-gradient section with segregated LWJ: LWJ aggregated in the low-gradient sections of the Little Carp River at the scale of 5 m, and the Upper Carp River at scales of 50 m to 95 m and 350 m; LWJ segregated in the mid-gradient section of the Little Carp River at 5 m, the mid-gradient section of the Upper Carp River at 10 m, and in the low-gradient section of Scott Creek at 5 m and 500 m.

A sense for the general tendency toward non-random aggregation or segregation of LWJ in sections can also be obtained by considering the mean and standard deviation of the proportional rank (PR) of the empirical data (Table 4.3). Roughly half of the sections (8 of 18) showed an overall PR greater than 0.70 (suggesting aggregation), while three sections showed an overall PR less than 0.30 (suggesting segregation). However, we detected no tendency toward aggregation or segregation of LWJ based on forest age.

**Large wood dam distribution**

Twenty one percent (n = 18, SD = 0.1) of LWJ we surveyed spanned at least 50% of the bankfull channel. These dams occurred less frequently in higher gradient sections with rock-plane bedding than in less steep sections (Figure 4.4). No dams occurred in the high-gradient section of the Union River or in the clay-lake plain of the Little Iron River, and only one occurred in the clay-lake plain of the Big Carp River.
Long sections of contiguous geomorphic sections showed aggregation of dams at many scales from about 50 m to 1 km or more; the exception was dams in the Upper Carp River which did not show patterns different from random at any scale we evaluated (Figure 4.5 through Figure 4.8). Contiguous sections of the Big Carp River showed clear aggregation of dams at scales from about 50 m to 1 km, because of a cluster of dams in the mid-gradient section (Figures 4.4, 4.5). Segregation appeared at scales of about 1 km, 2 km, and 3 km in the Big Carp River, reflecting wide spacing of dams up to 2.8 km. Most dams in the Little Carp River contiguous section clustered in the mid-gradient section, leading to aggregation at almost all scales from 70 m to 8.5 km (Figures 4.4, 4.6). However, dams in the Little Carp River were uniformly spaced overall with 5 m between them (i.e., segregation at the scale of 5 m). Dams on the Union River were aggregated at scales from approximately 100 m to 1 km and at about 1500 m because of clustering in the low-gradient section, but no segregation of dams was apparent (Figures 4.7, 4.8).

As with LWJ, most dams were distributed in patterns not different from random in almost every separate geomorphic section, as can seen from plots of the proportional rank of empirical-$K$ over the range of scales evaluated (Figures 4.9, 4.7 through 4.13). Aggregation of dams occurred only in the Big Carp River mid-gradient section at scales of 75 m to 1.1 km. Dam segregation occurred only in the mid-gradient section of the Little Carp River at the scale of 5 m, and in the low-gradient section of Scott Creek at the scale of 450 m. Mean PR of $K$ from dams in four sections suggested aggregation (PR > 0.70), but only one suggested overall segregation (PR < 0.30; Table 4.3).
Discussion

Patterns within geomorphic sections (small scale)

Most LWJ (in 14 of 18 geomorphic sections) showed random distribution patterns of LWJ within sections of relatively similar geomorphology regardless of the length of the section or the scale of evaluation. Large wood jams occurred in a variety of sizes and orientations along streams we studied, so their association with channel structure varied (Wallerstein et al. 1997, Abbe 2000, Chapter 2), resulting in spatially random distributions in almost all cases. Large wood dams tend to associate more strongly with stream channel structures like pools (Abbe 2000), so large wood dams would be more likely than other LWJ to have uniform distribution patterns along stream channels. Dams comprised 21% of all LWJ, resulting in slightly different distribution patterns when all LWJ were considered together than when dams were considered alone. Nevertheless, when only dams were considered, aggregation was apparent in only one section (Big Carp River mid-gradient section at 75 m to 1090 m), and segregation was only apparent in two geomorphic sections.

Segregation (uniform spacing) of dams occurred in the mid-gradient section of the Little Carp River (at 5 m spacing), and in the low-gradient section of Scott Creek (at 450 m spacing). Segregation of LWJ (including those spanning less than 50% of the channel) also occurred in the same sections and at the same scales where dams segregated but also in the Big Carp River mid gradient section (at 10 m) and at 500 m in Scott Creek. Uniform spacing appeared on visual inspection of plotted points to occur at small scales in other sections (e.g., Figure 4.4), but random distributions of points during Monte Carlo simulations frequently resulted in similar spacings, so segregation was not statistically
significant in any other sections. In some cases the lack of segregated pattern resulted from so few LWJ in a section that no pattern could exist (e.g., dams in the Big Carp River, clay-lake plain section, Figure 4.4).

**Patterns among geomorphic settings (large scale)**

Both LWJ and dams occurred at a higher abundance in different geomorphic settings, resulting in aggregated patterns when several contiguous geomorphic sections were considered together. Uniform spacing of dams also became evident in two of the four cases when several contiguous geomorphic sections were evaluated together: Big Carp River at various scales over 1 km (see Table 4.3); Little Carp River at 5 m. Patches of clustered dams did not prevent the determination of uniform spacing of dams in the Big Carp and Little Carp Rivers because there were many points over long distances in each river that were separated with at least the indicated scale distance. However, in the Union River, the concentration of most points in the low-gradient section and the presence of a tight, central clump in that section influenced strongly the identification of linear distribution pattern (only aggregation was identified).

Differences in distribution patterns between the Big and Little Carp Rivers in old-growth forests and the Union River in second-growth forest may reflect different histories. Rivers in the old-growth forests have had a longer history of LWJ interactions with channel structure. However, our results suggest that old-growth conditions do not necessarily lead to spatially segregated LWJ or dams, as represented by the distribution of LWJ and dams in the Upper Carp River (in old-growth forest) which showed random distribution patterns.
The patterns we observed in the rivers we examined suggest the following hypotheses regarding the spatial patterns of wood in streams of this region of the northern Lake States: First, we found that LWJ and dams in clay-lake plain and high-gradient sections always distributed with locations not discernibly different from random because the clay-lake plain and high-gradient sections transport wood effectively and channel structure is controlled by the rock bedding. Dams did not occur at most pools in plane-bed channels in our study, probably because there are few effective anchoring mechanisms but relatively high water flow in these sections. Because stream structure was rock-controlled and provided few trapping locations, channel structures like pools that might have been uniformly spaced (e.g., Montgomery et al. 1995) did not correspond with enough dams to reveal patterns different from random.

Second, random distributions of LWJ we found in some low and mid-gradient sections probably resulted from dispersed recruitment of wood to streams that are too small to effectively move many of the large pieces. Swanson (2003) predicted that where wood inputs are disperse and streams have very limited transport capacity, wood will be randomly distributed; a prediction supported in small, headwater streams (Gurnell 2003). Streams have limited transport capacity where water flow is low, and channels are narrow and shallow compared to the length and diameter of pieces of wood, and where sinuosity and/or channel obstruction (roughness) is high (Lienkamper and Swanson 1987, Bilby and Ward 1989, Braudrick and Grant 2001, Gurnell 2003). Some of the low and mid-gradient sections in this study appeared to have the most limited transport ability because they included the narrowest channels (3 m) and generally had higher sinuosity than clay-lake plain or high-gradient geomorphic sections. Because large pieces of wood often
form the basis for LWJ (Gurnell 2003), random distribution of the largest pieces falling into streams would likely lead to random distribution of LWJ in settings such as some of those in this study where streams were too small to move the large pieces (Gurnell et al. 2002, Swanson 2003).

Third, in those low and mid-gradient geomorphic sections where LWJ were non-randomly distributed, LWJ distributions reflect interactions most strongly among riparian forests, pieces of large wood, and geomorphology compared to other geomorphic settings (Gurnell et al. 2002). Non-random distributions could have derived in low and mid-gradient sections where transport potential of wood was high from patchy recruitment (e.g., from slope failures, which might be influenced by channel sinuosity), patchy trapping zones (e.g., at the base of slope failures, or at channel bends), or association of LWJ with regularly spaced stream structures like pools (Swanson 2003).

**Potential strengths and limitations of the K-function approach**

The linear $K$-function analysis we used provides clear information about the spatial nature of jam distributions along the rivers. The addition of an edge correction and consideration of points only in one direction improve on the algorithm reported by Kraft and Warren (2003). Strengths of a $K$-function analysis include its simplicity (the statistic is relatively easy to calculate and the required data may be collected quickly) and its ability to differentiate between aggregated and segregated spatial patterns at various scales. In comparison, Wing et al. (1999), and Keim et al. (2000) used a geographic information system (GIS) and semivariance analysis to quantify large wood distribution in streams of western Oregon. Semivariance analysis of lattice data performed by Wing
et al. (1999) was able to compare autocorrelation of wood volumes at several scales. In contrast, $K$-function analysis only provides information about location. Variogram analysis may not be as appropriate, however, as spatial point pattern analysis (like the $K$-function) for spatial grids with many zero observations that are common with large wood. Additionally, $K$-function analysis provides means for identifying segregated distributions, which semivariogram analysis is unable to do. These advantages have been recognized and explained by other researchers using $K$-function analysis for identification of linear patterns (O’Driscoll 1998, Kraft and Warren 2003). The $K$-function analysis provides a sensitive quantification of pattern for situations when more information than the frequency or size of points (LWJ) is desired (Cressie 1993).

There are two methodological caveats to be addressed. First, representing LWJ as points on lines provides information about the aggregation of individual LWJ but does not always reflect the amount of wood aggregated in any area. Several small LWJ would appear as a higher aggregation of large wood than one huge LWJ in linear $K$-function analysis, although the single LWJ may contain many more pieces of large wood, have a greater volume, and cover more space than the smaller LWJ. One way to address this concern of relative sizes might be to represent larger LWJ with several points; one point corresponding to some minimum length. We suggest that these points would probably need to be randomly distributed over the length of the LWJ. Second, in natural stream channels, geomorphology might change over scales too small to create discernible patterns of LWJ distribution. For the $K$-function to effectively reveal significantly non-random linear patterns, enough points must be included from a single distribution pattern that random distributions do not reproduce it. For linear distances where few points
occur, randomly distributing the same number of points will more likely result in segregated or aggregated distributions. With few points, therefore, empirical distributions from some ecological process(es) cannot be discerned from aggregated or segregated distributions arising from random linear processes. The need for many points in a discernible pattern requires that long sections of stream be surveyed. Where geomorphology leads to relatively large spacings of LWJ, sections of consistent geomorphology may not be long enough to include enough LWJ for discernment of pattern. For example, Montgomery et al. (1995) reported pool spacings exceeding 9 channel widths for plane-bed channels in southeast Alaska and Washington, which would correspond to spacings of at least 27 m for the narrowest rock-plane bedded channel in our study (channel width is 3 m in the Union River clay-lake plain section). Surveyed sections would need to be many 100’s of m long to discern uniformly segregated patterns in a channel where LWJ were spaced more than 27 m apart.

**Implications for stream restoration**

Anchoring mechanisms in the old-growth settings of our study consisted primarily of interactions between pieces of wood and riparian trees, banks, or the channel bed, so small-scale analysis of channel structure and pieces size is likely needed to identify conditions under which wood will be most stable before direct placement of LWJ, such as is being pioneered with soft engineering techniques by Abbe and others (Abbe et al. 2003, Bisson et al. 2003).

Our study supports the idea that riparian management or direct restoration of large wood should foster and monitor patterns of wood distribution corresponding to channel
metastructure, which is the arrangement of landscape elements along a river (Poole 2002). Restoring wood jams to emulate the wood in old growth streams similar to the ones we studied would entail placing structures at different distances from each other within different geomorphic settings in the landscape: fewer, more widely spaced large wood structures would be placed in high-gradient or clay-lake plain settings than in low-gradient or mid-gradient settings. In low and mid-gradient settings, random LWJ placement at large scales (on the order of 100’s of meters in systems like those we studied) would mimic observed distributions in most cases. One implication of including river metastructure in restoration of LW to streams is that evaluation of the success of restoration projects will depend on wood counts that correspond to different geomorphic settings; the number of pieces of wood in any one reach will not define the effectiveness of the restoration effort.

References


Attachment 4.A. Illustrative distribution

Example of K-function analysis with a segregated distribution

Because interpretation of the $K$-function may not be intuitive, we illustrate the procedure with a distribution of uniformly-spaced (segregated) points over a line of the same length as the longest contiguous section we studied in the Little Carp River. We constructed an illustrative distribution of 10 LWJ each separated by 500 m (from 0 m to 5000 m), followed by 71 LWJ separated by 28.2 m each (from 5000 m to 7000 m), followed by another four LWJ also separated by 500 m each (from 5000 m to 9386 m; total of 85 points) (Figure 4.14).

Results: illustrative distribution

The plot of $K:T$ vs. $T$ (Figure 4.15) shows points below the random line (the random line is $K:T = 1$) to scales ($T$) of 25 m, then points well above the random line for all the rest of the scales up to approximately 8370 m, which was the largest scale evaluated. The empirical-$K$ value (represented by $K$ of the illustrative distribution) at 25 was significant with the probability of a type I error equal to 0.00; in this case none of the 1000 random distributions showed $K$-values as low as the empirical $K$ at $T = 25$ m. The $K$-value of the illustrative distribution was much greater than $K$ from random distributions (i.e. $K:T > 1$ and empirical $K:T >$ the maximum random $K:T$) at all scales greater than 25 m. The proportional rank of the empirical-$K$ value was 1.0 for all scales between 25 m and 8315 m (Figure 4.16).
Discussion: illustrative distribution

The significantly low empirical-$K$ value at small scales in the illustrative distribution reflects the fact that fewer LWJ occurred within 25 m of every point than occurred in any random distribution. We also know from our construction of the illustrative distribution that 13 LWJ occurred at an evenly spaced 500 m from other LWJ. Segregation at 500 m did not appear, however, from $K$ function analysis because 71 points were not uniformly distributed at 500 m and the contribution of those points to the total $K$ value outweighed the contribution of the 14 points that were segregated at 500 m. The negligible contribution of a few points spread over a large area compared to a few points in a much smaller area is an important observation for understanding the meaning of the $K$-function analysis; it shows that the number of points with a given distribution is important for the value of $K$ than in addition to the distance over which the points are distributed, and emphasizes the fact that the $T$ value represents a scale of consideration from every point rather than the distance of points along the channel.

Clearly points on the illustrative distribution were significantly more aggregated than random regardless of the significance cutoff level ($\alpha$) at all scales greater than 25 m. The reason a distribution with uniform spacing resulted in significant aggregation at all scales is because spacing was not uniform throughout the length of the line. The cluster of 71 points at relatively close spacing (28.2 m) near the middle of the line resulted in most points having more neighbors at every scale than occurred in random distributions. In other words, when 85 points were randomly spread over a line of 9386 units, 71 of them were not clumped together over only 2000 units of line length. Therefore, because of the cluster of points, most points in the illustrative distribution had more points closer
to them than a random distribution would have had. Notice that because of the edge correction, at the largest scales the widely spaced points close to the initial end of the distribution are the only ones contributing to $K$ computations and their wide spacing maintains the indication of an aggregated distribution. The wide spacing of the initial points in the distribution maintains the indication of aggregation because the analysis occurs in only one direction (toward the cluster of points). The illustrative distribution appears to be aggregated because random distributions place more points “behind” the initial points so that fewer points are detected within the scale of interest. (e.g., the fourth point along the line, $T = 2000$, has 81 points in front of it, while random distributions place more than 3 points at distances less than 2000 m so they have fewer than 81 points between 2000 m and the end). It is important to the interpretation of the $K$-function to recognize that the $K$-function does not necessarily reveal where along the line a cluster or space occurs, but just whether most points “experience” the cluster or space. The relative number of points in a cluster, the location of the cluster on the line of evaluation, and the linear extent of the cluster all impact the $K$ value.
<table>
<thead>
<tr>
<th>Gradation (m/m)</th>
<th>Width (m)</th>
<th>Sinuosity (m/m)</th>
<th>Channel Bedding</th>
<th>Valley Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Old Growth (virgin)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay-Lake Plain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Carp R</td>
<td>0.016</td>
<td>9</td>
<td>1.2</td>
<td>Rock-plane/Cobble</td>
</tr>
<tr>
<td>Little Carp R</td>
<td>0.018</td>
<td>7</td>
<td>1.2</td>
<td>Rock-plane/Cobble</td>
</tr>
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<td>High-Gradient</td>
<td></td>
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<tr>
<td>Big Carp R</td>
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<td>8</td>
<td>1.1</td>
<td>Rock-plane/Cobble</td>
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<td>0.035</td>
<td>7</td>
<td>1.2</td>
<td>Rock-plane/Boulder</td>
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<td>1.2</td>
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<tr>
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<td></td>
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</tr>
<tr>
<td>Big Carp R</td>
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<td>1.5</td>
<td>Cobble/Gravel</td>
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<td>4</td>
<td>1.3</td>
<td>Cobble/Gravel</td>
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<td>4</td>
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<td>Cobble/Gravel</td>
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<td>Cobble/Gravel</td>
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<td>Mid-Gradient</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Carp R</td>
<td>0.018</td>
<td>7</td>
<td>1.5</td>
<td>Cobble/Gravel</td>
</tr>
<tr>
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<td>Cobble/Gravel</td>
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<tr>
<td><strong>Second-Growth (logged)</strong></td>
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<td>1.1</td>
<td>Rock-plane</td>
</tr>
<tr>
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<td>1.8</td>
<td>Rock-plane/Cobble</td>
</tr>
<tr>
<td>High-Gradient</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Union R</td>
<td>0.030</td>
<td>4</td>
<td>1.1</td>
<td>Rock-plane</td>
</tr>
<tr>
<td>Low-Gradient</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Little Iron R</td>
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<td>5</td>
<td>1.7</td>
<td>Cobble/Sediment</td>
</tr>
<tr>
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<td>0.017</td>
<td>3</td>
<td>1.8</td>
<td>Cobble/Gravel</td>
</tr>
<tr>
<td>Mid-Gradient</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Union R</td>
<td>0.018</td>
<td>3</td>
<td>1.4</td>
<td>Cobble/Gravel</td>
</tr>
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Table 4.1. Characteristics of geomorphic sections surveyed in the Porcupine Mountains.
<table>
<thead>
<tr>
<th>River</th>
<th>Section</th>
<th>Section Length</th>
<th>Number of LWJ</th>
<th>LWJ/100m</th>
<th>Scale of Aggregation (m)</th>
<th>Scale of Segregation (m)</th>
<th>Mean PR</th>
<th>St. Dev.</th>
<th>Maximum scale (T) evaluated (m³)</th>
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<tbody>
<tr>
<td>Big Carp</td>
<td>Mouth to 3.9 km upstream¹</td>
<td>3935</td>
<td>85</td>
<td>2.2</td>
<td>500</td>
<td>--</td>
<td>0.694</td>
<td>0.188</td>
<td>3625</td>
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<tr>
<td>Big Carp</td>
<td>Clay Lake Plain</td>
<td>1199</td>
<td>17</td>
<td>1.4</td>
<td>--</td>
<td>--</td>
<td>0.277</td>
<td>0.22</td>
<td>760</td>
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<tr>
<td>Big Carp</td>
<td>High-gradient</td>
<td>718</td>
<td>12</td>
<td>1.7</td>
<td>--</td>
<td>--</td>
<td>0.372</td>
<td>0.171</td>
<td>370</td>
</tr>
<tr>
<td>Big Carp</td>
<td>Low-gradient</td>
<td>1000</td>
<td>38</td>
<td>3.8</td>
<td>--</td>
<td>--</td>
<td>0.793</td>
<td>0.135</td>
<td>810</td>
</tr>
<tr>
<td>Big Carp</td>
<td>Mid-gradient</td>
<td>2018</td>
<td>56</td>
<td>2.8</td>
<td>--</td>
<td>--</td>
<td>0.809</td>
<td>0.106</td>
<td>1720</td>
</tr>
<tr>
<td>Little Carp</td>
<td>Mouth to 9.4 km upstream²</td>
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<td>255</td>
<td>2.7</td>
<td>200-2315</td>
<td>--</td>
<td>0.925</td>
<td>0.095</td>
<td>9120</td>
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<tr>
<td>Little Carp</td>
<td>Clay Lake Plain</td>
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<td>51</td>
<td>1.6</td>
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<td>--</td>
<td>0.793</td>
<td>0.09</td>
<td>2660</td>
</tr>
<tr>
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<td>High-gradient</td>
<td>1412</td>
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<td>--</td>
<td>--</td>
<td>0.317</td>
<td>0.186</td>
<td>1080</td>
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<td>Low-gradient</td>
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<td>16</td>
<td>2.7</td>
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<td>0.812</td>
<td>0.172</td>
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<td>Little Carp</td>
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<td>164</td>
<td>3.4</td>
<td>--</td>
<td>5</td>
<td>0.264</td>
<td>0.256</td>
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<tr>
<td>Upper Carp</td>
<td>2.3 km³</td>
<td>2344</td>
<td>114</td>
<td>4.9</td>
<td>50-90</td>
<td>--</td>
<td>0.263</td>
<td>0.282</td>
<td>2210</td>
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<tr>
<td>Upper Carp</td>
<td>High-gradient</td>
<td>718</td>
<td>27</td>
<td>3.8</td>
<td>--</td>
<td>--</td>
<td>0.88</td>
<td>0.109</td>
<td>1020</td>
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<td>Upper Carp</td>
<td>Low-gradient</td>
<td>459</td>
<td>33</td>
<td>7.2</td>
<td>50-95,350</td>
<td>--</td>
<td>0.991</td>
<td>0.007</td>
<td>360</td>
</tr>
<tr>
<td>Upper Carp</td>
<td>Mid-gradient</td>
<td>1167</td>
<td>54</td>
<td>4.6</td>
<td>--</td>
<td>10</td>
<td>0.372</td>
<td>0.182</td>
<td>1040</td>
</tr>
<tr>
<td>Union</td>
<td>Culvert to 2.6 km upstream⁴</td>
<td>2600</td>
<td>79</td>
<td>3</td>
<td>320</td>
<td>--</td>
<td>0.791</td>
<td>0.146</td>
<td>2405</td>
</tr>
<tr>
<td>Union</td>
<td>Clay Lake Plain</td>
<td>1050</td>
<td>34</td>
<td>3.2</td>
<td>--</td>
<td>--</td>
<td>0.381</td>
<td>0.181</td>
<td>805</td>
</tr>
<tr>
<td>Union</td>
<td>High-gradient</td>
<td>480</td>
<td>6</td>
<td>1.3</td>
<td>--</td>
<td>--</td>
<td>0.543</td>
<td>0.263</td>
<td>135</td>
</tr>
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<td>Union</td>
<td>Low-gradient</td>
<td>980</td>
<td>40</td>
<td>4.1</td>
<td>--</td>
<td>--</td>
<td>0.556</td>
<td>0.096</td>
<td>825</td>
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<td>Union</td>
<td>Mid-gradient</td>
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<td>33</td>
<td>2.9</td>
<td>--</td>
<td>--</td>
<td>0.346</td>
<td>0.134</td>
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<td>na</td>
<td>na</td>
<td>na</td>
<td>0.936</td>
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<td>35</td>
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<td>44</td>
<td>4.3</td>
<td>--</td>
<td>--</td>
<td>0.803</td>
<td>0.156</td>
<td>870</td>
</tr>
<tr>
<td>Scott Creek</td>
<td>Low-gradient</td>
<td>1027</td>
<td>44</td>
<td>4.3</td>
<td>--</td>
<td>5, 500</td>
<td>0.148</td>
<td>0.226</td>
<td>880</td>
</tr>
</tbody>
</table>

Table 4.2. Frequency and distribution of large wood jams (LWJ) in geomorphic sections of rivers of the Porcupine Mountains. Notes: ¹ Contains the clay-lake plain, high-gradient, and mid-gradient sections. ² Contains the clay-lake plain, mid-gradient, and high-gradient sections. ³ Contains the low-gradient, high-gradient, and mid-gradient sections. ⁴ Contains the high-gradient, mid-gradient, and low-gradient sections. ⁵ LWJ (large wood jams): at least two pieces of wood 10 cm or more diameter and at least 1 m long, in contact with each other and the bankfull channel. ⁶ PR is proportional rank of empirical-K: (1 + number of random-K values less than empirical-K) / 100. ⁷ The K statistic was computed for scales from 5 m to the maximum T per section, at 5-m increments.
<table>
<thead>
<tr>
<th>River</th>
<th>Section</th>
<th>Length</th>
<th>Number of dams</th>
<th>dams/100m</th>
<th>Scale of Aggregation</th>
<th>Scale of Segregation</th>
<th>Mean PR</th>
<th>St. Dev. PR</th>
<th>Max scale evaluated (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Carp</td>
<td>Mouth to 3.9 km upstream</td>
<td>3935</td>
<td>29</td>
<td>0.74</td>
<td>55-1045</td>
<td>2730-2820</td>
<td>0.482</td>
<td>0.425</td>
<td>2900</td>
</tr>
<tr>
<td>Big Carp</td>
<td>Clay Lake Plain</td>
<td>1199</td>
<td>1</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Big Carp</td>
<td>High-gradient</td>
<td>718</td>
<td>3</td>
<td>0.4</td>
<td>na</td>
<td>na</td>
<td>0.767</td>
<td>0.126</td>
<td>60</td>
</tr>
<tr>
<td>Big Carp</td>
<td>Low-gradient</td>
<td>1000</td>
<td>7</td>
<td>0.7</td>
<td>--</td>
<td>--</td>
<td>0.482</td>
<td>0.27</td>
<td>420</td>
</tr>
<tr>
<td>Big Carp</td>
<td>Mid-gradient</td>
<td>2018</td>
<td>24</td>
<td>1.2</td>
<td>75-1090</td>
<td>--</td>
<td>0.931</td>
<td>0.148</td>
<td>1580</td>
</tr>
<tr>
<td>Little Carp</td>
<td>Mouth to 9.4 km upstream</td>
<td>9386</td>
<td>85</td>
<td>0.91</td>
<td>70-8285, 8480-8505</td>
<td>5</td>
<td>0.999</td>
<td>0.032</td>
<td>8650</td>
</tr>
<tr>
<td>Little Carp</td>
<td>Clay Lake Plain</td>
<td>3151</td>
<td>6</td>
<td>0.2</td>
<td>--</td>
<td>--</td>
<td>0.663</td>
<td>0.244</td>
<td>1000</td>
</tr>
<tr>
<td>Little Carp</td>
<td>High-gradient</td>
<td>1412</td>
<td>6</td>
<td>0.4</td>
<td>--</td>
<td>--</td>
<td>0.341</td>
<td>0.171</td>
<td>395</td>
</tr>
<tr>
<td>Little Carp</td>
<td>Low-gradient</td>
<td>582</td>
<td>7</td>
<td>1.2</td>
<td>--</td>
<td>--</td>
<td>0.718</td>
<td>0.184</td>
<td>160</td>
</tr>
<tr>
<td>Little Carp</td>
<td>Mid-gradient</td>
<td>4823</td>
<td>73</td>
<td>1.5</td>
<td>--</td>
<td>--</td>
<td>0.674</td>
<td>0.148</td>
<td>4275</td>
</tr>
<tr>
<td>Upper Carp</td>
<td>2.3 km</td>
<td>2344</td>
<td>44</td>
<td>1.88</td>
<td>--</td>
<td>--</td>
<td>0.202</td>
<td>0.205</td>
<td>1975</td>
</tr>
<tr>
<td>Upper Carp</td>
<td>High-gradient</td>
<td>718</td>
<td>12</td>
<td>1.7</td>
<td>--</td>
<td>--</td>
<td>0.653</td>
<td>0.177</td>
<td>435</td>
</tr>
<tr>
<td>Upper Carp</td>
<td>Low-gradient</td>
<td>459</td>
<td>13</td>
<td>2.8</td>
<td>--</td>
<td>--</td>
<td>0.868</td>
<td>0.161</td>
<td>250</td>
</tr>
<tr>
<td>Upper Carp</td>
<td>Mid-gradient</td>
<td>1167</td>
<td>19</td>
<td>1.6</td>
<td>--</td>
<td>--</td>
<td>0.606</td>
<td>0.17</td>
<td>800</td>
</tr>
<tr>
<td>Union</td>
<td>Culvert to 2.6 km upstream</td>
<td>2600</td>
<td>28</td>
<td>1.08</td>
<td>1660-1680</td>
<td>--</td>
<td>0.987</td>
<td>0.031</td>
<td>1970</td>
</tr>
<tr>
<td>Union</td>
<td>Clay Lake Plain</td>
<td>1050</td>
<td>10</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>0.35</td>
<td>0.185</td>
<td>500</td>
</tr>
<tr>
<td>Union</td>
<td>High-gradient</td>
<td>480</td>
<td>0</td>
<td>0</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Union</td>
<td>Low-gradient</td>
<td>980</td>
<td>23</td>
<td>2.3</td>
<td>--</td>
<td>--</td>
<td>0.488</td>
<td>0.168</td>
<td>710</td>
</tr>
<tr>
<td>Union</td>
<td>Mid-gradient</td>
<td>1140</td>
<td>5</td>
<td>0.4</td>
<td>--</td>
<td>--</td>
<td>0.494</td>
<td>0.2</td>
<td>220</td>
</tr>
<tr>
<td>Little Iron</td>
<td>Clay Lake Plain</td>
<td>900</td>
<td>0</td>
<td>0</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Little Iron</td>
<td>Low-gradient</td>
<td>1020</td>
<td>20</td>
<td>2</td>
<td>--</td>
<td>--</td>
<td>0.324</td>
<td>0.09</td>
<td>680</td>
</tr>
<tr>
<td>Scott Creek</td>
<td>Low-gradient</td>
<td>1027</td>
<td>30</td>
<td>2.9</td>
<td>--</td>
<td>--</td>
<td>450</td>
<td>0.201</td>
<td>775</td>
</tr>
</tbody>
</table>

Table 4.3. Frequency and distribution of dams (large wood jams spanning at least 50% of the bankfull channel) in streams of the Porcupine Mountains, Northern Michigan. Notes: 1 Contains the clay-lake plain, high-gradient, and mid-gradient sections. 2 Contains the clay-lake plain, mid-gradient, and high-gradient sections. 3 Contains the low-gradient, high-gradient, and mid-gradient sections. 4 Contains the high-gradient, mid-gradient, and low-gradient sections. 5 Range for which proportional rank (PR) of the empirical-K = 1.00, interspersed with a few scales at which PR = 0.999. 6 Not enough points for spatial analysis: Big Carp River clay lake plain had 1 dam; Big Carp River high-gradient section had 3 dams; Union River high-gradient section had 0 dams; and the Little Iron River clay lake plain had 0 dams.
Figure 4.1. Study areas in the Porcupine Mountains. See Table 4.2 for actual study-section-lengths. Dotted line represents the boundary between old-growth and second-growth forest. The northern second-growth forest along the shore of Lake Superior was logged prior to 1910. CLP is clay-lake plain, HG is high-gradient, LG is low-gradient, and MG is mid-gradient geomorphic study section.
a. Big Carp River (old-growth)

<table>
<thead>
<tr>
<th>Clay Lake Plain</th>
<th>High Gradient</th>
<th>Mid Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

b. Little Carp River (old-growth)

<table>
<thead>
<tr>
<th>Clay Lake Plain</th>
<th>Mid Gradient</th>
<th>High Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

c. Upper Carp River (old-growth)

<table>
<thead>
<tr>
<th>Low Gradient</th>
<th>High Gradient</th>
<th>Mid Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

d. Union River (second-growth)

<table>
<thead>
<tr>
<th>High Gradient</th>
<th>Mid Gradient</th>
<th>Low Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Distance (m)

Figure 4.2. Large wood jam distribution in four sections of contiguous sections of different geomorphology as labeled. Distance is zero downstream.
Figure 4.3. Rank of empirical-$K$ value as a proportion of 1000 random simulations representing all large wood jams (LWJ) in four rivers of the Porcupine Mountains, Northern Michigan.
Figure 4.4. Distribution of dams (LWJ that spanned 50% or more of the bankfull channel) in four sections of contiguous sections of different geomorphology as labeled. Distance is zero downstream.
Figure 4.5. Plot of $K:T$ vs. $T$ for dams in three contiguous geomorphic sections of the Big Carp River. Dashed lines indicate maximum and minimum values from 1000 random distributions. Arrows indicate $T$ values at which the empirical-$K$ value was tested for significant difference from the simulated, random-$K$ values: at $T = 10$, PR = 0.11, empirical-$K$ is not significantly different from random; at $T = 2155$, PR = 0.07, empirical-$K$ is not significantly different from random.
Figure 4.6. Plot of $K$ vs. $T$ for dams in three contiguous geomorphic sections of the Little Carp River. Dashed lines indicate maximum and minimum values from 1000 random distributions. Arrows indicate $T$ values at which the empirical-$K$ value was tested for significant difference from the simulated, random-$K$ values: at $T = 5$, the proportional rank of the empirical-$K$ (PR) = 0.02, indicating significant segregation; at $T = 90$, PR = 1.00 indicating significant aggregation.
Figure 4.7. Plot of $K:T$ vs. $T$ for dams in three contiguous geomorphic sections of the Upper Carp River. Dashed lines indicate maximum and minimum values from 1000 random distributions.
Figure 4.8. Plot of $K/T$ vs. $T$ for dams in three contiguous geomorphic sections of the Union River. Dashed lines indicate maximum and minimum values from 1000 random distributions. Arrow indicates $T$-value at which the empirical $K$-value was tested for significant difference from the simulated, random-$K$ values: at $T = 1500$, $PR = 1.00$, indicating significant aggregation.
Figure 4.9. Proportional rank of empirical-$K$ from dams to $K$ from 1000 random distributions. The unit for the scale factor, $T$, is meters.
Figure 4.10. Proportional rank of empirical-$K$ from dams in the Big Carp River to $K$ from 1000 random distributions. The scale factor, $T$, is in meters. The clay-lake plain section of the Big Carp River is not represented because only one dam occurred in that section.
Figure 4.11. Proportional rank of empirical-$K$ from dams in the Little Carp River to $K$ from 1000 random distributions. The scale factor, $T$, is in meters.
Figure 4.12. Proportional rank of empirical $K$ from dams in the Upper Carp River and Scott Creek to $K$ from 1000 random distributions. The scale factor, $T$, is in meters.
Figure 4.13. Proportional rank of empirical-$K$ from dams in the Union River and Little Iron River to $K$ from 1000 random distributions. The scale factor, $T$, is in meters. The high-gradient section of the Union River, and the clay-lake plain section of the Little Iron River are not represented because no dams occurred in those sections.
Figure 4.14. Illustrative example: distribution of 85 points representing uniformly distributed (segregated) LWJ. Larger separations are 500 m each, and smaller separations are 28.2 m.
Figure 4.15. Illustrative example: Plot of $K/T$ vs. $T$ for uniformly distributed points with two different spacings. Arrow indicates point tested for statistical significance of difference between $K$ of the target distribution (which represented empirical $K$) and the $K$ of 1000 random distributions.
Figure 4.16. Illustrative example: Plot of the proportional rank (PR) of empirical-K (represented by $K$ from an illustrative uniform distribution) for a range of scales ($T$). The unit for $T$ is m. Note that the X-axis is the scale factor, $T$, for which $K$ was evaluated in 5-m intervals. The X-axis is not the distance along the stream channel. The $K$ statistic represents the number of “neighbor” points (LWJ) occurring within distance $T$ from every large wood jam. A PR of 0.5 indicates random distribution, 1 indicates aggregation, and 0 indicates segregation. The reference line is drawn at $T$ equivalent to the separation between most (71 of 85) points in the illustrative distribution (28.2 m).
CHAPTER 5

RELATIONSHIPS BETWEEN LARGE WOOD JAMS AND STREAM CORRIDOR GEOMORPHOLOGY IN RIVERS OF MIXED CONIFER-HARDWOOD FORESTS

Introduction


Despite the influential role of large wood jams (LWJ) in stream systems and increased attention to LWJ ecology and restoration in the past 30 years (Gregory 2003), much remains to be learned about LWJ characteristics in riverine landscapes.

Previous studies have primarily evaluated characteristics of individual pieces of LW, and most studies have focused on streams in the Pacific Northwest (Wildman 2005; Chapter 2). Abbe (2000) developed the most complete characterization of LWJ to date, identifying 11 LWJ types in three categories related to stream order in the Queets River.
drainage in Washington. Other researchers have also documented changes in LWJ composition and structure with increasing river order and size (e.g., Richmond and Fausch, 1995, Wallerstein et al. 1997, Streb 2001, Abbe et al. 2003). We have similarly documented changes in LWJ abundance, size, and orientation that correspond with geomorphic factors measured in old-growth and second-growth mixed conifer-deciduous forests of Upper Michigan at the reach scale (300 m; Chapter 2). We found that the characteristics of LWJ evaluated at the reach scale appeared to be strongly related to the geomorphic setting, as there was relatively little variation in LWJ among reaches of similar geomorphic settings (Chapter 2). Subsequent study of additional rivers further verified that LWJ abundance consistently clustered in certain geomorphic settings along the stream corridor (Chapter 3). Based on these results, we believe it is likely that the abundance and the structural characteristics of LWJ also cluster at larger scales and are related to stream corridor geomorphology.

Evaluating LWJ in discontinuous geomorphic riverine patches is important for several reasons. First, riverine landscapes have often been historically modeled as continuua (Vannote et al. 1983), but are increasingly being understood as dynamically patchy environments (Stanford and Ward 1993, Poole 2002, Swanson 2003). Few studies have examined the distribution and characteristics of large wood in relation to patch dynamics. Second, evaluating LWJ in riverine patches helps us understand how the physical structure of the environment relates to LWJ structure. Third, evaluating LWJ in geomorphic riverine patches helps to inform and guide stream and forest management, particularly restoration of LW to streams. Current restoration trends emphasize soft engineering and passive restoration techniques that rely on understanding
hierarchical and patchy natural processes to stabilize LWJ in streams (Abbe et al. 2003, Bisson et al. 2003). In addition, further evaluation of LWJ characteristics in discontinuous geomorphologies of rivers in old-growth deciduous or mixed conifer-deciduous forest will complement pioneering work on LWJ from the Pacific Northwest (Abbe 2000, Abbe et al. 2003, Swanson 2003) and provide valuable baseline reference information for ecological restoration of streams in the eastern and northeastern United States.

Based on previous studies, we predict that patches of relatively long sections of similar valley geomorphology create unique LWJ signatures or combinations of LWJ characteristics, and that these signatures should exist in all similar geomorphic patches. We specifically hypothesize that LWJ is more abundant, of smaller (individual) size, spans more of the channel and contains more pieces in stream segments with lower-gradient, unconstrained valley types than in steeper, more constrained settings (Abbe 2000, Rot et al. 2000, Gurnell et al. 2002, Gurnell 2003, Chapter 2, 3). We undertook a study to test these hypotheses by identifying and evaluating LWJ characteristics related to geomorphic factors in several sections of streams in old-growth and second-growth forest of upper Michigan. Our objectives were to 1) determine how LWJ abundance, size, and orientation varied together with geomorphic settings at large scales (stream corridor scale) and 2) identify specific characteristics of the stream channel and riparian forest that correspond most strongly with differences in LWJ abundance, size, and orientation. This study differs from previous studies by considering LWJ and geomorphic factors measured only at the scale of entire geomorphic sections, and by including data from several rivers. We did not intend to identify a widely applicable geomorphic
classification system for streams, as Rosgen (1996) and others have done. Such complete classification models are beyond the scope of our study and its geographic extent. Rather, we classified sections of rivers in the Porcupine Mountains to test whether simple visual classification of geomorphology at the stream corridor scale could predict LWJ characteristics.

Methods

Study sites

Most of the study area occurred in the Porcupine Mountains Wilderness State Park (PMWSP) which preserves one of the largest (13,000 ha) virgin, old-growth, hardwood-hemlock forest in the Lake States (Frelich 2002). We studied four rivers in virgin old-growth forest in the PMWSP: the Little Carp River, the Big Carp River, Scott Creek, and the Upper Carp River. Logging occurs currently and has occurred continuously for the last century in areas around the PMWSP. We studied segments of two rivers in this second-growth forest landscape near the northeastern boundary of the PMWSP: the Union River (mostly inside the PMWSP) and the Little Iron River.

Old-growth forests of the PMWSP are mixed conifer-hardwood forests dominated by eastern hemlock (Tsuga canadensis, (L.) Carr.), northern white cedar (Thuja occidentalis, L.), yellow birch (Betula alleghaniensis, Britt.), and sugar maple (Acer saccharum, Hook). The furthest upstream portions of the Big and Little Carp Rivers, and the segments of Upper Carp River we studied contained a relatively higher proportion of hardwood species than the downstream portions of the Little and Big Carp Rivers. Maximum tree height is approximately 40 m, with mean canopy tree height of 25 m and
60 cm mean diameter at breast height. The segments of these rivers that we studied were forested to the edge of the bankfull channel. Human influences in these old-growth forests is limited, primarily consisting of recreational hiking, camping, and fishing. Beaver activity was apparent in all rivers we studied in old-growth forest. No well-established beaver dams occurred in segments of stream that we studied during the period of data collection, however, because of high flows in the spring of 2003.

Second-growth forests in the study area of the Porcupine Mountains are similar in terms of species composition to the old-growth forests. Second-growth forests contain, however, a high proportion of hardwood species and smaller trees in some areas, especially maple (Acer spp), birch (Betula spp.), and ash (Fraxinus spp.). Dense patches of small balsam fir (Abies balsamea (L.) Mill.) also occur in riparian areas. Most of the Union River and Little Iron River forests grew to the edge of the river channels in segments we studied, and narrow strips (<10m) of uncut trees remained in the clay-lake plain of the Little Iron River where timber harvest has occurred within the last five years. Unlike the old-growth areas studied, the second-growth forests have experienced a variety of human-related disturbances including timber harvesting, limited mining, localized camping, and road building. Beaver dams in various states of repair were located in the upstream portions of the Union River and Little Iron River, although no active beaver dams occurred in streams segments we studied. Most beaver dams on the Little Iron River in our study area had been abandoned and washed through, but the thatching of wood from old dams was visible under current vegetation.

Bank slope failures and individual mortality associated with windthrow appear to be the most common sources of LW recruitment to streams in both old-growth and
second-growth forests of the Porcupine Mountains. Seasonal precipitation can be heavy with 800-900 mm precipitation, up to 7 m of which occurs as snow (McNab and Avers 1994). The topography is, however, not conducive to avalanches, landslides, or other forms of mass wasting that are significant factors associated with large wood dynamics in the Pacific Northwest. Fires occur infrequently in these forests. Windstorms are common, however, and are responsible for mortality of individual trees and stands. The last major windstorm responsible for mass mortality in the study area occurred in 1953, affecting 1800 ha near the center of the PMWSP, around the northern, upstream end of the Little Carp River.

**Geomorphic sections**

We identified four similar types of stream valley geomorphology in the Porcupine Mountains. These include:

1. *Clay-lake plain*, marked by deep lacustrine sediment overlying bedrock. Streams in the clay-lake plain have many plane-bed reaches, and channels tend to be incised through the sediment in relatively wide floodplains (low valley constraint).

2. *High-gradient sections*, marked by bedrock control with little sediment. High-gradient segments of stream were not incised and occurred in narrow valleys (high valley constraint) with plane-bed or relatively coarse bed material (colluvial).

3. *Low-gradient sections*, marked by relatively large amounts of gravel and cobbles in bedrock controlled channels. Low-gradient channels were not incised and
generally occurred in relatively open (unconstrained) valleys. Low-gradient sections tended to be alluvial although they often occurred closest to the headwaters.

(4) *Mid-gradient* sections, marked by medium amounts of gravel, cobbles, and boulders in bedrock controlled channels. Mid-gradient stream segments generally formed in transition areas between low (or clay-lake plain) and high-gradient segments, and although relatively alluvial they also had larger channels and apparently more transport of stream materials than in low-gradient segments.

**Study Design**

We chose one study reach from each of the geomorphic types in the Little Carp River, Big Carp River, and Union River. We also designated for study high, low, and mid-gradient segments of the Upper Carp River, clay-lake plain and low-gradient sections of the Little Iron River, and a low-gradient section of Scott Creek (for a total of 18 study sections). We designated stream segments of at least 1000 m for study when possible, but in some cases geomorphic patches limited study reaches (noted as geomorphic sections hereafter) to less than 1000 m.

**Geomorphology measurements**

As part of another study (Chapter 2) we surveyed the channel of the Little Carp River, the Little Iron River, and the high and mid-gradient sections of the Union River with a Pentax® 24 total station. We georeferenced many points in these sections with global positioning systems (Satloc SLXg3® backpack, Trimble® or Eagle Explorer®...
handheld). To obtain spatial information about additional study sites, we used GPS (Satloc SLXg3®) to georeference the channels of the Big Carp River, the Upper Carp River, Scott Creek, and the low-gradient and clay-lake plain sections of the Union River. We used plane-surveyed and GPS data to plot points on geographic information system (GIS) maps, using ARCGIS (v. 9.0, ESRI, Redlands, CA). We drew stream channel polylines by manually connecting survey points over the satellite images in each geomorphic section. These polylines were used to compute the sinuosity index, which is the length of the studied channel divided by the straight line between endpoints of that channel segment (Allan 1995; hereafter referred to as sinuosity).

Section gradient was computed from elevations at the upstream and downstream end of each section obtained from 1:24,000 30 m digital elevation models (DEM; Michigan 2005). Topographic lines were used to compute stream elevation change for gradient in the lowest two sections of the Big Carp River where DEM data does not exist. Distance from the headwaters to each study section was measured as the distance from the furthest upstream end of the longest tributary (intermittent or perennial) to the upstream end of the study section, and determined stream order. Mean wet width for each section was computed from measurements of at least five points (endpoints and three randomly selected internal points). We visually classified valley constraint of study sections relative to other sections based on the valley width (nearest points clearly beyond fluvial control) compared to the bankfull channel width; wider valleys were rated as lower constraint. We also visually classified channel bedding material as rock-plane bedding where many plane-bed reaches were present.
Large wood jam measurements

Large wood jams (LWJ) in this study consisted of two or more pieces of large wood in contact with each other and extending into the bankfull channel. We computed several metrics of LWJ for each section. These included:

1. LWJ abundance: We divided the number of LWJ by the length of channel in each geomorphic section multiplied by 100 to obtain the number of LWJ per 100 m.

2. Dams: We divided the number of LWJ that spanned 100% of the wetted channel in each section by the total number of LWJ to obtain the proportion of dams in each section.

3. Contact with water at low-flow: We divided the number of LWJ that contacted water by the total number of LWJ for each section to obtain the proportion of LWJ interacting with water flow when streams were below flood stage.

4. Size, small: We divided the number of LWJ containing 2 pieces to 5 pieces by the total number of LWJ to obtain the proportion of small LWJ in each section.

5. Size, large: We divided the number of LWJ containing more than 20 pieces by the total number of LWJ to obtain the proportion of large LWJ in each section.
**Riparian Forest Measurements**

We used point quarter transects to quantify forest overstory composition and structure (Fitzpatrick et al. 1995). Transects were established 10 m from the bankfull channel edge for 300 m or 500 m on both sides of the rivers near the upstream end of each study section (600 m or 1000 m total distance counting both sides). An exception was the Upper Carp River low and high-gradient sections where transects measured 100 m and 200 m respectively (on each side of the river). Every 20 m along each transect we measured the distance from the transect point to the nearest stem in four directions (quadrants). Only stems at least 10 cm diameter-breast-height (dbh) were considered. For each of the nearest stems we identified species, noted alive or dead, and measured dbh. From point quarter transects we computed the percent conifer, percent snags, mean diameter, and mean stem density for each geomorphic section. To compute mean stem density per section we calculated density at each point, then averaged all point densities along a transect (both sides of the river included), after Jost (1993):

\[
D = \frac{1}{N} \sum_{j=1}^{N} \frac{12}{\prod_{i=1}^{4} \left( r_{ij}^2 \right)} \quad \text{Eq. 1}
\]

Where D is mean stem density (number m\(^{-2}\)), N is the number of points along the transect, and r is the distance from transect point to stem (m).
**Statistical Analysis**

Geomorphic sections were the unit of statistical analysis. We assumed that LWJ characteristics were not unimodally distributed over the range of geomorphic and forest variables we measured.

We used principal component analysis (PCA) to identify patterns of variability in LWJ characteristics of study sections. Principal component analysis allowed us to determine whether combinations of response variables were more similar in sections of the same geomorphic type, forest age, or river regardless of specific environmental factors. Large wood jam characteristics were measured in different units, so they were centered and standardized before analysis; ordinations were performed with correlation matrices. We used broken-stick eigenvalues to test the significance of gradients (PC-ORD for Windows, MjM Software, Gleneden Beach, Oregon). We also evaluated the correlation between LWJ characteristics and PCA axes (MINITAB Inc. v. 14.1, State College, PA).

We performed redundancy analysis (RDA) to evaluate differences in LWJ characteristics between LWJ factors as constrained by geomorphic section. We represented geomorphic sections with 4 binary dummy variables. To elucidate linear relationships between LWJ characteristics and geomorphic section we used simple linear regression with geomorphic class (n = 4) as the independent variable. We ordered geomorphic classes to maximize regression-line $r^2$ values.

To further investigate contributions of specific geomorphic factors (like gradient, sinuosity, channel width, etc.) on LWJ characteristics, we performed RDA with all of the environmental factors measured. In total, 8 continuous and 2 categorical environmental
variables were included in the ordination (Table 5.1). Categorical variables were represented by binary dummy variables (i.e., three dummy variables for constraint: high, low, and medium constraint, and one for rock-plane bedding). We did not include stream order in RDA because it is a proxy measure for factors such as stream width and distance from headwaters that were explicit in our model. As in PCA, response variables were centered and standardized before analysis. Tests of the relationship between environmental and response variables were done with 199 permutations under the full model (CANOCO v. 4.02 for Windows, Centre for Biometry Wageningen, Wageningen, The Netherlands). We also determined correlations between environmental variables, response variables, and the first two RDA axes, as well as significance of the first axes and all axes as described for PCA.

We performed linear regression analyses to identify which geomorphic variables associated most strongly with specific LWJ characteristics. We performed regression analysis using as independent variables the entire set of 10 variables (11 counting two dummy variables for constraint) to evaluate how well the combination of all measured variables corresponded with each LWJ factor. To determine which subset of environmental variables correlated most strongly with LWJ factors we performed three additional sets of linear regression for each LWJ factor, drawing from three sets of environmental data: (1) all environmental factors, (2) only geomorphology factors (excluding distance from headwaters and all riparian forest factors), and (3) only the factors that correlated most strongly with the first RDA axis. We performed regressions with all possible combinations of factors in each subset, and then chose the model with the highest adjusted $r^2$-value. Response variables were transformed to meet the
assumptions of normality for parametric regression. Regression analysis was performed using PROC REG with command ADJRSQ in SAS/STAT (SAS v. 9.1, Cary, NC).

Results

Characteristics of geomorphic sections

The longitudinal order of geomorphic sections was not the same in every stream (Table 5.1). Lower gradient channels tended, however, to have lower valley constraint and few or no plane-bed reaches. Lower gradient channels also tended to have higher sinuosity and to be narrower than higher-gradient channels. Distance from headwaters served as a good representation for stream order; all third-order streams but no streams of second or first-order occurred more than 12 km from the headwaters, and the two first-order streams occurred at two of the shortest distances from the headwaters (1 km and 3 km). Riparian forest characteristics appeared to be similar among geomorphic sections.

Unconstrained variability in LWJ characteristics (PCA)

Principal components analysis represented 68.0% of the variability in LWJ characteristics along the first two axes, which were the only two axes along which significant gradients existed (i.e., broken-stick eigenvalues > 1; Table 5.2). The first principal component (PC; axis 1) represented a gradient comprised of the percent dams, percent LWJ contacting the water, and number of LWJ per 100 m (factor loadings = 0.59, 0.53, and 0.52 respectively). The second PC (axis 2) represented a gradient from low to high proportion of small LWJ (factor loading = -0.80)
Scores from similar geomorphic sections did not form exclusive groups in ordination space, but trends relating LWJ characteristics to geomorphic section were apparent (Figure 5.2). Low-gradient sections tended to have more large wood dams, more LWJ in contact with the water, and a higher number of LWJ than other geomorphic sections. Clay-lake plain sections tended to have a higher proportion of small (few-piece) LWJ than did mid-gradient sections, while high-gradient sections appeared to be intermediate in the proportion of small LWJ between clay-lake plain and high gradient sections. Large wood jam characteristics did not group by river or forest age along the first two axes (Figure 5.3).

Correlations between PC’s and environmental variables provide an idea of how combinations of LWJ characteristics relate to specific geomorphic and riparian factors (Table 5.3). Axis 1 correlated significantly only with sinuosity ($r^2 = 0.65, P < 0.01$) and rock-plane bedding ($r^2 = -0.60, P < 0.01$), suggesting that at high sinuosity without rock-plane bedding there were more LWJ that spanned the channel (dams), more LWJ in contact with the water, and more frequent LWJ. Axis 2 correlated only with distance of the section from the headwaters ($r^2 = -0.59, P = 0.01$), suggesting that a greater proportion per section of small LWJ occur at greater distances from the headwaters in streams we studied.

**LWJ variability related to geomorphic section**

When the variability in LWJ was constrained by geomorphic section (RDA with geomorphic section dummy variables as the environmental variables), 35% of the variability was explained (sum of all canonical eigenvalues is 0.345, $P = 0.02$; Table 5.4).
Relationships among geomorphic sections were essentially the same as in PCA, and 33% of the variance was explained by the first two RDA axes (Figure 5.4).

The number of LWJ, the percent of dams, and the percent of small LWJ showed the strongest linear correlation with geomorphic section class, although variability was fairly high within classes (Figures 5.4, 5.5, and 5.8). In contrast, the percent of LWJ contacting the water and the percent of large LWJ did not correlate significantly with geomorphic section classes (Figures 5.7, and 5.9).

**LWJ variability related to specific geomorphic and riparian variables**

When all (11) environmental variables constrained the variability in LWJ characteristics (RDA), it resulted in a model that was not statistically different from random associations between the sets of environmental variables and LWJ characteristics (first axis $P = 0.47$; all axes $P = 0.26$; Table 5.5). We found, however, that subsets of the data significantly predicted LWJ characteristics. For four of the five LWJ variables, regression models with the highest adjusted-$r^2$ values and lowest $P$-values included one or more factors representing characteristics of the riparian forest (Table 5.6). The one LWJ variable (percent of LWJ contacting the active channel) for which the model with the highest adjusted-$r^2$-value and lowest $P$-value did not contain a factor representing riparian forest, did include riparian factors in the model with the highest adjusted-$r^2$ value.

All of the best models for the abundance of LWJ (LWJ 100 m$^{-1}$) included the terms for channel width (WIDT) and rock-plane bedding (RKPN), and these two terms alone were fairly good predictors of LWJ 100 m$^{-1}$ (adjusted-$r^2 = 0.56$, $P < 0.01$). All of
the best models for predicting percent of dams and the percent of LWJ contacting the water included sinuosity (SINU), and SINU plus WIDT formed the two terms in the best, most reduced models (% dams: adjusted-$r^2 = 0.47$, $P = 0.00$; % LWJ touching water: adjusted-$r^2 = 0.33$, $P = 0.02$). Neither the percent of small or large LWJ could be predicted effectively only with linear combinations of geomorphic variables we measured ($P > 0.05$ for all models including only geomorphology variables). In a model with mean riparian tree diameter and abundance, the percent of small LWJ was significantly predicted by a combination of gradient, sinuosity, width, low valley constraint, distance from the headwaters, and rock-plane bedding ($P = 0.02$). High valley constraint together with the proportion of riparian conifers and snags explained a significant amount of variability in the proportion of large LWJ ($P = 0.01$).

Discussion

Variability in LWJ characteristics

We found high variability in LWJ characteristics among sampled geomorphic sections, resulting in a wide dispersion of site scores in both the PCA and RDA. Nevertheless, points from similar geomorphic sections tended to group in similar regions, supporting the prediction that geomorphic settings had unique combinations of LWJ characteristics. Variability in LWJ characteristics was significantly represented by gradients along more than one axis, demonstrating that changes in one or more LWJ characteristics did not always correlate with changes in other LWJ characteristics that we measured. The reason that some LWJ characteristics did not relate consistently to each
other is because different LWJ characteristics corresponded differently with geomorphology and riparian forest characteristics.

**LWJ characteristics related to geomorphic sections**

Our results show that in spite of other co-variables, geomorphic setting alone corresponded with significant amounts of variability in section-level LWJ characteristics, providing support for the idea that LWJ characteristics correspond with patchy geomorphology of the river corridor. Differences in the correspondence of individual LWJ characteristics with changes in geomorphology, as well as high variability of all LWJ characteristics within geomorphic settings resulted in geomorphic setting explaining only 35% of the variability we measured in all LWJ characteristics considered together. Specifically, the abundance of LWJ, the proportion of dams, and the abundance of small LWJ corresponded with geomorphic setting, showing that in addition to LWJ abundance a measure of the orientation and a measure of the number of pieces in LWJ varied consistently with geomorphic changes at large scale. In contrast, the proportion of LWJ contacting the active channel, and the proportion of large LWJ did not correspond significantly with geomorphic setting, showing that variability in these LWJ characteristics responded strongly to environmental factors that we did include in our evaluation.

**LWJ characteristics related to geomorphic and riparian factors**

Linear combinations of geomorphic and riparian factors significantly corresponded with individual, section-level LWJ characteristics, but most strongly with
the same three characteristics that corresponded most strongly with geomorphic setting classifications (LWJ abundance, the proportion of dams, and the proportion of small LWJ), reinforcing our observations that geomorphic sections comprised repetitions of similar combinations of environmental factors. Regression analyses identified stronger correlations between sets of individual environmental factors and individual LWJ characteristics than we found between LWJ characteristics and geomorphic settings.

The strong presence of riparian forest variables in the best regression models supports the idea that LWJ in stream segments reflects interactions of the channel with the forest, not just within the stream (Collins and Montgomery 2002, Boyer et al. 2003). Identification of channel or valley geomorphology alone is not enough to predict as well as possible the abundance, orientation, or number of pieces in LWJ. Nevertheless, geomorphic variables alone corresponded strongly with variability in the abundance of LWJ and the proportion of dams (as we also found in previous studies; Chapter 2 and Chapter 3), and significantly but with low correlation with the proportion of LWJ contacting the active channel.

Stream channel width and rock-plane bedding seem to be the most important factors for explaining the abundance of LWJ: fewer LWJ occurred where width was high and rock-plane bedding was present. We also determined that rock-plane bedding was the most important geomorphic predictor for the abundance of LWJ, and that the abundance of LWJ corresponded with stream width, in shorter reaches of three of the study rivers (Chapter 2). The mobility of LW has been shown in many studies to depend highly on channel width (Wing and Skaugset 2002, Gurnell 2003), so higher numbers of LWJ in smaller channels in our study probably reflect low mobility of more pieces of
wood that anchor LWJ than in wider channels. Other studies have also found higher numbers of LW and LWJ in smaller channels, explaining this finding by suggesting that stream flow in small channels is too low to effectively move much of the wood in them (Gurnell et al. 2002, Abbe 2000). Fewer LWJ have also been reported for plane-bedded streams in other areas (Montgomery et al. 1995), probably because rock-plane bedding provides poor anchoring for LWJ. In our study area, low and mid-gradient geomorphic sections had the narrowest channels and no rock-plane bedding, so LWJ abundance was highest in these sections, as indicated by ordination analysis.

Stream channel width and sinuosity appeared to be the most important factors associated with the percentage of dams: there were fewer dams in wider channels and more dams occurred where sinuosity was higher. The potential for dams is highest in sinuous, narrow streams because of variable water flow, high contact of potential key pieces with the bed and bank, and because shorter pieces can span the channel (Gurnell et al. 2002). Higher number of dams most likely correlate with sinuous channels because sinuosity increases LW anchoring capacity and moderates water flow along the channel during floods (Braudrick and Grant 2001, Abbe 2000). In our study area, channel width tended to be lowest and sinuosity highest in low and mid-gradient sections, so more dams occurred there, again as indicated by ordination analysis. In our previous study of shorter stream reaches, sinuosity and stream width both corresponded with the percent of the channel spanned by LWJ, but neither was the best predictor of percent channel spanned (Chapter 2). Sinuosity at the section scale may therefore affect LWJ differently compared to sinuosity at the reach scale. In addition, LWJ that spanned 100% of the
channel block the entire stream flow and so comprise a subset of LWJ that are probably particularly sensitive to channel sinuosity and width.

Stream channel width and sinuosity together explained a significant amount of the variability in the proportion of LWJ contacting the active channel, but the predictive ability of the model was low (adjusted-$r^2 = 0.33$), suggesting that factors we measured are not primarily controls over the number of LWJ that are in contact with the water at low-flow conditions. The proportion of LWJ contacting the active channel therefore does vary consistently with geomorphic setting. Including this variable (the proportion of LWJ contacting the active channel) in ordination analysis contributed substantially to unexplainable variability.

Neither the proportion of small LWJ (2 to 5 pieces) nor large LWJ (more than 20 pieces) could be significantly predicted by geomorphic variables alone, but all best models for the number of LWJ pieces included valley-constraint terms. The necessary presence of riparian factors for significant correlation of environmental variables with the number of LWJ pieces suggests that the number of pieces in LWJ is especially sensitive to recruitment types and amounts. We did not measure recruitment directly so cannot connect recruitment to particular geomorphic sections.

Distance of study sections from headwaters represents the position of the segment along the river, for which consistent changes may be expected in accordance with concepts similar to the unidirectional change conceptualized in the river continuum concept (Vannote et al. 1980) or over large scales by other authors (e.g., Nakamura and Swanson 2003). If conditions affecting LWJ changed predictably as a function of downstream position of the stream segment, then we would expect distance from
headwaters to be an important factor associated with LWJ characteristics, and it was, although distances were small enough in our study area that changes in stream form relating to distance along the stream were relatively minor (e.g., change from 1st to 3rd order between source and mouth). Distance from headwaters only appeared as a term in the best regression models for the proportion of dams and the proportion of LWJ with the fewest pieces. The abundance of LWJ, percent of LWJ contacting the active channel, and percent of LWJ with more than 20 pieces varied more similarly to variations in other LWJ characteristics than distance, suggesting that patches of similar geomorphology (and riparian forest) exert a greater influence than just distance along the line of the river on some LWJ characteristics.

Some of the differences in LWJ characteristics we observed probably result from relative position of the study section in the stream system. For instance, the low-gradient section in the Upper Carp River, and the mid-gradient section of the Little Carp River both occurred just downstream from high-gradient, rock-plane bedded sections, and appeared to have collected particularly large amounts of LW from upstream. More research is needed to evaluate physical and biological effects of LWJ patch structure, order, and juxtaposition (metastructure; Poole 2002).

Refinement of the geomorphic classification system we used in this study would be possible for specific needs, emphasizing factors known to be most important for the LWJ characteristics of interest. While the geomorphic classification we used would perhaps be difficult to replicate between observers because classification included subjective elements, measurement of component factors is straightforward and measured criteria can be used to predict LWJ characteristics. Information about LWJ in relatively
long stream segments in other streams and in other geographic areas together with specific environmental variables like those we measured would complement this data from the Porcupine Mountains.

**Implications for stream restoration**

Roni et al. (2002) advocated identification of the most ecologically healthy and unhealthy areas in ecosystems so that restoration practitioners could concentrate efforts on bolstering and connecting already healthy areas and remediating the unhealthy ones. Some segments of old-growth river we studied naturally contained fewer and different kinds of LWJ than other segments, suggesting that relative scarcity of LWJ in some areas does not necessarily indicate an unhealthy ecosystem, but rather probably the opposite. Considering the stream as a combination of patches with different LWJ characteristics may help when identifying restoration priorities, which could include restoration of large-scale patch structure.

It appears that a few geomorphic factors at the scale of the stream corridor associate with LWJ characteristics and can help to indicate where LWJ of different types are naturally more favored. Specifically, more LWJ may be restored to narrow channels in geomorphic sections without rock-plane bedding; more dams (LWJ spanning 100% of the channel), and more LWJ contacting the active channel may be restored to geomorphic settings where streams have greater sinuosity and larger width. The presence of riparian factors in all the strongest predictive models for LWJ size, abundance and orientation provides support for restoration practices that include management of riparian forests (Boyer et al. 2003).
References


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<th>Valley constraint</th>
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<th>Riparian snags (%)</th>
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Table 5.1. Geomorphic section characteristics (environmental variables). Notes: ^1 Section abbreviations: CLP = clay-lake plain, HG = high-gradient, LG = low-gradient, MG = mid-gradient. ^2 Forest age abbreviations: OG = old-growth, SG = second-growth
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Table 5.2. Summary table principal components analysis (PCA).
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<tr>
<td>CONS</td>
<td>0.253</td>
<td>0.134</td>
</tr>
<tr>
<td>DIST</td>
<td>-0.367</td>
<td>0.587 *</td>
</tr>
<tr>
<td>RKPN</td>
<td>-0.604 **</td>
<td>0.401</td>
</tr>
<tr>
<td>RIPC</td>
<td>0.309</td>
<td>-0.252</td>
</tr>
<tr>
<td>RIPS</td>
<td>-0.283</td>
<td>0.055</td>
</tr>
<tr>
<td>RIPD</td>
<td>-0.029</td>
<td>-0.393</td>
</tr>
<tr>
<td>RIPA</td>
<td>-0.249</td>
<td>0.113</td>
</tr>
</tbody>
</table>

Table 5.3. Correlation of geomorphic sections and specific environmental factors with principal components analysis (PCA) first two axes. Note: <sup>1</sup> * indicates significance ≤ 0.05; ** indicates significance ≤ 0.01
<table>
<thead>
<tr>
<th>Variable</th>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>0.234</td>
<td>0.095</td>
<td>0.016</td>
</tr>
<tr>
<td>Sample- environment correlation</td>
<td>0.772</td>
<td>0.604</td>
<td>0.278</td>
</tr>
<tr>
<td>Cumulative % variance of LWJ characteristics</td>
<td>23.4</td>
<td>32.3</td>
<td>33.9</td>
</tr>
<tr>
<td>Cumulative % variance of LWJ-geomorphic</td>
<td>68.9</td>
<td>95.4</td>
<td>100.0</td>
</tr>
<tr>
<td>section relationship</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum of all canonical eigenvalues</td>
<td>0.339</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permutation test $P$-value</td>
<td></td>
<td></td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 5.4. Summary table of redundancy analysis (RDA) representing large wood jam (LWJ) characteristics and geomorphic section classes. Note: $^1$ There are only three axes because there were only three (dummy) variables.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
<th>Axis 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>0.312</td>
<td>0.199</td>
<td>0.081</td>
<td>0.066</td>
</tr>
<tr>
<td>Sample-environment correlation</td>
<td>0.897</td>
<td>0.834</td>
<td>0.768</td>
<td>0.739</td>
</tr>
<tr>
<td>Cumulative % variance of LWJ characteristics</td>
<td>31.2</td>
<td>51.1</td>
<td>59.3</td>
<td>65.9</td>
</tr>
<tr>
<td>Cumulative % variance of LWJ-geomorphic section relationship</td>
<td>44.3</td>
<td>72.5</td>
<td>84.1</td>
<td>93.4</td>
</tr>
<tr>
<td>Sum of all canonical eigenvalues</td>
<td></td>
<td></td>
<td></td>
<td>0.705</td>
</tr>
<tr>
<td>Permutation test P-value</td>
<td></td>
<td></td>
<td></td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 5.5. Redundancy Analysis (RDA) and correlation of large wood jam (LWJ) and environmental variables with primary axes. Only correlations with Pearson correlation coefficient at least 0.50 are reported.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Variables in model</th>
<th>Adj-$r^2$</th>
<th>$r^2$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWJ/100m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>full model</td>
<td>ALL</td>
<td>0.62</td>
<td>0.87</td>
<td>0.07</td>
</tr>
<tr>
<td>best model with all EV</td>
<td>+GRAD -SINU -WIDT -RKPN +RIPC -RIPA</td>
<td>0.78</td>
<td>0.86</td>
<td>0.00</td>
</tr>
<tr>
<td>best model with only geomorphology</td>
<td>+GRAD -WIDT -RKPN</td>
<td>0.60</td>
<td>0.67</td>
<td>0.00</td>
</tr>
<tr>
<td>best model with RDA axis</td>
<td>-WIDT -RKPN</td>
<td>0.56</td>
<td>0.61</td>
<td>0.00</td>
</tr>
<tr>
<td>% Dams</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>full model</td>
<td>ALL</td>
<td>0.29</td>
<td>0.75</td>
<td>0.28</td>
</tr>
<tr>
<td>best model with all EV</td>
<td>+SINU -DIST +RIPC -RIPS</td>
<td>0.66</td>
<td>0.74</td>
<td>0.00</td>
</tr>
<tr>
<td>best model with only geomorphology</td>
<td>+GRAD +SINU -WIDT +LOCON</td>
<td>0.48</td>
<td>0.60</td>
<td>0.01</td>
</tr>
<tr>
<td>best model with RDA axis</td>
<td>+SINU -WIDT</td>
<td>0.47</td>
<td>0.53</td>
<td>0.00</td>
</tr>
<tr>
<td>% Contacting water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>full model</td>
<td>ALL</td>
<td>0.00</td>
<td>0.65</td>
<td>0.53</td>
</tr>
<tr>
<td>best model with all EV</td>
<td>+SINU +HICON +DIST -RKPN +RIPC -RIPD</td>
<td>0.40</td>
<td>0.61</td>
<td>0.06</td>
</tr>
<tr>
<td>best model with only geomorphology</td>
<td>+SINU +WIDT</td>
<td>0.33</td>
<td>0.41</td>
<td>0.02</td>
</tr>
<tr>
<td>best model with RDA axis</td>
<td>+SINU +WIDT</td>
<td>0.33</td>
<td>0.41</td>
<td>0.02</td>
</tr>
<tr>
<td>% Piece-class 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>full model</td>
<td>ALL</td>
<td>0.49</td>
<td>0.82</td>
<td>0.13</td>
</tr>
<tr>
<td>best model with all EV</td>
<td>+GRAD +SINU -WIDT +LOCON +DIST +RKPN -RIPD + RIPA</td>
<td>0.63</td>
<td>0.81</td>
<td>0.02</td>
</tr>
<tr>
<td>best model with only geomorphology</td>
<td>+SINU +RKPN +LOCON</td>
<td>0.18</td>
<td>0.32</td>
<td>0.13</td>
</tr>
<tr>
<td>best model with RDA axis</td>
<td>+SINU +RKPN +LOCON</td>
<td>0.18</td>
<td>0.32</td>
<td>0.13</td>
</tr>
<tr>
<td>% Piece-class 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>full model</td>
<td>ALL</td>
<td>-0.06</td>
<td>0.63</td>
<td>0.58</td>
</tr>
<tr>
<td>best model with all EV</td>
<td>-HICON +RIPC -RIPS</td>
<td>0.47</td>
<td>0.57</td>
<td>0.01</td>
</tr>
<tr>
<td>best model with only geomorphology</td>
<td>+GRAD -HICON +LOCON</td>
<td>0.21</td>
<td>0.35</td>
<td>0.10</td>
</tr>
<tr>
<td>best model with RDA axis</td>
<td>-HICON</td>
<td>-0.03</td>
<td>0.03</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Table 5.6. Best regression models of 11 environmental variables (EV) with LWJ characteristics of geomorphic sections
Figure 5.1. Map of geomorphic sections studied in the Porcupine Mountains. See Table 5.1 for actual section lengths. Dotted lines represent boundaries between old-growth and second-growth forest. The northern second-growth forest along the shore of Lake Superior was logged prior to 1910. CLP is clay-lake plain, HG is high-gradient, LG is low-gradient, and MG is mid-gradient.
Figure 5.2. Principal components analysis (PCA) on 5 characteristics of LWJ at the geomorphic-section level in 18 stream segments in the Porcupine Mountains. The two axes shown significantly explain 68.3% of the variability in jam characteristics (Axis 1: 42.2%, Axis 2: 26.1%, broken-stick eigenvalues > 1.0).
Figure 5.3. Principal components analysis (PCA) scores for sites in old-growth (virgin) and second-growth (harvested) forest.
Figure 5.4. Redundancy analysis (RDA) triplot showing relationship of large wood jam (LWJ) characteristics with geomorphic sections. Labeled symbols representing geomorphic section are 4 points (6 points for low-gradient) on top of each other; because sample scores are linear combinations of the variables, when environmental variables are binary dummy variables (as they are here) all sample scores from one category have the same coordinates on the triplot. The open circle represents the environmental score for the low-gradient section, and is a point rather than an arrow, because it represents a binary, categorical condition rather than a continuous gradient. Other environmental variables occur at the same points as the sample scores.
Figure 5.5. Linear abundance of large wood jams (LWJ) in geomorphic settings of 6 streams in the Porcupine Mountains of Northern Michigan.
Figure 5.6. Percentage of large wood jams that spanned 100% of the wetted channel (dams).
Figure 5.7. Percentage of large wood jams in contact with water during the time of sampling (low flow).
Figure 5.8. Percentage of large wood jams comprised of two to five pieces of large wood. Note that order of geomorphic sections is different than for Fig 2a,b,c, and e.
Figure 5.9. Percentage of large wood jams comprised of more than 20 pieces of large wood. Note that order of geomorphic sections is different from Figure 5.2.a, b, c, and d.
CHAPTER 6

INFLUENCE OF LANDSCAPE GEOMORPHOLOGY ON LARGE WOOD JAMS AND SALMONIDS IN AN OLD-GROWTH RIVER OF UPPER MICHIGAN

Introduction

Stream and riparian restoration projects often include the addition of large wood (pieces greater than 10 cm diameter and 1 m in length, Gregory and Davis 1992, Slaney and Zaldokas 1997, e.g., Booth et al. 2001). Large wood has a variety of functions in stream ecosystems including an influence on stream channel morphology and dynamics, riparian forest structure and dynamics, sediment storage, stream flow, organic matter processing, and the formation of wildlife habitat (Naiman and Bilby 1998, Gurnell et al. 2002, Naiman et al. 2002, Gregory et al., 2003). Because of the potential for large wood to provide valuable in-stream habitat, wood additions to streams often aim at improving habitat for fish species (Lowe, 1996, Cederholm et al. 1997a, 1997b, Dominguez and Cederholm 2000, Lehane et al. 2002). However, in many cases the most effective amounts and arrangements of added wood for both fish habitat and other ecosystem functions remain unclear (Cederholm et al. 1997a, Hilderbrand et al. 1997a, 1997b, DuBois et al. 2001).

Uncertainty associated with addition of large wood to streams is apparent when considering the potential influences of large wood on salmonids. While some studies
have suggested that young salmonids preferentially use large wood habitat, especially when several pieces have aggregated to form large wood jams (LWJ) (Bilby and Bisson 1998, Sundbaum and Näslund 1998, Flebbe 1999), other studies have found that large wood habitat in streams has a variable or negligible effect on the distribution of juvenile salmonids (e.g., Cederholm et al. 1997a, Berg et al. 1998). For example, Ford and Lonzarich (2000) found no significant correlation between density of juvenile coho salmon (*Oncorhynchus kisutch* Walbaum) and large wood in two Lake Superior tributaries. DuBois et al. (2001) similarly documented no significant change in brook trout or total salmonid biomass in stream reaches up to three years after the amount of large wood was increased in three Lake Superior tributaries. Discrepancies between studies suggest that much remains unknown regarding how salmonids use large wood in streams of the northern Lake States, and thus many stream restoration professionals remain undecided about the most effective use of large wood for restoring salmonid habitat.

It is becoming increasingly evident, however, that an improved understanding of the connection between landscape characteristics and the arrangement of large wood fish habitat may increase the effectiveness of LWJ additions to streams (Flebbe 1999 Dominguez and Cederholm 2000, Streb 2001, Bisson et al. 2002, Wing and Skaugset 2002). Large wood jams in a river system influence stream characteristics in a variety of ways depending on hydrology, stream materials, and the characteristic of the wood itself (Abbe 2000, Gurnell et al. 2002, Dolloff and Warren 2003). Consequently, the influence of large wood on stream fish assemblages likely changes with the landscape. Within different geomorphic settings, certain LWJ characteristics or distributions appear to be
typical (Swanson 2003), and it follows that fish use of jams reflects the larger-scale setting. Where flow is highest and stream channel least amenable to trapping wood, (as is characteristic of larger streams) jams form along channel margins (Bilby and Bisson 1998) where they may be less likely to directly influence fish populations. Bilby and Ward (1989) also found that the characteristic and function of wood in forming pools and trapping sediment changed relative to stream size. Because the aggregation of wood in channels reflects stream size and other aspects of large-scale geomorphology, the influence of LWJ on fish assemblages is probably not the same everywhere along a stream, partly in response to position in the watershed (Richmond and Fausch 1995) and other aspects of spatial context (Warren and Kraft 2003).

In 2003, we began a study to investigate the formation and distribution of LWJ along the Little Carp River, a small river flowing through an old-growth, hardwood-conifer landscape of the northern Lake States, and the effects of these LWJ on salmonid populations. The Little Carp watershed is one of the few remaining watersheds in the northern Lake States that was never harvested, providing a unique opportunity to study the character and distribution of natural LWJ and their associated fish assemblages in order to develop reference information for stream restoration projects aimed at returning manipulated systems to less anthropogenically altered conditions. Our overall objective was to examine the relationships between LWJ and salmonid populations in different geomorphic settings of this old-growth watershed. Although we evaluated the composition and structure of the entire fish assemblage associated with the LWJ, most attention was given to salmonids, particularly brook trout, an endemic species in the waters of our study area. In addition to resident stream brook trout, coaster brook trout (a
native, anadromous form) were found in our study area until the mid 1900s. Recently, restoration efforts have included stocking thousands of young coaster brook trout in these streams, but the fate and behavior of these young fish remains unknown. A first step in understanding the fate of these stocked brook trout in the Little Carp River will be to evaluate the association of resident brook trout with habitat components like LWJ, providing a baseline for comparison with stocked brook trout over time. Thus, the specific study objectives of this study were to: 1) quantify how LWJ differ among different geomorphic sections; 2) determine how fish abundance and size differ between portions of stream at LWJ and away from LWJ, with particular attention to resident salmonids; and, 3) examine environmental factors of geomorphology and LWJ structure that influence any apparent associations of salmonids (particularly resident brook trout) with LWJ. Our overall hypothesis was that the distribution and structure of LWJ would vary by geomorphic setting, which in turn would correspond with the abundance and length of salmonids near LWJ.

**Methods**

**Study Site**

Along the south shore of Lake Superior in the Porcupine Mountains Wilderness State Park (PMWSP) occurs the largest contiguous tract of virgin northern hardwood-conifer forest between the Adirondack and Rocky Mountains (Davis 2003). The Little Carp River flows through the south-central portion of this old-growth landscape for a length of about 20 km (Figure 6.1). The river channel passes from a low-gradient (1%), relatively open valley near the source (Mirror Lake) through a high-gradient (3-5%),
constrained section with rock-plane bedding, into a mid-gradient (2-3%), relatively unconstrained section, and then finally onto a mid-gradient (1-3%) section of clay-lake plain before emptying into Lake Superior.

Riparian forests consist of eastern hemlock (Tsuga canadensis (L.) Carr.), northern white cedar (Thuja occidentalis L.), yellow birch (Betula alleghaniensis Britt.), and sugar maple (Acer saccharum Marsh.). Maximum tree height is approximately 40 m, with mean height of the tallest trees in the study area roughly 25 m and mean dbh about 60 cm. Most of the river is forested to the edge of the bankfull channel. The major source of mass mortality of riparian trees is windthrow. Seasonal precipitation can be heavy (800-900 mm precipitation, up to 7 m snowfall; Frelich 2002); however, the topography is not conducive to avalanches, landslides or other forms of mass wasting except localized streambank failures. Fire is infrequent in these northern hardwood-conifer forests.

The substrate of the Little Carp River generally consists of loose cobble and gravel with rock-plane bedding in high-gradient and clay-lake plain sections. The mean bankfull channel of this river measures 9.6 m wide (SE = 1.4, n = 12). Floodplain development varies between sections of the river. Few records of streamflow exist for the Little Carp River. Goebel et al. (2003) reported discharge during annual floods ranging from 4.7 m$^3$ sec$^{-1}$ in the low gradient sections of the river to 9.4 m$^3$ sec$^{-1}$ in the lower, high gradient portions of the River. The discharge associated with 50-year flood events has been estimated to range between 17.5 to 38.1 m$^3$ sec$^{-1}$ (Goebel 2001). Most of these extreme events occur in the spring as dense snowpacks (ranging from 1-3 m thick) melt, often very rapidly (Goebel 2001).
Human influence to the shape or condition of the Little Carp River channel and surrounding forest is minimal. The most consistent human activity along the river consists of recreational hiking, camping, and fishing. Our observation is that fishing pressure along the river remains light but consistent during the summer. No timber harvesting or mining is known to have occurred along the Little Carp River.

More than 10 species of fish occur in the Little Carp River, including several species of dace (*Rhinichthys atratulus* Hermann; *Rhinichthys cataractae* Valenciennes; *Phoxinus eos* Cope), two species of sculpin (*Cottus bairdi* Girard; *Cottus cognatus* Richardson), brook trout, introduced rainbow trout (*Oncorhynchus mykiss* Walbaum) and coho salmon (USDA Forest Service, unpublished data). Historically, coaster brook trout reproduced in the Little Carp River. Currently brook trout occur in the river, although it is not known to what extent (if any) they demonstrate the anadromous lifestyles of coaster brook trout. Restoration efforts by the Michigan Division of Natural Resources currently include attempts to re-establish coaster brook trout in the Little Carp River. Approximately 20,000 to 30,000 three to five inch brook trout from a strain of known coasters (Nipigon Lake strain) have been planted in the Little Carp River each year from 1999 to 2003. Less than one month prior to our study, 35,000 brook trout were released into the Little Carp River from an access bridge approximately 10 km from the mouth of the river in the high-gradient section. Since 1999, all brook trout have been released from that point with the exception of one year when 20,000 were carried by hand in buckets and released approximately 3 km upstream from the mouth in the clay lake plain section. Newly stocked fish in 2003 had their right pectoral fins clipped, allowing differentiation from other brook trout. Brook trout stocked in previous years had other
fins clipped. We refer to brook trout as resident brook trout if they have no fin clips or fins other than right-pectoral fins clipped.

**Study design**

We designated four zones with similar large-scale geomorphic characteristics (hereafter referred to as geomorphic sections) along the Little Carp River (Figure 6.1, Table 6.1), and measured the characteristics of nine LWJ within each section using a standard monitoring program adapted from Washington State’s Timber-Fish-Wildlife program for monitoring large wood in streams (Schuett-Hames et al., 1999). For the purposes of this study, LWJ was an aggregation of wood with at least one piece exceeding 1 m in length and 10 cm in diameter. We randomly selected three LWJ for fish surveys from each of the four geomorphic settings. Each selected LWJ formed the midpoint of a study reach (i.e., 3 reaches per section for a total of 12 reaches). We divided each reach into three channel geomorphic units relative to the LWJ: upstream (US), downstream (DS), and directly at the jam (J). The jam unit lay immediately adjacent to the LWJ for the width of the LWJ as determined by wood in the LWJ and the pool formed by the LWJ. Upstream and downstream units began at the edges of the LWJ or the pool clearly formed by the LWJ and continued for a distance approximately two bankfull channel widths or halfway to the next LWJ, depending on the proximity of other LWJ. For example, if the upstream edge of the focal LWJ was only 10 m away from the downstream edge of the nearest upstream LWJ, we sampled approximately 5 m upstream from the edge of the focal LWJ. At each of the jams where the fish assemblage was sampled, we also noted the length of the associated pool, and whether riffles or pools...
occurred immediately adjacent upstream and downstream. Fish surveys were conducted by single-pass electrofishing (Smith-Root model LR-24) during the week of 20 to 24 October 2003. We typically started our sample at a natural barrier downstream of the LWJ (e.g., riffle) and proceeded upstream to include the area of the LWJ up to the next adjacent natural barrier. Captured fish were identified, measured, and released after surveying the portion of the reach where they were collected. Juvenile rainbow trout and coho salmon were grouped, as were dace and sculpin species for ease in tallying and because our primary focus was brook trout. Brook trout stocked in 2003 might have associated with jams differently than trout that had resided in the river for a longer period of time, so we evaluated newly stocked brook trout (right pectoral fin clipped; 2003) separately from “resident” brook trout and other salmonids that had other or no fins clipped.

**Data analysis**

We used principal components analysis (PCA) to quantify the relationship between LWJ and geomorphic setting and determine the influence of large-scale geomorphology on LWJ characteristics using the data from all nine of the LWJ characterized in each geomorphic section (36 jams total). Variables used in the PCA included: valley gradient (%), valley constraint (high, medium, or low), distance to nearest downstream LWJ (m), distance to nearest upstream LWJ (m), volume of large wood in the LWJ (m³), number of large wood pieces in the LWJ, number of large wood pieces contacting the water, proportion of the bankfull channel spanned by the LWJ (%), and the proportion of conifer pieces in the LWJ (%). We performed PCA after general
data relativization, and also computed broken-stick eigenvalues to test for significance (broken-stick eigenvalues greater than one indicate significant gradients; PC-ORD 3.01, MJM Software Design, Gleneden Beach, OR, USA). We calculated Pearson correlation coefficients to measure the correlation between environmental variables and factor scores with MINITAB software (Minitab Inc. Rel 14, State College, PA, USA).

We compared differences in the abundance and length of salmonids (rainbow trout/coho salmon, resident brook trout, and newly stocked brook trout) and the abundance of non-salmonids relative to LWJ using one-way ANOVA. We calculated abundance as the number of fish per meter of each stream portion sampled, a metric we considered appropriate because wetted channel widths remained relatively constant between reaches we sampled (approximately 7 m). Locations within sampled reaches relative to LWJ (US, DS, J) formed the independent variable. We included abundance data from above and below LWJ in ANOVA rather than just grouping data into two locations (away from LWJ and at LWJ) because we believed that there could be association of fish with LWJ related to flow direction. Reaches were only included for analysis if fish were captured there (some species of fish were not caught in some reaches, e.g., rainbow trout/coho salmon did not occur in any reaches upstream from the clay-lake plain geomorphic section). We also used a one-way ANOVA to check for differences in the length of brook trout between geomorphic settings, using a Tukey’s mean comparison test to differentiate between groups if ANOVA indicated an overall significance between groups. We conducted ANOVA using PROC GLM with SAS software (V8, SAS institute, Cary, NC, USA). Abundance data for resident brook trout was transformed by dividing the data by 10 then computing the arcsine of the double
square root. All other abundance data was square root transformed, while length data did not require transformation to meet the assumption of normality for parametric statistical evaluation.

We used multiple regression to relate the length and proportion of resident salmonids (resident brook trout with rainbow trout and coho salmon and resident brook trout alone) occurring at LWJ to the characteristics of the LWJ and geomorphic setting. We used as environmental variables the LWJ and geomorphic characteristics shown to be most related along the first two (significant) PCA axes. We computed the proportion of fish at LWJ by dividing the abundance at the LWJ by the total abundance (at and away from the LWJ). To account for sampling effort, we adjusting total abundance for the proportional length of sampled portions of the reach upstream and downstream (US and DS). We adjusted total abundance for the relative length of portions of the reach by first calculating abundance (number m\(^{-1}\)) for the US and DS portions, then multiplying abundance by the ratio of away-from-LWJ lengths, which yielded a representation of the abundance of fish away from LWJ:

\[
A_{\text{away}} = A_{\text{US}} \cdot \left(\frac{D_{\text{US}}}{D_{\text{US}} + D_{\text{DS}}}\right) + A_{\text{DS}} \cdot \left(\frac{D_{\text{DS}}}{D_{\text{US}} + D_{\text{DS}}}\right)
\]

where \(A\) represents abundance (number m\(^{-1}\)) and \(D\) is the length of the portion of the reach (m). Subscripts indicate the portion of the reach: “away” indicates the combined portions not at LWJ, and DS and US indicate positions relative to LWJ as explained previously. By computing relative abundances in this way we standardized data to the portions of streams sampled at LWJ, so if fish were distributed in equal numbers
throughout the sampled reaches, the proportion at LWJ and away from LWJ would be equal (e.g., 0.5 at LWJ and 0.5 away from LWJ). Mean length and proportion were approximately normally distributed so did not require transformation. We used SAS General Linear Model (GLM) type 3 mean square errors and $P$-values to select the smallest subset of independent LWJ and geomorphic setting variables to explain the variability in the dependent fish variable (abundance, length or proportion at jams). The best model was considered the one that explained the most variability (had the highest correlation coefficient) while at the same time showed the most change when any single term was removed, and had the lowest overall $P$-value. Because it was possible that differences in the abundance of salmonids could reflect the recent stocking of brook trout in the high-gradient section, we also included the distance from the point of release to the section as an explanatory variable in our original model.

Results

Characteristics of large wood jams by geomorphic setting

Large wood jams in the Little Carp River differed in size and position, varying generally with the larger-scale geomorphology of the river corridor. The first two principal components accounted for 51% of the variance in jam characteristics, and exceeded broken-stick eigenvalues, indicating a significant gradient along each axis (Figure 6.2). The first principal component related most strongly with percent of channel spanned by the LWJ ($r = 0.79, P < 0.001$), valley gradient ($r = -0.61, P < 0.001$), valley constraint (high constraint $r = -0.66$, low constraint $r = 0.85, P < 0.001$ for both), and the number of pool forming pieces in the LWJ ($r = 0.60, P < 0.001$). The second principal
component related most strongly with volume of wood in the LWJ ($r = -0.57$, $P < 0.001$) and the number of pieces in the LWJ ($r = -0.55$, $P = 0.001$).

**Fish assemblages by geomorphic setting**

Trout were the dominant species numerically throughout the reaches we electrofished, except in two reaches of the low-gradient section (Table 6.2). In the clay lake plain section (less than 3 km from the river’s mouth) juvenile rainbow trout (steelhead) and coho salmon were the most numerous species. We found and captured only one brook trout during our electrofishing surveys in the clay-lake plain (and it was at a LWJ). No rainbow trout or coho salmon were observed in geomorphic sections other than the clay-lake plain. In the mid and high-gradient sections (8-12 km from the mouth) both wild-born (unclipped fins) and stocked brook trout were collected more frequently than any other species. We did not find newly stocked brook trout downstream in the clay-lake plain or upstream in the low-gradient section. In the high-gradient section we captured 6 resident brook trout, all away from LWJ. Ten of the resident brook trout we captured in the mid-gradient section, and three captured in the high-gradient section appeared to have fin clips other than right pectoral; all other resident brook trout were wild-born. In the low gradient section, which was the furthest upstream (20 km from the mouth), wild-born brook trout comprised the only population of trout and were less abundant than dace in two reaches we sampled in that section (Table 6.2).
Salmonid and non-salmonid abundance and length near LWJ habitat

Although there appeared to be greater salmonid (resident brook trout, rainbow trout/coho salmon) and non-salmonid fish abundance near LWJ (Figures 6.3 and 6.4, Tables 6.3 and 6.4) these associations tended to be highly variable. The abundance of resident brook trout, newly stocked brook trout, rainbow trout/coho salmon and non-salmonids did not differ overall between portions of reaches relative to LWJ when all reaches were considered together (all $P$-values > 0.10, 1-way ANOVA).

Lengths of resident brook trout also did not differ between portions of reaches relative to LWJ ($P = 0.75$), nor did the lengths of rainbow trout/coho salmon ($P = 0.31$). The length of resident brook trout did vary, however, with geomorphic section ($P < 0.01$): smaller resident brook trout occurred in the low-gradient section, but we observed no difference in resident brook trout size among other sections (Figure 6.5). Fish stocked in 2003 comprised a single size class (approximately 102 mm), thus size differences relative to LWJ did not exist between portions of stream away from or at LWJ ($P = 0.40$) or between the two geomorphic sections (high and mid gradient) where newly stocked brook trout occurred ($P = 0.67$).

Factors influencing salmonid association with LWJ

Eight explanatory variables were examined for correlation with the mean proportion and length of salmonids (brook trout, rainbow trout, and coho salmon together) that occurred at LWJ habitat ($n = 12$; Table 6.5). Variability in the proportion of resident salmonids (rainbow trout/coho salmon and resident brook trout) occurring at LWJ most reflected high valley constraint and total wood volume combined with the
number of pieces of wood in LWJ ($r^2 = 0.74, P = 0.04$). By comparison, the best regression model for the proportion of resident brook trout occurring at jams explained 89% of the variability in terms of valley gradient and the percent of channel spanned by LWJ ($P < 0.01$). Variability in the length of resident brook trout occurring at LWJ was best explained by valley gradient alone ($r^2 = 0.81, P = 0.01$).

**Discussion**

Large wood jams in this relatively undisturbed river associated with an old-growth landscape of the northern Lake States differed structurally with geomorphic setting. We found that large wood jams that spanned more of the channel and had a higher number of pieces in contact with the water occurred in lower gradient sections which tended to have to have lower valley constraint, higher sinuosity, and smaller channel bed materials than the higher gradient sections of the river. Within recognizably different geomorphic settings, structural characteristics of LWJ also varied considerably.

When all study reaches were considered together, neither the abundance nor length of salmonids or nonsalmonids corresponded significantly with portions of stream at LWJ compared to portions away from LWJ. This is surprising, given the common understanding that LWJ benefits salmonids and seems to represent preferred habitat for many species of fish (Dolloff and Warren 2003). The lack of statistically significant association of salmonids with large wood in the Little Carp River agrees, however, with findings from other studies (Berg et al., 1998, Ford and Lonzarich, 2000, DuBois et al., 2001, Warren and Kraft 2003), and most likely reflects variability related to environmental factors of the stream landscape.
Geomorphic and LWJ characteristics explained most of the variability in the proportion of salmonids occurring at LWJ, suggesting that structural characteristics of the LWJ (which varied significantly among geomorphic settings) and the availability of geomorphically-influenced habitat influenced the function of LWJ as fish habitat. Regression analyses indicated that variability in the proportion of resident salmonids at LWJ was best explained by a combination of geomorphic setting (high valley constraint) and LWJ characteristics (number of pieces of wood, wood volume in the LWJ). The results of the PCA suggest that LWJ characteristics such as the number of pool forming pieces also corresponded with large-scale geomorphic characteristics (e.g., valley constraint). We tested for the effects of LWJ in and out of the water by considering in the regression the number of pieces in the jam in contact with the water and the percent of channel spanned by the jams. The number of pool forming pieces did not explain a substantial amount of variability in salmonid abundance or length at jams, however, the percent of the channel spanned by LWJ and valley gradient were related significantly to the proportion of resident brook trout occurring at LWJ. We conclude that the size and volume of LWJ influence fish in ways other than just contacting the water (such as by creating high-flow refuges, or affecting temperature or prey abundance; Dolloff and Warren, 2003) or that these factors correlated with other habitat variables influencing fish abundance (Richmond and Fausch 1995, Zalewski et al. 2003). Wondzell and Bisson (2003) suggested that many studies have not shown increased biodiversity near large wood in rivers because the functional role of wood depends on a variety of factors (such as the presence of other structure) whose total effect determines biodiversity, not just the presence of large wood. The correlation of salmonid proportions at LWJ with a
combination of geomorphic and LWJ characteristics suggests that other factors in addition to LWJ may also influence the relative abundance of brook trout at LWJ in the Little Carp River. In relatively undisturbed systems like the Little Carp River ecosystem, high habitat diversity may mean that functions of LWJ which affect their correlation with fish abundance will be relatively less significant than in less complex systems.

We found that resident brook trout length at LWJ also was correlated with stream valley gradient, measured at the scale of geomorphic sections. Smaller resident brook trout occurred in the low-gradient upper reaches of the Little Carp River than in the middle sections, possibly because lower flows and complex habitats in the low gradient section favored wild reproduction and the survival of small fish. Resident brook trout in the high and mid-gradient sections have also faced annually repeated competition from thousands of stocked brook trout of around 100 mm length, which might have contributed to excluding smaller brook trout. Rainbow and coho were relatively even-sized because they represented a small segment of the population (most adults appear to have migrated to Lake Superior). Further study could examine resident brook trout reproduction and competition to determine reasons why lengths varied more between sections than relative to LWJ as well as why longer brook trout occurred where they did.

There are other factors could have influenced the occurrence of salmonids near LWJ, including the fact that brook trout spawn in the fall and travel to spawning areas during this time of year (Josephson and Youngs 1996). Three of the larger resident brook trout we captured were spawning, and so might have moved away from LWJ to find or utilize spawning areas. Although spawning might have drawn brook trout away from LWJ, brook trout have been shown to maintain high levels of movement throughout the
year (Gowan and Fausch 1996). Consequently, associations of brook trout with LWJ may be dynamic throughout the year, and perhaps strongest in the spring during high flows (Warren and Kraft 2003). The large number of new brook trout planted at the upstream end of the high-gradient section could have also induced behavioral changes in resident brook trout as newly stocked fish saturated available habitat in the high-gradient section where LWJ was sparse. Even though the timing and design of this study limit the generalization of its results, the data show that the role of LWJ in the Little Carp River does not seem to be as an unequivocal focus of salmonid abundance across all settings.

The association of brook trout and other fish with large wood in streams in the Lake States should be explored further by sampling a larger set of LWJ to represent more completely the spatial and temporal scales of variability for factors similar to those we measured. Our results confirm, however, first that association of young salmonids with LWJ is not always apparent, and second that the association of brook trout with LWJ when it occurs corresponds with a few physical characteristics of LWJ and setting that are related to larger-scale geomorphology.

**Implications for Stream Restoration**

If emulating an old-growth system is the desired goal for large wood addition to streams, attention should be given to the correlation of LWJ with larger scale geomorphology of the reference river. Our results suggest that restoring LWJ to streams should not be expected to influence habitat selection by salmonids the same way in all areas. While further work is needed to ascertain geomorphic factors that are most correlated with fish use of LWJ in a variety of settings as well as the structure and
function of LWJ in different settings, both the ordering of LWJ along environmental
gradients and the association of fish with LWJ that we observed correlated with variables
representing geomorphology of the river corridor. When evaluating reference streams,
the restoration practitioner should therefore consider not only the mean amount, size, or
type of wood in LWJ, but also the distribution and form of those LWJ relative to
recognizable geomorphology like valley gradient and constraint.

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### Geomorphic Setting

<table>
<thead>
<tr>
<th>Geomorphic Setting</th>
<th>Valley Gradient</th>
<th>Valley Constraint</th>
<th>Channel Bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay-Lake Plain</td>
<td>2%</td>
<td>Moderate</td>
<td>Rock-plane</td>
</tr>
<tr>
<td>Mid-Gradient</td>
<td>3%</td>
<td>Low</td>
<td>Cobble/Gravel</td>
</tr>
<tr>
<td>High-Gradient</td>
<td>5%</td>
<td>High</td>
<td>Rock-plane</td>
</tr>
<tr>
<td>Low-Gradient</td>
<td>1%</td>
<td>Moderate</td>
<td>Gravel/Cobble</td>
</tr>
</tbody>
</table>

Table 6.1. Characteristics of the study sections examined along the Little Carp River, Upper Michigan. Notes: 

1. Valley gradient measured from a 1:64,000 topographic map.
2. Valley constraint was classified visually, based on relative distance from the stream channel to the nearest large terraces or valley walls.
3. Channel substrate was classified visually based on apparent predominance of substrate material.
Table 6.2. Counts of fish captured in different geomorphic sections of the Little Carp River, Upper Michigan. Note: \(^1\) We did not differentiate some similar species for ease in tallying and because our focus was primarily on brook trout. Juvenile rainbow trout and coho salmon were grouped, as were dace and sculpin species.

<table>
<thead>
<tr>
<th>Species</th>
<th>Section of the Little Carp River</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clay-lake plain</td>
<td>Mid-gradient</td>
<td>High-gradient</td>
<td>Low-gradient</td>
</tr>
<tr>
<td>\textit{Salvelinus fontinalus}</td>
<td>1</td>
<td>168</td>
<td>367</td>
<td>33</td>
</tr>
<tr>
<td>\textit{Oncorhynchus mykiss}(^1)</td>
<td>192</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>\textit{Oncorhynchus kisutch}</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>\textit{Semotilus atromaculatus}</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>\textit{Rhinichthys atratulus, Rhinichthys cataractae, Phoxinus eos}(^1)</td>
<td>24</td>
<td>8</td>
<td>13</td>
<td>56</td>
</tr>
<tr>
<td>\textit{Umbra limi}</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>\textit{Cottus bairdi, Cottus cognatus}(^1)</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>0</td>
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</tbody>
</table>
Table 6.3. Mean (± 1 SE) brook trout abundance (number per m) and mean (± 1 SE, n) length (mm) by geomorphic section and stream portion (DS, J, US); see text for explanation) associated with large wood jams (LWJ) of the Little Carp River, Upper Michigan. For abundance data, n = 3; n = number of reaches.

<table>
<thead>
<tr>
<th>Abundance</th>
<th>Clay-lake</th>
<th>Mid-gradient</th>
<th>High-gradient</th>
<th>Low-gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stocked in 2003</td>
<td>1.78 0.97 0.78</td>
<td>5.02 2.36 5.94</td>
<td>(1.02) (0.58) (0.40)</td>
<td>(0.87) (1.59) (0.26)</td>
</tr>
<tr>
<td></td>
<td>0.01 0.16 1.18</td>
<td>0.13 0.10 0.37</td>
<td>(0.12) (1.04)</td>
<td>0.10 (0.12) (0.07)</td>
</tr>
<tr>
<td>Resident</td>
<td>(0.01)</td>
<td>(0.12)</td>
<td>(1.04)</td>
<td>(0.13)</td>
</tr>
<tr>
<td></td>
<td>(0.10)</td>
<td>(0.12)</td>
<td>(0.07)</td>
<td>(0.03)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Length</th>
<th>Clay-lake</th>
<th>Mid-gradient</th>
<th>High-gradient</th>
<th>Low-gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stocked in 2003</td>
<td>103 (4,2) 96 (4,2) 103 (3,2)</td>
<td>101 (2,3) 101 (2,3) 102 (2,3)</td>
<td>119</td>
<td></td>
</tr>
<tr>
<td></td>
<td>147 (9,2)</td>
<td>142 (0,1)</td>
<td>127 (0,1)</td>
<td>66 (5,3) 80 (13,3) 87 (6,3)</td>
</tr>
</tbody>
</table>
Table 6.4. Mean (± 1 SE) combined rainbow trout and coho salmon fingerling abundance (per m) and length (mm) by stream portion associated with large wood jams (LWJ) of the clay lake plain geomorphic section of the Little Carp River, Upper Michigan. For all reported values, n = 3 reaches. Rainbow trout and coho salmon did not occur in any geomorphic section other than the clay-lake plain.

<table>
<thead>
<tr>
<th>Stream Portion</th>
<th>DS</th>
<th>J</th>
<th>US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abundance</td>
<td>0.59 (0.25)</td>
<td>1.98 (0.63)</td>
<td>0.97 (0.05)</td>
</tr>
<tr>
<td>Length</td>
<td>82 (3)</td>
<td>88 (1)</td>
<td>80 (5)</td>
</tr>
</tbody>
</table>
Table 6.5. Characteristics of large wood jams surveyed for fish in the Little Carp River, Upper Michigan. Notes: 1 Valley gradient and valley constraint are shown in Table I. 2 Used as independent variable in regression analysis. 3 Salmonids: rainbow trout, juvenile coho salmon, resident brook trout, and brook trout planted in 2003.
Figure 6.1. Geomorphic sections of the Little Carp River watershed, Upper Michigan
Figure 6.2. Principal components analysis (PCA) of large wood jams (LWJ) based on LWJ and geomorphic characteristics in different geomorphic settings of the Little Carp River watershed, Upper Michigan. Ellipses were drawn to highlight groups.
Figure 6.3. Relative abundance (± 1 SE) of fish other than brook trout relative to large wood jams (LWJ) in the Little Carp River watershed, Upper Michigan. Abundance represents the number of captured fish divided by the length of stream sampled.
Figure 6.4. Brook trout abundance (± 1 SE) relative to large wood jams (LWJ) in the Little Carp River watershed, Upper Michigan. Abundance represents the number of captured fish divided by the length of stream sampled. See text for explanation of resident versus stocked brook trout.
Figure 6.5. Length of resident brook trout (± 1 SD) in geomorphic sections of the Little Carp River. For clay-lake plain n = 1, mid-gradient n = 4, high-gradient n = 2, and low-gradient n = 9. ** indicates significance at $\alpha < 0.01$. 

Geomorphic Section
CHAPTER 7

ASSOCIATION OF BROOK TROUT (SALVELINUS FONTINALIS) AND OTHER FISH WITH LARGE WOOD JAMS IN POOLS OF A RIVER IN NORTHERN HARDWOOD-CONIFER OLD-GROWTH FOREST

Introduction

Large wood (LW; pieces at least 10 cm in diameter and longer than 1 m) in streams provides important habitat for a variety of animal species (Benke and Wallace 2003, Steel et al. 2003). Large wood functions in dynamically patchy riverine landscapes that create a variety of habitat environments for stream organisms (Robinson et al. 2002). Although some studies have shown that LW in streams increases biodiversity, the results are not consistent between studies, with some studies showing no increase in biodiversity corresponding with LW in streams (Wondzell and Bisson 2003). Wondzell and Bisson (2003) suggested the effects of wood on stream biodiversity reflect the combined effect of a variety of factors that influence the functional significance of LW to stream organisms. The functional importance of LW in streams may therefore vary within rivers as local stream structure and geomorphic context changes (Richmond and Fausch 1995).

The interaction of fish and LW in streams provides an example for understanding changes in the relations of organism with LW associated with changes in stream environmental context. Many species of fish associate positively with LW in streams
(Dolloff and Warren 2003, Zalewski et al. 2003). The presence of wood in streams has been shown to benefit fish in a variety of ways (Dolloff and Warren 2003). Sundbaum and Näslund (1998), for example, found that brown trout (*Salmo trutta* Linnaeus) in experimental channels with LW lost less mass over time, had heavier gut contents, lower swimming activity, and lower aggression rates than counterparts in channels without LW. However, the effects of wood on fish do not appear to be equal everywhere. Several studies have noted that LW in streams does not seem to always be the primary factor in habitat selection by trout (Simondet 1997, Berg et al. 1998, Ford and Lonzarich 2000). Miesbauer (2004) noted significant but weak correlations between trout and LW structure in streams. Dubois et al. (2001) noted statistically insignificant changes in brook trout (*Salvelinus fontinalis* Mitchill) abundance after the addition of LW to streams, while Warren and Kraft (2003) noted both increases and decreases in brook trout numbers after wood structure was removed from streams. Warren and Kraft (2003) concluded that the presence of LW in streams affects brook trout in different ways in streams of different order or in different stream contexts. Dolloff and Warren (2003), in their very complete compilation of information about fish relationships with wood in small streams, similarly suggested that the presence of large wood in streams is often facultative for fish species where other habitat components can substitute for the functions of wood structure (shelter, source of prey, reproduction substrate, etc.).

Although rivers have often been conceptualized as gradients of smooth, systematic change from the headwaters downstream (i.e., continua, Vannote et al. 1980), riverine landscapes usually consist of discontinuous patches of markedly different geomorphology (Ward and Stanford 1983, Poole 2002). Geomorphically controlled
habitat patches influence system dynamics (Poole 2002), so they also influence ecological functioning, including interactions between animals and the physical structure of the environment.

This paper examines associations of fish with LWJ in pools of different geomorphic patches along a river in old-growth mixed conifer-deciduous forest in Northern Michigan. We focused our study on fish relationships with large wood jams (LWJ; at least 2 pieces of LW contacting each other and the wetted channel) because LWJ may have a greater impact on fish populations than single pieces of LW (Dolloff and Warren 2003) and because stream restoration often includes wood constructions of several pieces (e.g., Hunt 1993, Cederholm et al. 1997, Slaney et al. 1997). We hypothesized that in similar pools (i.e., pools with similar physical dimensions and appearance) occurring in different geomorphic settings, differences would exist in the length and proportion of fish in pools with LWJ compared to pools without LWJ. Because of the remote nature of the site, our study occurred in one stream where channel size differences were not large, but where geomorphic discontinuities along the course of the river gave rise to large changes in stream channel gradient and other factors of valley shape. Because other studies have linked LW abundance, structural characteristics, and geomorphic function with stream channel size and gradient (and other concomitant geomorphic structure; Richmond and Fausch 1995, Abbe 2000, Rot 2000, Braudrick and Grant 2001, Gurnell 2003), we also used stream gradient as the basis for our selection of study sites. The old-growth nature of our study system provided a currently unique representation of environmental interactions independent of human influences. Documenting ecosystem interactions that are as free as possible from human
manipulations helps to inform our understanding of ecological processes and provides reference information for ecological restoration.

In addition to the unique nature of this old-growth landscape, coaster brook trout were once a common type of brook trout in the northern Great Lakes region of our study but are now rare. Young fish of a known coaster strain (Nipigon Lake strain) have been stocked into the study stream for several years in a reestablishment effort. We therefore afforded special attention to coaster brook trout, considering that their status and a comparison of the way they associate with LW compared to other resident fish is of practical interest to management professionals and others.

Methods

Study Sites

The Little Carp River begins in and flows through probably the largest (13,000 ha) virgin, old-growth, hardwood-hemlock forest in the Lake States (Frelich 2002). The forest and stream are protected in the Porcupine Mountains Wilderness State Park in Northern Michigan. The overstory forest of the Little Carp River consists primarily of eastern hemlock (Tsuga canadensis, (L.) Carr.), northern white cedar (Thuja occidentalis, L.), yellow birch (Betula alleghaniensis, Britt.), and sugar maple (Acer saccharum, Hook). Mean height of the tallest trees in the study area is roughly 25 m and mean diameter at breast height about 60 cm. Most of the river is forested to the edge of the bankfull channel.

Few records of streamflow exist for the Little Carp River. Goebel et al. (2003) reported discharge during annual floods ranging from 4.7 m$^3$ sec$^{-1}$ in the upper, low-
gradient sections to 9.4 m$^3$ sec$^{-1}$ in the lower, high gradient portions. Discharge associated with 50-year flood events in the Little Carp River has been estimated to range from 17.5 to 38.1 m$^3$ sec$^{-1}$ (Goebel 2001). Most extreme flood events associate with snowmelt in the spring (Goebel 2001).

Direct human influences to the geomorphology of the river consist of minor changes incidental to recreational hiking, camping, and swimming. Beaver activity was apparent, but no well-established beaver dams occurred in segments of stream that we studied during the period of data collection because the dams were removed by high flows in the spring of 2003.

The Little Carp River begins at a lake (Mirror Lake), flows through a low-gradient valley then descends steeply across a resistant lava inclusion, and finally flows through the deep lacustrine remnants of an ancient lake (clay-lake plain) before entering Lake Superior. We identified four distinct types of valley geomorphology along the river corridor, and designated a section of 1 km or more of channel length for study in each geomorphic setting. Previous work has identified patterns of LWJ abundance and structure associated with the geomorphic settings (Chapters 2 through 5; Figure 7.1):

1) **Clay-lake plain.** 2$^{nd}$ order. The upstream end of this stream section occurs 16 km downstream from the headwaters. Streams in the clay-lake plain have many plane-bed reaches, and channels tend to be incised through deep, ancient lacustrine sediment and they flow through relatively wide floodplains (low valley constraint). Bank failures occur in many places. Many pools occur without LWJ, although large LWJ occur and appear to be integrally
associated with some pools. The upstream end of the clay-lake plain is a waterfall thought to be impassable to potadromous fish.

2) **Mid-gradient.** 2nd order. The upstream end of this stream section is 10 km from the headwaters. The mid-gradient stream segment formed in the transition area between the high-gradient segment and the low-gradient clay-lake plain. Valley constraint is moderate, with bank failures evident in a few places. There is relatively good floodplain development and higher sinuosity than in the high-gradient section. The channel has varying levels of incision. Bedding consists of medium amounts of gravel, cobble, and boulders in bedrock controlled channels. Large LWJ occur throughout the mid-gradient section, particularly just downstream from the high-gradient section upstream. It appears that wood has been trapped in the mid-gradient section after being transported through the high-gradient section. The volume of wood is much higher in the mid-gradient setting than in other geomorphic settings along the Little Carp River. Pools appear to have often formed and to currently be reinforced by the presence of LWJ. Almost every pool contains some LW. The deepest pools along the river occur here. Trees with rootwads in the river are common, apparently from streambank undercutting and slope failures.

3) **High-gradient.** 2nd order. The upstream end of this stream section is 9 km from the headwaters; the downstream end is the upstream end of the mid-gradient section. Valley constraint is high and floodplain development minimal. The channel is not incised. Bedding is commonly rock-plane or coarse rock material with little sediment. Large wood jams occur in relatively
low abundance in the high-gradient setting, generally span less of the channel than in other geomorphic settings, and contain moderate numbers of LW. Pool formation appears to be predominantly rock-controlled. Most pools do not contain LW. All brook trout stocked in 2003 and 2004 were released from a bridge at the upstream end of this section.

4) **Low-gradient.** 1st order. The upstream end of this stream section is approximately 1 km downstream from Mirror Lake. The stream here flows through an unconfined channel with gravel and cobble in bedrock controlled channels. Floodplains are well developed. The channel occurred as 3 branches over part of its length during the study period. Large wood jams are most abundant here and span more of the channel but contain fewer pieces of wood than in other geomorphic settings. Pools appear to be formed by LWJ and some LW occurs in almost every pool.

More than 10 species of fish occur in the Little Carp River, including several species of dace (*Rhinichthys atratulus* Hermann; *Rhinichthys cataractae* Valenciennes; *Phoxinus eos* Cope), two species of sculpin (*Cottus bairdi* Girard; *Cottus cognatus* Richardson), brook trout, introduced rainbow trout (*Oncorhynchus mykiss* Walbaum) and coho salmon (*Oncorhynchus kisutch* Walbaum).

Roughly 20,000 brook trout have been planted in the Little Carp River every year since 1999. Thirty thousand of these Nipigon Lake strain brook trout were stocked in the Little Carp River in 2003, and 40,000 in 2004, both at the same location approximately
10 km upstream from the river mouth. Stocked brook trout have clipped fins indicating the year of release.

**Sampling Methods**

We identified channel geomorphic units (McCain et al. 1990) and estimated the surface area and depth of every pool for the entire length of channel in each geomorphic section. At each pool we also noted the presence of LWJ. We chose 10 pools in each section for study: 5 containing LWJ and 5 without LWJ (total of 40 pools). We paired pools in geomorphic sections so that each pool with wood was matched by a control pool without wood. We also chose pools in different geomorphic sections that were as much as possible like pools in other geomorphic sections. Where more than one pool existed that was an appropriate match for other chosen pools, we randomly chose one for study. We excluded the largest LWJ (generally with more than 50 pieces and spanning the entire channel) from this study because fish were not accessible under these complex structures. Excluding the largest LWJ eliminated up to 5 LWJ from each geomorphic section.

We conducted fish surveys by triple-pass electrofishing (Smith-Root model LR-24) with upstream and downstream block nets. We surveyed all pools over the course of one week in June, 2004, and then again over the course of one week in October, 2004. We surveyed all pools in one geomorphic section before moving to another section for logistical reasons. Weather conditions remained fairly constant during the weeks of sampling; there were no unusual shifts in temperature, and no rainfall to noticeably change water clarity or level.
Captured fish were identified and measured. Juvenile rainbow trout and coho salmon were grouped (referred to hereafter as *Oncorhynchus*) for ease in tallying and because our focus was brook trout. Wild born brook trout (no fin clips) and brook trout that had been stocked prior to 2003 were considered resident. We evaluated newly stocked brook trout (right pectoral fin clipped, 2003, left ventral fin clipped, 2004) separately from resident brook trout and rainbow/coho.

We measured the length of the pool between block nets. At each net and at the approximate midpoint of the pool we measured bankfull channel width and the width of the active (wet) channel. We measured depth in the thalweg at the upstream and downstream ends of the pool, and at the deepest point. At the approximate midpoint of the pool we measured depth and flowrate in the thalweg and at points halfway between the thalweg and each bank. We estimated pool surface area by multiplying the mean width (averaged upstream end, downstream end, and pool midpoint width) by length. We noted what appeared to be the main substrate in each pool (rock-plane, boulder, cobble, sand, or sediment). Pool residual depth was computed as the depth of the deepest point in the pool minus the depth of stream at the downstream end of the pool.

The abundance of fish was computed by dividing fish counts by pool surface area. Length was averaged for species by pool. When the lengths of several species of fish were averaged for a pool (e.g., the length of *Oncorhynchus* in a pool is the mean length of rainbow trout, coho salmon, and their parr) mean length was computed as the average length weighted by species abundance.
**Data Analysis**

We initially used estimated pool surface area and depth to classify and pair pools, with the assumption that the presence of LWJ would be the major physical difference affecting fish between pools of similar surface area and depth. Before evaluating the data, however, we attempted to match pools more carefully using measured surface area, residual depth, flow rate, and whether or not rock-plane bedding was common in the geomorphic section. We performed principal components analysis (PCA) for each geomorphic section, and then paired pools that were closest together along the first two-axes in ordination space. Data were centered and standardized prior to PCA (CANOCO v. 4.02, Centre for Biometry Wageningen, Wageningen, The Netherlands). We assumed that paired pools (one with LWJ and the other without) represented similarities in the major features affecting fish in the pools as well as possible under field conditions. Pools without LWJ therefore represented control treatments for the pools with LWJ (Table 1).

We computed the proportion of fish at pools with LWJ by dividing fish abundance (number of fish m$^{-2}$) in each pool containing LWJ by total fish abundance in the pool with LWJ and its counterpart without LWJ. Proportional abundance greater than 0.5 indicates greater abundance of fish at pools with LWJ compared to pools without LWJ. Proportional abundance was only computed for paired pools if the target fish species occurred in at least one of the pools. We also computed the ratio of the mean length of fish in pools with LWJ divided by the mean length of fish in pools without LWJ. This ratio (proportional length) is greater than 1.0 when fish are longer in pools with LWJ. Proportional length was only computed if the target fish occurred in both pools.
We compared the overall proportional abundance to the expected value (0.5) for equivalent numbers of fish at pools with and without LWJ using a single-factor \( t \)-test, with data averaged by pool for both sampling seasons (June and October). We compared proportional length to the expected value for equivalent lengths (1.0) by using a single-factor \( t \)-test, also with data averaged together for season by pool. Differences between geomorphic section and season in the proportion of fish and the proportional length of fish at pools with LWJ was evaluated by a repeated measures analysis of variance. The proportion or of fish at pools with LWJ was treated as a block (\( n = 20 \)). Geomorphic section (GEO, \( n = 4 \)) was considered a fixed factor, and season of sampling (SEA, \( n = 2 \)) was considered a within-geomorphic sections (repeated), fixed factor (Zar 1999). To test the hypothesis that the proportion of fish at pools with LW was the same at all geomorphic sections we used pools within geomorphic section as the error term (denominator of the \( F \)-test). To test the hypothesis that the proportion of fish was the same at pools with LW regardless of season, and to test the hypothesis that the proportion of fish at pools with LW among geomorphic sections was independent of season, we used the interaction of season with pools within geomorphic section as the error term. Proportional length was analyzed using the same hypotheses and error terms as were used to test proportional length comparisons. No transformations of the data were needed for residuals to satisfy the assumptions of parametric analysis. Tests were performed using PROC GLM in SAS/STAT (SAS v. 9.1, Cary, NC).
Results

Brook trout occurred primarily in geomorphic sections other than the clay-lake plain, while *Oncorhynchus* occurred only in the clay-lake plain section. *Oncorhynchus* in the clay-lake plain comprised a wild potadromous population whose upstream movement was blocked by the falls at the upstream end of the clay-lake plain (3 km from Lake Superior). We captured 4 wild-born (no clipped fins) brook trout in the clay-lake plain study section, and one brook trout that had been stocked in 2003. All other brook trout that had been stocked in 2003 or 2004 remained in the high-gradient geomorphic section close to where they had been stocked, or just downstream less than 2 km into the mid-gradient geomorphic section. Only wild-born brook trout were found in the low-gradient geomorphic section which was furthest upstream. Non-salmonids occurred in moderate numbers throughout all geomorphic sections (Table 7.2). Brook trout averaged 100 mm to 150 mm, *Oncorhynchus* and non-salmonids averaged closer to 50 mm (Table 7.3). The high abundance and small length of *Oncorhynchus* reflect natural reproduction.

When averaged between seasons, brook trout did not generally occur in greater abundance in pools with LWJ (mean proportional abundance of resident brook trout = 0.59, SD = 0.33, $n = 18$ pool pairs, $P = 0.28$, all other species showed similar means, standard deviations, and $P$-values). Based on repeated measures ANOVA (Table 7.4), we cannot reject the null hypothesis that the proportional abundance of any fish species is the same at all geomorphic sections ($P \geq 0.10$), or in both seasons ($P \geq 0.07$). Although differences in proportional abundance among sections were not statistically significant at the 5% level, the mean proportion of fish in pools with LWJ was consistently low in the
high-gradient geomorphic section for all species that occurred there (Figure 7.2 through Figure 7.6).

The interaction between geomorphic section and season was statistically significant for non-salmonids ($P = 0.04$) and resident brook trout ($P = 0.03$), indicating that the proportion of those fish in pools with LWJ changed differently with season in different geomorphic settings. For non-salmonids the primary difference between seasons was that the proportion of fish in pools with LWJ in the clay-lake plain was lower in June than in October, and that trend was not repeated in other geomorphic sections (Figure 7.2). For resident brook trout a similar situation existed in which the proportion of individuals in pools with LWJ was lower in June in the clay-lake plain and low-gradient section than in October, but the reverse trend occurred in the high-gradient section (Figure 7.4).

Longer resident brook trout occurred in pools with LWJ than without LWJ (mean length difference $= 39$ mm, proportional length $= 1.51$, SD $= 0.49$, n $= 12$, $P < 0.01$). Longer *Oncorhynchus* also appeared to occur in pools with LWJ, although the difference was less certain (mean length difference $= 7$ mm, proportional length $= 1.21$, SD $= 0.20$, n $= 5$, $P = 0.08$). When compared between geomorphic sections, only brook trout stocked in 2003 showed a significant change in length difference in pools with LWJ compared to pools without LWJ between geomorphic sections (Figures 7.7 through Figure 7.11). Brook trout stocked in 2003 were relatively evenly sized in pools with and without LWJ in the high-gradient section, but significantly shorter individuals occurred in pools with LWJ in the mid-gradient geomorphic section ($P = 0.03$; Fig 7.10) causing brook trout stocked in 2003 to be the only group for which the overall proportional length
was less than 1.0 (mean length difference = 10 mm, proportional length = 0.94, SD = 0.09, n = 8 pool pairs). Brook trout stocked in 2004 comprised a single size class (100 mm), and length differences did not exist between individuals in pools ($P = 0.18$) or between geomorphic sections ($P = 0.22$). Changes in length difference between seasons were not significantly different among geomorphic sections for non-salmonids or for resident brook trout, the only two groups for which the interaction between geomorphic section and season could be computed (non-salmonids $P = 0.08$; resident brook trout $P = 0.90$).

**Discussion**

The occurrence of brook trout primarily in upstream portions of the Little Carp River may reflect competition with non-native *Oncorhynchus* in the clay-lake plain where *Oncorhynchus* reproduces. Brook trout reproduction in the Little Carp River currently appears to be mainly in the furthest upstream reaches where no *Oncorhynchus* or stocked brook trout are found.

We found that resident brook trout and other species did not occur in significantly greater abundance in pools with LWJ than in pools without LWJ. One possibility for the apparent lack of overall positive relationship between fish abundance and LWJ is that in some geomorphic sections fish associate in higher numbers with LWJ than in other sections. We found, however, no unequivocal evidence that resident brook trout, stocked (presumably coaster) brook trout, or non-salmonids associated with LWJ differently in settings of different geomorphology along the river corridor. It appeared that fewer fish associated with LWJ habitat in the high-gradient geomorphic section than in other
sections, although differences were not statistically significant in this study. Statistical significance of fish abundance in pools with LWJ was affected by high variability in proportional abundance among sampled pools, suggesting that fine-scale factors affected fish abundance in pools.

This study indicates that LWJ of the size evaluated in this study do not exert an overriding effect on the abundance of brook trout or the other fish we sampled relative to other habitat factors. Other physical structures (such as boulders, complex rock bedding, and undercut banks) provided pool conditions at least as acceptable to fish as LWJ in the Little Carp River. Where LWJ associated positively with pools and fish abundance, the relationship was apparently mediated by other factors. In the high-gradient setting, LWJ was scarcer than in other sections, but that appeared to be the section where the lowest proportion of brook trout and a low proportion of non-salmonids occurred in pools with LWJ. The relative scarcity of LWJ in the high-gradient section did not create higher concentrations of fish in pools near LWJ, probably because pools in the high-gradient section were mostly formed by rock while most LWJ occurred peripherally in that section. Consequences of physical structure and interactions of the physical environment with LWJ correspond also with biotic interactions.

Patterns of fish abundance associated with LWJ in the high-gradient section were probably not a result of the presence of newly stocked brook trout but because proportional abundances were similar among sections in June and October. In June new fish had not been stocked in 2004, and the numbers of brook trout stocked in 2003 were relatively low in study pools. Changes in proportional abundance between June and October could have reflected new brook trout, however. The mean proportion of fish in
pools with LWJ decreased most sharply for both non-salmonids and resident brook trout in the high-gradient section where new brook trout were released, while increasing in other sections between June and October. High numbers of newly stocked brook trout in the high-gradient section may have created extremely competitive conditions among all species for space and resources.

Longer resident brook trout appeared to prefer pools with LWJ. The presence of larger resident brook trout near LWJ might have diminished the abundance of smaller fish in pools with LWJ (Layman and Winemiller 2004). If wood is a preferred habitat by fish that have a disproportionately large influence on the numbers of other fish (through competition or predation) then the abundance of fish near LWJ is not a direct measure of the preference of fish for LWJ habitat. Further research is needed to evaluate competitive relations among fish species and sizes under settings of different LWJ abundance and structure. Development of methodology is also needed to more effectively sample the largest LWJ because they provide the most complex and therefore potentially most desirable habitat for fish (Dolloff and Warren 2003).

References


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Table 7.1. Pools sampled for fish in the Little Carp River.
Table 7.2. Total counts of fish in pools of the Little Carp River. Ten pools were sampled in each geomorphic section. Each pool was sampled once during the last week of June and once during the third week of October, 2004.

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Table 7.3. Mean fish abundance and lengths in pools of the Little Carp River. Forty pools were sampled, once in June and again in October. Notes:\(^1\) mean abundance includes pools where abundance was zero. \(^2\) mean length only averages lengths for pools where fish were present.
### Table 7.4. Analysis of variance table comparing the proportional abundance and length of fish in pools with LWJ among geomorphic settings and between June and October. Proportional abundance is the abundance of fish in a pool with LWJ divided by the summed abundance in the pool with and without LWJ. Proportional length is the mean length of fish in a pool with LWJ divided by the mean length of fish in the control pool without LWJ. Null hypothesis 1 (GEO): The proportional abundance (or length) is the same at all geomorphic sections. Null hypothesis 2 (SEA): The proportional abundance (or length) is the same in both seasons (June and October). Null hypothesis 3 (GEO*SEA): Differences in the proportional abundance (or length) are independent of season. Error terms for specific tests are explained in the text. Notes: ¹ *Oncorhynchus* only occurred in the clay-lake plain, so comparisons between geomorphic sections could not be made. ² Yr. 2004 brook trout were all stocked in October, so comparisons between seasons could not be made. ³ Yr. 2003 brook trout did not occur in enough pools in both seasons for seasonal comparisons of length differences to be made.

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Figure 7.1. Map of study areas on the Little Carp River.
Figure 7.2. Proportional abundance of non-salmonids. Values above the dotted line indicate greater abundance in pools with LWJ than in pools without LWJ.
Figure 7.3. Proportional abundance of *Oncorhynchus* spp. Values above the dotted line indicate greater abundance in pools with LWJ than in pools without LWJ.
Figure 7.4. Proportional abundance of resident brook trout (no clipped fins). Values above the dotted line indicate greater abundance in pools with LWJ than in pools without LWJ.
Figure 7.5. Proportional abundance of brook trout stocked in 2003. Values above the dotted line indicate greater abundance in pools with LWJ than in pools without LWJ.
Figure 7.6. Proportional abundance of brook trout stocked in 2004. Values above the dotted line indicate greater abundance in pools with LWJ than in pools without LWJ.
Figure 7.7. Proportional length of non-salmonids. Values above the dotted line indicate longer fish in pools with LWJ than in pools without LWJ.
Figure 7.8. Proportional length of *Oncorhynchus* spp. Values above the dotted line indicate longer fish in pools with LWJ than in pools without LWJ.
Figure 7.9. Proportional length of resident brook trout (no clipped fins). Values above the dotted line indicate longer fish in pools with LWJ than in pools without LWJ.
Figure 7.10. Proportional length of brook trout stocked in 2003. Values above the dotted line indicate longer fish in pools with LWJ than in pools without LWJ.
Figure 7.11. Proportional length of brook trout stocked in 2004. Values above the dotted line indicate longer fish in pools with LWJ than in pools without LWJ.
Streams in old-growth forests of this study showed high variation in the abundance and characteristics of both LWJ and loose LW pieces. LWJ and LW characteristics were generally more similar among reaches within geomorphic setting than between geomorphic settings, from which we infer general control of LW and LWJ by processes related to stream-corridor geomorphology. The number and size of individual pieces of LW and pieces in LWJ appeared to relate similarly to geomorphic setting and riparian characteristics (increase with increasing conifer in the riparian forest, increasing channel width, and forest age). The abundance of LW appeared, however, to be inversely related to the abundance of LWJ, suggesting that research on loose LW pieces should only be cautiously applied to predicting LWJ abundance.

Stream corridor geomorphology appeared to control the abundance of LWJ, the percent of the channel spanned by LWJ, and the number of smallest LWJ (2-5 pieces) in the streams of this study. Structural characteristics of the stream channel that varied with stream corridor geomorphology (such as channel bedding, width, and sinuosity) corresponded with LWJ characteristics, leading to patches of LWJ abundance, size, and span of the channel. In addition, most LWJ were randomly distributed within
geomorphic settings, but contiguous sections of dissimilar geomorphic elements gave rise to aggregated LWJ spatial patterns and revealed uniform spacing in two of four cases. A concept of systematic, continuous changes in stream characteristics associated with stream order is therefore insufficient for explaining patches of LWJ in small streams in the hemlock-hardwood forest of this study. Rather, LWJ structures may be understood to vary with stream corridor geomorphology that varies discontinuously along the stream channels.

Further work is needed to investigate how the metastructure of geomorphic elements along stream corridors influences LWJ structure and function. Further work is also needed to determine the consequences of LWJ restoration on the geomorphology of stream corridors and riparian forests. Understanding associations of brook trout and other fish with LWJ would be benefited by sampling in the winter and early spring when fish may find refuge in pools with LWJ, and by evaluating further the effects of larger fish in pools with LWJ on the abundance of other fish in those pools. Currently investigations of fish with LWJ are limited because sampling methods do not allow effective capture of fish from the largest and most complex LWJ. Development of alternative methods that would allow complete sampling of the largest LWJ would therefore be of real value to the evaluation of fish associations with LWJ. Finally, identifying and understanding patterns of LWJ distribution and structure would be benefited by standardizing sampling methods so that data can effectively be combined from work in different geographic areas.


