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

Bridget Livers1 and Ellen Wohl1

1Department of Geosciences, Colorado State University, Fort Collins, Colorado, USA

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

1. Introduction

Small streams, defined here as having drainage area <100 km², can occupy two-thirds or more of the total length of stream networks [Freeman et al., 2007]. These streams are heavily influenced by terrestrial processes and play a key role in hydrologic connectivity and biotic diversity [Freeman et al., 2007; Meyer et al., 2007]. Small streams are areas of sediment production and are essential in delivering nutrients downstream through channel networks [Milliman and Syvitski, 1992; Gomi et al., 2002; Benda et al., 2005]. Small mountain streams have heterogeneous forms, habitats, and species compositions because of their diversity of physical characteristics such as gradient, light, chemistry, temperature, and substrate [Meyer et al., 2007]. Despite their abundance and their influence on the whole river network, small streams can be underestimated and inadequately acknowledged in natural resources management [Gomi et al., 2002]. Given the importance of small streams, it would be useful to characterize their physical complexity with respect to different forms of complexity (e.g., bed versus banks) and degree of complexity in relation to characteristics such as valley geometry and land use history.

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

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

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

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

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

Land use history is important in the context of geomorphic complexity as it influences the size and abundance of wood available for recruitment to streams (forest stand age, proximity of road corridors that correspond to reduced riparian forest cover) and the ability of streams to retain recruited wood (history of instream wood removal) [Swanson et al., 1976; Richmond and Fausch, 1995; Hedman et al., 1996; Nowakowski and Wohl, 2008; Wohl and Beckman, 2014]. Channel-spanning logjams were much more common in streams and rivers prior to European settlement in North America and thus small streams likely no longer function as they did historically [Wohl, 2011b, 2014]. Previous studies in the Colorado Front Range show that
contemporary streams flowing through old-growth, unmanaged forests have up to ten times more wood volume than streams flowing through younger-growth, managed forests [Beckman and Wohl, 2014a; Wohl and Jaeger, 2009; Wohl and Cadol, 2011; Wohl and Beckman, 2014]. Although some of these management activities have long since ceased, reduced wood loads in managed streams persist due to the time required for trees to reach old-growth age (>200 years) [Veblen, 1986; Kaufmann, 1996] and removal of instream wood to maintain infrastructure. The widespread changes in mountain streams due to these activities have led to reduced frequencies of natural channel-spanning logjams in managed streams. Younger forests with a history of natural disturbances such as wildfire, insect infestations, and blowdowns occur in the study area. These natural disturbances, however, do not typically remove all dead and downed trees from the channel and floodplain, in contrast to land uses such as timber harvest or log floating [Young et al., 1994; Ruffing et al., 2015]. We expect managed streams with a history of timber harvest, tie drives, and wood removal to have lower riparian and instream wood loads than unmanaged streams, and thus lower geomorphic complexity.

Our understanding of the influences of forest stand age, valley geometry, and land use on geomorphic complexity leads to a conceptual model and a series of hypotheses (Figure 1). We hypothesize that the three independent variables of forest characteristics, valley geometry, and land use correlate with instream wood abundance and other measures of geomorphic complexity in small streams of the Southern Rockies (H1) (Figure 1a). We hypothesize that streams flowing through old-growth forest in laterally unconfined valley segments will exhibit the greatest geomorphic complexity, whereas streams flowing in managed stream corridors will exhibit the least geomorphic complexity, regardless of confinement (H2). Because laterally confined channels are typically steeper, have correspondingly higher stream power to flush out instream wood and logjams, have fewer wood recruitment sources, and have less floodplain with which to meander and create viable habitat, H2 also hypothesizes that confined channels will have lower instream wood and geomorphic complexity than their less confined counterparts, and thus managed and confined stream reaches will be similar in wood and complexity metrics. We further hypothesize that the relationship between forest characteristics, land use, and geomorphic complexity exhibits a threshold such that streams in old-growth forest and in younger, naturally disturbed forest differ significantly from managed streams (H3).

Implicit in this conceptual model and hypotheses are the assumption that instream wood load is the primary instream source of geomorphic complexity. Physical heterogeneity within a channel can also result from differences in substrate grain size or downstream variations in local gradient associated with bed forms, each of which can correspond to differences in substrate, channel width, bed elevation, and cross-sectional shape. We hypothesize that, in the context of promoting nutrient retention, biomass, and biodiversity, physical heterogeneity directly associated with instream wood in the study streams is more effective than heterogeneity associated with factors such as grain size in the absence of wood (H4) (Figure 1b). Another way to express this conceptualization is to distinguish structural complexity, which includes all forms of physical heterogeneity in the channel, from functional complexity, which includes physical heterogeneity that promotes a specified function such as nutrient retention. In the context of this study, H4 states that we expect functional complexity to be greatest in wood-rich streams.

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

2. Study Area

Study reaches are in the Big Thompson, Cache la Poudre, and North St. Vrain drainages in northern Colorado, USA and the North Platte River drainage in southern Wyoming, USA (Figure 2). The Colorado drainages, which constitute the majority of stream channels in this study, head on the east side of the continental divide in Rocky Mountain National Park at ~4050 m in elevation and flow eastward through Roosevelt National Forest, eventually flowing into the South Platte River beyond the mountain front at ~1500 m in elevation [Anderson et al., 2006]. The drainages for the Wyoming streams head in the mountains of Medicine Bow National Forest at lower elevations than those in Rocky Mountain National Park,
flowing west, then north to east through Medicine Bow National Forest before meeting the North Platte River.

Precambrian Silver Plume granitic crystalline rocks are the dominant core of the study area, and consist of granite with some biotite schist and granodiorite [Braddock and Cole, 1990]. Tectonic activity in the Front Range has been uncommon since the end of the Tertiary [Anderson et al., 2006]. The headwaters of the catchments in this study were glaciated during the Pleistocene epoch. The last major glaciation in the central Rocky Mountains, the Pinedale glaciation, extended down to approximately 2430 m elevation, leaving a

---

**Figure 1.** Conceptual model and hypotheses to be tested for small streams in the Southern Rocky Mountains. (a) We hypothesize that the combined effects of forest stand age, valley geometry, and land use correlate with instream wood load and geomorphic complexity in a manner that will create significant correlations between the driver and response variables (H1). We hypothesize that old-growth forest and laterally unconfined valleys will correlate with the greatest wood loads and geomorphic complexity, indicated by plus symbols, whereas valley confinement and land use will correlate with lower values of wood load and geomorphic complexity, indicated by minus symbols (H2). We hypothesize a threshold effect such that natural streams differ significantly from managed streams, symbolized by the vertical dashed line (H3). (b) We hypothesize that physical heterogeneity associated with large wood (LW) is greater than that associated with gradient (S) or grain size (Dx) (H4), as indicated by solid rather than dashed outlines for arrows. We expect this greater heterogeneity to result in greater flow separation, retention of fine sediment and organic matter, habitat diversity, and biomass and biodiversity, although we do not test these assumptions in this paper.
Figure 2. Location map of the study area showing the location of stream channels in southern Wyoming and northern Colorado and the distribution of treatment categories within the Medicine Bow National Forest and the Colorado Front Range.

Base map: modified from U.S. Geological Survey 10-meter resolution DEM
Hydrology: U.S. Geological Survey National Hydrography Dataset
Projection: UTM, Zone 13N, NAD 1983
prominent terminal moraine [Polvi et al., 2011; Wohl et al., 2004]. Pleistocene glacial advance and retreat removed bedrock and sediments in pulses associated with glacial-interglacial cycles, and glacial erosion widened and deepened valleys, leaving steep valley walls and headwalls and flattened valley bottoms, as well as steps in the longitudinal profile at tributary junctions [Anderson et al., 2006].

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

Valley width and channel geometry in the study area can alternate through the longitudinal profile at scales of $10^2$–$10^3$ m. Lower-gradient stream segments (0.01–0.03 m/m) with wide valleys can have single or multithread channels with sand to cobble-size sediment (Figure 3). If the floodplain is at least eight times the bankfull width of the stream channel, these segments are referred to as unconfined (with respect to potential floodplain development). Unconfined valleys can allow the formation of multithread channels throughout a floodplain (Figure 3a), and have been shown to retain much more instream wood and closely spaced logjams than confined or single-thread stream segments [Wohl, 2011a; Wohl and Cadol, 2011; Wohl and Beckman, 2014]. Multithread stream channels only occur when biotic drivers such as beaver dams or logjams create obstructions to flow and sufficient backwater to promote overbank flow and avulsion that lead to secondary channels (Figure 3b) [John and Klein, 2004; Wohl, 2011a; Collins et al., 2012]. Conversely, relatively steep stream segments (>0.03 m/m) in the study area with bedrock-confined valleys (valley width <2x bankfull width) only have single-thread channels with cobble to boulder-sized sediments and cascade or step-pool morphology (Figure 3b) [Montgomery and Buffington, 1997].

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

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

3. Methods

3.1. Field Methods

Field reaches were chosen based on land use and management history (human activity), as well as natural disturbance history. Surveyed channel reaches were located on second to fourth-order streams in subalpine forests of Rocky Mountain National Park (RMNP) and Arapaho-Roosevelt National Forest (ARNF), Colorado and the Medicine Bow Mountains, Wyoming (Figure 2). Channel segments were categorized into three
treatments: old-growth unmanaged forests (OU), younger-growth unmanaged forests (YU), and younger-growth managed (YM) forests. These categories are based on watershed land use, management history, and history of natural disturbance. Riparian stand age in OU forests is 200 years or more and there is no history of timber harvest, flow regulation, or placer mining. YU forests have a riparian stand age less than 200 years because of natural, stand-killing disturbances such as wildfire, blowdown, or insect infestation. YM forests...
forest streams have a riparian stand age less than 200 years and historical timber harvest (all YM forests are at least 50 years in age) and/or log floating. Some of the streams also have contemporary flow regulation or road corridors.

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

Site selection was based on knowledge of watershed land use and management history, as well as accessibility. We aimed to have an even number of streams for each treatment, along with a range of valley confinement between reaches. Stream segments were chosen to have similar elevation, drainage area, gradient, and climate to the greatest extent possible. However, forest disturbance history made it impossible to find OU stream reaches with drainage area greater than 18 km² and YU stream reaches with drainage area less than 20 km².

Table 1 provides a detailed summary of the methods used to characterize each variable. Valley bottom width was determined in the field using indicators such as change in slope, vegetation, and area likely to be inundated in higher flows or digitally using changes in slope.

<table>
<thead>
<tr>
<th>Group of Variables</th>
<th>Variable</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control variables</td>
<td>Treatment</td>
<td>Forest stand age, occurrence or no occurrence of logging and tie-drive activities</td>
</tr>
<tr>
<td></td>
<td>Forest cover (basal area, m²/ha)</td>
<td>Panama basal area angle gage: ~3/m/reach</td>
</tr>
<tr>
<td></td>
<td>Drainage area (km²)</td>
<td>USGS StreamStats for CO reaches; 10 m DEMs in ArcGIS 10 for reaches in WY</td>
</tr>
<tr>
<td></td>
<td>Gradient (m/m)</td>
<td>Laser rangefinder, measured water-surface gradient ~5 m/reach</td>
</tr>
<tr>
<td></td>
<td>Valley width (m)</td>
<td>Laser rangefinder, 10 m DEMs in ArcGIS 10, or Google Earth; measured ~5 m/reach</td>
</tr>
<tr>
<td></td>
<td>Confinement</td>
<td>Categorical: confined: valley bottom width (vbw) &lt; 3/m; bankfull width (w); partly confined: vbw ~3–8/m; unconfined: vbw &gt;8/m; continuous: vbw/w</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed and bank</td>
<td>Bank survey</td>
<td>Total station, using tape stretched to follow bankfull (banks left and right) location, surveyed bankfull at 1 m increments for ~100 m, 2–3 surveys/reach</td>
</tr>
<tr>
<td>surveys</td>
<td>Thalweg survey</td>
<td>Total station, surveyed thalweg elevation at 1 m increments for ~100 m, 2–3 surveys/reach</td>
</tr>
<tr>
<td></td>
<td>Longitudinal roughness</td>
<td>(Σ[thalweg residuals]/n) [Gooseff et al., 2007]</td>
</tr>
<tr>
<td></td>
<td>Bankfull depth</td>
<td>Stadia rod to measure bankfull depth using indicators mentioned in text; three measurements/sample, equally spaced across channel</td>
</tr>
<tr>
<td></td>
<td>Bankfull width</td>
<td>Laser rangefinder using bankfull indicators mentioned in text</td>
</tr>
<tr>
<td></td>
<td>Width coefficient of variation</td>
<td>Width SD/mean width [Laub et al., 2012]</td>
</tr>
<tr>
<td>Cross-section</td>
<td>Total channel length and valley length</td>
<td>Followed each channel with GPS to convert to length in ArcGIS 10 or Google Earth, or used GPS endpoints to measure lengths in Google Earth; lengths of individual channels summed for multithread reaches; valley length digitally calculated using GPS endpoints</td>
</tr>
<tr>
<td>variables</td>
<td>Channel area (m²)</td>
<td>Total channel length * mean bankfull width for each channel</td>
</tr>
<tr>
<td></td>
<td>Valley area (m²)</td>
<td>Followed valley edges with GPS to convert to area in ArcGIS 10 or Google Earth, or mean valley width * valley length</td>
</tr>
<tr>
<td>Planform variables</td>
<td>Large wood pieces</td>
<td>Measured diameter and length of all pieces &gt;0.1 m diameter and &gt;1 m length, including all pieces this size in jams; orientation and decay class GPS location, measured average length, depth, width with measuring tape, visually estimated porosity, and % particulate organic matter (OM)</td>
</tr>
<tr>
<td></td>
<td>Jams</td>
<td>Measured average length, depth, and width of pools, estimated volume particulate OM finer than minimum wood piece size by measuring average length, depth, and width of stored OM</td>
</tr>
<tr>
<td></td>
<td>Jam backwater pools</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Field Methods and Calculations for Measured Variables in this Study

aThese field methods and associated variables only evaluated on extensive sites.


cTruPulse 350B, horizontal accuracy +/− 0.1 m.

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

Streams evaluated during the extensive field season were measured at 4–5 subreaches with approximately equal spacing along the reach. For each reach, endpoints and sampling points were mapped using a handheld GPS device (Garmin eTrex, typically 3–5 m horizontal accuracy). At each sampling point, a number of quantitative variables were measured: bankfull width, water-surface gradient, bankfull depth, valley width, and basal area of the riparian forest (henceforth referred to as forest cover). For multithread channels, each channel was sampled across a transect perpendicular to the valley, aligned with the original sampling point. Because of the predominance of multithread channels in our study, bankfull width measurements were used to create two mean width variables for each reach: mean width of an individual channel and mean total width of all channels across transects. Type of stream morphology [Montgomery and Buffington, 1997] was noted at each subreach, as well as the predominant substrate size (e.g., boulder, cobble). With the exception of forest cover, all variables were also collected several times at all intensive sites.

Bankfull width and valley width data collected in the field were used to create two continuous variables for confinement: confinement using mean width of individual channels and confinement using mean total width of all channels across transects. We calculated both because of the arbitrary nature of the category designations; multithread channels may be considered unconfined when evaluating individual channel widths compared to valley width, but are nearly confined when all channel widths across the valley are summed and compared to valley width. Category of lateral valley confinement was then assigned to each reach based on the categorical designations in Table 1.

For each reach, the total channel length and valley length were calculated (Table 1). We calculated the ratio of total channel length to valley length, which is different from sinuosity only in that it accounts for multithread channels. Bankfull channel area and valley area were then calculated for each reach and were used to calculate ratio of channel area to valley area.

For all of the reaches in this study, we evaluated all large instream wood pieces (Table 1), including orientation in the stream and decay class. Orientation types were: bridge, ramp, buried, pinned, and unattached. Pieces were assigned to one of three decay classes based on presence of bark, limbs, cones, and needles, and whether the piece was decayed or rotten. If three or more large wood pieces were clustered together, we considered this a logjam and recorded a number of measurements, including backwater pool characteristics (Table 1).

### 3.2. Statistical Analyses

For variables that cumulatively reflect characteristics throughout a reach, such as wood and pool metrics, the totals of the data were normalized for each reach by dividing quantities to achieve the quantity per 100 m of valley length. This was done to account for multithread and sinuous channels. For each reach, the proportion of bridge and ramp wood pieces, which are believed to be essential for jam formation [Beckman and Wohl, 2014b], relative to other orientation types was calculated. In order to calculate the average drop in longitudinal profile caused by logjams, a metric of average logjam height divided by frequency of logjams per 100 m of valley was calculated for each reach that had at least one logjam. Variables representing geomorphic complexity were organized into cross section variables, planform variables, wood piece, and logjam variables (supporting information Table S1).

For the 22 raw quantitative variables in supporting information Table S1, we calculated mean, range, and standard deviation for the three treatments (supporting information Table S2). Using all individual measurements of bankfull depth, bankfull width, and water-surface gradient, the standard deviation of each of the three variables for each reach was calculated. In addition, the coefficient of variation of width was calculated for each reach (Table 1) [Laub et al., 2012].
Variables were divided into control and response variables. Wood and complexity variables (response variables) are potentially regulated by individual or a combination of control variables, which includes our hypothesized controls (treatment, confinement, and forest cover), as well as other possible controls such as drainage area, gradient, and bankfull and valley widths (supporting information Table S2; Table 1).

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

We ran a correlation matrix using all variables and used Pearson’s correlation test to determine significant correlation between variables (supporting information Table S3). To address whether the three treatment types exhibit significantly different mean values of control and response variables, we performed an ANOVA test for each of the transformed variables to determine whether there was a significant difference in means of that variable between treatments. Tukey’s HSD test was then run for pairwise comparisons to determine which groups had significant differences [Ott and Longnecker, 2010]. For variables that were not normally distributed, we performed the nonparametric Kruskal-Wallis analysis of variance test to determine whether there was a significant difference in that variable between treatments, followed by Dunn’s test with Bonferroni adjustment to test significant differences in pairwise comparisons [Dunn, 1964; Ott and Longnecker, 2010]. We performed the same tests between the three confinement types regardless of treatment category for each variable in order to evaluate which variables are specifically influenced by confinement and not just forest history and management. Boxplots for each variable between the three treatments, as well as box plots between the three confinement types for each variable, were created in order to visualize the differences between treatments and confinement types.

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

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

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

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

4. Results

4.1. Instream Wood and Channel Complexity Differences Between Treatments

A total of 24 reaches were evaluated: nine OU reaches, nine YU reaches, and six YM reaches (supporting information Table S1). Mean total channel width, valley width, and confinement variables are not significantly different between the three treatments, but mean individual channel width is significantly higher in YM reaches (Table 2; supporting information Table S2). Forest cover is significantly different between all treatments, with OU reaches having the greatest forest cover and YM reaches having the least forest cover (Table 2; Figure 4, left). This is the general trend of nearly all wood and complexity variables (Figure 4, left): OU has the highest mean values for wood storage and complexity, whereas YM has the lowest mean values (supporting information Table S2). OU multithread reaches have the greatest channel length to valley length ratio, logjam backwater pool volumes, logjam organic matter storage, and backwater pool organic

| Table 2. Significant Differences of Wood and Complexity Variables Between Treatments*
<table>
<thead>
<tr>
<th>Group of Variables</th>
<th>Variable Transformation</th>
<th>ANOVA/KW p-Value</th>
<th>Pairwise Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control variables</td>
<td>Confinement (ind. ch. width) (m/m) log 0.74 1.00 0.77 0.76</td>
<td>OU-YU OU-YM YM-C OU-C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Confinement (tot. ch. width) (m/m) log 0.11 0.35 0.10 0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forest cover (basal area, m²/ha) Normal &amp;0.01 &amp;0.01 &amp;0.01 &amp;0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drainage area (km²) 1/log &amp;0.01 &amp;0.95 &amp;0.01 &amp;0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gradient (m/m) log +0.01 0.03 0.82 0.03 0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Valley width (m) log 0.09 0.99 0.13 0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean individual channel width (m) log 0.04 0.99 0.05 0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean total channel width (m) log 0.08 0.17 0.88 0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood piece variables</td>
<td>Jams/100 m valley () &amp;0.01 &amp;0.77 &amp;0.01 &amp;0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wood volume/100 m valley (m³) log &amp;0.01 &amp;0.27 &amp;0.01 &amp;0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pieces/100 m valley () log +10 &amp;0.01 0.07 &amp;0.01 &amp;0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proportion of bridges &amp; ramps 0.02 0.61 0.06 &amp;0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bridges &amp; ramps/100 m valley () log +1 &amp;0.01 0.69 &amp;0.01 &amp;0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planform variables</td>
<td>Area ratio (m²/m²) normal 0.03 0.11 0.04 0.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Length ratio (m/m) 0.09 0.06 0.17 1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross section variables</td>
<td>Depth SD log 0.69 0.99 0.69 0.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Width SD log 0.56 0.54 0.92 0.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Width CV log 0.10 0.45 0.07 0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gradient SD sqrt 0.01 0.65 0.06 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jam variables</td>
<td>Pool volume/100m valley (m³) log +1 &amp;0.01 0.14 &amp;0.01 &amp;0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jam OM volume/100 m valley (m³) log +0.1 0.04 0.45 0.03 0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pool OM volume/100 m valley (m³) 0.04 1.00 0.04 0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Avg jam height/jam frequency (m/#) log +10 &amp;0.01 0.67 &amp;0.01 &amp;0.03</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*ANOVA was performed on variables that could be transformed to normal distribution while Kruskal-Wallis was performed on variables with no transformation. Bolded p-values indicate statistically significant differences. OU: Old-growth, unmanaged; YU: Younger-growth, unmanaged; YM: Younger-growth, managed; C: Confined.

bOnly extensive sites evaluated.

cOnly intensive sites evaluated and only displaying pairwise comparisons with relatively low p-values.
matter storage, whereas YM single-channel reaches and confined reaches have the smallest values of these variables. With respect to other control variables, drainage area, gradient, and mean individual channel width are significantly different between some of the treatments, whereas mean total channel width, valley width,
and continuous measures of confinement are not. OU reaches tend to have small drainage areas, steep gradients, smaller individual channel widths, and variation in confinement, whereas YM reaches have larger drainage areas, flatter gradients, and are consistently partly confined. Trends for some of the variables, particularly cross section variables related to width, depth, and gradient, are better defined between confinement types rather than treatment types (Figure 4, right). Width and confinement variables are significantly correlated with many wood and complexity variables (supporting information Table S3).

All wood piece and logjam variables have significant differences between at least two of the treatment categories, but cross-section variables typically do not (Table 2). Despite significant differences in forest cover, OU versus YU reaches do not have significant differences in other control variables, wood variables, or complexity variables. However, both of the unmanaged treatments typically are significantly different than the managed reaches in wood and complexity variables, with the exception of cross section variables. The strength and occurrence of significant differences between OU and YM reaches are almost always greater than differences between YU and YM reaches, indicating a gradient of wood storage and complexity across the treatments.

4.2. Bed and Streambank Complexity Analyses of Intensive Reaches

Data from bed and bank surveys, as well as calculated longitudinal roughness, did not indicate significant differences between treatments at \( \alpha \) of 0.05, but a few of the comparisons with \( p \)-values between 0.05 and 0.10 are notable (Table 2). Standard deviation of bankfull surveys between OU and YM reaches are significant at \( \alpha \) values of 0.10. Longitudinal roughness between OU and confined reaches are also significant at \( \alpha \) of 0.10. Results of the thalweg surveys had the least significance among survey data.

4.3. Multivariate Analyses of Variables That Control Stream Complexity

Figure 5 shows the orientation of the response variables and the location of reaches in PCA space for the three possible combinations of response variables. Table 3 explains the patterns seen in Figure 5: it displays the proportion of variance explained for each PC in Figure 5, \( R^2 \) values for the linear regression models, and the significant control variables for each linear regression on individual PC axes. \( p \)-Values in Table 3 are only listed for the control variables used in that linear regression, as chosen by stepwise regression and AIC values described in statistical methods; \( p \)-values in bold denote statistical significance for that control variable in the regression, whereas non-bold \( p \)-values were not significant in the linear regression. Reaches in Figure 5 are labeled by their treatment, categorical confinement, and presence of multithread planform, respectively.

In each plot in Figure 5, PC1 is the \( x \)-axis and PC2 is the \( y \)-axis, and reaches and response variables are plotted using their PC1 and PC2 scores, respectively. Significant control variables in Table 3 for each axis influence reach PC scores and thus their locations on each plot, as well as the response variable PC scores and their locations on each plot. For example, in Figure 5, bottom left, depth SD, gradient SD, and area ratio are oriented with PC2, with low values of PC2 corresponding to high values of these response variables and high PC2 values corresponding to low values of these response variables. Because PC2 is significantly controlled by mean gradient (Table 3), the response variables that orient with the PC2 axis and the \( y \)-values (PC2 scores) for reaches are controlled by mean gradient (Figure 5, bottom left); confined reaches have the highest mean gradient (Figure 4, right). Many of the longitudinal complexity variables and wood variables are oriented on PC1 and are significantly controlled by a combination of confinement and management history (Table 3; Figure 5), with relatively confined reaches and managed reaches having low \( x \)-values (PC1 scores) and low values of longitudinal complexity and wood variables.

Management history, or treatment YM, and confinement are the most significant controls on wood and complexity, as they influence all PC1 axes that explain the greatest proportion of variance and have greater \( R^2 \) values than analyses on PC2 axes; channel width variables also control complexity variables when control variables are modeled against the complexity-only PC (Table 3). PC2 axes are controlled by mean gradient or drainage area, which are significantly correlated to one another (supporting information Table S3) and are significantly different for YM reaches (Table 2). When complexity-only PCs are regressed using wood variables as controls, wood variables are only significant for PC1 (Table 3). Many of the complexity variables are oriented with PC2 (Figure 5), indicating that wood variables alone cannot explain many of the complexity variables.
Response variables have opposing influences on complexity, as seen by their orientation to one another on the biplots in Figure 5. For example, high values of complexity related to width correspond to low values of depth SD, gradient SD, and area ratio. Wood piece variables, with the exception of proportion of bridge and ramp pieces, have the same influence in PCA space as many of the logjam variables and length ratio.

Table 3. Control Variables on Wood and Complexity Responses as PC Data

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Prop. Variance Expl.</th>
<th>p-Value</th>
<th>R²</th>
<th>YU Mean Total Width (m/m)</th>
<th>YU Mean IND. CH. Width (m/m)</th>
<th>YU Mean Total Ch. Width (m)</th>
<th>YU Mean ind. Ch. Width (m)</th>
<th>DA (km²)</th>
<th>Mean Gradient (m/m)</th>
<th>Mean Valley Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood PC ~ control</td>
<td>1</td>
<td>0.72</td>
<td>&lt;0.01</td>
<td>0.86</td>
<td>0.83</td>
<td>0.01</td>
<td>0.01</td>
<td>0.06</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.17</td>
<td>&lt;0.01</td>
<td>0.29</td>
<td>0.21</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Comp. PC ~ control</td>
<td>1</td>
<td>0.46</td>
<td>&lt;0.01</td>
<td>0.92</td>
<td>0.21</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.19</td>
<td>&lt;0.01</td>
<td>0.60</td>
<td>0.48</td>
<td>0.02</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Wood + Comp.</td>
<td>1</td>
<td>0.52</td>
<td>&lt;0.01</td>
<td>0.90</td>
<td>0.48</td>
<td>0.02</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.13</td>
<td>&lt;0.01</td>
<td>0.60</td>
<td>0.48</td>
<td>0.02</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>PC ~ control</td>
<td>2</td>
<td>0.13</td>
<td>&lt;0.01</td>
<td>0.60</td>
<td>0.48</td>
<td>0.02</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prop. Variance Expl.</th>
<th>p-Value</th>
<th>R²</th>
<th>Jams/100 m Valley (#)</th>
<th>Wood vol/100 m Valley (m³)</th>
<th>Pieces/100 m Valley (#)</th>
<th>Prop. Bridges and Ramps</th>
<th>Bridges and Ramps/100 m Valley (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp. PC ~ Wood Var.</td>
<td>1</td>
<td>0.46</td>
<td>&lt;0.01</td>
<td>0.94</td>
<td>&lt;0.01</td>
<td>0.19</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.19</td>
<td>0.16</td>
<td>0.16</td>
<td>0.48</td>
<td>0.02</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

*p-Values for Control Variables

*aPC axes and proportion variance explained correspond to data in Figure 5. Variables with bolded p-values indicate statistically significant control on the response PC. YU: Younger-growth, unmanaged; YM: Younger-growth, managed; DA: drainage area.
meaning those complexity and wood variables are redundant in explaining complexity. Many of these variables are significantly correlated (supporting information Table S3).

5. Discussion

5.1. Instream Wood and Channel Complexity Differences Between Treatments

The results support $H_1$ by indicating significant differences in wood load and other measures of geomorphic complexity in relation to forest stand characteristics, valley geometry, and land use. The results also support $H_2$ in that streams flowing through old-growth forest in laterally unconfined valley segments have the largest wood loads and the greatest functional geomorphic complexity as indicated by backwater pool volume, storage of organic matter in backwater pools, standard deviation of channel width and depth, and the ratio of channel area to valley area (Table 2; Figures 4, left and Figure 5).

The greater volumes of wood in OU reaches confirm previous work on streams in unmanaged and managed forests in the study area [Beckman and Wohl, 2014b]. Wood loads in YU reaches are not different from OU but do differ significantly from YM, indicating that forest cover does not control wood loads. The same pattern is typical of complexity variables that have significant differences, with YM having significantly less complexity than unmanaged streams (Table 2; Figure 4, left). These results support $H_3$ and suggest that legacy effects of logging and removal of instream wood lead to lower wood loads and complexity in managed streams, even when managed streams are compared to streams flowing through natural forest of an age similar to the riparian forest in the managed streams.

The proportion of bridge and ramp pieces is highest in YM and confined streams and lowest in OU streams despite the opposite trend in number of bridge and ramp pieces/100 m (Figure 5; supporting information Table S2). This indicates that the frequency of bridge and ramp pieces, rather than proportion of those pieces relative to wood with other orientations, results in greatest wood storage and complexity. Average logjam height/jam frequency is also greatest in YM reaches because of the low frequency of logjams (Figure 5). This variable, like proportion of bridge and ramp pieces, is lowest in OU reaches because it represents the inverse of how much elevation drop is caused by logjams. These two variables are redundant in PCA space but represent a different measure of complexity from other categories due to their independence from other groups of variables on a biplot. Small values of logjam height/jam frequency result in a high longitudinal drop from logjams, and this complexity metric is a separate longitudinal metric from others such as pool volume and organic matter storage.

The location of cross-section variables in PCA space explains why there are few significant differences in these variables between treatments. Cross-section variables are loaded on PC2, meaning they explain less of the variability in the data than variables loaded on PC1, which supports $H_4$ (Figure 5). In addition, PC2 is generally explained by gradient and valley width, both of which correlate significantly to confinement (supporting information Table S3). Greatest values of depth SD and gradient SD are found in confined channels regardless of treatment, which is likely a reflection of greater clast sizes and steepness of confined channels. Cross-section variables thus represent structural complexity, but may not contribute to functional complexity in the study reaches. Complexity variables related to width are greatest in multithread, relatively unconfined channels because there are multiple channels in each reach that can have a greater range of widths than a single channel sampled many times; the significantly smaller individual channel widths in OU and YM also contribute to the retention of greater wood volumes, as large wood pieces are less likely to be mobile in smaller channels. Polvi et al. [2014] also found that cross-section variables were not significant in analyzing complexity across a gradient of treatments related to management history. Even where variables were not significant between treatments in the ANOVA, there are larger ranges of values in OU reaches than in YM, indicating greater complexity through variability in complexity values (Figure 4, left).

Confinement plays a role in the ANOVA results (Figure 4, right), as all three confinement categories occurred in each treatment. Because confinement, which is dependent on valley width, influences gradient and potential for multithread planform, having a range of confinements in each treatment prevents length ratio, valley width, and cross-section variables from being significantly different between treatments. More channel measurements of width, depth, and gradient for each reach could also help in understanding how cross section variables contribute to channel complexity.
In summary, the significant differences in geomorphic stream complexity depend on the complexity metric being evaluated. Significant differences between treatments appear to result primarily from differences in individual channel widths, individual wood pieces, and logjams within the streams, and to a lesser extent from differences in the ratio of channel area to valley area (which primarily reflects the presence of multithread channels in OU reaches). Significant differences in geomorphic complexity as measured by the ratio of channel length to valley length, and the cross-sectional metrics of standard deviation of channel gradient, bankfull width, and depth, correlate more strongly with differences in valley lateral confinement than differences between treatments. Measures of functional complexity related to stream retention (pool volume and organic matter storage) correlate more strongly with wood and logjam variables than with cross-sectional metrics.

5.2. Bed and Streambank Complexity Analyses of Intensive Reaches

ANOVA analyses for surveys and longitudinal roughness were run with low n values for treatments, which is one explanation for why significant differences were difficult to achieve. More surveys per treatment, including confined reaches as a separate treatment, could provide more insights into differences reflected in bed and bank surveys. We expected confined channels to have greater values of thalweg SD and longitudinal roughness because of steeper gradients (Figure 4, right), step-pool and cascade morphology, and clast sizes of confined channels. Although thalweg SD differences between the four groups were not statistically significant, the confined reach had the greatest value, followed by OU, YU, and YM, suggesting thalweg complexity has the expected pattern between treatments.

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

5.3. Multivariate Analyses of Variables That Control Stream Complexity

Results of the PCA biplots and linear regression analyses indicate that treatment and confinement are the dominant controls on stream channel complexity, and YM, or a history of management, results in low values of complexity variables. The analysis also revealed that the variables we analyzed represent four different groupings of complexity measures, related to wood pieces, channel width, other cross-sectional measures (depth, gradient, area), and logjams (Figure 5, bottom left). Most wood piece variables represent the same complexity characteristics as backwater pool volume/100 m valley, both organic matter storage variables, and length ratio. Wood characteristics appear to directly influence these complexity variables and could represent a mediator between forest history and complexity (Table 3). However, these are the only complexity variables that appear to be directly influenced by wood characteristics.

Complexity variables associated with width measurements represent the second group of complexity characteristics, while depth SD, gradient SD, and area ratio represent the third. These two groups represent different aspects of complexity, but share an axis in PCA space. This axis is controlled by gradient, mean individual channel width, and valley width (Table 3), all of which are dominated by the influence of confinement and multithread channel planform (Figures 4, right and 5). Confined channels have the greatest variability in gradient and depth, hence their location in PCA space. Area ratio, or the amount of valley space the stream occupies, is high in confined channels and in multithread channels (Figure 4, right), which is why that variable loads between these two channel types in PCA space. This complexity metric is thus not very useful in determining high levels of complexity. Width variables are highest in multithread channels, likely because of the variation in widths associated with measuring many separate channels rather than multiple width measurements from a single-channel stream. Because multithread planform equates to high complexity, but is different than how width changes in a single channel, a braiding index applied to anastomosing channels, or average number of anabranch channels, may be a more appropriate measure of complexity than width SD or width CV. Greater numbers of individual channels in a valley likely equate to greater opportunities for pools, nutrient storage, and habitat diversity for aquatic biota (Figure 1b). The fourth grouping includes proportion of bridge and ramp pieces and logjam height/jam frequency, and...
distinguishes low-wood managed and confined streams; in other words, these variables define low-complexity channels.

Mean gradient is a significant control variable for PC2 axes assessing complexity variables in Table 3, but because YM has a significantly lower slope from other treatments, corresponding to greater drainage area, we believe these results may be responding more to treatment and confinement rather than high gradients corresponding to high complexity and wood storage.

Although Figure 4, left plot appears to suggest a uniform gradient of wood characteristics and channel complexity based on forest age and management history, the two unmanaged treatments are not typically significantly different from one another, whereas both are typically significantly different from managed reaches (Table 2). In addition, all three biplots show YM reaches clearly distinguished in PCA space from the other two treatments, suggesting a threshold effect related to management history (Figure 5). In order to evaluate the relevance of YM reaches for channel complexity, we ran the same PCAs and regressions against control variables without YM reaches and found that PCs explained less variance in the data and only PC1 was ever significant. Thus, patterns of complexity are more difficult to discern without YM reaches, which represent a baseline for noncomplex stream channels in our analyses. Despite gradient of forest cover (Figure 4, left), management history creates a threshold, and the effect on complexity of removing wood and wood sources is greater than the effect of natural disturbances to previously undisturbed forests (Figure 1a). In other words, old-growth riparian forests are not required for greater complexity as long as wood is not removed from stream channels.

We find that high levels of complexity and wood storage in mountain streams of the Southern Rockies are related to high forest cover, lack of human disturbance, and relatively unconfined valleys. Some complexity variables represent different aspects of heterogeneity which are trade-offs, such as variation of depth and variation of width, indicating the need for explicit ecological and functional complexity goals in stream restoration projects. The greater physical heterogeneity provided by wood through flow separation and hydraulic diversity hypothetically leads to greater potential habitat and nutrient retention in pools and irregular banks, as well as greater biomass and biodiversity (Figure 1b): whether our measures of complexity lead to these responses is a possibility that will be tested in subsequent papers.

6. Conclusions

The results of this investigation of small mountain streams in subalpine forests of the Southern Rockies suggest that riparian forest stand age and management history, along with valley geometry, significantly influence instream wood load and characteristics of wood pieces, such as number of bridges and ramps and number of channel-spanning logjams. Wood load and wood characteristics in turn influence variables such as pool volume, organic matter storage, and the ratio of channel length to valley length (Figure 5; Table 3). Despite slightly lower wood loads and complexity values in younger versus old-growth forests in unmanaged streams, we find that management history of riparian forests exerts the strongest control on reduced functional stream channel complexity, regardless of riparian forest stand age. Lateral valley confinement is a primary influence on cross-sectional variables such as the standard deviation of bankfull depth and local gradient, and on the ratio of channel area to valley-bottom area. Overall, the most geomorphically complex streams are those in old-growth forest with laterally unconfined valleys and multithread planform. Streams in younger unmanaged riparian forest and laterally unconfined valleys are more similar to these streams than are streams in younger riparian forest with some history of land use. The results also support our initial conceptual model (Figure 1) and suggest that instream wood is a primary driver of physical heterogeneity in these streams.

Our results also indicate that the legacy effects of removal of riparian forests and instream wood have resulted in long-lasting reductions of instream wood loads and geomorphic complexity in small stream channels within subalpine forests of the Southern Rockies. Management or restoration projects aiming to restore wood loads and functional geomorphic complexity should focus on maintaining or allowing growth of riparian forests, which is of particular importance in stream channels with relatively unconfined valley bottoms that have the potential to form a multithread planform. Our results indicate that natural disturbances are as important as old-growth forest in sustaining geomorphic complexity, suggesting that retaining dead wood in the stream corridor is a key passive restoration technique for streams. Any restoration
Acknowledgments

We thank the National Science Foundation grant DEB-1145616 for financial support for this research. Rocky Mountain National Park and the U.S. Forest Service provided access to research sites. We thank Gus Womeldorph and Reed Waldon for field assistance. The authors also wish to thank the Franklin Graybill Statistical Laboratory at Colorado State University for statistical consulting. The data used in this article are listed in supporting information Table S1. The paper was improved by the comments of two anonymous reviewers.

References


Dunn, O. J. (1964), Multiple comparisons using rank sums, Technometrics, 6, 241–252.


McClain, M. E. et al. (2003), Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems, Ecosys- tems, 6, 301–312.


Milliman, J. D., and J. P. M. Syvitski (1992), Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers, J. Geol., 100, 525–544.


