DISSERTATION

CROSSING A THRESHOLD: THE LEGACY OF 19TH CENTURY LOGGING ON LOG JAMS AND CARBON STORAGE IN FRONT RANGE HEADWATER STREAMS

Submitted by

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ABSTRACT

CROSSING A THRESHOLD: THE LEGACY OF 19TH CENTURY LOGGING ON LOG JAMS AND CARBON STORAGE IN FRONT RANGE HEADWATER STREAMS

Instream wood has an important effect on the geomorphic and ecological function of streams, but human impacts have altered both the forests that supply wood and the streams themselves. These changes may have pushed many stream systems over a threshold past which the stream morphology and ecology do not return to their pre-disturbance state, but instead settle into a "new normal." This dissertation addresses the question of whether logging which took place in the 19th century has had lasting and significant effects on the instream wood and carbon storage of headwater streams in Colorado's Front Range. The distribution of logs within the headwaters of the Big Thompson River, North Saint Vrain Creek and Cache la Poudre River in northern Colorado were assessed to quantify the ways in which logs and forest characteristics relate to carbon storage within a stream.

The results indicate that old growth forests are significantly different than younger forests. Streams in old growth forests have more total wood, more closely spaced ramps and bridges that can act as key pieces for jams, and more jams per kilometer. There appears to be a positive feedback between total wood load and downstream spacing of jams. The presence of jams can influence the characteristics of wood in the channel, with jams increasing the retention of smaller diameter wood pieces in streams.

No significant difference was found between the proportion of organic matter (OM) in fine sediment between jams and non-jam areas in a reach, but old growth generally has a higher proportion of OM and a faster rate of increase in the proportion of OM stored behind a jam with increasing jam volume. Most OM in jams is stored as wood, but the proportion stored as wood is lowest in old growth, which suggests that old growth jams can be more retentive of the more bioavailable fine OM in sediment.

Stand age, valley type, and disturbance history explain 73% of the variation in total carbon (wood and sediment) stored within a reach. Natural disturbances such as fire can increase jams per kilometer, but

human disturbances such as logging reduce the number of jams/km. Natural and human disturbances have a correspondingly different effect on the carbon stored in streams, with natural disturbances increasing carbon storage, and human disturbances reducing storage. Streams through logged forests have an order of magnitude less carbon stored within the channel than streams in forests of equivalent age with natural disturbance. This implies that past and contemporary forest management not only changes terrestrial forest ecology and nutrient cycling, but also riverine nutrient dynamics and, presumably, aquatic ecology.

Characteristics of jams (size, number per kilometer) and carbon storage correlate most closely with reach-scale variables, implying that management would be most effective at the reach scale. Increased total wood load and decreased spacing between key pieces are the most important changes that can be made to promote the formation of jams within a reach. Old growth forest creates significantly different total carbon storage and partitioning of carbon storage, which extends previous work on the effects of old growth forest on terrestrial carbon to riverine environments.

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DEDICATION

Dedicated to the memory of Clarice Georgette Hollman Neal,

who loved knowledge, but put her family ahead of her academic goals.

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Instream wood, log jams, log jam density, log dynamics, key pieces, organic matter, carbon storage, CPOM, FPOM, biogeochemical hotspots, mountain streams, Front Range, Colorado, Rocky Mountains.

INTRODUCTION

1.1 A NOTE ON THE STRUCTURE OF THIS DISSERTATION

This research project began with three questions regarding: the effect of log jams on streams; the effect of old growth forest on instream wood; and the ways that these two factors interact to increase or decrease the organic carbon stored within streams. As the project evolved, it became clear that the easiest way to answer these three questions was to first understand the ways that forests and instream wood interact, and then address the question of changes to carbon storage. Consequently, this dissertation is divided into three chapters. The first provides general background information about previous studies, the project area and data collection methods. The second chapter addresses log dynamics and teases out the interactions of stand age, piece characteristics and the number of jams that form along a reach. The third chapter investigates the factors which influence sediment retention behind jams and the proportion of organic matter stored with that sediment. Overall, this work addresses the question of whether logging which took place in the 19th century has had lasting and significant effects on the instream wood and carbon storage of headwater streams in Colorado's Front Range.

1.2 LITERATURE REVIEW

Previous studies hypothesize that one of the effects of the cumulative human-induced changes within the Colorado Rockies during the past two centuries has been to reduce the instream wood loads and frequency of natural wood jams along most forested streams [*Wohl*, 2001; *Goode and Wohl*, 2007; *Wohl and Jaeger*, 2009]. It is assumed that human activities such as timber harvest, flow alteration and active wood removal combine to decrease the volume of instream wood and thus cause a net decrease in the frequency and wood content of logjams in affected (altered) streams. Conversely, streams which are relatively un-altered by humans (no recent history of logging, flow diversion or active wood removal from the channel) should contain more wood and jams. This study tests that assumption by quantitatively comparing jam frequency and carbon storage, and using that comparison to estimate a magnitude of change. These results can aid management decisions in Rocky Mountain National Park and adjacent national forests. Although log jams are typically thought of by the public as negative features which impede fish passage, limit recreational kayaking, or pose a hazard to infrastructure [*Piégay et al.*, 2005; *Chin et al.*, 2008], resource managers now recognize that increasing instream wood loads can help restore some of the historical characteristics of stream networks.

Instream wood performs several geomorphic and ecological functions. Wood adds roughness to channels and can result in finer streambed substrate than would otherwise be present [*Manga and Kirchner*, 2000]. Wood increases boundary roughness and hydraulic resistance [*Curran and Wohl*, 2003; *Keller and Tally*, 1979]. Wood modifies alluvial bedforms [*Baillie and Davies*, 2002; *MacFarlane and Wohl*, 2003] and enhances habitat diversity and abundance [*Fausch and Northcote*, 1992; *Maser and Sedell*, 1994]. Wood also modifies channel planform [*Collins and Montgomery*, 2002] and enhances lateral connectivity between channels and floodplains [*Wohl*, 2011;*Collins et al.*, 2012].

Concentrations of wood in the form of logjams can have an even larger effect on the channel than individual pieces. These effects are commonly non-linear, in that adding more wood in the form of jams creates a greater change than simply adding more individual pieces. Channel spanning log jams can be particularly effective in creating boundary roughness and flow separation [*Manners et al.*, 2007], as well as promoting hyporheic exchange and thus nutrient retention and processing [*Lautz et al.*, 2006; *Fanelli and Lautz*, 2008; *Wondzell et al.*, 2009]. Log jams can also retain substantial volumes of fine sediment and organic matter [*Bilby*, 1981; *Assani and Petit*, 1995; *Manga and Kirchner*, 2000] and alter floodplain dynamics [*Collins et al.*, 2012]. Because organic matter regulates stream respiration, these effects likely extend beyond streams and into riparian zones, given that stream insects provide critical nutrient and energy subsidy to riparian consumers [*Baxter et al.*, 2005].

Less well documented is the longitudinal distribution of wood in various settings [*Wing et al.*, 1999; *May and Gresswell*, 2003] , although wood is likely to be non-randomly distributed [*Kraft and Warren*, 2003; *Wohl and Jaeger*, 2009; *Wohl and Cadol*, 2011]. Several studies indicate declines in volume of wood per unit area of channel downstream through a drainage basin [*Keller and Swanson*, 1979; *Keller and Tally*, 1979; *Hassan et al.*, 2005; *Wohl and Jaeger*, 2009], partly in response to increased transport capacity downstream [*Marcus et al.*, 2002; *Wohl and Jaeger*, 2009], although high spatial variability in wood recruitment and retention appears to be common [*Hassan et al.*, 2005]. More limited work suggests that jams form preferentially in portions of a basin where the combined effects of wood supply and transport capacity are maximized [*Wohl and Jaeger*, 2009]. Previous studies suggest that old growth forest provides larger trees and more key pieces to anchor jams, leading to more jams than areas of non-virgin forest [*Abbe and Montgomery*, 2003; *Wohl and Goode*, 2008], although these observations have not been systematically tested.

Wood retention and jam formation are also likely to be non-linear processes in which increasing volumes of instream wood help to retain newly recruited wood and enhance the formation and persistence of jams [*Wohl and Goode*, 2008; *Wohl*, 2011]. Despite recent advances in understanding the forces acting on a piece of instream wood and the mechanics of fluvial wood transport [*Braudrick and Grant*, 2000; *Manners et al.*, 2007; *Bocchiola et al.*, 2008; *Merten et al.*, 2010], the complex interactions among wood recruitment, channel form, and channel hydraulics make it challenging to quantitatively predict wood retention and distribution [*Hassan et al.*, 2005], particularly at the scale of a channel reach (10^1-10^2 m) or a small catchment (10^1-10^2 km^2). Channel process and form at these scales are commonly of particular interest to resource managers trying to enhance fish habitat or stabilize an eroding channel using engineered log jams [*Abbe et al.*, 2003; *Collins et al.*, 2012]. It is therefore important to refine our understanding of wood transport and retention at these spatial scales by collecting and analyzing field data from diverse settings.

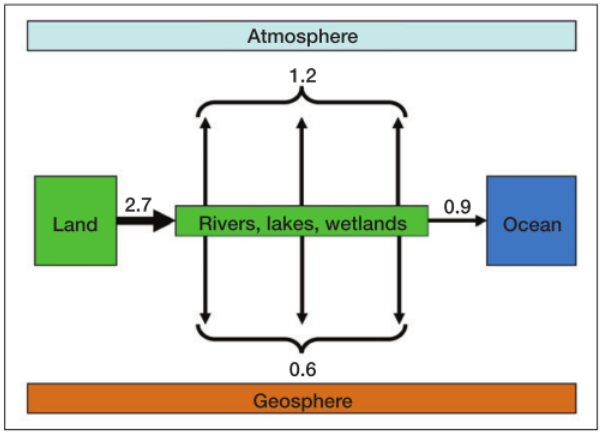


Figure 1: Estimated carbon fluxes (in Pg C yr^{-1}) between rivers, terrestrial environments, oceans, the atmosphere and the lithosphere (Figure 3 from Aufdenkampe et al., 2011)

Recent work on the carbon cycle emphasizes the influence of fluvial dynamics on the export and processing of terrestrial carbon (Figure 1) [*Galy et al.*, 2008a, 2008b; *Hilton et al.*, 2008a, 2008b; *Battin et al.*, 2009; *Aufdenkampe et al.*, 2011]. Metabolism of terrestrial organic carbon in freshwater ecosystems is responsible for a large amount of CO_2 outgassing to the atmosphere [*Battin et al.*, 2008; *Aufdenkampe et al.*, 2011]. Hydrological storage and retention zones can extend the residence time of organic carbon during downstream transport when dissolved organic carbon (DOC, smaller than 0.45 µm), as well as fine particulate organic matter (FPOM, between 0.45 µm and 1 mm) and coarse particulate organic matter (CPOM, larger than 1 mm), is stored at sites of flow separation and reduced transport capacity. Fluvial examples of storage and retention zones include marginal eddies, lee deposits downstream from obstacles [*Thompson*, 2008], river segments ponded by logjams or downstream constrictions [*Lautz et al.*, 2006], and hyporheic zones [*Harvey and Fuller*, 1998]. These sites provide *geophysical opportunities* for microorganisms to develop as attached biofilms or suspended aggregates and to metabolize organic carbon and other nutrients for energy and growth [*Battin et al.*, 2008]. Sites of increased nutrient retention and processing have also been described as *biogeochemical hot spots* that show disproportionately high reaction rates relatively to the surrounding matrix [*McClain et al.*, 2003]. Any physical feature that promotes flow separation, lower velocity, and at least temporary fine sediment storage can facilitate the formation of biogeochemical hot spots. The concepts of both geophysical opportunities and biogeochemical hot spots thus emphasize the importance of localized retention zones in streams. Presumably, the efficiency with which streams retain and oxidize organic carbon rests on the evolution of microbial physiological capacities in response to retention zones [*Battin et al.*, 2008], as well as the abundance and quality of retention zones [*Peterson et al.*, 2001; *Hall et al.*, 2002]. Headwater streams are particularly important in this respect. Because of their relatively close coupling to adjacent uplands, headwater streams receive most of the terrestrial DOC [*Battin et al.*, 2008]. These streams are likely to have substantial retention zones because of longitudinally and laterally variable channel geometry, relatively poorly-sorted grain-size distributions that include large, protruding clasts, and instream wood [*Wohl*, 2000]. Because the flow paths through, and residence times of water in, headwater catchments are among the primary controls on DOC variation through time in these streams [*Boyer et al.*, 1995], it becomes vital to document types of retention zones and the processes that maintain these zones in headwater streams.

Because streams play a significant role in the sequestration, transport, and mineralization of organic carbon, knowledge of fluvial processes must be integrated into the traditional conceptualization of the carbon cycle [*Battin et al.*, 2009; *Aufdenkampe et al.*, 2011]. Enhancing our understanding of fluvial influences on carbon dynamics is also vital because the hydrologic cycle is exceptionally sensitive to climate change and water-borne carbon fluxes will respond to climate change [*Battin et al.*, 2009]. More intense storms, for example, may result in greater transport of terrestrial carbon to streams. To date, studies quantifying fluvial sequestration and export of organic carbon have been limited to a few environments and it is not clear how adequately the results from these studies describe catchments with different characteristics of climate, geology, land cover, or fluvial form and process. Additionally, a consensus is developing that we need to identify the "hot spots" within freshwater networks where carbon processing is concentrated [*McClain et al.*, 2003; *Warren et al.*, 2007; *Mulholland*, 2012]. These hot spots can be regional (temperate storage vs tropical fluxes), reach-scale (wide segments vs steep, narrow segments), and unit-scale (behind jams vs non-jam sections).

A potential model for the formation of these biogeochemical hotspots is illustrated below in Figure 2. In this model, forests with older stands have a higher basal area, which results in more wood entering the stream. The increased stream wood creates anchored pieces (ramps and bridges) or snags on existing anchored pieces and starts to form jams that have multiple effects. Jams can increase the water surface level, forcing high flows out of the channel into the floodplain, allowing for lateral movement of carbon and nutrients. They can also provide an area of lower velocity where fine sediment and any organic matter being carried by the river can deposit. In addition, the wood trapped within the jam itself can provide a source of carbon to the stream as it decays.

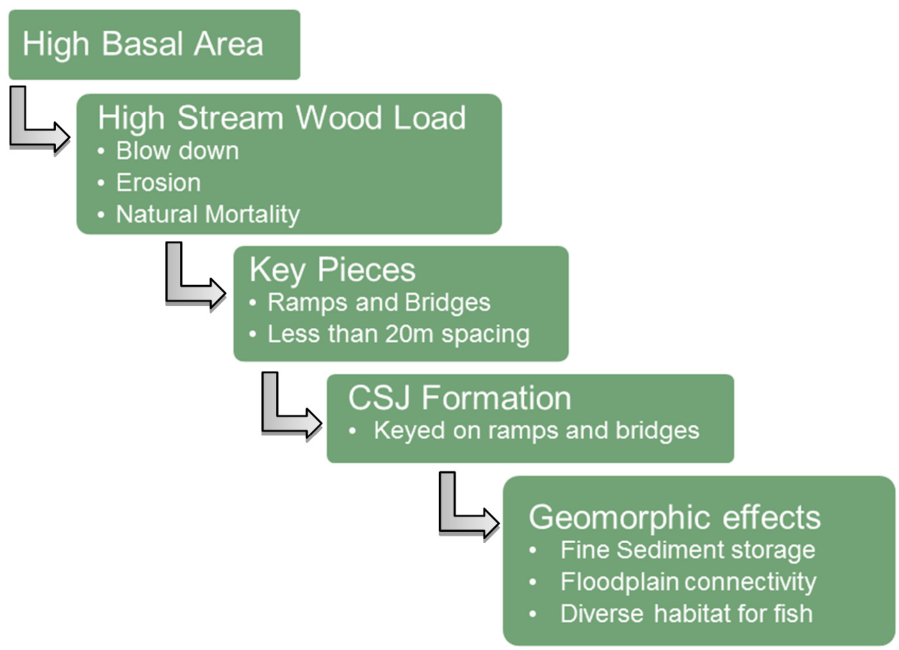


Figure 2, Conceptual model for the formation of biogeochemical hotspots within a mountain river system. A channel spanning jams (CSJ) is defined a jam which crosses the entire channel width and affects the water surface across the entire channel.

1.3 PRIMARY OBJECTIVES AND HYPOTHESES

This study aims to provide a detailed census of log jams and carbon storage in headwater streams within mountainous regions of Colorado, in order to better understand the mechanisms that lead to increased instream wood, and the ways in which this can impact the carbon storage in headwater streams in Colorado's Front Range.

The primary objectives of this research are to:

- conduct surveys of selected stream reaches representing diverse channel geometry, forest stand age, and history of disturbance in order to test for relationships between (i) the volume and longitudinal spacing of jams and (ii) channel characteristics (drainage area, bed gradient, channel width) and forest stand age,
- conduct detailed measurements of selected jams in order to physically characterize jams in different environments, specifically the log characteristics, sediment storage, and organic matter retention, and
- develop a linear statistical model to identify the major influences on jam density and organic matter retention, and make a first-order approximation of instream carbon storage.

In addressing these objectives, I test the following hypotheses:

(H1) Influence of jams: Log jams have different effects on the channel than other features that result in fine sediment storage. Specifically, log jams more effectively promote the retention and deposition of organic matter within the stream than do other sources of boundary roughness such as large clasts.

This hypothesis, which examines the influence of jams on streams, is supported if the proportion of organic matter in sediment samples taken from the fine sediment directly above log jams is higher than in samples taken from other fine sediment within the stream for all sites, or if the proportion of organic matter is the same but the total volume of fine sediment stored behind log jams is larger than the volume stored in other areas of the channel, regardless of stand age.

(H2) Influence of forest type: Local forest age is more important to the quantity and characteristics of instream wood than basin characteristics.

This hypothesis, which examines the effect of forest type on instream wood, is supported if forest stand age, or derivative variables such as basal area, show better correlation with instream wood variables (total wood stored within the stream, length, diameter, and piece type of that wood) than do basin level variables such as drainage area or channel gradient. Forest type is a reach scale variable, since a given basin can consist of a spatial mosaic of stand ages due to past disturbances.

(H3) Combined influence of stand age and jams: Jams have higher overall volume of wood and higher relative organic sediment content in streams draining old growth forests. As a result, headwater streams in the Colorado Front Range draining altered forests are currently "dam-impoverished" ecosystems with greatly reduced organic matter storage capacity relative to unaltered streams.

This hypothesis, which examines the joint influence of stand age and jams, is supported if there is a significant statistical difference between jam volume and stored organic matter between old growth forest streams and altered forest streams. The forest categories used in this study are explained more fully in Section 1.3, but as a guide, old growth forest is defined as a forest having standing trees more than 200 years old and altered forests are defined as stands with trees younger than 200 years which have a history of logging. Support for this hypothesis could include either an increase in the proportion of organic matter stored as fine sediment in old growth streams, or a greater total volume of organic matter because of increased fine sediment storage in old growth reaches.

1.4 Study Area

Selected study sites are in the Cache la Poudre, Big Thompson, and St. Vrain River drainages (Figure 3). Each of these streams heads near the Continental Divide at > 4000 m elevation and flows down to ~1900 m at the base of the mountains, where the stream is tributary to the South Platte River. Mean annual precipitation is 70-90 cm in the upper basins. Flow is dominated by snowmelt, which produces an annual hydrograph with a sustained May-June peak. In 2010 and 2011, the hydrology along the Front Range was unusual, with larger than average magnitude and duration of the snowmelt peak. In 2010, the Allenspark stream gauge along North Saint Vrain Creek recorded above-average flows starting June 4th and ending June 15th, with a peak of approximately 17 m^3/s on June 8. The gauge has a 20-year historic average June flow of approximately 6.2 m^3/s. In 2011, the snowmelt peak was both larger in magnitude and longer in duration than it has been historically. The same gauge recorded above-average flows starting June 6th, and continuing until mid-July with a peak of approximately 16.3 m^3/s on July 8 (Colorado Division of Water Resources gauge "North Saint Vrain Creek near Allenspark").

The basins are underlain by Precambrian-age Silver Plume granite [*Braddock and Cole*, 1990]. Although bedrock lithology does not vary substantially in the study area, valley geometry is quite variable as a reflection of Pleistocene glacial dynamics [*Wohl et al.*, 2004] and variations in joint geometry and associated susceptibility to weathering and erosion [*Ehlen and Wohl*, 2002]. The width and gradient of stream channels vary downstream at lengths of 10^2-10^3 m; small bedrock gorges in which both channel and valley-bottom width are < 30 m regularly alternate longitudinally with lower gradient (1-2%), wider (several times active channel width) valley segments, and waterfalls > 10 m tall are present in the uppermost part of each basin. Step-pool channels are most common, although cascade, plane-bed, and pool-riffle morphologies [*Montgomery and Buffington*, 1997] are also present. Substrate is primarily cobble- to boulder-size clasts, although finer sand and gravel is present in zones of flow separation such as upstream from logjams.

Sample reaches were selected from the area a short distance below timberline (~3200 m elevation) down to ~2400 m. These portions of the catchments are above the Pleistocene terminal moraines and are predominantly covered by subalpine forests of Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), lodgepole pine (*Pinus contorta*), aspen (*Populus tremuloides*), and limber pine (*Pinus flexilis*) [*Veblen and Donnegan*, 2005]. Lodgepole pine forests dominate large areas of the subalpine zone, forming the most extensive forest type in the Front Range [*Veblen and Donnegan*, 2005]. More mesic subalpine sites are dominated by Engelmann spruce and subalpine fir, whereas lodgepole dominate more xeric sites and are successional to the spruce-fir community. Riparian communities include large numbers of conifers such as Douglas-fir (*Pseudotsuga menziesii*) and spruce, as well as aspen. Age and size of individual trees vary greatly with site-specific conditions.

Figure 3: Map of study area, showing location of study sites (open circles)

Disturbance in Front Range forests takes the form of wildfire, persistent drought, insect outbreak, wind blowdowns, hillslope mass movements such as debris flows, and floods. The study area does not have frequent landslides or debris flows that can introduce large volumes of wood to the streams. Fire and insect outbreaks are the most significant in terms of extent, severity, and frequency in the laterally confined mountain valleys of this study, and time-since-fire appears to be the single most important control on volume of dead wood in a stand [*Rebertus et al.*, 1992; *Hall et al.*, 2006]. Infrequent, high-severity fires that kill all canopy trees over areas of hundreds to thousands of hectares recur at intervals greater than 100 years in the subalpine zone [*Veblen and Donnegan*, 2005]. Patches of stand-killing disturbance in the North Saint Vrain basin date to 1654, 1695, 1880, and 1978 AD, and for the portions of the Big Thompson drainage within Rocky Mountain National Park, disturbance patches date to 1730, 1893 and 1915 [*Sibold et al.*, 2006]. For areas outside the park, no large scale disturbance maps were available, but tree coring done as part of this study indicates that riparian stands germinated after 1770, 1810, 1850, and 1880 in the Big Thompson basin and 1710, 1790, 1860, 1870, 1910, 1930 and 1940 in the Poudre River Basin. Although the causes of stand-killing disturbances are not known for certain, they are assumed to be natural if they occurred more than 200 years ago, or if they occurred in Wild Basin where there was no known logging. In areas with a known history of logging (including lands managed by the Forest Service and most lands managed by the Park Service), stands younger than 200 years old were assumed to be re-growth after logging.

Regrowth of woody plants following a disturbance is slow in the semiarid Front Range relative to other temperate forests. Recruitment period following disturbance varies with site conditions, seed sources, and climate, but is typically 30-60 years for the subalpine zone [*Veblen and Donnegan*, 2005]. Old-growth characteristics, however, typically do not emerge for at least 200 years in subalpine forests [*Veblen*, 1986]. Wood recruitment to streams flowing through the disturbed area can thus increase substantially for a period of decades following a disturbance as dead and dying trees slowly topple, but is then likely to decrease during the period when all dead trees have fallen and new trees are not yet large enough for recruitment; the whole process may require two centuries to reach pre-disturbance wood dynamics [*Bragg*, 2000]. Examples of different reach types can be seen in Figure 4. For this study, streams were classified as either disturbed (stand age less than 200 years, but no known history or evidence of logging), old growth (stand age greater than 200 years), and altered (stand age less than 200 years and history or evidence of logging).

Starting in 2009 and ongoing, subalpine and montane forests in the study area are experiencing increased tree mortality due to a severe infestation by mountain pine beetle (*Dendroctonus ponderosa*). Such outbreaks recur every few decades throughout the Colorado Rocky Mountains [*Romme et al.*, 2006]. The instream wood surveyed for this study was not affected by the most recent infestation for two reasons. First, riparian trees are less susceptible than upland trees, and second, the dead trees were still standing during the summers of 2010 and 2011 and so did not contribute to the instream loads. Future surveys may find an increase in wood loads as the dead trees start to fall, though currently it is thought that trees killed by mountain pine beetles tend to snap well above the ground, resulting in smaller piece length.

1.5 METHODS

In order to test the above hypotheses, two different datasets at different levels of detail were collected. Thirty reaches of channel were surveyed, and 30 individual channel-spanning log jams were surveyed. The data and methods are described in the following sections.

1.5.1 Reach level data

Reach level data were intended to give an overall picture of the wood dynamics in a stream and the number and character of jams present. When possible, one kilometer of the river was surveyed for each reach. In some cases, shorter reaches were surveyed because the reach was interrupted by confluences, lakes, willow thickets or waterfalls.

Disturbed: Middle Ouzel reach, disturbed by fire, stand age is 33 years

Old growth: Middle Cony reach, no history of disturbance, stand age is >500 years.

Altered: Willow Creek reach, logged, stand age is approximately 110 years.

Figure 4: Typical views of reaches with different forest age and disturbance history (age estimated in 2011).

Selection of reaches

Study reaches were chosen only on the east side of the Continental Divide to minimize between-reach differences in regional factors such as snowpack accumulation and precipitation. Reaches were chosen so that there were no major tributaries entering the stream within the reach. Basins containing known old growth forest were scarce, as were basins with flow gauges. In order to minimize differences due to streamflow, non-old growth basins were chosen to match the approximate drainage area and elevation of the known old growth reaches. Thirty-one reaches were surveyed, all having varied channel width, valley geometry, forest characteristics, and channel slopes. A total of 12 old growth reaches and 19 reaches in younger forest were surveyed over the summers of 2009, 2010 and 2011. Of the 31 reaches surveyed, one (Boulder Creek) was removed from the dataset prior to analysis because it had an unusually large drainage area and low elevation in comparison to the other reaches.

If secondary channels were present, a decision was made in the field as to whether they were stable and carried a significant amount of flow. If they did, the wood in the secondary channels was included in the analysis and the channel width of both channels was recorded. If not, they were not included in the survey.

Data collection at reach level

Latitude, longitude and elevation for the start and end points of the reach were recorded in the field using an eTrex H handheld GPS with a horizontal accuracy of ~ $\pm$ 3m and varying vertical accuracy. These points were then used to find drainage area and stream order for each reach using Stream Stats [*Ries et al.*, 2008], which calculates basin parameters using 10 m DEMs. Drainage areas were measured from the most downstream point of the reach, and thus are a maximum drainage area for the reach.

Each reach was assigned to a valley type based on ratio of bankfull channel width to valley bottom width (W_c/W_v) using criteria developed in *Wohl et al* [2012]. Confined valleys are steep and narrow, with limited floodplain development: $W_v \leq 2X\ W_c$. In partially confined valleys, W_v 2-8X W_c. Unconfined valleys are relatively wide and of low gradient, allowing more extensive floodplain development and the potential for a multithread channel planform: $W_v > 8X\ W_c$.

For streams surveyed in 2009 and 2010, every piece of wood located within the bankfull width of the stream with a diameter greater than 10 cm and a length greater than 1 m was surveyed. During the 2011 season, an unusually high magnitude and long duration peak flow dramatically shortened the field season. A decision was made to alter data collection techniques so that only pieces meeting the above criteria that were also in jams were surveyed in detail. A piece was considered to be part of a jam if it touched at least two other pieces of minimum 10 cm diameter and 1 m length. For reaches surveyed in 2011, ramps and bridges within each 10 m segment of the reach were counted. This was done to decrease the amount of time required for each reach survey, and is justified based on the preliminary results from 2009 and 2010 reaches, which showed a strong linear relation between jam density and total wood load, as well as a strong threshold for ramp/bridge spacing and jam density.

Basal area measurements of the standing wood in the forest were taken at the start, middle and end of each reach using a handheld Panama Angle Gauge sampler. Measurements were taken no more than 10 m from the stream banks within the surrounding stand. In addition to the number of trees which filled the scope, a record was kept of the number of standing dead trees tallied and an estimate was made of the percent of standing dead trees in the visible forest.

Channel width was measured at 10 m intervals. During 2009 and 2010 this was done using a manual rangefinder calibrated using a survey tape. In 2011, widths were taken using a laser rangefinder (Laser Technology TruPulse 360B). Channel gradient was measured at major breaks in slope or every 100 m, whichever distance was shorter. A Suunto clinometer was used to estimate channel slope in 2009 and 2010, while a TruPulse 360B laser rangefinder was used in 2011. Longitudinal spacing of pieces and jams through each reach was established using a 100 m tape in 2009 and 2010, and a laser rangefinder in 2011.

INSTREAM WOOD MEASUREMENTS

For each piece of wood surveyed within the stream, six pieces of information were collected: longitudinal spacing, total piece length (including length outside the channel), piece diameter, piece type, decay class and whether the piece was located within a jam. Longitudinal spacing was measured as described above. Length and diameter were measured using a tape measure, laser rangefinder or visual estimate.

PIECE TYPE

Each surveyed piece was assigned to one of 6 categories: bridge, left ramp, right ramp, pinned, buried, or unattached. The criteria for each category are described in Table 1.

Table 1: Field classification of piece type

Piece Type	Field indicators
Bridge	crossing the stream with two ends above bankfull elevation
Left/Right Ramp	one end in the stream, one end outside the bankfull elevation on the left/right (looking downstream) side of the stream
Pinned	held in place by a relatively stable feature, such as a boulder or ramp/bridge
Buried	partially or completely buried by sediment in the bed or bank
Unattached	floating or loose, not anchored at any point; moved under light pressure

DECAY

Each log was assigned a numerical value corresponding to its state of decay. The 2009 data used a three part decay classification where 1 meant needles, bark and branches present, 2 meant most branches and bark still present, and 3 meant everything else. For the reaches surveyed in 2010 and 2011, logs were classified using a seven part system modified from *Hyatt and Naiman* [2001], as described below in Table 2. Because most logs in the stream lack bark and leaves/needles, no effort was made to identify species for the logs.

Table 2: Field decay classification ranging from 1 (no decay) to 7 (most decayed), after Hyatt & Naiman, 2001

Decay Class	Field indicators
1	Green leaves/needles, bark present
2	Brown leaves/needles, bark present
3	Small twigs and bark present, leaves absent
4	Large branches and/or bark present, small twigs absent, some bark missing
5	Some large branches may be present, small branches and twigs absent, bark missing, no structural decay
6	Large branches absent, evident structural decay (can hold some weight)
7	Large branches absent, significant structural decay (cannot hold weight, crumbles when touched)

1.5.2 Individual jams

SELECTION OF JAMS

Detailed log jam surveys were made of 30 individual jams, chosen along reaches known to have jams, but not necessarily reaches chosen for 1 km surveys. Criteria for surveyed jams were that they 1) be accessible by foot while carrying survey equipment, 2) be channel spanning, and 3) include fine sediment stored behind the jam.

DATA COLLECTION AT JAMS

Once a jam was selected, latitude, longitude and elevation were recorded using an eTrex H handheld GPS. Local site surveys were also made using a Topcon GTS-235W total station, prismatic survey rod and Carlson Explorer II datalogger. At each jam, measurements were made of the water elevation upstream, through pool and jam, and downstream. Upstream and downstream water elevations were taken to a distance of either three channel widths or to the limit of visibility, whichever was shorter. Survey points were also taken to outline the area of fine sediment behind the jam, and the depth of sediment was recorded using a 1.5 cm diameter metal rod which was pounded into the sediment using a hand sledge until refusal [*Lisle and Hilton*, 1992]. Fine sediment depth measurement locations were taken to form an approximate grid over the area of fine sediment, at an approximate spacing of 0.3-0.5 m (Figure 5). A list of survey codes used to describe data points is included in Appendix B.

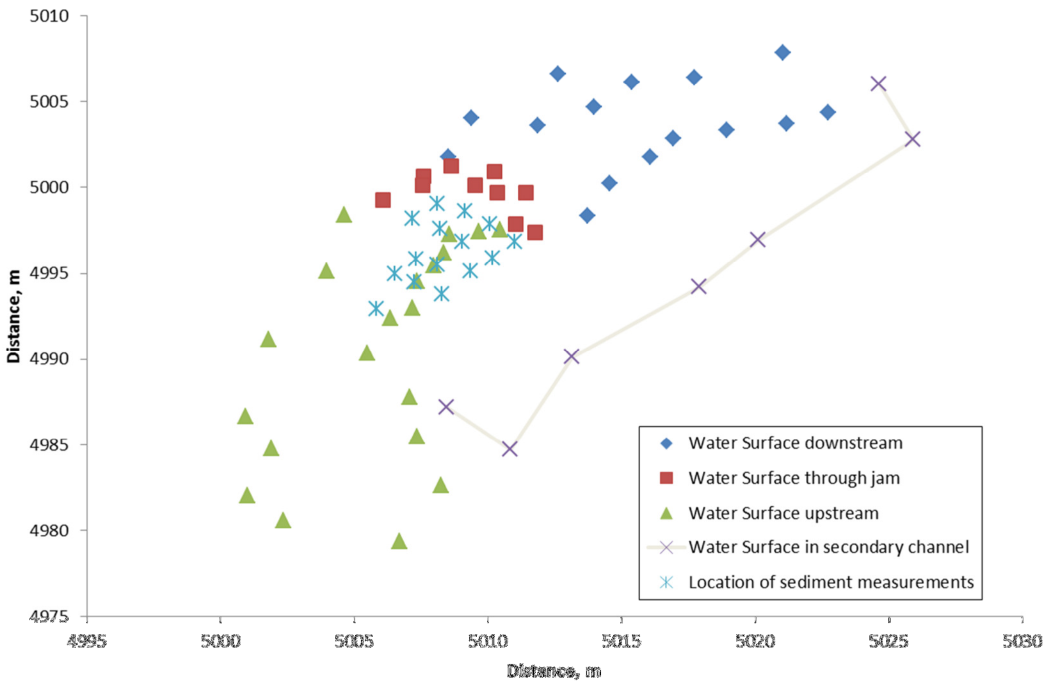


Figure 5: Plan view of jam survey points for Cony 2. Triangles represent the upstream banks, diamonds represent the downstream banks, squares show points surveyed in the log jam, asterix mark the sediment stored upstream of the log jam, and crosses mark the location of a side channel which bypasses the log jam. Axes distances are measured from an arbitrary base point, and are for scale only.

At each jam, photos were taken of the jam, instrument setup and stream features from multiple angles. A sketch was made of each jam showing the instrument setup, benchmarks if any were set, large boulders or other obstructions in the channel, key pieces of the jam and general extent of the jam, locations of fine sediment storage and any secondary channels or landmarks around the jam. Also at each jam, length, diameter, piece type and decay (as described in section 1.4.1) were recorded for all the logs in the jam which were larger than 10 cm diameter and 1 m length. These data give a minimum volume of wood in the jam, but not necessarily an accurate volume because large jams might include pieces not visible from the surface because they were hidden under other logs or partially buried in streambed sediment. To characterize the forest cover around each jam, basal area was measured using angle count sampling [*Avery and Burkhart*, 2002]. In addition to the total number of tallied trees, a note was made of the number of tallied trees which were dead, and a visual estimate was made of the percent of standing dead trees in the surrounding forest.

In each area of fine sediment, samples were taken for laboratory analysis. At least three samples were taken of the sediment trapped by the jam, as well as comparison samples from areas of fine sediment not associated with a jam (if any were available). An attempt was made to take comparison samples both upstream and downstream of the jam. Comparison sites storing fine sediments included deposits behind boulders, in channel margins, and at bend bars. Comparison samples were not taken in slackwater areas created by instream wood. If no fine sediment was found stored in areas not associated with instream wood, then no samples were taken and a note was made.

1.5.3 Forest age

The forest in a given drainage basin is commonly a spatial mosaic of differently aged stands due to local stand replacing events such as fire or blow down. Stand ages (measured in years since germination) and forest types were determined for each reach. Reaches were assigned one of three forest types: old growth (standing trees surrounding the reach germinated more than 200 years ago), altered (standing trees surrounding the reach germinated less than 200 years ago and there was a history of logging which removed wood volume), or disturbed (standing trees surrounding the reach germinated less than 200 years ago and there was a history of natural disturbance which killed trees but did not remove wood volume). At the reach level only two reaches were considered "disturbed," so they were included with the altered reaches for analysis. In the individual jam dataset, all three reach types were considered separately for analysis.

Old growth forest can be defined based on many different criteria, such as stand structure, stand age, presence of large trees or lack of human disturbance. For the purposes of this study, we defined old growth forest as forest which has not been subject to a large scale disturbance in 200 years. This was based on work by *Sibold et al.* [2006] in their study area south of the Big Thompson River in Rocky Mountain National Park. For areas not mapped in the Sibold study, tree core samples were used to estimate stand age. In order to get a measure of current stand age, cores were taken from live trees. In two cases cores were also taken from dead trees. The exceptions were made for cores taken along Joe

Wright Creek and North Fork Joe Wright Creek, where the standing dead trees were obviously much older than the live trees, and appeared to be the major source of instream wood. Cores were taken from spruce trees when they were present, because spruce/fir is the late successional species composition for this area and previous studies have found that spruce trees are often the oldest in a stand [*Veblen*, 1986; *Roovers and Rebertus*, 1993]. When spruce was not present, pines and aspen were cored.

The coring protocol was designed to estimate the age of a given tree within 15 years. Coring was done by the author and/or a field assistant, and all cores for a reach were taken at the same time. When possible, core samples were taken by angling the increment borer down in order to intercept the tree pith at ground level. If this was not feasible, samples were taken as low on the tree as possible. No correction has been made to account for the height at which the sample was taken because potential errors in tree age introduced in this manner fell within the acceptable range of variation in measurements. Tree cores were mounted, sanded and annual rings were counted using a stereomicroscope. For cores that did not intercept the tree pith, no estimate was made of the number of additional rings surrounding the pith. Because of the decision not to correct for sample height or missing rings at the pith, stand ages determined by coring are conservative and should be considered minimum ages.

1.5.4 Loss on ignition (LOI)

Fine sediment samples were taken in the field using a sieve with a jelly bag over it. Samples were taken from the top layer of fine sediment, including any organic matter which had settled on the surface (Figure 6). This method consistently retained all particles sand sized and larger. Samples were transported and stored in labeled 1 gallon Ziploc plastic bags, and air dried in an enclosed, ventilated space.

Figure 6: Example of an air-dried sediment sample with a large amount of organic matter.

In the lab, samples were processed using loss on ignition techniques, as described by *Heiri et al.* [2001]. The total air-dry sample weight was recorded using a Sartorius ELT-602 mass balance with 0.01 g resolution and a maximum capacity of 600 g. Samples were then passed through an ASTM 2mm sieve and particles larger than 2 mm were divided into organic and non-organic portions, weighed, and recorded. The greater than 2 mm organic fraction (small wood, pine needles and pine cones) was assumed to be 50% carbon by mass.

The finer than 2 mm fraction was then well mixed, and three 10-15 g subsamples were placed in pre-weighed ceramic tins. The tins were placed in a muffle furnace set for 550 °C (1000 °F) for 24 hours and re-weighed. The lost weight is assumed to be the organic fraction of the <2 mm portion of the sample. The limit of detection was approximately 1%, so any sample with less than 1% of organic matter will show up in the dataset as 1%. The amount of organic matter contained within a sample was calculated as:

$$\%\,OM = \frac{grams\ of\ carbon\ in > 2\ mm\ portion + \ grams\ of\ carbon\ in < 2\ mm\ portion}{Total\ mass\ of\ sample\ (g)}$$

1.5.5 Non-field data

Stream order and drainage area were estimated using the USGS StreamStats website for Colorado [*Ries et al.*, 2008]. Stream order was determined based on the underlying map image and the stream layer at a scale of 1:24000. Drainage area was calculated using the “watershed delineation from a point” mapping tool, which calculates drainage area from a point by transferring that point and creating a drainage boundary using an underlying 10 m Digital Elevation Map (DEM). The DEMs used by StreamStats for most states have been enhanced by adding a dataset of known stream locations and drainage boundaries, so delineations made on StreamStats are generally more accurate than delineations made from a standard DEM [*Ries et al.*, 2008].

LOG DYNAMICS

2.0 INTRODUCTION TO LOG DYNAMICS

2.0.1 Effects of instream wood on streams

Humans have changed the rivers of the Rocky Mountains in many ways. During the past 200 years, watersheds have been logged, streams have been used for tie drives, and flow has been diverted across basins to provide water supply for growing communities. Prior to European settlement, forests were impacted primarily by fire, wind and insect attack [*Rebertus et al.*, 1992]. Although old growth forests (>200 years) were patchy due to natural disturbance, they most likely existed in greater quantities than are seen today along Colorado's Front Range. Qualitative assessments [*Wohl*, 2001; *Wohl and Jaeger*, 2009] indicate that the intense human induced landscape alteration over the last 200 years has reduced the incidence of instream wood and especially log jams along impacted reaches.

The effects of the large scale removal of instream wood are increasingly of concern to ecologists, geomorphologists, and habitat managers. Previous studies have shown that log jams can affect the local slope and channel morphology of a stream, especially in steep streams [*Abbe and Montgomery*, 2003]. Jams store alluvial material, particularly fine organic matter, and can be especially important for small order streams [*Bilby and Likens*, 1980]. Jams can alter channel planform and channel-floodplain connectivity by raising the local water surface until it overtops the bankfull stage [*Wohl*, 2011; *Collins et al.*, 2012]. In steep streams, jams may be especially important to stream ecology because they increase the number and size of pools and increase fish biomass [*Fausch and Northcote*, 1992].

Studies of the effects of instream wood concentrate in mountainous regions because wood is actively removed from lowland streams for infrastructure protection. Numerous studies have been conducted in the Pacific Northwest [*Fausch and Northcote*, 1992; *Featherston et al.*, 1995; *Abbe and Montgomery*, 2003; *May and Gresswell*, 2003; *Collins et al.*, 2012], California [*Berg et al.*, 1998; *Bendix and Cowell*, 2010], and the southern Rocky Mountains [*Bragg et al.*, 2000; *Wohl and Goode*, 2008; *Polvi et al.*, 2011;

Wohl and Cadol, 2011]. Mountain streams may be one of the few remaining places where instream wood and jams exist, but that does not mean that these streams have escaped human influence.

2.0.2 Factors which affect instream wood loads

The amount of wood within a particular channel reach is fundamentally controlled by two processes: the supply of wood to the reach, and the ability of the stream to transport that wood. Wood supply can change through time [*Nakamura et al.*, 2000; *Gurnell et al.*, 2002], and the presence of adjacent forest with old growth characteristics increases the amount and size of instream wood in Colorado streams [*Richmond and Fausch*, 1995]. Disturbances such as insect outbreaks, blow downs, and avalanches can temporarily increase supply, but decrease the long term supply by removing stands of mature trees. Traditional logging and clear cutting decrease the supply without an initial increase in large wood to the channel. For natural disturbances, both the pre-disturbance stand age and the type of disturbance have an effect on the eventual supply of wood to a reach [*Spies et al.*, 2012].

The ability of a stream to transport wood is controlled by both channel characteristics and the characteristics of the pieces which fall in. Channel characteristics that reflect potential transport capacity for wood include flow width and depth. Channel width and the ratio of channel width to piece length are most often linked to the impact wood can have on a channel and the amount of wood stored in the channel [*Gurnell et al.*, 2002; *Bocchiola et al.*, 2008]. Previous studies in the Front Range have shown an exponential decrease in total wood load with increasing stream width [*Bragg et al.*, 2000]. Flume studies suggest that wood retention increases with debris roughness [*Braudrick and Grant*, 2000]. Debris roughness in this context refers to changes in channel configuration that locally reduce transport capacity for wood, including channel bends, constrictions and expansions, and the presence of immobile wood. Flume studies also indicate that for pieces shorter than the channel width, log diameter and the presence of a rootwad can influence movement more than length [*Braudrick and Grant*, 2000]. Species can also play a role in whether a piece is transported, with some evidence that conifers are more likely to be retained in a reach than hardwoods [*Collins et al.*, 2012].

At the local scale, controls on jam formation such as valley and channel geometry (valley bottom width, local slope and the downstream sequence of changes to the channel), exert a larger influence on jam formation than either forest age or increasing drainage area [*Wohl and Cadol*, 2011]. The presence of bedrock gorges or meadow reaches can also influence the supply and transportability of wood [*Wohl and Jaeger*, 2009]. Another local control is the proximity of wood recruitment. Locally recruited pieces are larger (measured by volume) and are more likely to have one or both ends anchored outside the channel than fluvially transported wood [*May and Gresswell*, 2003].

The effect of old growth forest on instream wood characteristics such as piece size or jam spacing is currently poorly understood, though studies have linked forest age and total wood load within streams. Richmond and Fausch [1995] found substantially larger wood loads in old growth forest streams in the Colorado Rocky Mountains than at more recently disturbed sites (92–254 m^3/ha versus 12–147 m^3/ha). A later study in the same region of Colorado found a less substantial difference in wood loadings, with a range of 64- 415 m^3/ha in old growth and 12-378 m^3/ha in younger forests, though their sites were connected longitudinally and there may have been some transport of logs from old growth areas into non-old growth areas [*Wohl and Cadol*, 2011].

Previous studies have attempted to create conceptual models to understand the interactions between forest processes and wood recruitment to streams. *Benda and Sias* [2003] identified tree growth and mortality, bank erosion, frequency of debris flows, rate of decay and the ability of the stream to transport wood as key factors influencing instream wood loads. They specifically included the presence, spacing, and longevity of jams in their calculation of transport capacity within a stream, as well as the proportion of the channel blocked by each jam. When they tested their conceptual model with a 150 year and a 500 year fire disturbance cycle, they found that the largest recruitment came from fire-killed standing tress which fell during the decades immediately following a fire. Under the 500 year disturbance regime, overall rates of wood recruitment were higher than under the 150 year cycle, which they attributed to the increase in available woody biomass and tree height with forest age. One omission in the model, however, is that the log jam characteristics which control transport (spacing, longevity and proportion of channel blocked) do not do not alter with forest age, even though in older forests the recruited logs presumably will be larger, taller, and more likely to form log jams. Although *Benda and Sias* tested only one disturbance type (fire), additional modeling to simulate the different effects of natural and logged disturbances indicates that local instream wood recruitment peaks approximately 30 years after a natural disturbance. In contrast, forests which have been logged can take more than 200 years to regain pre-harvest instream wood recruitment, with the difference caused by the removal of biomass that might otherwise enter the stream [*Bragg et al.*, 2000]. For this study, reaches with a stand age greater than 200 years are considered old growth. Because only two of the surveyed reaches had stand ages less than 200 years due to natural disturbances, disturbance history was not considered in this chapter and reaches younger than 200 years were considered altered, whether they were logged or impacted by natural disturbances.

2.0.3 Gaps in current knowledge

A majority of studies describe the physical effects of log jams upon the channel, but few include quantitative observations of log jam characteristics or address the factors which control log jam formation in streams of the southern Rocky Mountains. In addition, few studies in any region describe the role of different piece types in jam formation, or characterize the distribution of piece size between the general population of logs within the channel and the subset of logs found as parts of jams within the channel. Also, there is a need to explicitly link forest characteristics to instream wood to highlight the role that forest history (and long forgotten impacts) may have on the supply of wood in a channel and the number and size of log jams.

2.1 OBJECTIVES AND HYPOTHESES FOR LOG DYNAMICS

In this chapter, I use the data I collected in the Front Range to test whether basin and reach-scale characteristics (slope, channel width, drainage area, elevation or stream order) are strongly correlated with the number or size of log jams. If they are, this indicates that basin and reach characteristics are more important to jam formation than wood or forest characteristics (stand age, piece length, piece diameter).

I then quantify the impacts of stand age on the number of jams, distribution of wood, wood diameter and length through a space for time substitution comparing reaches with old growth and altered forest. I also compare the physical characteristics of wood in jams and wood not in jams to evaluate the effect of jams on the total population of wood in a stream, and extrapolate what piece types are necessary for jam formation. Finally, I use generalized linear models to assess the interactions among all of these factors and develop a predictive model for the number of jams expected on a given reach and the size of jams.

In addressing these objectives, I will also test my second hypothesis, that local forest age is more important to the quantity and characteristics of instream wood than basin characteristics.

2.2 METHODS

Statistical analyses used in this chapter include Analysis of Variance (ANOVA), hierarchical and k-means cluster analysis, and generalized linear modeling (GLM). ANOVA assumes that the input variables are normally or near-normally distributed. In order to meet this assumption, right skewed variables were transformed using the natural log function. Natural log transformations were used with jam density, slope, drainage area, ramp and bridge spacing.

For cluster analysis, drainage area and slope were natural log transformed. All variables (stream order, transformed slope, transformed drainage area, channel width and elevation) were normalized by subtracting the mean and dividing by standard deviation. Normality for each variable was checked using the Shapiro Wilk Normality test, (*H0* is that data are normal) and standard Q-Q plots.

For the GLM selection, right skewed variables were transformed using the natural log fundtion. A natural log transform was applied to jam density, slope, drainage area, ramp and bridge spacing and jam wood load. Jam density (number of jams per kilometer of channel) and jam volume (average volume of wood in a jam, per reach) were used as response variables. Jam density was modeled as both Poisson and negative binomial distributed, and the model with the best Akaike Information Criterion (AIC) was chosen.

2.3 RESULTS

2.3.1 Describing the dataset

A condensed list of the reaches surveyed and variables measured can be found in Table 3. The complete dataset, including a table of summary variables and raw data for each reach, is available in Appendix A. Table 3 contains variables averaged at the reach scale, but individual reaches also include substantial variations. Figure 7 shows the irregular distribution of log jams and slope changes along two reaches of the North Fork Big Thompson (NFBT). NFBT R1, shown at the top of the figure, is located within an old growth portion of the stream. NFBT R2, which is located upstream of NFBT R1 in an area of altered forest, has a similar slope but lower jam density and more variation in jam location.

Table 3: Summary of reach level data. Shaded rows indicate old growth reaches (stand age >200 years). The two bold rows (Middle Ouzel and NSV3) indicate disturbed reaches, where the stand age is less than 200 years due to natural events and no logging occurred. For the analyses in this chapter they have been grouped with the altered reaches

Reach name	Date surveyed	Reach length	Basin	Strahler Stream order at 1:24,000	Reach Average Slope	Reach Average Channel Width	Drainage Area at Down-stream End	Average Elevation	Reservoir Upstream Logical	Number of pieces surveyed	Basal Area	Stand Age	Old Growth Logical	Total Wood load	Proportion of Wood Load in Jams	Ramp and Bridge Spacing	Jam Density	Average Log Diameter (jam)	Average Log Diameter (reach)	Avg log length (jam)	Avg log length (reach)
					%	m	km^2	m	y/n		m^2/ha	yrs	y/n	m^3/ha channel surface	%	m	#/km	cm	cm	cm	cm
Middle Ouzel	**2009**	**1000**	**NSV**	**3**	**5%**	**10.1**	**12.7**	**4329**	**n**	**1412**	**6.9**	**33**	**n**	**247.7**	**69%**	**2.8**	**77**	**20**	**20**	**329**	**354**
NSV3	**2009**	**1000**	**NSV**	**3**	**7%**	**12.54**	**20.51**	**4239**	**n**	**767**	**87.2**	**129**	**n**	**91.4**	**83%**	**5.6**	**49**	**21**	**21**	**281**	**273**
Boulder Brook	2010	1000	BT	2	12%	2.27	10.0	4112	n	176	43.6	117	n	51.4	4%	11.4	12	14	14	311	419
Mill Creek	2010	1000	BT	2	8%	3.95	11.4	3953	n	293	16.1	117	n	71.7	16%	11.1	23	15	15	369	398
La Poudre Pass Creek	2010	1000	Poudre	2	2%	13.24	22.7	4584	y	58	4.6	70	n	5.0	52%	125.0	5	20	21	282	266
Hague Creek	2010	1000	Poudre	3	4%	9.05	35.2	4479	n	58	13.8	150	n	12.8	34%	52.6	4	20	19	452	163
Poudre River South	2010	1000	Poudre	4	2%	14.4	87.8	4444	n	31	6.9	100	n	2.7	36%	125.0	2	15	16	322	97
Corral Creek	2010	1000	Poudre	2	3%	4.2	16.5	4572	n	31	9.2	80	n	5.3	0%	111.1	0	n/a	16	n/a	78
Willow Creek	2010	1000	Poudre	2	6%	7.1	15.3	4571	n	89	13.8	110	n	17.2	27%	37.0	6	18	18	408	182
Bennet Creek	2010	1000	Poudre	2	2%	14.69	20.5	3720	n	351	29.8	150	n	27.4	47%	5.8	22	16	16	299	391
Cow Creek	2011	1000	BT	1	12%	2.12	15.3	3915	n	124	11.5	130	n	1.2	--	11.0	9	19	19	523	--
Glacier Creek	2011	1000	BT	2	5%	6.16	19.7	4484	n	--	11.5	117	n	--	--	16.4	10	19	--	351	--
Pennock Creek	2011	1000	Poudre	3	5%	5.96	32.1	3994	n	--	20.7	140	n	--	--	19.6	4	19	--	488	--
Beaver Brook	2011	1000	BT	1	5%	1.27	6.1	3909	n	--	13.8	100	n	--	--	3.5	34	15	--	257	--
Beaver Creek	2011	1000	Poudre	3	1%	7.71	54.1	4123	y	--	12.2	100	n	--	--	40.0	4	14	--	303	--
Fall River	2011	1000	BT	2	4%	4.7	17.9	4200	n	--	16.8	120	n	--	--	6.0	23	17	--	360	--
Roaring Creek	2011	1000	Poudre	2	1%	4.3	22.9	4041	n	--	17.4	90	n	--	--	12.5	11	15	--	251	--
NFBT2	2011	1000	BT	2	3%	5.16	43.3	3589	n	--	18.4	160	n	--	--	12.0	15	16	--	301	--
Lower Hunters	2009	1000	NSV	3	28%	6.67	12.5	4046	n	626	57.4	355	y	99.6	30%	6.7	47	16	16	291	330
Upper Hunters	2009	1000	NSV	3	14%	5.73	11.7	4441	n	632	84.9	355	y	151.4	37%	5.6	49	18	18	302	331
Upper Cony	2009	1000	NSV	3	4%	8.33	14.1	4456	n	858	103.3	500	y	158.7	56%	5.8	63	20	20	299	311
Middle Cony	2009	1000	NSV	4	7%	8.7	19	4213	n	971	107.9	500	y	116.7	56%	5.4	62	17	17	297	307
Upper Ouzel	2009	630	NSV	2	15%	9.95	7.25	4620	n	339	80.3	500	y	132.5	43%	9.8	37	25	26	280	322
NSV1	2009	1000	NSV	3	14%	6.1	10.2	4669	n	504	91.8	355	y	146.2	25%	10.6	44	20	22	253	277
NSV2	2009	1000	NSV	3	4%	8.56	16	4553	n	621	107.9	355	y	121.3	60%	6.0	45	22	22	289	289
Joe Wright Creek	2010	1000	Poudre	2	2%	6.59	19.1	4460	y	247	34.4	220	y	78.5	28%	11.8	11	20	21	441	445
Black Canyon Creek	2011	1000	BT	2	3%	1.3	11.8	4121	n	--	18.4	200	y	--	--	2.8	26	18	--	337	--
NFJW	2011	1000	Poudre	2	4%	4.3	9.0	4434	n	--	27.5	300	y	--	--	9.6	9	19	--	310	--
Fern Creek	2011	640	BT	2	18%	4	7.3	3914	n	--	13.8	280	y	--	--	4.6	52	17	--	303	--
NFBT1	2011	1000	BT	2	4%	5.13	45.3	3523	n	--	10.6	240	y	--	--	5.8	35	19	--	325	--

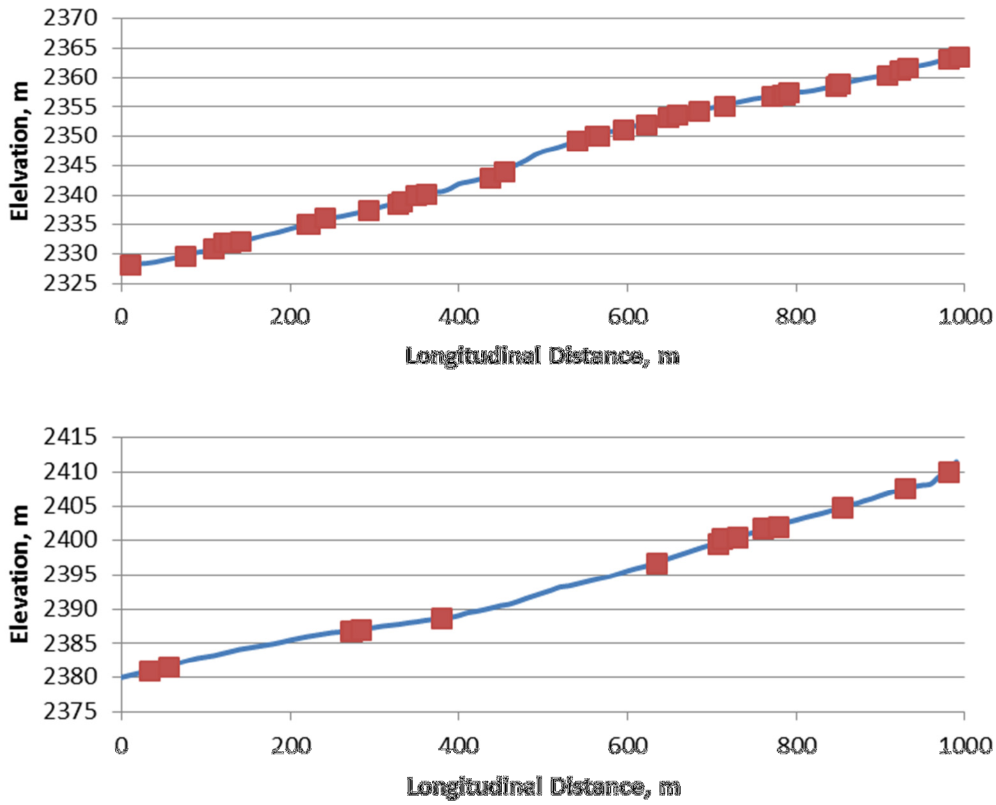


Figure 7: Reach scale variations in slope and jam density for an old growth (NFBTR1, top) and altered (NFBTR2, bottom) reaches along the same river showing non-uniform distribution of jams within a reach.

Because jam density and total wood load are highly correlated (Figure 8) and jam density is much easier and faster to measure in the field, only jam density was measured during the shortened 2011 field season (see section 1.4.1 for further explanation). For analyses in this chapter, jam density is treated as an indicator of total wood load within a stream.

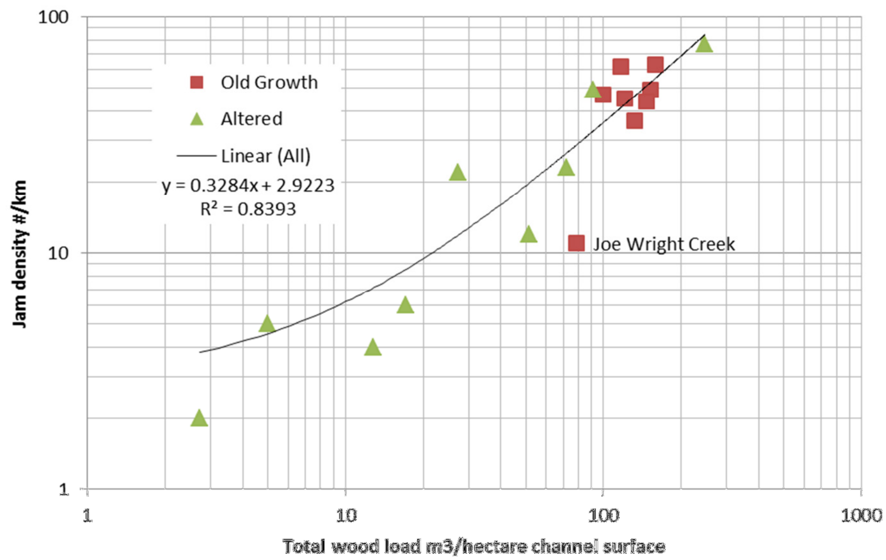


Figure 8: Jam density versus total wood load for reaches surveyed in 2009 and 2010, showing strong linear correlation.

2.3.2 Basin characteristics

It is possible that basin and reach-scale characteristics (slope, channel width, drainage area) are strongly correlated with the number or size of log jams. Because the basins included in this study are largely ungauged, drainage area is used as a surrogate for discharge. Previous studies have shown that channel width and jam density both increase in the downstream direction in the Colorado Front Range [*Wohl and Jaeger*, 2009]. However, for the data collected for this study, there was no clear downstream trend in channel widths (Figure 9) or jam density (Figure 10), indicating poorly developed hydraulic geometry, and suggesting that local controls may be more important than basin-scale controls. This can be the case in areas where there are longitudinal changes to the channel such as those observed in the study area [*Wohl et al.*, 2004]. Reach scale channel width also appears to have little effect on jam density (Figure 11). Given the lack of evidence that basin- or reach-scale characteristics strongly influence the number of log jams in a channel reach, the next step is to evaluate whether forest age and disturbance history correlate with jam characteristics.

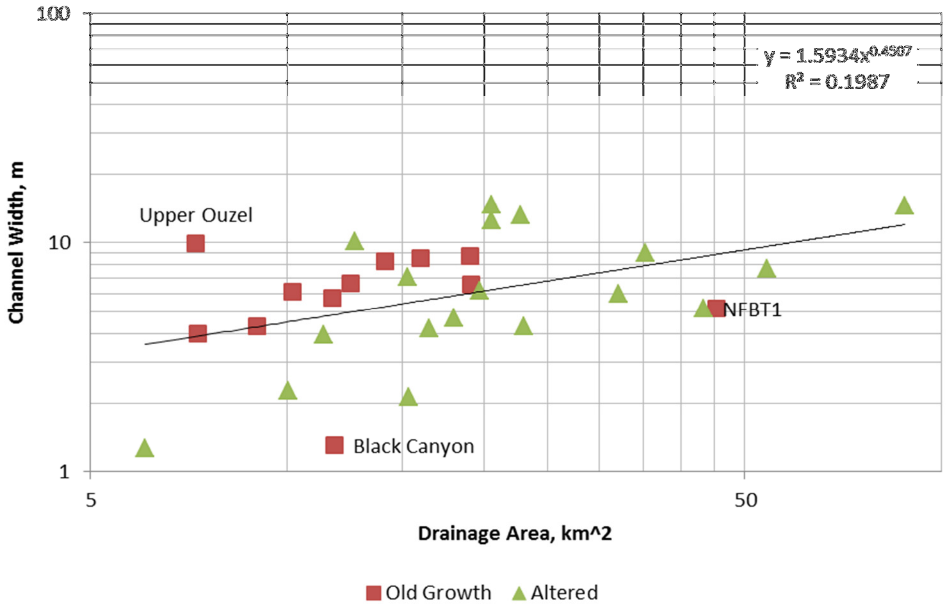


Figure 9: Width-drainage area plot for the reaches surveyed in this study, showing a weak log-linear relationship. Low R^2 value can also reflect lack of well developed downstream hydraulic geometry, presumably reflecting longitudinal variations in valley geometry.

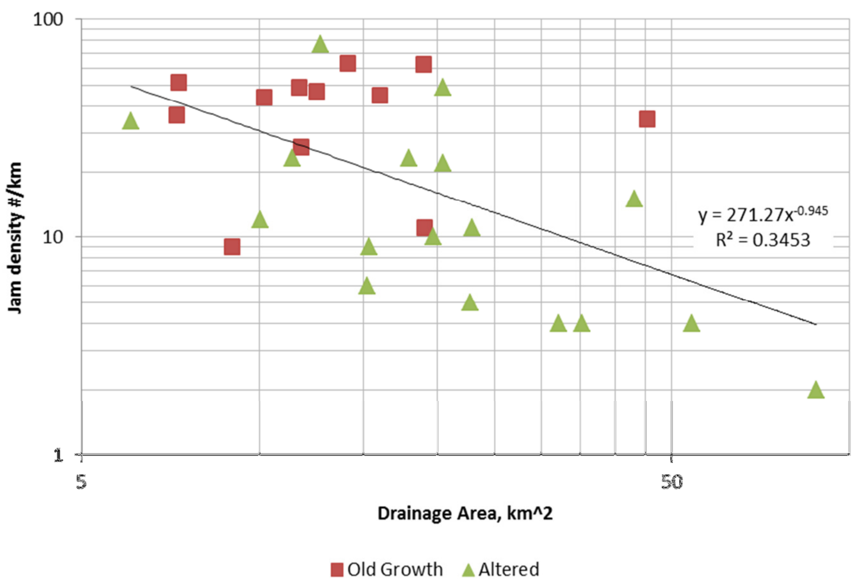


Figure 10: Jam density versus drainage area plot shows a small downstream trend in jam density. A lack of progressive downstream trends suggests that local controls (forest or valley characteristics) may be more influential for jam formation.

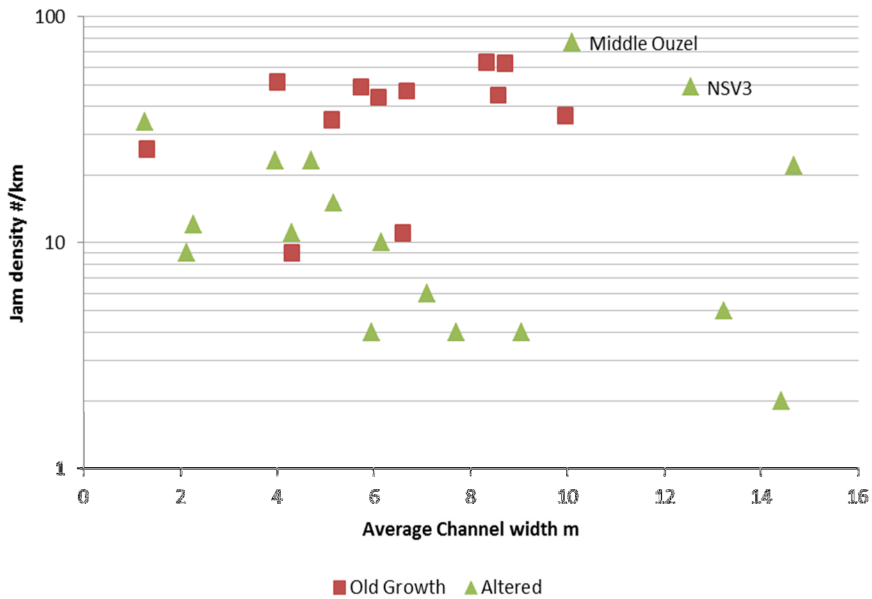


Figure 11: Plot of jam density versus channel width showing a possible bi-modal reaction to increasing channel width depending on stand age. Outliers Middle Ouzel and NSV3 are in areas of disturbed old growth, where the instream wood loads may still be influences.

2.3.3 Forest age and disturbance history

One local control that may exert a large influence on jam formation is the age of the adjacent forest. Stand age can change both the amount of wood available to the channel and the character of the wood supply (diameter, length, species). Considering stand age alone, Figure 12 and Figure 13 indicate that old growth forests tend to have more jams per kilometer than younger forests, and thus more total wood load within the stream.

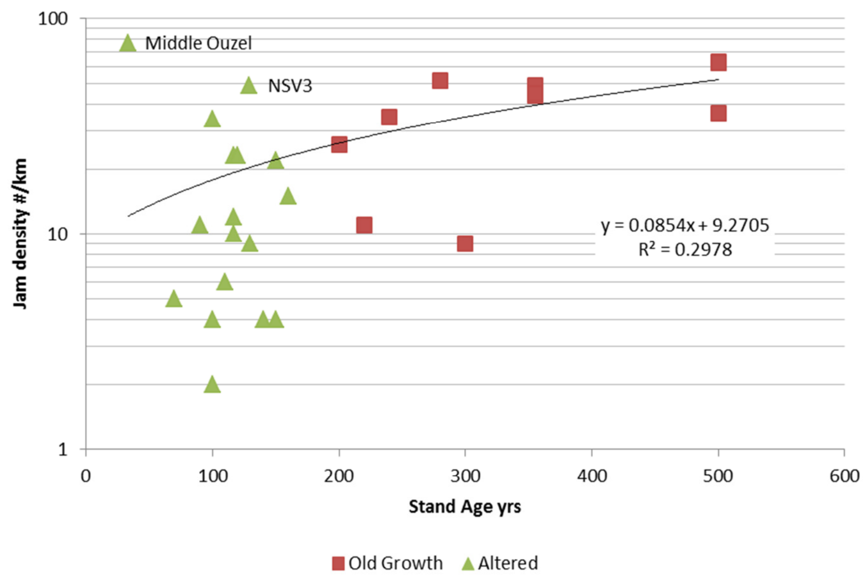


Figure 12: Jam density (in number per km) versus stand age (in years). Although there is a trend observable, there are also conspicuous outliers such as Middle Ouzel and NSV3, which are disturbed old growth.

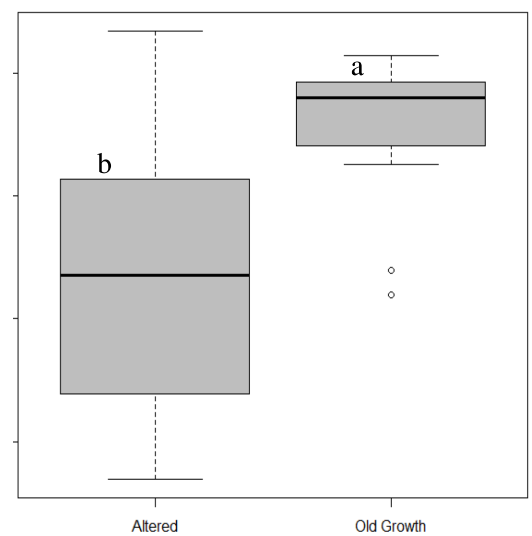


Figure 13: ANOVA on transformed jam density in old growth and altered reaches, ANOVA and Tukey HSD analysis indicates that there are significant differences between the two groups (p=0.002). The letters above the boxes indicate statistically significant groupings.

Old growth streams have a larger basal area (a measure of standing wood volume) within 10 m of the stream than altered stands (Figure 14). A larger crop of standing wood is important to jam formation because wood that enters the channel locally is more likely to have one or both ends anchored outside the channel than fluvially transported wood [*May and Gresswell*, 2003], which allows locally recruited wood to act as an anchor point for jam formation. Figure 15 shows that although there is a possible direct relationship between basal area and jam formation for some reaches, other reaches show increased jam density with no corresponding increase in basal area, so local basal area alone cannot be used to directly predict jam density.

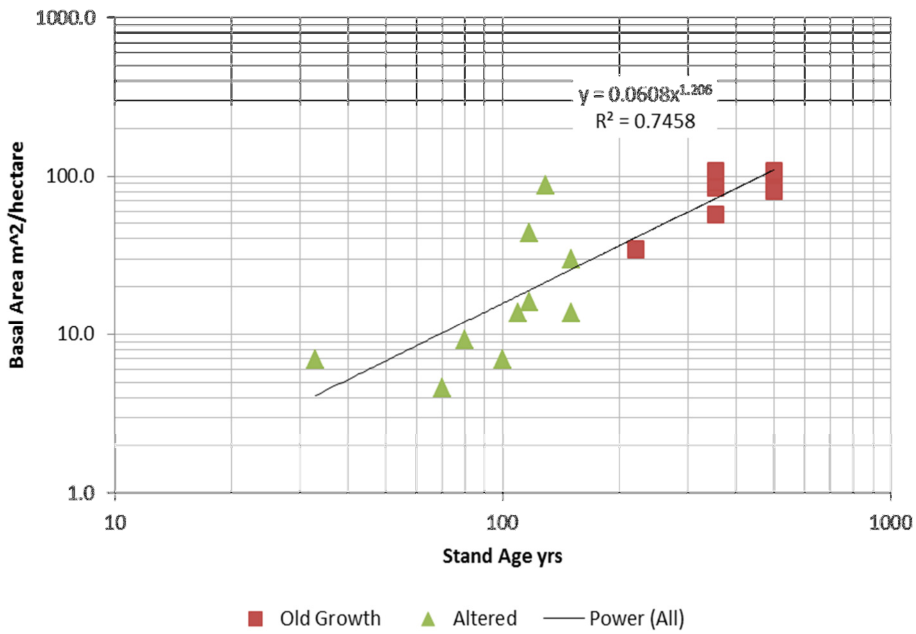


Figure 14: Basal area versus stand age. There is more standing wood in old growth forests, and therefore a greater potential supply of local wood to the stream.

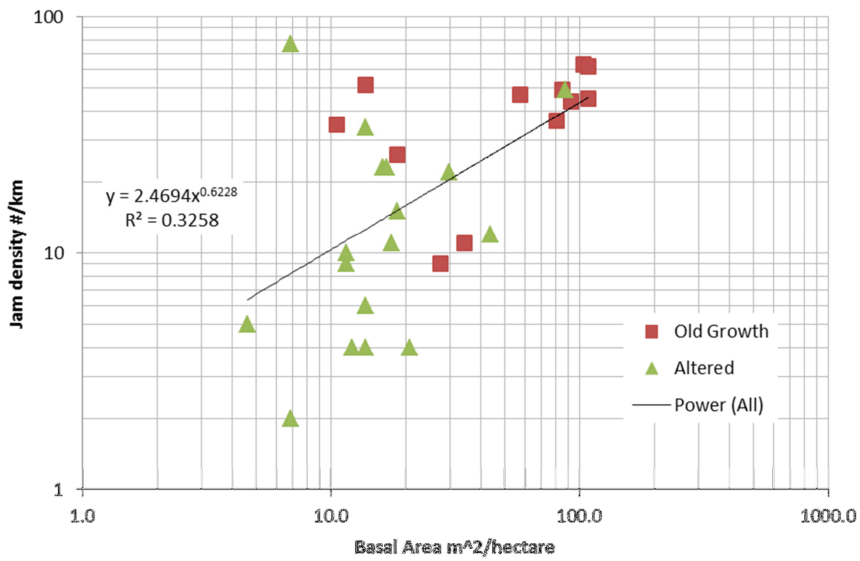


Figure 15: Jam density versus basal area, showing that local basal area is not a good predictor of jam formation

2.3.3.1 CHANGES TO PIECES BECAUSE OF STAND AGE

If potential wood supply alone cannot explain the differences in jam density between old growth and altered reaches, it is possible that the wood from old growth forests has different characteristics than wood supplied by altered reaches. Old growth pieces may have a larger diameter/length, or be more likely to form anchored pieces such as ramps and bridges. Because total wood loads were not measured for every stream, results which compare total (reach) instream wood to instream wood trapped in jams are only comparing the 19 reaches for which total wood loads are available. Figure 16 shows the difference in the diameter distributions for logs in or not in jams on selected reaches.

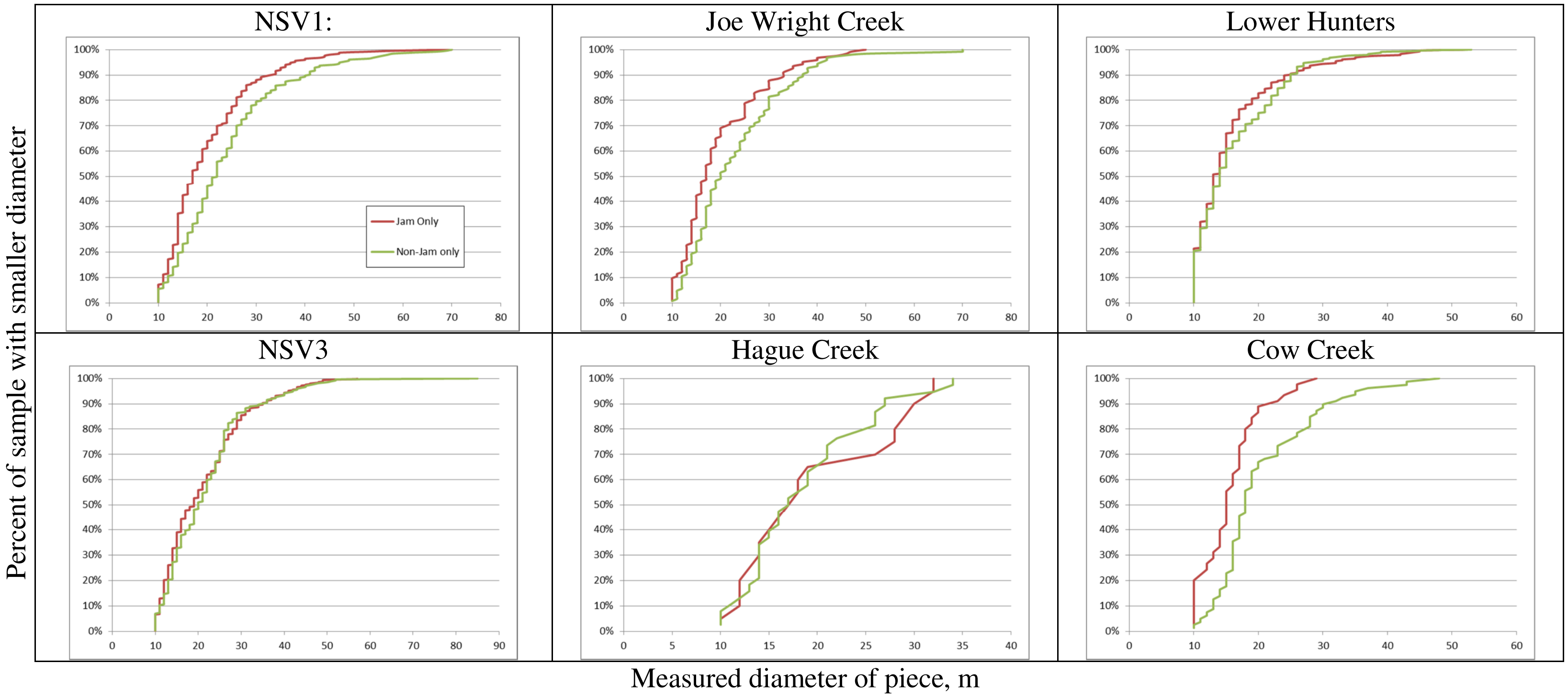


Figure 16: Diameter distribution of logs in jams (red) and not in jams (green) for six of the surveyed reaches. Old growth reaches are shown on the top row and altered reaches on the bottom row.

Logs in jams show overall smaller diameters than the general population of logs in the stream (Figure 16). Overall, the logs in jams have a lower D_{16}, D_{50} and D_{84} than the total population of logs in a stream. This suggests that smaller, more mobile logs are more likely to be trapped in a log jam, and that without log jams or key pieces, those smaller pieces are not stable within a reach. Smaller pieces are more likely to move, and therefore more likely to get trapped by a jam or key piece. On the other hand, because smaller pieces are more likely to move, they are more likely to be removed from a reach if no jams or key pieces are present. Figure 17 and Figure 18 indicate that the effect of stand age on diameter of instream wood can only be seen in the 84th percentile and maximum diameter measurements.

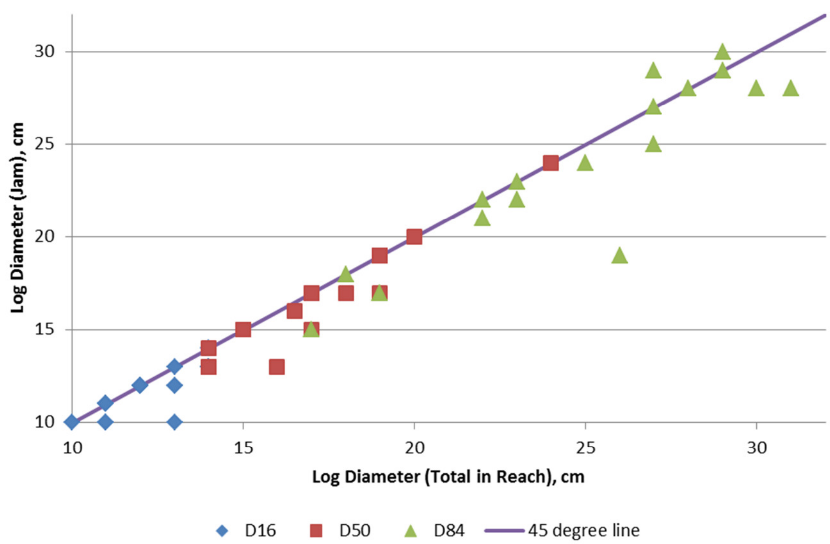


Figure 17: Comparison of log diameters in the total population of instream wood and in jams

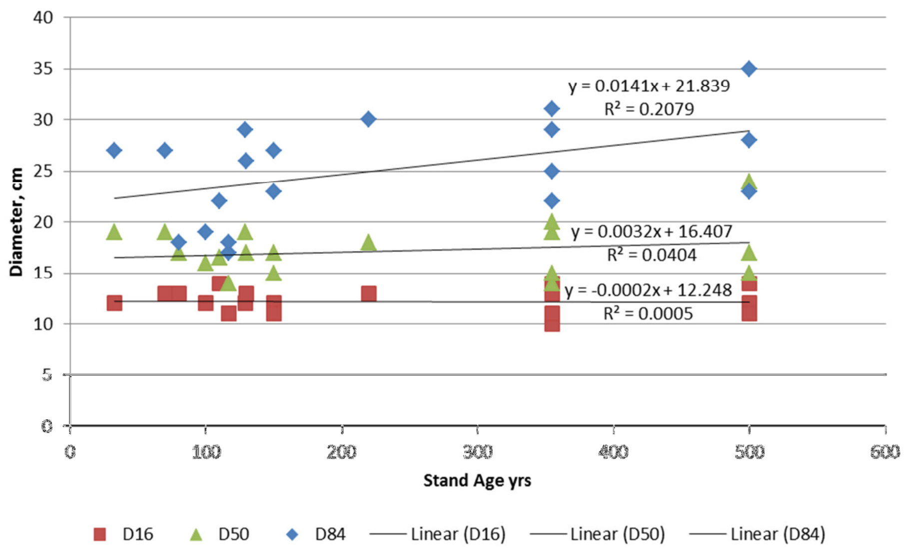


Figure 18: Diameter versus stand age for all logs within the reach, showing that stand age has little to no effect on the diameter distribution for the smaller diameter logs, but does have a small influence on larger log diameters.

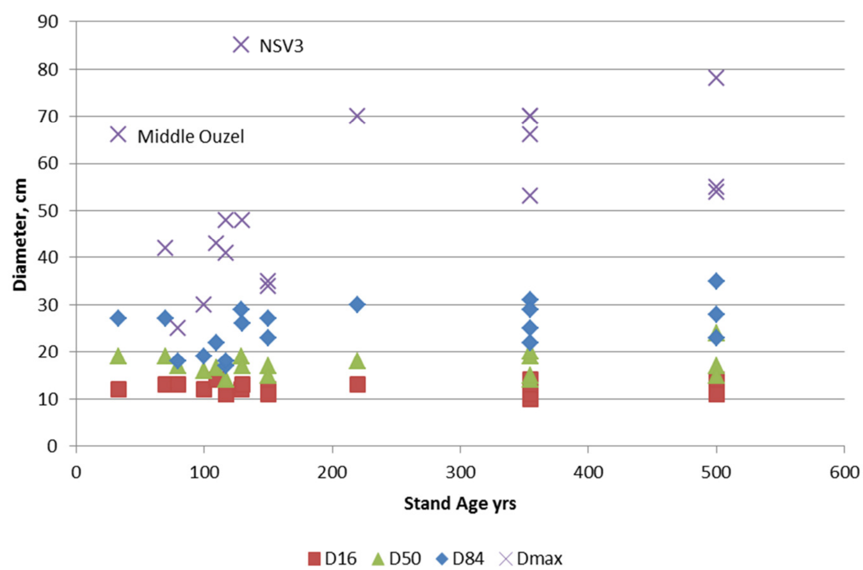


Figure 19: Diameter of logs found within the reach, by stand age, showing that the maximum diameter found within a reach is related more to current or pre-disturbance stand age than are smaller diameters.

The ratio of log length to stream width can be an important factor in jam formation [*Gurnell et al.*, 2002], and it is possible that old growth reaches have a higher ratio of length to width than altered stands. This could occur for many reasons, including the possibility that old growth trees are taller, or less likely to break apart. Figure 20 indicates that this is not the case for the observed reaches in this study. Old growth stands seem to have average or below-average log lengths relative to channel width, while altered reaches show large variability.

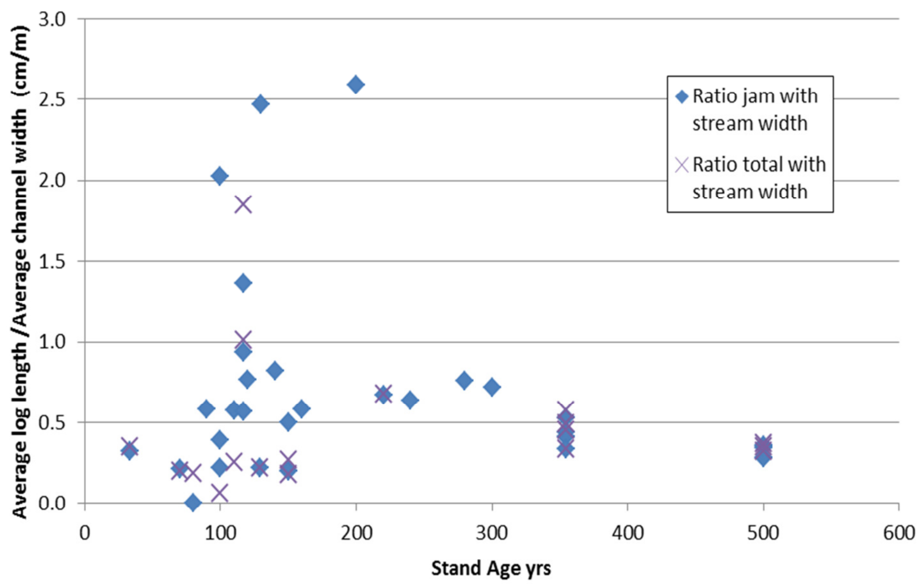


Figure 20: Average log length (cm) divided by average channel width (m) versus stand age for the total population of logs in the stream and only logs found in jams.

One way that stand age may affect instream wood loads is by increasing the number of anchored pieces in the channel. Old growth stands tend to grow closer to channel banks and have higher natural mortality, so there may be a higher incidence of anchored pieces (ramps and bridges) in older stands. Figure 21 indicates that it is possible to have closely spaced ramps and bridges in altered reaches, but that old growth reaches show consistently shorter downstream spacing for these key pieces. Figure 22 shows the strong relationship between key piece spacing and jam density, with an apparent threshold at 20 m between key pieces. All of the old growth reaches have spacing less than 20 m.

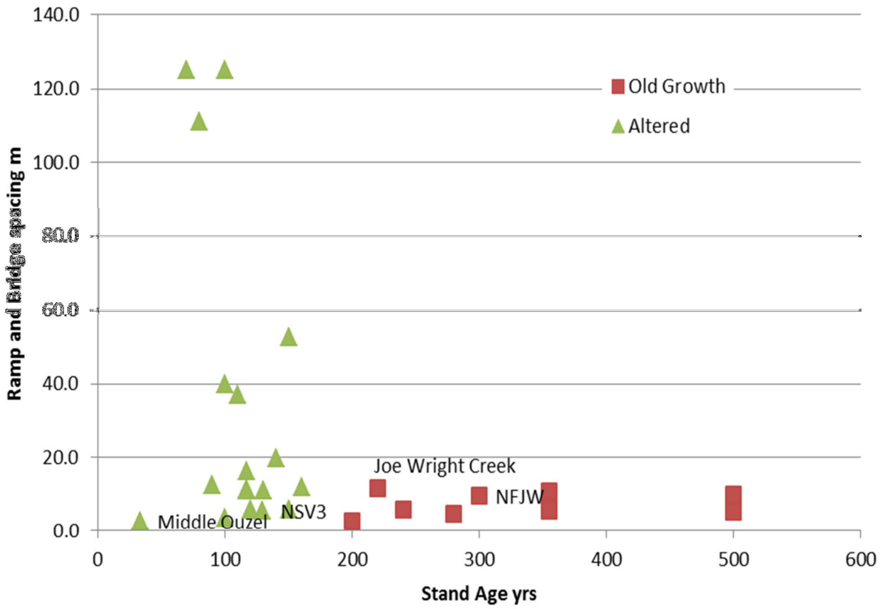
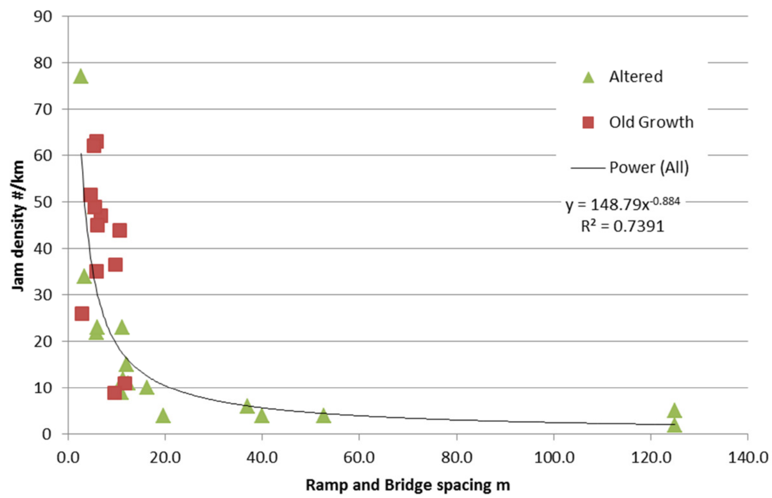


Figure 21: Ramp and bridge spacing versus stand age. A higher value for ramp and bridge spacing corresponds to a larger distance between key pieces. Although altered forests can have closely spaced ramps and bridges, spacing is not as consistent as in old growth forest.



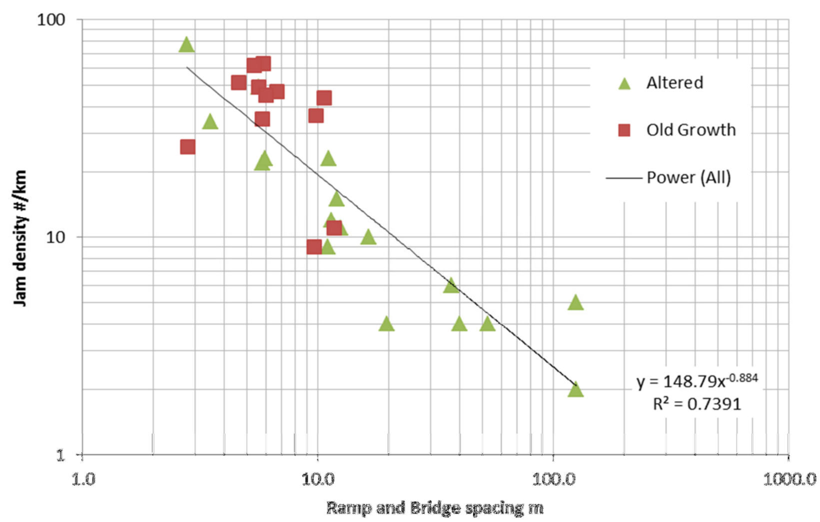


Figure 22: Ramp and bridge spacing versus jam density plotted on normal (top) and log transformed (bottom) axes. The top figure demonstrates the strong threshold at approximately 20m spacing, while the bottom figure shows the strong relationship between spacing of ramps and bridges and the density of log jams within a reach.

In summary, analyses of correlations between forest age and instream wood characteristics indicate that old growth forests have more jams per kilometer of stream, greater basal area, slightly larger logs in the D_{84} and D_{max} categories, and closer downstream spacing between ramp and bridge pieces that can serve as key pieces in log jams. The closer downstream spacing between ramps and bridges appears to be the most significant influence on downstream jam spacing and therefore on differences in total wood load between old growth and altered forest streams.

2.3.4 Model Fitting

2.3.4.1 Cluster Analysis

The surveyed reaches cover a range of slopes, drainage areas and channel widths, but are all located within three basins: the Cache la Poudre River (Poudre), North Saint Vrain Creek (NSV) and the Big Thompson River (BT). Before testing for differences based on local controls, I evaluated whether there is an underlying pattern to the channel characteristics for each basin that might influence the models. For this analysis, I assumed that any effect of instream wood on channel width or slope is negligible compared to basin characteristics. I chose to use a cluster analysis to evaluate whether basins naturally group themselves by basin when compared based on slope, channel width, drainage area and elevation. For this analysis, drainage area and slope were natural log transformed and all variables were scaled as described in section 2.2. Stream order was considered, but was removed from the analysis because it correlated highly with natural log transformed slope.

Figure 24 shows the results of a hierarchical cluster analysis, and shows that although reaches tend to group with other reaches from their basin, there is no definitive basin structure to the clustering. Figure 25 indicates that clustering reflects mostly drainage area. A k-means cluster analysis was also performed on the data with two clusters, which divided the reaches into different clusters than the hierarchical and produced an average silhouette width of 0.24 (an indication of weak or artificial cluster structure). Both of these results suggest that clusters are not strongly self-identifying, and that basin level processes do not have a strong influence on reach characteristics. This justifies a focus on the influence of forest stand age on instream wood.

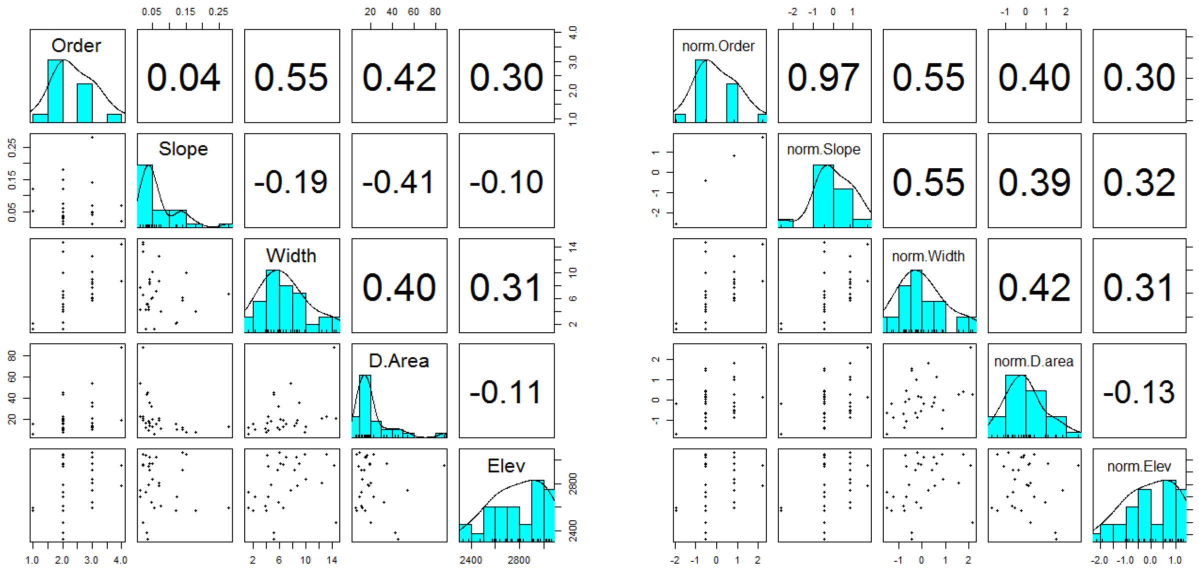


Figure 23: Raw data (left) and transformed data (right) for basin characteristics of 30 reaches showing the two way correlation, histograms and scatter plots of basin characteristics.

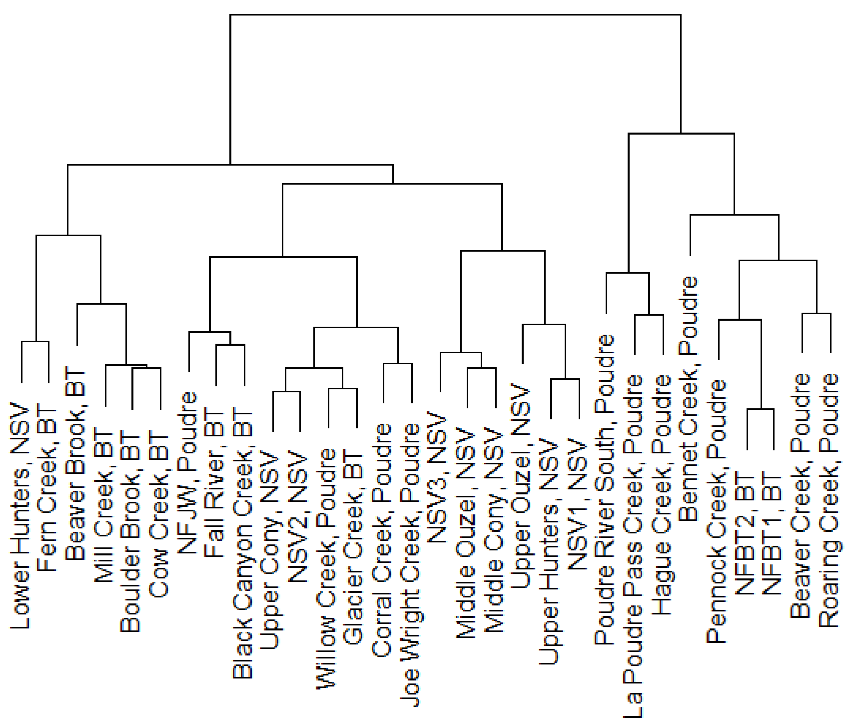


Figure 24: Hierarchical clustering based on basin characteristics using log transformed and normalized data for slope and drainage area, and normalized (but not log transformed) data for channel width and elevation. Labeled with reach names and basins.

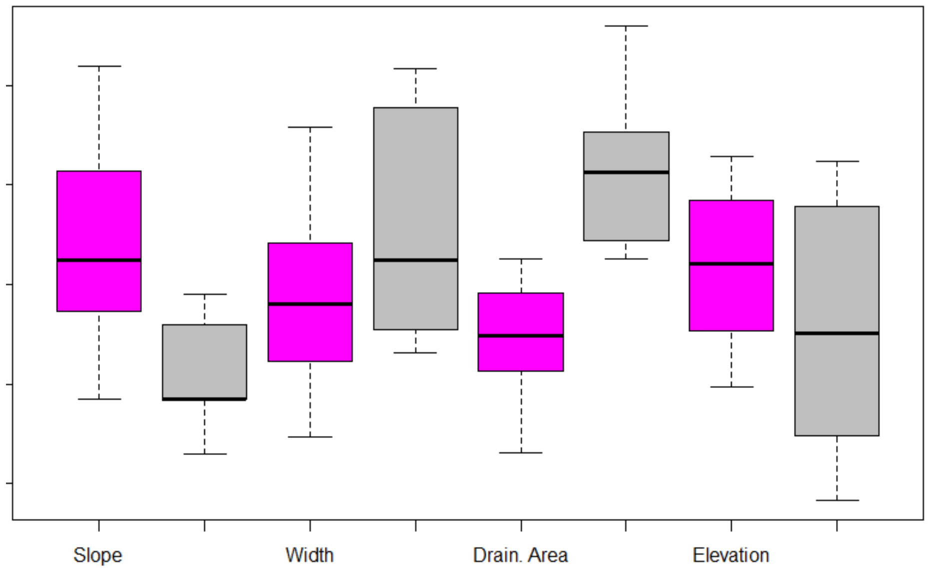


Figure 25: Box plot of normalized variable for cluster 1(pink) and cluster 2 (gray) showing that normalized drainage area and elevation have the least overlap between clusters and so are the most controlling variables for cluster selection

2.3.4.2 GENERALIZED LINEAR MODEL (GLM) FOR JAM DENSITY

Based on simple bivariate regression models, the best predictor of jam density is total wood load (Figure 8). However, total wood load is so well correlated with jam density that wood load tends to dominate any predictive model of jam density. In order to test the relative importance of other factors, a backward step selection for a generalized linear model was performed without including total wood load as an independent variable. Instead, slope, drainage area, channel width, stand age, and ramp/bridge spacing were used to predict jam density. Basal area was highly correlated with forest age (0.85), and so was not included in the model. The distribution of jam density was assumed to be either Poisson with a log transformation or negative binomial, and in both cases the jam density represented the expected number of jams within a 1 km reach, regardless of the actual surveyed channel length.

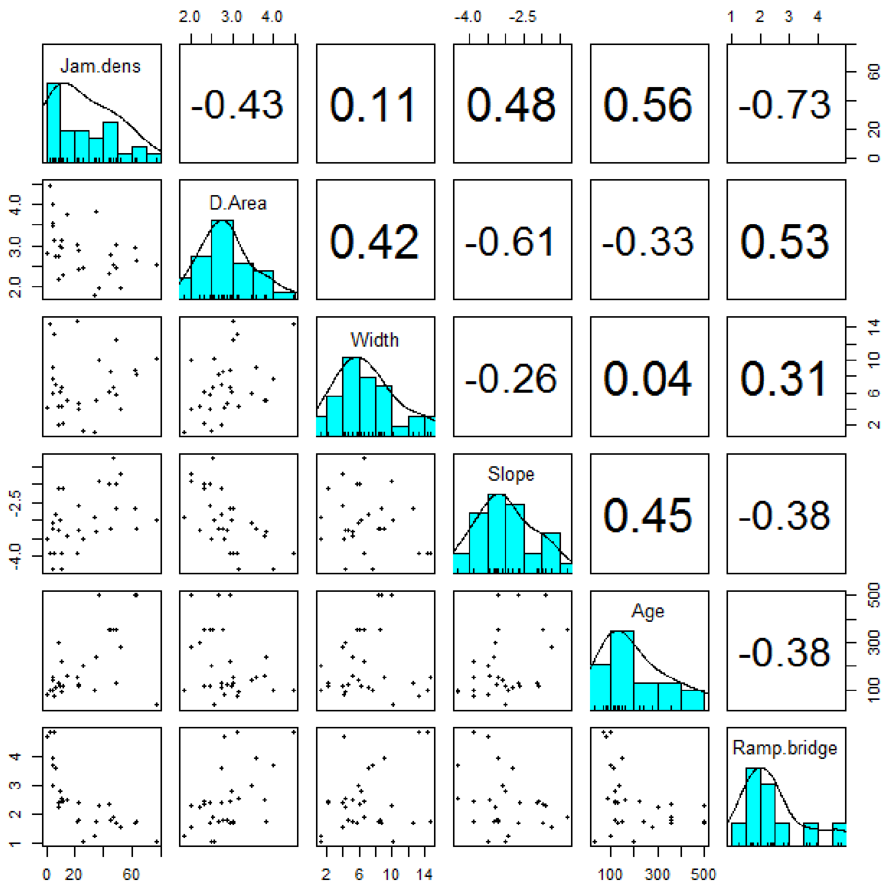


Figure 26: Distribution of transformed variables used in backward selection

The AIC model fit criteria for the Poisson and negative binomial distribution and assumptions for each distribution were not significantly different, so both results have been included here. The best fit model for the generalized linear model with an assumption that jam density followed a Poisson distribution included average slope, forest age, channel width, and ramp/bridge spacing. Of these, the most significant variable was ramp and bridge spacing (Table 4). The two distribution assumptions produced equivalently good models (AIC of 206.07 for Poisson and 207.34 for negative binomial), and included forest age (correlated with basal area), channel width, and ramp/bridge spacing. The Poisson model also identified reach average slope as significant, but in both cases, the most significant variable was ramp and bridge spacing (Table 4).

Table 4: Summary of general linear model results for the 29 reaches with jams, and without piece characteristics as a variable. Bold variables were identified as significant during the backward step selection process. Coefficients, standard errors and p-values have been included for all significant variables.

Response variable	Assumed distribution	AIC for model	Tested Independent variables	Significant independent variables		
				Coefficient	Std. error	p value
Jam Density (#/km)	Poisson with a log transformation	206.07	**Intercept**	5.217	0.210	< 2e-16
			ln(Slope, m/m)	0.270	0.052	2.13E-07
			ln(Drainage area, km^2)			
			Channel width, m	0.065	0.011	5.57E-10
			Stand age, yrs	0.001	0.000	4.11E-07
			ln(Ramp/bridge spacing, m)	-0.931	0.063	< 2e-16
			Drainage area*Slope			
			Drainage area*Channel width			
			Slope*Channel width			
Jam Density (#/km)	Negative Binomial	207.34	**Intercept**	4.379	0.260	< 2e-16
			ln(Slope, m/m)			
			ln(Drainage area, km^2)			
			Channel width, m	0.059	0.020	2.84E-03
			Stand age, yrs	0.002	0.000	1.36E-04
			ln(Ramp/bridge spacing, m)	-0.935	0.092	< 2e-16
			Drainage area*Slope			
			Drainage area*Channel width			
			Slope*Channel width			

A second set of backward step GLMs was run with the same variables, but with the addition of average diameter and average length to the backwards step selection. This model was run using only the 18 reaches for which all pieces in the stream had been surveyed, to avoid biasing the model with only logs in jams. Figure 27 shows the distribution of variables for this analysis. Again, the Poisson and negative binomial distributions produced equally good models, with AICs of 121.24 for the Poisson and 123.15 for the negative binomial. Forest age (correlated with basal area), ramp and bridge spacing and piece length were found to be significant in both models, with ramp and bridge spacing being the most significant (Table 5).

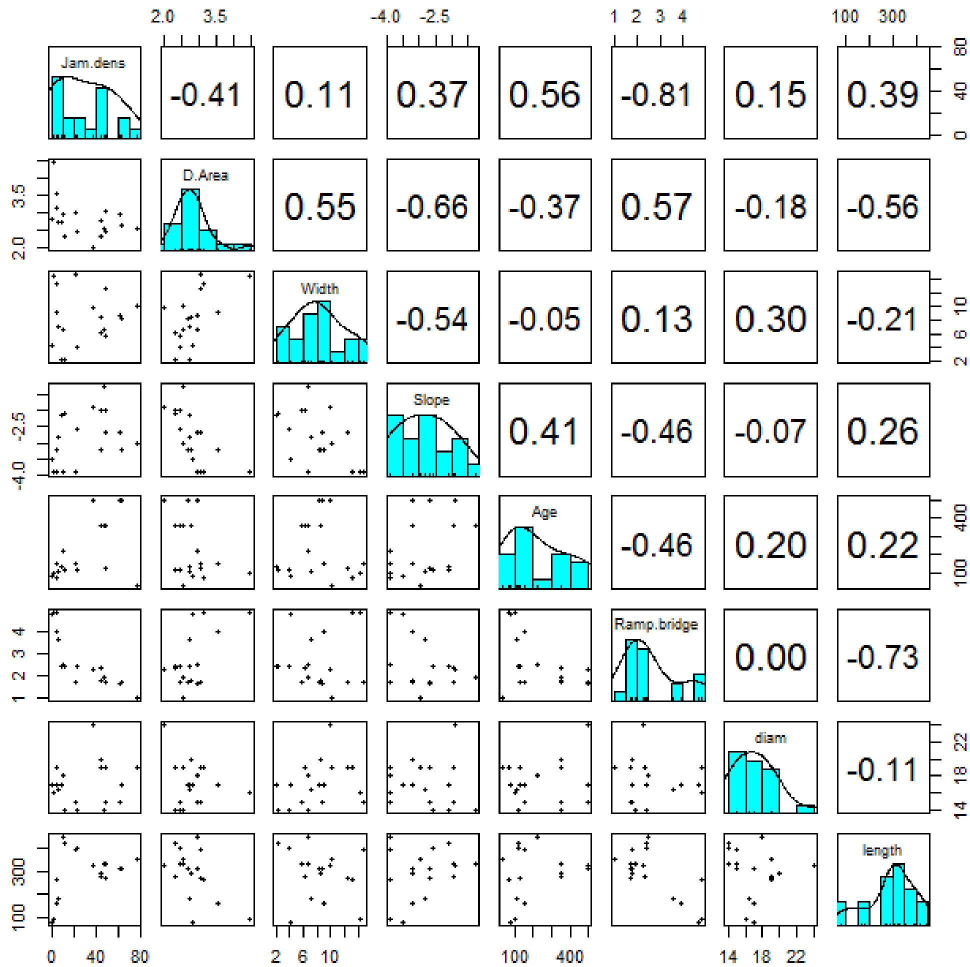


Figure 27: Correlations, histograms and scatter plots for the variables used in the GLM to predict jam density. Only reaches with total wood surveys were included so that average log diameter was known for all logs in the reach.

Table 5: Summary of general linear model results for the 18 reaches with total wood surveys, and including piece characteristics as a variable. Bold variables were identified as significant during the backward step selection process. Coefficients, standard errors and p-values have been included for all significant variables

Response variable	Assumed distribution	AIC for model	Tested Independent variables	Significant independent variables		
				Coefficient	Std. error	p value
Jam Density (#/km)	Poisson with a log transformation	121.24	**Intercept**	6.276	0.400	< 2E-16
			ln(Slope, m/m)			
			ln(Drainage area, km^2)			
			Channel width, m			
			Stand age, yrs	0.001	0.000	9.96E-06
			ln(Ramp/bridge spacing, m)	-1.076	0.080	< 2E-16
			Reach avg diameter, cm			
			Reach avg piece length, cm	-0.003	0.001	3.43E-03
			Drainage area*Slope			
			Drainage area*Channel width			
			Slope*Channel width			
Jam Density (#/km)	Negative Binomial	123.15	**Intercept**	6.241	0.428	< 2E-16
			ln(Slope, m/m)			
			ln(Drainage area, km^2)			
			Channel width, m			
			Stand age, yrs	0.001	0.000	4.30E-05
			ln(Ramp/bridge spacing, m)	-1.074	0.085	< 2E-16
			Reach avg diameter, cm			
			Reach avg piece length, cm	-0.003	0.001	6.62E-03
			Drainage area*Slope			
			Drainage area*Channel width			
			Slope*Channel width			

The results of the generalized linear modeling thus strongly support the results of the analyses summarized in section 3.3. Forest stand age and the downstream spacing of ramps and bridges best predict the downstream spacing of jams, with the latter variable being the single best predictor of jam spacing. The results support the hypothesis that instream wood differs in relation to forest stand age in that streams draining old growth forest have more instream wood than streams draining altered forests. The results also indicate significant differences in the available wood (stand age or basal area), and piece length, but are less conclusive with respect to differences in piece diameter. The more closely spaced ramps and bridges and log jams in old growth reaches strongly support the hypothesis that local forest age is more important to the quantity and characteristics of instream wood than basin characteristics.

2.3.4.3 LINEAR MODEL (LM) FOR AVERAGE VOLUME OF WOOD IN A JAM

In addition to modeling the number of jams along a given reach, it would be useful to be able to identify the variables which influence the size of the jams. Jam size at the reach level is measured as the total volume of wood in jams divided by the number of jams in a reach to give an average volume of wood per jam on a particular reach. Because this is a continuous variable and is not right skewed, it can be modeled using a linear model (LM) instead of a generalized linear model. The independent variables used in the backward step selection included jam density within a reach, drainage area, channel width, slope, stand age, ramp and bridge spacing, the median diameter of logs in jams, and the median length of logs in jams. Of these, drainage area, slope and ramp and bridge spacing were natural log transformed to remove right skewness.

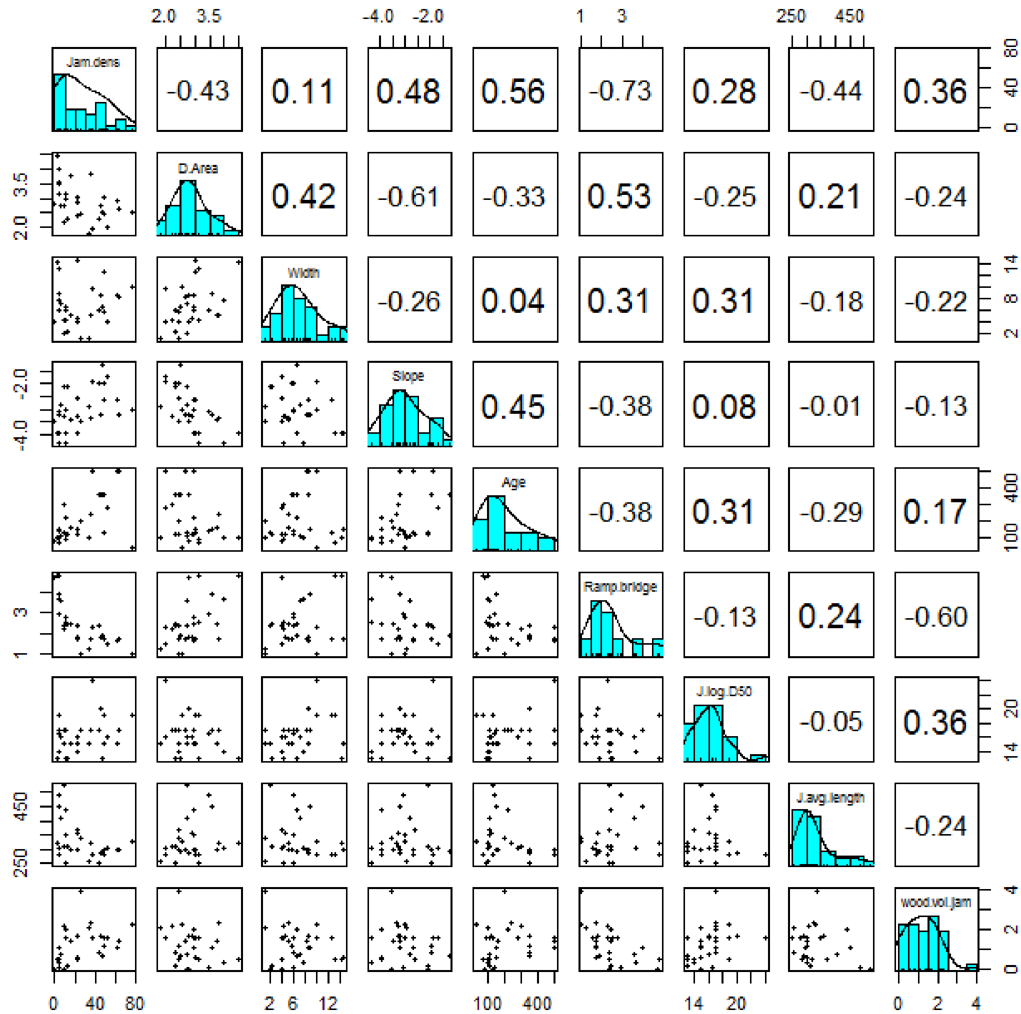


Figure 28: Histograms, correlations and scatter plots for the variables used to predict jam volume. Drainage area, slope, and ramp and bridge spacing have been log transformed to remove skewness.

Table 6: Summary of linear model results for the 29 reaches with jams, and including jam piece characteristics as a variable. Bold variables were identified as significant during the backward step selection process. Coefficients, standard errors and p-values have been included for all significant variables

Response variable	Assumed distribution	R2 for model	Tested Independent variables	Significant independent variables		
				Coefficient	Std. error	p value
Jam Volume, m^3/jam	Gaussian	0.6344	Intercept	-1.111	0.907	2.32E-01
			Jam Density (#/km)			
			ln(Drainage area, km^2)			
			ln(Slope, m/m)	-0.528	0.143	1.19E-03
			Stand age, yrs			
			Channel width, m	-0.073	0.035	4.58E-02
			ln(Ramp/bridge spacing, m)	-0.479	0.124	7.57E-04
			Jam avg diameter, cm	0.150	0.048	4.36E-03
			Jam avg piece length, cm			
			Width*Jam avg piece length			
			Drainage area*Slope			
			Drainage area*Channel width			
			Slope*Channel width			

The backward step selection found that the important factors in jam volume are channel width, log transformed slope, log transformed ramp and bridge spacing, and median diameter of logs in jam. Of these, the most significant is ramp and bridge spacing, which has a negative effect on jam size (Table 6). This result does not directly support my hypothesis (H2) that forest characteristics affect instream wood characteristics, although old growth forests are more likely to have closely spaced key pieces than altered forest, so there is likely to be an indirect effect of forest age.

2.3.4.4 LINEAR MODEL (LM) FOR TOTAL VOLUME OF WOOD IN JAMS IN A REACH

Using the same independent variables as in section 2.3.4.3, a backward step selection was used to identify the variables which are related to the total amount of wood stored in jams. The response variable was natural log transformed to remove right skewness, and three reaches were removed from the dataset due to negative or missing values of transformed total volume of wood in jams within a 1km reach. The resulting significant variables were channel width, log transformed ramp and bridge spacing, and the median diameter of logs in jam (Table 7). The results were similar in magnitude and direction to the factors which influence individual jam size.

Table 7: Summary of linear model results for the 27 reaches with non-zero total jam wood volume, including jam piece characteristics as a variable. Bold variables were identified as significant during the backward step selection process. Coefficients, standard errors and p-values have been included for all variables used in the model.

Response variable	Assumed distribution	R^2 for model	Tested Independent variables	Significant independent variables		
				Coefficient	Std. error	p value
ln(Total volume of wood in jams, m^3/km)	Gaussian	0.8987	**Intercept**	4.945	0.822	3.91E-06
			Jam Density (#/km)			
			ln(Drainage area, km^2)			
			ln(Slope, m/m)			
			Stand age, yrs			
			Channel width, m	-0.139	0.036	7.15E-04
			ln(Ramp/bridge spacing, m)	-1.197	0.123	1.36E-09
			Jam avg diameter, cm	0.152	0.048	4.16E-03
			Jam avg piece length, cm			
			Width*Jam avg piece length			
			Drainage area*Slope			
			Drainage area*Channel width			
			Slope*Channel width			

2.4 DISCUSSION

The effect of old growth stands on instream wood characteristics seems to be an increased amount of wood entering the channel, an increase in the number of large diameter logs entering the channel, and close spacing of key anchoring pieces that can trap other pieces and form jams. Of these effects, generalized linear modeling suggests that the presence of closely spaced key pieces is the most important to overall jam density and average jam size within a reach.

Jam density is not directly related to basal area in all reaches, but a subset of reaches show a strong relationship. Basal area measures only the standing wood volume, not how much of that wood actually enters the channel or the characteristics of that wood. For reaches where there is no strong connection, it is possible that either the wood is not entering the channel or that there is some other control that counteracts the amount of available wood. Examples of possible factors include a lack of key pieces, smaller diameter logs, or insect-damaged, standing dead logs that tend to snap into smaller, more mobile pieces when they fall.

Jam volume for individual jams is related to channel width, slope, ramp and bridge spacing, and median log diameter, while the total volume of jams in a reach is related to channel slope, ramp and bridge spacing and median log diameter. In both cases, the most significant variable is ramp and bridge spacing, which has a negative effect on jam size. The implication is that more closely spaced ramps and bridges lead to smaller jams, presumably because wood is not able to travel far before it is trapped and each jam has a smaller "tributary area" within which to recruit wood than it would if the key pieces were more widely spaced. Tributary area is a structural engineering term which refers to the area of a structure supported by a given element. For example, the tributary area of a column is the area of floor space plus other elements whose weight has to be carried by that column. Here, this term is used to describe the area of stream channel upstream from a key piece to the next upstream jam or key piece. Wood which enters a channel within a piece's tributary area is available to be trapped by that key piece or jam. At a certain density of key pieces, it may not be possible for wood to travel far enough to accumulate into channel spanning jams, which suggests there is an upper threshold to the number of jams along a reach.

Although this result does not directly support the hypothesis that forest characteristics affect instream wood characteristics, forest age can be a control on the recruitment of ramps and bridges. The overall number of key pieces recruited in a reach should reflect individual tree mortality, mass mortality, and bank erosion. The retention of key pieces should reflect piece size (diameter, length), hydraulic forces (which can lift or break pieces), decay, and the amount of wood in transport, which could either break or shield key pieces.

Because this is an observational study, there are many confounding factors. Specifically, the reach data were collected during three different years, but all of the data in the NSV basin (which includes 7 of the 12 old growth reaches) were collected in 2009 before the unusually large snowmelt runoff seasons of 2010 and 2011 (see section 1.4). The sample size and design of this study did not allow me to test for effects based on the year in which a reach was surveyed. Another possible confounding effect occurs because logs are recruited from upstream, and adjacent forest age may not reflect the primary recruitment source for most logs in a reach. There is known old growth forest upstream of Middle Ouzel and NSV3, but in other basins it was not feasible to determine the age of upstream forest stands, so it was not possible to control for upstream old growth. Another reason for the elevated wood loads on Middle Ouzel is that the reach was burned during the Hourglass Fire in 1978. A study done for forests in Wyoming found that peak loads from natural disturbances occur ~30 years after the disturbance [*Bragg*, 2000]. Because Middle Ouzel was burned approximately 30 years ago, the data analyzed here may reflect the effect of this fire on number of jams and instream wood loads.

Stand age has an impact on jam density within a reach, and outliers to this trend suggest that natural stand-replacing disturbances can actually increase the number of jams in a reach, while human disturbances that remove wood from a watershed decrease jam density. Stand age is sometimes used as a proxy for disturbance history, but the type of disturbance and stand age prior to disturbance may be as important as the time since disturbance. Although this study did not have a sufficiently large sample to test this, preliminary indications are that disturbed old growth reacts like old growth in many cases, despite a temporarily lower input of wood to the stream. This may be because of the overall importance of key pieces, which tend to increase after a natural disturbance such as fire, insect outbreak or blow down. Although there are general trends, local conditions may decide which of the identified variables has the greatest effect on a particular reach.

2.5 CONCLUSIONS

The results support the hypothesis that local forest age is more important to the quantity and characteristics of instream wood than basin characteristics (H2). This study found both higher wood loads (as measured by jam density) and changes to piece characteristics in old growth reaches. The differences appear to be driven by both increased wood supply (as measured by basal area) and the increased number of key pieces for jam formation.

Instream wood in old growth stands tends to have larger maximum diameters, although this does not appear to directly increase the total number of jams within a reach. Instream wood in jams tends to have a slightly smaller diameter distribution than wood not trapped in jams, which indicates that jams trap pieces that would otherwise wash through the reach. Factors such as slope, stand age, channel width, and the spacing of key pieces may create favorable conditions for jams.

Total wood load is the main variable correlated with jam density, and there is likely a positive feedback mechanism through which streams with increased wood loads tend to form more jams and jams tend to trap more wood within a reach. In other words, both increased wood load and increased jam frequency create debris roughness that enhances wood retention.

Jam size is negatively correlated with channel width, slope, ramp and bridge spacing, and positively correlated with median log diameter. Closely spaced ramps and bridges have a smaller "tributary area" that provides mobile pieces relative to more widely spaced key pieces.

Several aspects of the results summarized in this chapter have implications for managing instream wood loads and the associated sediment storage and ecosystem productivity. Downstream spacing of jams shows little correlation with basin size, but does correlate with reach-scale characteristics including stand age, spacing of ramps and bridges and to a lesser extent average channel gradient. This suggests that management of instream wood can be focused most effectively at the reach scale. Given the usual desire to increase instream wood loads in order to enhance fish habitat, management can emphasize either preserving old growth stands along lower gradient stream reaches, or mimicking the effects of old growth by enhancing debris roughness through manipulating the spacing of ramps and bridges. Among the more important findings of the analyses summarized here are that average downstream spacing between jams declines as wood load increases, which suggests that the most effective way to create and retain jams is to ensure abundant sources of wood recruitment, with a particular emphasis on larger pieces that are less mobile because they have at least one anchor point outside the active channel.

CARBON STORAGE

3.0 INTRODUCTION TO CARBON STORAGE IN STREAMS

3.0.1 How carbon moves through rivers

Freshwater systems are a major component of the global carbon cycle because they offer a connection between terrestrial systems, oceans, the atmosphere and the lithosphere (Figure 1) [*Battin et al.*, 2009; *Aufdenkampe et al.*, 2011]. Only a small part of the carbon entering a stream network is delivered to the oceans. The rest is stored within the river and floodplain, or outgassed to the atmosphere [*Aufdenkampe et al.*, 2011]. Carbon (in the form of organic matter) can enter a stream as fossil carbon from sedimentary bedrock, as terrestrial biomass including litter (leaves, wood) and sediment, dissolved in groundwater, or through primary production within a stream [*Tank et al.*, 2010]. Once it has entered a stream, organic carbon (also known as organic matter, or OM) is classified by size. Dissolved organic carbon (DOC) is generally smaller than 0.45 µm, fine particulate organic matter (FPOM) is between 0.45 µm and 1 mm, and coarse particulate organic matter (CPOM) is larger than 1 mm [*Tank et al.*, 2010]. FPOM and CPOM are sometimes referred to jointly as simply POM.

Carbon within the channel can either be stored or transported out of the reach. Most carbon processing takes place on material stored within the stream channel, and can include removal of DOM from the water column, and storage of FPOM and CPOM in low velocity areas [*Tank et al.*, 2010]. The degree to which carbon is stored or processed by streams varies with physical complexity and hydrograph characteristics, although most of the work investigating this processing has been done on small streams draining deciduous forests on the east coast of the United States [*Hall et al.*, 2002; *Fahey et al.*, 2005; *Meyer et al.*, 2007]. What is becoming clear is that headwater streams store a greater proportion of OM and have a greater ability to process CPOM than higher order streams [*Bilby and Likens*, 1980].

Headwaters are increasingly seen as biogeochemical hotspots - areas where the physical conditions allow for enhanced biological processing of nutrients through longer residence time and more contact with biologically active surfaces [*Peterson et al.*, 2001; *Hall et al.*, 2002; *McClain et al.*, 2003; *Battin et al.*, 2008, 2009; *Mulholland*, 2012]. Hotspots may be collectively more important in carbon processing than reach averages, and may also be more affected by the hydrologic changes expected with climate change [*Battin et al.*, 2009]. Carbon processing can take place anywhere that microorganisms come into contact with carbon, but surface storage and flow through hyporheic zones generally provide the longest time and largest area interface for nutrients and biofilm [*Hall et al.*, 2002]. Overall, a better understanding is needed of the current distribution of hot spots and the expected responses to climate change [*Aufdenkampe et al.*, 2011].

3.0.2 How wood can affect riverine carbon dynamics

Instream wood can alter a stream to create more geophysical hotspots [*Battin et al.*, 2008], but may also act as a carbon storage mechanism or food source [*Eggert and Wallace*, 2007; *Tank et al.*, 2010]. Individual pieces of instream wood can create depositional areas for organic matter [*Maser and Sedell*, 1994; *Featherston et al.*, 1995], or may create low velocity areas that increase channel heterogeneity [*Tank et al.*, 2010].

Small wood, such as twigs and branches, provides an alternative food source to leaves, and large wood can act as a food source as it decomposes or breaks down through physical processes. Leaves break down faster, but wood can be a long term substrate for biofilms and can support microbial biomass, algal biomass, exoenzyme activity and invertebrate density at higher levels than leaves [*Eggert and Wallace*, 2007]. Both the quantity and quality of a food subsidy are important for the ecosystem, so even though wood may not be the most easily utilized food source within a stream, the greater quantity of wood in streams draining old growth could be important to overall food web structure [*Marcarelli et al.*, 2011].

3.0.3 Differential effect of jams

Channel spanning jams, which cross the entire channel width and affect the water surface across the entire channel, can have an even more important effect on carbon than individual pieces of instream wood. Log jams trap bed load within a reach, providing a possible abiotic substrate for nutrient trapping and uptake

[*Assani and Petit*, 1995; *Warren et al.*, 2007]. Channel spanning jams can also form residual pools of water which are important areas of nutrient processing during low-flow periods [*Hall et al.*, 2002]. Previous studies have found that jams with a greater volume of wood have a larger upstream pool and larger surface area (but not necessarily volume) of stored sediment [*Bilby and Ward*, 1989]. The amount of sediment and POM behind jams decreases as streams get larger, but this trend is not as pronounced in old growth reaches with more instream wood and channel spanning jams [*Bilby and Ward*, 1991]. In the U.S. Pacific Northwest, instream wood and jams promote live salmonid biomass and retain salmon carcasses which are important to the biochemistry of the river and surrounding forest [*Fausch and Northcote*, 1992; *Hyatt and Naiman*, 2001].

Loss of jams on lower order streams can affect the entire river system because higher order streams have lesser ability to process CPOM [*Bilby and Likens*, 1980; *Cordova et al.*, 2008]. Within smaller reaches, jams are able to have a large effect on instream hydraulics, creating large low velocity areas which trap CPOM and reduce the distance it is able to travel downstream [*Cordova et al.*, 2008]. Jams also increase connectivity with the bioactive hyporheic zone by increasing hydraulic head and promoting flux into the stream bed upstream of the jam, which returns downstream of the jam [*Fanelli and Lautz*, 2008]. During floods, jams on small channels can raise local upstream water levels and cause increased flow over the floodplain, leading to "hot moments" where the biogeochemical activity is briefly increased [*McClain et al.*, 2003].

Forest age has been shown to impact above ground biomass and carbon storage in terrestrial systems. Old growth forest stores more carbon than younger forest (~610 vs ~270 Mg of C per hectare for Douglas fir and hemlock forests of the Western Cascades) [*Harmon et al.*, 1990]. Among even-aged sub-alpine stands of lodgepole pine in Colorado, carbon stored as biomass has been shown to increase from 61 Mg/ha in 40 year old stands to 90 Mg/ha in 245 year old stands [*Ryan and Waring*, 1992]. Stand age is not the only factor, since carbon can be stored both as living and dead biomass. Dead biomass is often referred to as coarse woody debris (CWD), and the amount of CWD in a forest has been shown to change depending on the disturbance type. *Tinker and Knight* [2000] found that clearcuts resulted in a net loss of carbon stored as CWD, while fires resulted in a net gain. In lodgepole pines forests in Wyoming, they found a starting value of 123-180 Mg/ha of CWD. Clearcut reduced the amount of CWD by 80 Mg/ha, while fire caused a 95 Mg/ha gain in total CWD. These changes can be long lasting, especially in the cold, high altitude environments of Colorado, where decay and growth rates are low. A recent study using radio-carbon dating found that the turnover in subalpine regions was on the order of centuries, with some present day CWD having died in the 1400s [*Kueppers et al.*, 2004]. In Colorado, roughly 30% of terrestrial carbon in forests is stored as soil organic matter, 33% as detrital biomass (including CWD) and 36% as living biomass [*Arthur and Fahey*, 1992], so dead biomass is roughly 60% of the stored terrestrial carbon. Although there are an increasing number of studies which quantify the effect of forest type on the amount and form of carbon in the terrestrial environment, there are no studies which explicitly link carbon storage and forest type within streams. Older forests have been shown to correlate with increased instream wood and jam formation [*Richmond and Fausch*, 1995; *Warren et al.*, 2007], which provides indirect evidence for an effect of forest type on in-stream carbon storage. Table 8 summarizes the published estimates for carbon storage in the Rocky Mountains at the landscape scale.

Table 8: Published estimates of carbon stored as dead biomass within terrestrial forest ecosystems. Although slightly different methodologies were used for each study, they provide a range of published values for forested mountain ecosystems. Low, mid and high refers to the ranges given in the papers. If only one value was given, it is considered a "mid" estimate.

	Estimate of Stored Carbon, Mg/hectare		
	low	mid	high
Arthur and Fahey (1990)		70	
Ryan and Waring (1992)	61	78	98
Tinker and Knight (2000)	123		180
Binkley et al (2003)		126.5	
Kueppers et al (2004)	4.7		54
Houghton (2005)		70	
Battaglia et al (2010)	27		54

Most of the work done so far on the interactions of instream wood, biota and carbon comes from small streams in the eastern United States. A majority of studies have come out of the Hubbard Brook Experimental Forest in New Hampshire and the Coweeta Hydrologic Laboratory in North Carolina [*Hall et al.*, 2002; *Meyer et al.*, 2007; *Warren et al.*, 2007]. Both systems are dominated by seasonal inputs from deciduous trees, so leaf litter is commonly treated as the major source of carbon to the stream. Some work has also been done in the Pacific Northwest, relating the contributions of fish to the biogeochemistry of riparian areas [*Fausch and Northcote*, 1992; *Hyatt and Naiman*, 2001]. No studies have addressed carbon loads on slightly larger streams in the conifer-dominated Rocky Mountains, or attempted to relate the physical characteristics of jams to the amount of carbon stored by the jam.

3.1 OBJECTIVES AND HYPOTHESES FOR CARBON STORAGE

In this chapter, I quantify the proportion of organic matter in the sediment stored by log jams and compare it to the proportion of OM found in other areas of fine sediment storage within the channel (e.g., behind boulders, at channel bends). I also quantify the volume of sediment found behind jams and attempt to relate this volume to forest age and jam characteristics (height of jam, volume of wood in jam). I make a first-order approximation of the amount of carbon stored as wood in jams and compare this to the amount of carbon stored as fine sediment in jams in old growth reaches (stand age >200 years), disturbed reaches (stand age is less than 200 years due to natural events and no logging occurred), and altered reaches (stand age is <200 years and logging occurred). Finally, I make a first-order approximation of the total carbon stored by jams within streams draining old growth, altered and disturbed forests in the Front Range.

In addressing these objectives, I will also test two of the hypotheses I laid out in Section 1.3: my first hypothesis that log jams have different effects on the channel than other features that result in fine sediment storage. Specifically, log jams more effectively promote the retention and deposition of organic matter within the stream than do other sources of boundary roughness such as large clasts. I will also test my third hypothesis that jams have higher overall volume of wood and higher relative organic sediment content in streams draining old growth forests. Combining the results of these analyses, I can better evaluate the assumption that headwater streams in the Colorado Front Range draining altered forests are currently "dam-impoverished" ecosystems with greatly reduced organic matter storage capacity relative to unaltered streams.

3.2 METHODS

Statistical analyses used in this chapter include Analysis of Variance (ANOVA) and backward step selection of variables through linear modeling. ANOVA assumes that the input variables are normally or near-normally distributed, which was tested using a Shapiro-Wilk test for normality [*Royston*, 1995]. In order to meet this assumption, right skewed variables were transformed using the natural log function . Natural log transformations were used with the percent OM, and total carbon in jams. Equality of variance for ANOVA was tested using a Bartlett test.

For the LM backward step selections, right skewed variables were transformed using the natural log function. A natural log transform was applied to the percent OM in a sample, stored sediment volume, wood volume and number of pieces in a jam. Percent organic matter, volume of stored sediment, sediment surface area, total volume of OM, volume of wood and total carbon (wood and sediment) were used as response variables. The models were evaluated based on their ability to explain the variation (R^2) in the response variable.

3.3 RESULTS

3.3.1 Describing the dataset

Two datasets were used for this analysis. The first, here called the "all sample" dataset, consists of individual sediment samples taken either behind jams or as non-jam comparisons (NJCs). Each sediment sample taken is treated as an independent observation of the proportion of OM in sediment (see Appendix C for full dataset). Figure 29 shows untransformed OM proportion in samples from the all-sample dataset.

A second dataset of jam characteristics groups samples by individual jams, because only one measurement of variables such as basal area, sediment volume, and water surface elevation drop were available for each jam surveyed. The OM samples taken from the sediment wedge behind a particular jam were averaged to provide a single estimate of the OM content for the jam. If comparison samples were taken upstream or downstream of the jam, they were included as a separate variable for that particular jam. Table 9 shows a summary of the variables for the jam characteristics dataset, and the complete dataset is available in Appendix B. Percent OM was natural log transformed in both datasets before analysis to reduce right skew.

Percent OM was calculated for both the total sample (including > 2 mm particles) and the fine sediment alone (< 2 mm). Many samples contained pine cones and small pieces of wood which were larger than 2mm and increased the total percentage of OM when included. However, some samples also contained pebbles, small gravel, or other inorganic elements which make the percent of OM in the total sample lower than the percent OM in only the fine sediment. Both percentages have been included below, but the total sample OM was used in the figures and calculations of this chapter unless otherwise noted.

Table 9: Summary of jam characteristic data. Blue shaded rows indicate old growth reaches (stand age >200 years). Gray shaded rows indicate disturbed reaches, where the stand age is less than 200 years due to natural events and no logging occurred, and orange shading indicates altered reaches where stand age is <200 years and logging occurred.

Jam n/ame	Reach n/ame	Stand Age Method	Forest Category	Basal Area	Sediment Surface Area	Sediment Volume	OM (LOI) w/o >2mm	OM (LOI) including >2mm	Mass carbon in sediment (bulk density of 1330 kg/m3)	Wood volume in jam	Mass OM in wood (@450 kg/m3)	Total Carbon	Proportion carbon as wood	NJC OM D/S (LOI) w/o >2mm	NJC OM D/S (LOI) including >2mm	NJC OM U/S (LOI) w/o >2mm	NJC OM U/S (LOI) including >2mm	Valley bottom width	Total WSEL drop through jam (low flow)	Water surface slope	Number of pieces in jam
				m^2/ha	m^2	m^3	%	%	kg	m3	kg	kg	kg/kg	%	%	%	%	m	m	m/m	
Bennet 1	Bennet Creek	cored	A	29.8	22.34	8.29	8.16	9.51	524.37	0.67	151.45	675.83	0.22	n/a	n/a	n/a	n/a	un	0.5	0.03	7
Boulder 1	Boulder Brook	Sibold	A	32.1	n/a	3.64	1.96	2.77	67.12	0.35	78.55	145.67	0.54	0.56	0.32	0.87	0.27	semi	0.8	0.12	6
Boulder 2	Boulder Brook	Sibold	A	34.4	2.35	0.80	0.51	0.49	2.60	0.19	42.18	44.79	0.94	0.67	0.41	0.56	0.32	semi	0.8	0.11	7
Cow Creek 1	Cow Creek	cored	A	13.8	5.50	1.92	0.94	0.95	12.11	0.80	180.71	192.82	0.94	n/a	n/a	1.36	1.19	semi	0.7	0.07	6
Cow Creek 2	Cow Creek	cored	A	20.7	7.72	3.01	1.58	1.38	27.63	0.46	104.04	131.68	0.79	0.72	0.61	1.94	1.63	semi	1.3	0.09	7
Cow Creek 3	n/a	cored	A	20.7	8.10	2.67	n/a	n/a	n/a	1.98	444.80	n/a	n/a	n/a	n/a	n/a	n/a	un	0.4	0.01	8
Hauge Creek 1	Hauge Creek	cored	A	32.1	3.21	1.91	1.74	1.62	20.62	0.44	99.40	120.03	0.83	n/a	n/a	2.31	2.31	semi	0.5	0.07	5
Hauge Creek 2	Hauge Creek	cored	A	32.1	0.84	1.56	1.53	1.43	14.87	1.07	240.28	255.15	0.94	1.69	1.67	n/a	n/a	semi	0.2	0.07	9
Mill 1	Mill Creek	Sibold	A	18.4	4.15	2.61	1.12	1.10	19.07	2.19	493.79	512.86	0.96	0.95	0.58	1.71	1.70	un	0.9	0.05	7
Mill 2	Mill Creek	Sibold	A	25.3	3.23	1.25	1.14	1.09	9.06	1.67	375.26	384.33	0.98	1.11	1.08	n/a	n/a	un	1.2	0.13	14
Coney 3	n/a	Sibold	D	39.0	4.81	1.57	4.66	3.36	34.99	2.88	648.73	683.72	0.95	n/a	n/a	2.60	4.28	confined	0.9	0.14	20
NSV 3	NSV3	Sibold	D	45.9	n/a	2.31	2.04	3.21	49.39	4.81	1081.55	1130.94	0.96	n/a	n/a	n/a	n/a	semi	1.5	0.06	29
NSV 4	NSV3	Sibold	D	20.7	3.36	0.91	3.07	4.24	25.78	2.80	629.10	654.88	0.96	n/a	n/a	n/a	n/a	confined	1.1	0.08	24
Ouzel 3	Middle Ouzel	Sibold	D	2.3	21.61	5.73	3.74	1.80	68.55	8.2	1835.78	1904.33	0.96	n/a	n/a	4.37	2.92	un	0.9	0.06	63
Ouzel 4	n/a	Sibold	D	13.8	3.49	0.77	12.81	12.69	64.98	6.8	1533.72	1598.70	0.96	n/a	n/a	4.88	4.17	un	1.3	0.09	40
Black Canyon 1	Black Canyon	cored	O	18.4	5.89	1.91	1.16	1.12	14.26	1.4	318.70	332.95	0.96	2.79	2.73	0.73	0.73	semi	0.3	0.03	5
Black Canyon 2	Black Canyon	cored	O	16.1	6.43	3.57	8.61	18.63	442.61	0.9	207.78	650.39	0.32	n/a	n/a	1.05	1.05	semi	0.5	0.05	4
Coney 1	Middle Cony	Sibold	O	39.0	24.13	10.21	13.18	15.57	1057.60	4.58	1031.62	2089.22	0.49	1.72	1.47	5.06	11.14	confined	0.9	0.03	58
Coney 2	Middle Cony	Sibold	O	41.3	13.69	6.20	7.92	9.50	391.55	2.04	460.03	851.57	0.54	1.31	2.31	2.46	1.85	confined	1.0	0.10	41
Hunter 1	Upper Hunters	Sibold	O	48.2	45.92	11.30	2.90	4.95	371.84	2.91	654.06	1025.89	0.64	0.63	0.60	0.58	0.49	semi	1.0	0.05	13
Hunter 2	Upper Hunters	Sibold	O	71.2	6.32	1.79	5.46	11.14	132.30	2.32	522.85	655.15	0.80	4.25	7.79	0.78	0.56	semi	0.9	0.05	13
NFBT 1	NFBT1	cored	O	18.4	8.93	3.10	2.50	3.32	68.42	3.07	689.85	758.27	0.91	0.76	0.91	11.16	16.04	confined	1.3	0.04	16
NFBT 2	NFBT1	cored	O	2.3	21.87	8.75	6.08	3.02	175.72	3.60	809.97	985.69	0.82	0.92	0.79	1.62	3.23	confined	1.2	0.04	21
NFBT 3	NFBT1	cored	O	11.5	20.16	4.95	3.11	5.04	166.05	3.75	844.62	1010.67	0.84	1.86	1.68	1.03	0.96	semi	0.8	0.02	30
NSV 1	n/a	Sibold	O	39.0	26.85	10.84	21.35	24.51	1767.21	9.68	2178.00	3945.21	0.55	1.28	1.22	1.34	2.62	seme	0.7	0.04	59
NSV 2	n/a	Sibold	O	23.0	3.89	0.92	3.16	5.47	33.52	0.96	215.57	249.09	0.87	n/a	n/a	n/a	n/a	semi	0.2	0.04	5
Ouzel 1	n/a	Sibold	O	27.5	7.03	2.07	20.98	21.58	297.10	5.8	1303.37	1600.47	0.81	n/a	n/a	7.43	3.80	confined	0.3	0.03	52
Ouzel 2	n/a	Sibold	O	23.0	3.92	0.79	19.99	17.25	90.64	4.9	1098.12	1188.76	0.92	n/a	n/a	4.32	4.90	semi	0.6	0.05	46
JW 1	Joe Wright	cored	O	32.1	15.00	4.22	3.49	2.74	76.80	1.97	443.04	519.84	0.85	2.06	0.42	10.14	0.68	semi	1.0	0.03	17
NFJW 1	NFJW	cored	O	36.7	16.96	9.31	5.81	6.59	407.99	1.77	397.98	805.97	0.49	7.13	6.67	6.54	5.67	semi	1.1	0.05	15

Because the dataset contains multiple jams per reach, and multiple reaches per basin, and data were collected over two years, a series of mixed effects models were created to treat individual jams, reaches, year of collection and drainage basin as random effects, with forest age and sample position (within the sediment wedge, or in a non-jam area of fine sediment) as independent variables and log transformed OM content as the response variable. Of these, only basin appeared to add significant variation. The samples are located in only three basins, so the effect of including basin as a random variable was borderline significant. Instead, basin has been added to models to test its significance as a fixed categorical variable.

A forest category was assigned to each individual jam based on both the forest age and the disturbance history of the reach. Jams with a known natural disturbance (e.g., fire in previously old growth forest) were marked as disturbed old growth. Jams with a human caused disturbance (e.g., logging) were marked as altered.

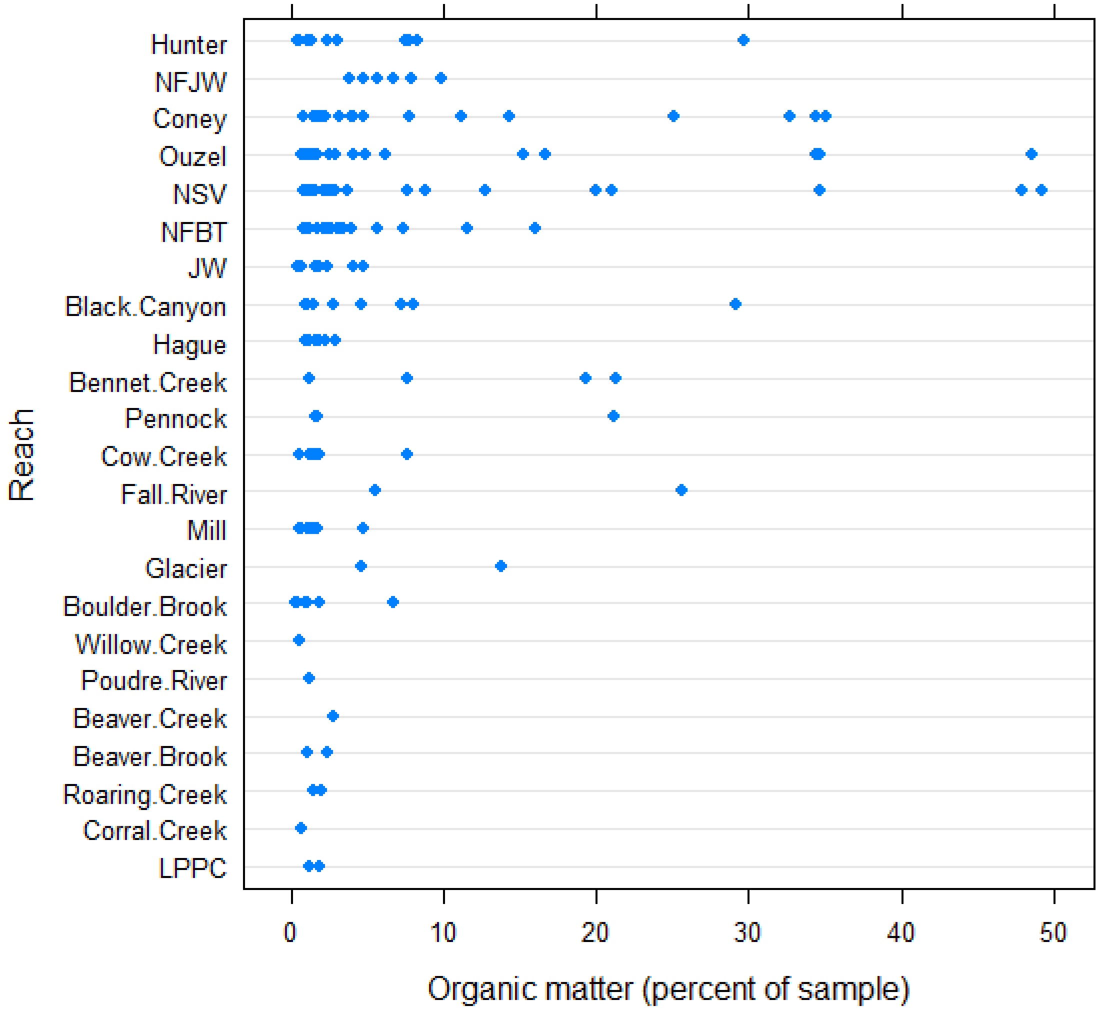
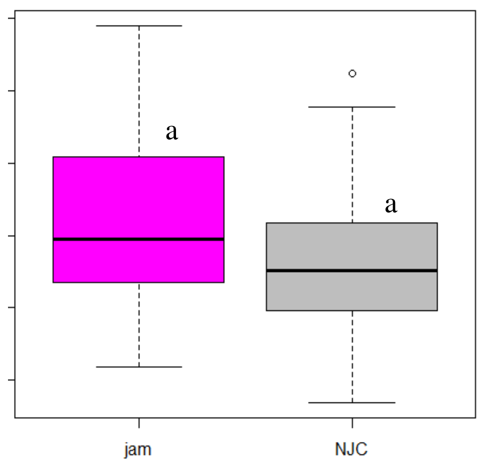


Figure 29: Raw data of organic content displayed by reach for the 23 reaches sampled. The limit of detection is 1%. Each reach had a non-jam sample, and if jams were present a jam sample was taken as well. Reaches with multiple jams had more intense sampling. The order of the reaches is by forest age, with oldest reaches at the top. Black Canyon is the last old growth reach.

3.3.2 Percent organic matter

The proportion of organic matter stored within sediment was measured through the loss on ignition (LOI) procedure described in section 1.5.4. Samples were taken from within the sediment stored by a jam (jam or sed), as well as from other areas of the channel in which fine sediment had been deposited, such as behind large clasts or at channel bends (non-jam comparison, or NJC). Samples were also taken upstream (us) and downstream (ds) of jams to evaluate whether there was a longitudinal trend in OM percentage.

ANOVA analysis on all of the jam (jam, sed) and non-jam (NJC, us and ds) sediment samples found no significant difference in OM fraction, indicating that jam sediments do not have a significantly higher fraction of organic matter than other areas of fine sediment storage within the channel. When samples were compared based on their longitudinal position, a significant difference was found between non-jam sediment sampled downstream of a jam and jam sediment, but there was no significant difference between upstream samples and either downstream or jam samples (Figure 30).



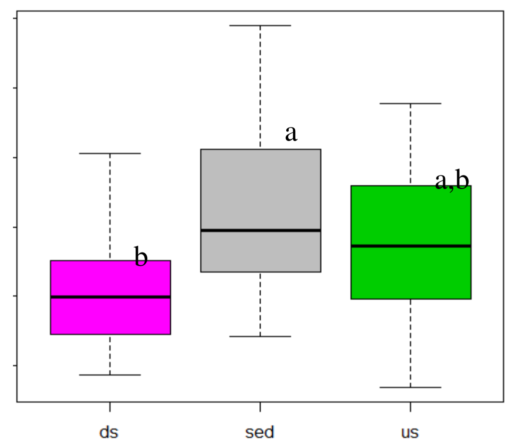


Figure 30: ANOVA tests comparing the amount of sediment in all jam and non-jam samples (left) as well as the downstream, stored sediment and upstream samples taken at all jams (right). There is no significant difference between the jam and non-jam samples for all basins. There is a significant difference between non-jam sediment sampled downstream of a jam and jam sediment, but there was no significant difference between upstream samples and either downstream or jam samples. The letters above the boxes indicate statistically significant groupings.

Because basin effects were identified as possibly significant through mixed effects modeling, an ANOVA was also run to test the differences between jam samples and non-jam samples in each basin (Figure 31). There was no significant difference between the jam and non-jam samples within basins, and few significant differences between basins, indicating that the proportion of OM is no greater in sediments stored behind jams than in other fine sediment within the channel. This indicates a lack of support for my first hypothesis, that jam sediment has a higher proportion of organic matter than non-jam sediment.

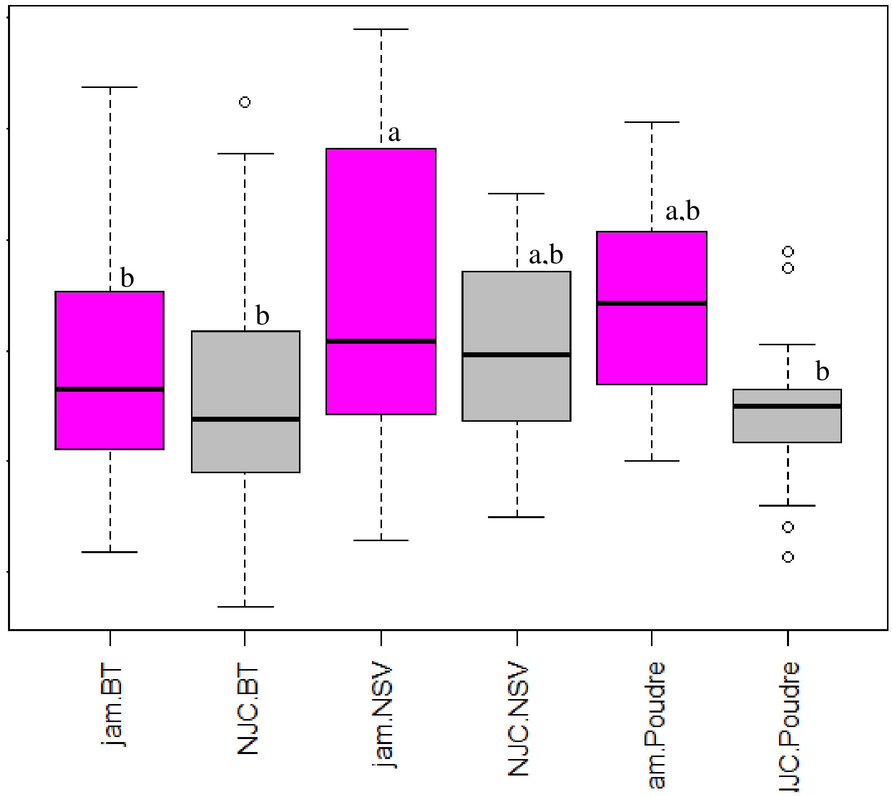


Figure 31: ANOVA of OM samples separated by basin and by samples taken at jams and at non-jam sites. Letters indicate Tukey's HSD groupings at the p>0.5 level. Within each basin there was no significant difference between jam and non-jam samples, though there were significant differences between basins. The letters above the boxes indicate statistically significant groupings.

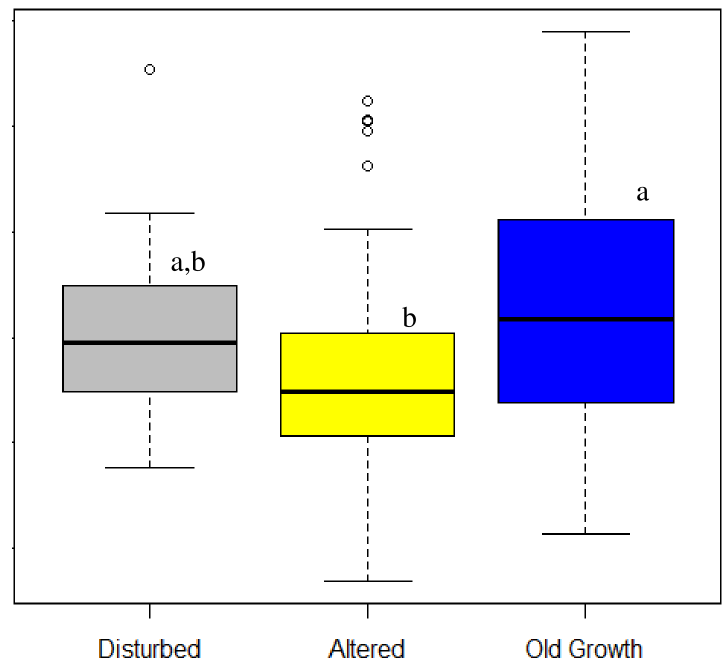


Figure 32: ANOVA comparing the log transformed percent of OM within streams comparing all samples based on forest history. Tukey's HSD indicates that there are significant differences between samples on old growth and altered reaches, but not between old growth and disturbed or disturbed and altered. The letters above the boxes indicate statistically significant groupings.

In addition to ANOVAs, a backward step linear model was constructed with transformed OM content of the sediment as the response variable. Variables included for selection were basin, forest age, valley type, water surface elevation (WSEL) drop through the jam, WSEL slope through the jam at low flow, natural log transformed OM in samples taken upstream and downstream of the jams, number of pieces in the jam, volume of sediment stored behind the jam and volume of wood in the jam. After backward step selection, forest age and log transformed volume of wood in the jam were the most significant variables, and explained approximately 53% of the variation in organic matter content (Table 10).

Starting with the backward stepped model with forest age and wood volume, I tried forward step selection with water surface elevation (WSEL) slope and volume of sediment behind the jam, as well as an age-basin interaction term to determine whether these variables significantly improved the model; however, in all cases they did not.

Table 10: Summary of linear model to predict OM content for the sediment samples taken at jams. Bold variables were identified as significant during the backward step selection process. Coefficients, standard errors and p-values have been included for all significant variables

Response variable	Assumed distribution	R^2 for model	Tested Independent variables	Significant independent variables		
				Coefficient	Std. error	p value
ln(Organic matter content, %)	Gaussian	0.5297	Intercept	0.189	0.298	5.32E-01
			Basin (NSV, BT or Poudre)			
			Stand age, yrs	0.004	0.001	1.00E-02
			ln(Upstream NJC, %)			
			ln(Downstream NJC, %)			
			Valley type			
			ln(Sediment volume, m3)			
			ln(Wood volume, m3)	0.517	0.141	1.12E-03
			WSEL drop, m			
			WSEL slope, m/m			
			ln(# of Pieces in jam)			

Based on these results, there is no support for my first hypothesis that jams store proportionally more organic matter per unit volume of sediment than other areas of fine sediment in the channel. The OM sediment content in jams is not significantly different than in non-jam sites in general, or the sediment upstream. The only significant difference found was between the proportion of OM in jam sediment and the sediment stored immediately downstream of jams.

The variation in OM content between jams was explained by forest age and wood volume in jam. Forest age is likely influencing the background OM content of sediment in the reach, based on results which show old growth samples have a significantly different OM content than altered reaches, and that across all samples old growth has the most OM content, followed by disturbed and altered reaches (Figure 32).

3.3.3 Sediment volume

Regardless of the fraction of OM contained within the sediment, the amount of fine OM stored by jams could be significant because of the large volume of sediment jams retain. Jam size and the effect of the jam on the water surface were considered to be the most likely factors influencing the volume of stored sediment, but bivariate plots of the volume of wood in jam, local WSEL slope through the jam, WSEL drop at the jam and the number of pieces in the jam showed no clear correlation (Figure 33).

To test the effect of multiple variables on stored sediment volume, a backward step selection was performed for a linear model with log transformed volume of sediment as the response variable. Variables included for selection were basin, forest age, valley type, WSEL drop through jam, local WSEL slope at jam, and log transformed wood volume and number of pieces within the jam. Of these, only WSEL slope was found to be significant (and explained 13% of the variation), although a forward step selection model containing WSEL drop and WSEL slope explained 20% of the variation (Table 11).

Sediment wedge surface area has been found to correlate well with local slope [*Bilby and Ward*, 1989], so a second model was run using log transformed sediment wedge surface area as the response variable, and the same explanatory variables. WSEL slope and WSEL drop through the jam were significant, and explained approximately 35% of the variation (Table 11). Since sediment wedge volume was calculated as the product of surface area and average depth of sediment, it is likely that the previous linear model identified the effects of WSEL slope and drop on surface area, and did not explain the variation in sediment depth.

Sediment volume is not well correlated with forest age or jam characteristics. No variable or combination of variables tested here explained a substantial amount of variation in sediment storage between jams, although a combination of local WSEL slope and WSEL drop though the jam was able to explain roughly a third of the variation in the area of fine sediment deposition.

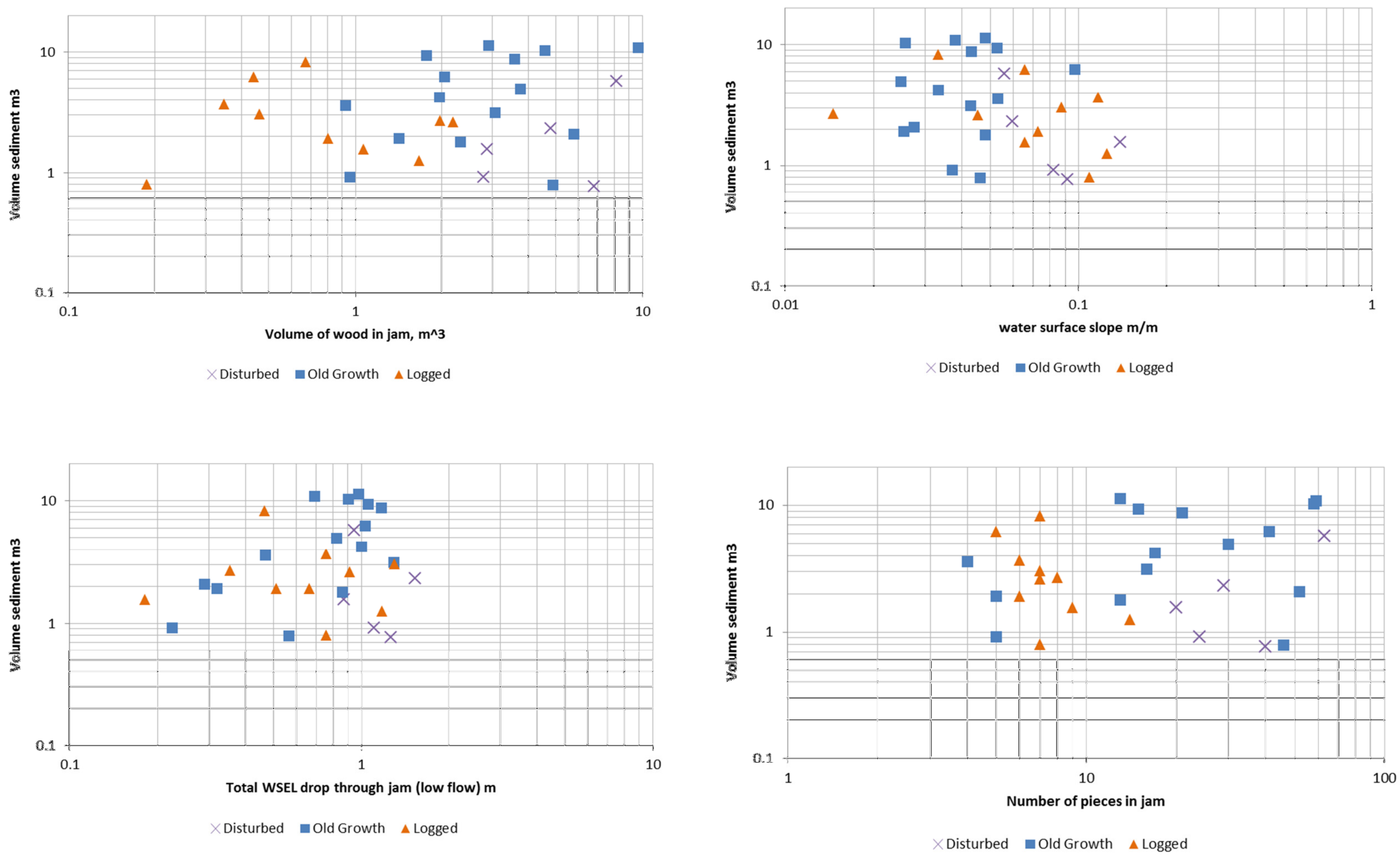


Figure 33: Bivariate plots of factors which were thought to influence sediment retention behind jams.

Table 11: Summary of linear models to predict fine sediment volume and surface area for 30 jams. Bold variables were identified as significant during the backward step selection process. Coefficients, standard errors and p-values have been included for all variables used in the model.

Response variable	Assumed distribution	R^2 for model	Tested Independent variables	Significant independent variables		
				Coefficient	Std. error	p value
ln(Volume of sediment, m^3)	Gaussian	0.2031	**Intercept**	1.274	0.401	3.74E-03
			Basin (NSV, BT or Poudre)			
			Stand age, yrs			
			Valley type			
			ln(Wood volume, m^3)			
			WSEL drop, m	0.663	0.439	1.42E-01
			WSEL slope, m/m	-12.165	4.802	1.74E-02
			ln(# of Pieces in jam)			
ln(Surface area of sediment, m^2)	Gaussian	0.3533	**Intercept**	1.990	0.379	1.53E-05
			Basin (NSV, BT or Poudre)			
			Stand age, yrs			
			Valley type			
			ln(Wood volume, m^3)			
			WSEL drop, m	1.220	0.414	6.51E-03
			WSEL slope, m/m	-15.069	4.530	2.54E-03
			ln(# of Pieces in jam)			

3.3.4 Total carbon stored in sediment (OM and volume)

Although it is difficult to predict the volume of sediment stored behind a jam, it may still be possible to find explanatory factors for the total amount of CPOM and FPOM stored behind a jam. Bivariate plots indicate that there is no relationship between the amount of stored sediment and the OM content (Figure 34). The total volume of OM stored in the sediment behind a jam was estimated by multiplying the percent OM by the volume of sediment. Because the OM percent was calculated for only the <2 mm fraction of the sediment sample, this is most likely an underestimate of the volume of OM in a sample.

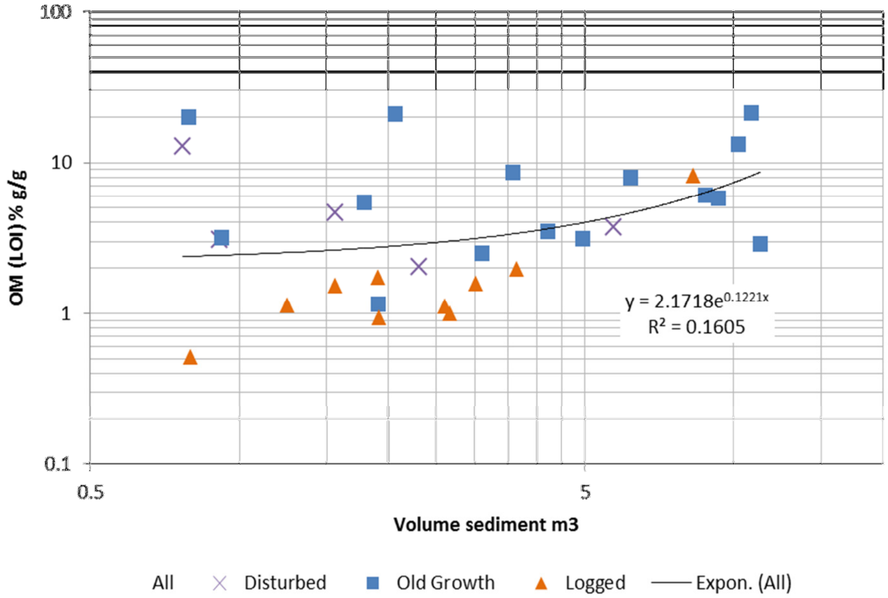


Figure 34: Bivariate plot of OM content in sediment versus the amount of stored sediment at a jam, indicating that there is a very weak exponential relationship between the two variables.

A backward step linear model was run starting with the variables basin, stand age, valley type, WSEL slope, WSEL drop through the jam, and log transformed non-jam OM, sediment surface area, wood volume in the jam, and number of pieces in the jam. Of these, stand age and log transformed wood volume in the jam were both significant, and accounted for 43% of the variation (Table 12). Figure 35 shows the log-linear relationship between the volume of OM stored by a jam and jam size (as measured by the volume of wood in a jam), and how that relationship changes in old growth and disturbed reaches. There does not appear to be a clear relationship for altered reaches, but Figure 35 indicates that (i) the volume of total OM stored behind a jam increases more rapidly in old growth jams (exponent on the regression line of 1.8 versus 1.2 for disturbed), and (ii) old growth generally has greater total OM stored as sediment than disturbed or altered reaches.

Table 12: Summary of linear model to predict total OM content stored as sediment for 29 jams. Bold variables were identified as significant during the backward step selection process. Coefficients, standard errors and p-values have been included for all significant variables

Response variable	Assumed distribution	R^2 for model	Tested Independent variables	Significant independent variables		
				Coefficient	Std. error	p value
ln(Total OM in sediment, m^3)	Gaussian	0.4344	**Intercept**	2.620	0.488	1.25E-05
			Basin (NSV, BT or Poudre)			
			Stand age, yrs	0.006	0.002	1.04E-02
			ln(Upstream NJC, %)			
			ln(Downstream NJC, %)			
			Valley type			
			ln(Sediment surface area, m^2)			
			ln(Wood volume, m^3)	0.595	0.231	1.58E-02
			WSEL drop, m			
			WSEL slope, m/m			
			ln(# of Pieces in jam)			

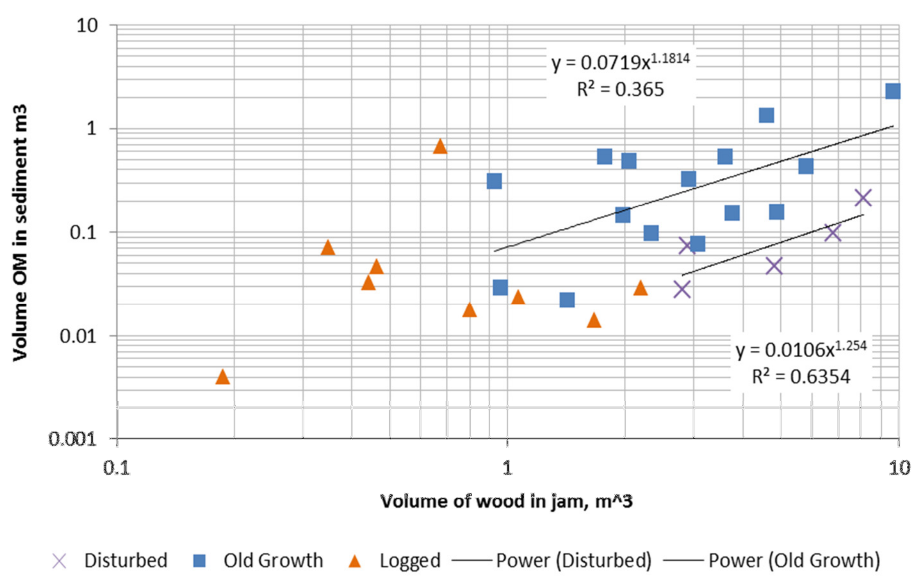


Figure 35: Volume of OM in the sediment versus volume of wood in the jam, showing a strong relationship for jams in old growth and disturbed forests, but no relationship for jams in altered (logged) forests.

In summary, stand age and wood volume within a jam together explain 43% of the variation of total organic carbon stored in sediment, and there appear to be clear differences between the altered, disturbed and old growth forest types. The volume of OM stored behind a jam is correlated to the volume of wood in a jam in old growth and disturbed areas, but there is no clear relationship in altered forests. Additionally, old growth jams show a larger incremental increase in sediment OM storage with increased volume of wood than do disturbed jams. This partially supports the hypothesis that jams in old growth have higher organic sediment content, although the evidence is not conclusive.

3.3.5 Carbon stored as wood versus carbon stored as sediment

Organic matter stored in the sediment is commonly mobile CPOM and FPOM such as pine needles, pine cones, and other organic debris. However, instream wood can also be considered a reservoir of carbon within the stream channel, and is typically less mobile. Figure 36 shows that, for altered and old growth streams, increasing stand age is correlated with increased volume of wood in jams, although this relationship does not appear to hold true for disturbed reaches. An ANOVA comparing the volume of wood in a jam based on stand age found that altered stands are significantly different than disturbed or old growth stands (Figure 37). If the amount of carbon stored as wood is larger than the amount stored as sediment, forest age may have a large impact on total carbon storage, especially in naturally disturbed areas with limited organic matter in the sediment, but large amounts of instream wood stored within the channel.

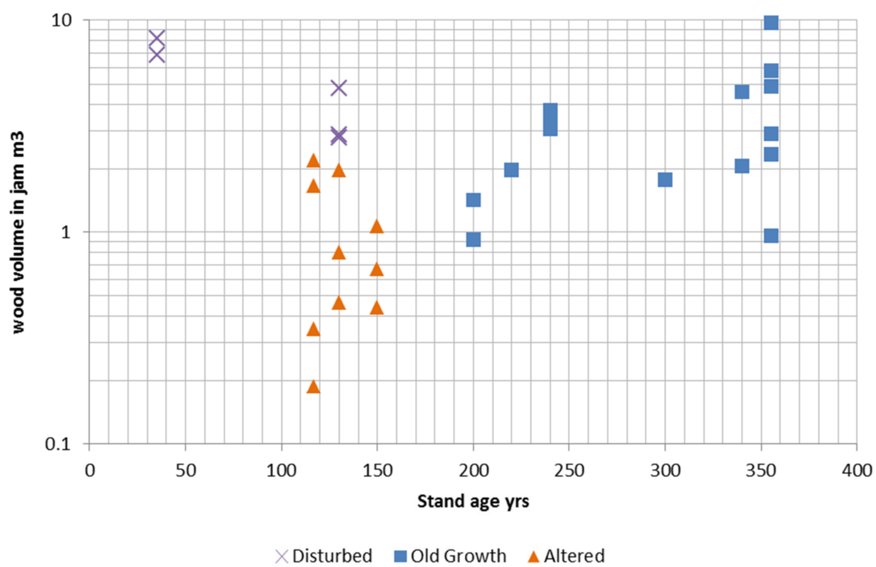


Figure 36: Wood volume in jams versus stand age of adjacent forest

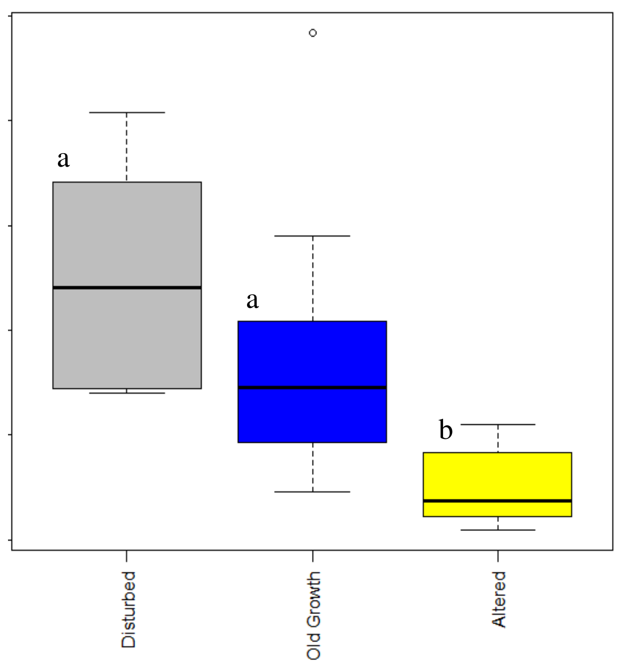


Figure 37: Results of an ANOVA for wood volume in jams by forest type. Tukey's HSD indicates that jams in old growth and disturbed stands are not significantly different, but jams in altered reaches are. The letters above the boxes indicate statistically significant groupings.

A first-order estimate of the total mass of carbon stored as wood was made by assuming a density of 450 kg/m^3 for all pieces [*Forest Products Laboratory*, 2010], and assuming that approximately 50% of the wood is carbon [*Lamlom and Savidge*, 2003]. For comparison, a total mass of carbon stored in the sediment was estimated by assuming a bulk density of 1330 kg/m^3 for the unconsolidated sediment [*Julien*, 1998] and multiplying the calculated OM percent by the resulting mass of sediment. Figure 38 shows the resulting estimate of kilograms of total carbon stored within an individual jam, partitioned by source (sediment or wood). In 28 of the thirty jams, and across all forest types, more carbon was stored as wood than as OM in sediment. Disturbed reaches had a much larger proportion of their carbon stored as wood than either altered or old growth jams, with an average of 93% carbon as wood. Altered reaches averaged 82% of carbon stored as wood. Old growth jams stored the largest amount of carbon as sediment, but still had an average 75% contribution to the total carbon stored from wood.

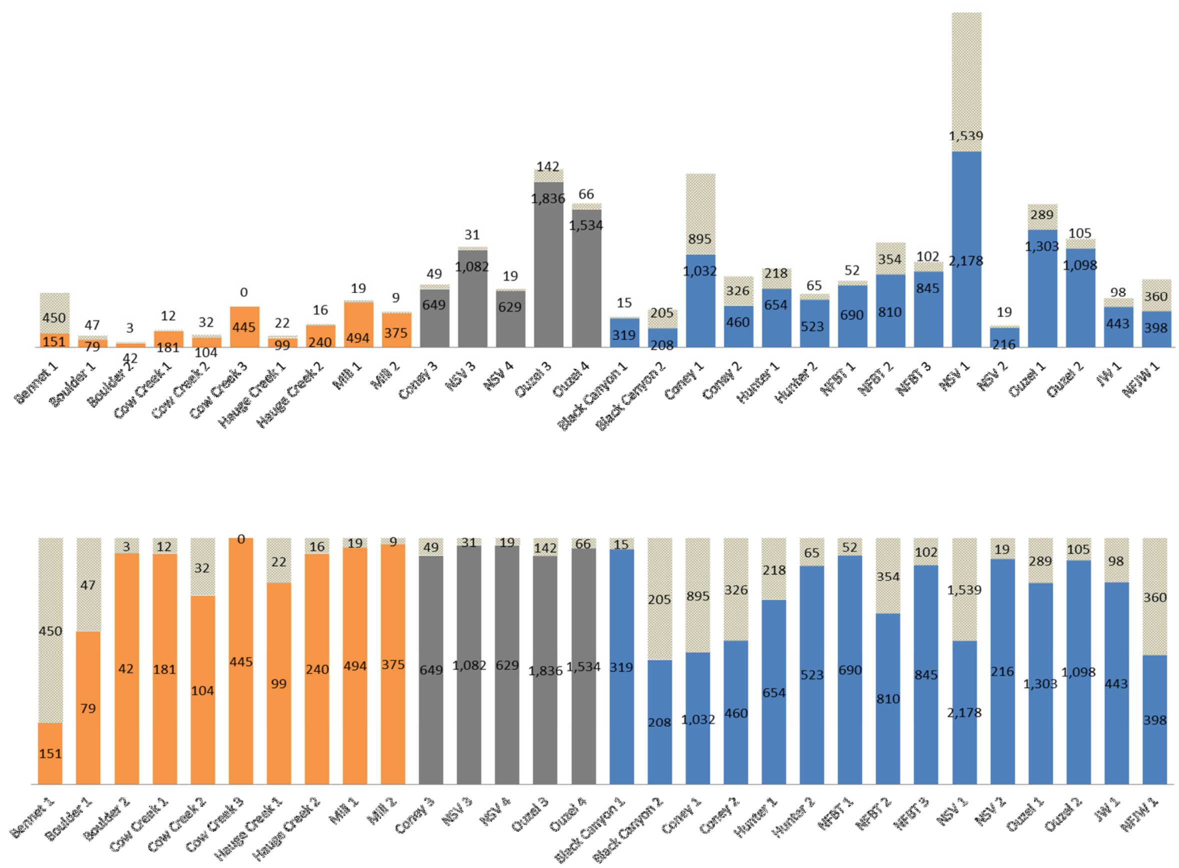


Figure 38: Bar graphs showing kg grams of carbon stored as sediment and wood for the 30 jams surveyed. The top figure shows total amounts of carbon, while the bottom figure shows the proportion of carbon as sediment or wood for each jam. In both figures the sites are sorted by forest type: altered (orange), disturbed (graygray) and old growth (blue).

As these results show, a majority of the carbon within jams is stored as wood, not as OM in sediment, even when the volume of sediment behind a jam is quite large. Wood volume is significantly larger in old growth and disturbed reaches than in altered reaches. Since the OM content and sediment volume are related to the volume of wood in a jam (sections 3.3.2 and 3.3.3), and wood volume is related to forest type, it follows that the total carbon stored in a jam may be related to forest type. In the next section, I examine the total carbon storage of jams (sediment and wood) in more detail.

3.3.6 Predicting carbon storage in a reach

Consideration of the total carbon in a jam, including both sediment and wood, suggests an effect based on the surrounding forest type, with old growth and disturbed significantly different from altered reaches (Figure 39). This result suggests that it may be possible to estimate the relative amount of carbon stored in individual jams based on stand age and disturbance history. A backward step selection was performed to evaluate the ability of basin, forest age, valley type, forest history, and local WSEL slope variables to predict natural log transformed total carbon. These variables were selected because they were the easiest to collect or estimate remotely. The linear model with forest age, valley type and forest history (disturbed, altered, old growth) was able to explain 73% of the variation in total carbon stored at an individual jam (Table 13).

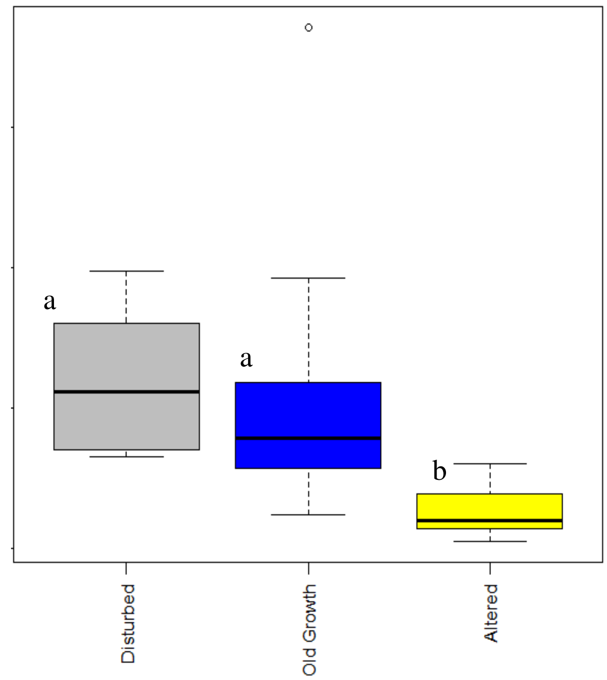


Figure 39: ANOVA of estimated total carbon from sediment and wood with Tukey's HSD, indicating that old growth and disturbed reaches group together, while altered reaches are significantly different. The letters above the boxes indicate statistically significant groupings.

Table 13: Summary of linear model to predict total OM content stored as wood and sediment for 29 jams. Bold variables were identified as significant during the backward step selection process. Coefficients, standard errors and p-values have been included for all variables used in the model.

Response variable	Assumed distribution	R^2 for model	Tested Independent variables	Significant independent variables		
				Coefficient	Std. error	p value
ln(Total OM in jam (wood & sediment), kg)	Gaussian	0.7316	**Intercept**	6.198	0.401	1.19E-13
			Basin (NSV, BT or Poudre)			
			Stand age, yrs	0.005	0.002	4.54E-02
			Valley type: confined (default)			
			Valley type: semi-confined	-0.283	0.271	3.06E-01
			Valley type: unconfined	1.082	0.388	1.04E-02
			Forest type: disturbed (default)			
			Forest type: old growth	-0.663	0.527	2.21E-01
			Forest type: altered	-1.648114	0.344899	8.09E-05
			WSEL slope, m/m			

Using the results of previous sections, it is possible to get a first-order approximation of the amount of carbon stored within a particular reach. Figure 40 and Table 14 show the estimated carbon loads (in kg/km of channel length) for the 13 reaches which had both reach and individual jam level surveys. Altered reaches averaged 5,200 kg/km, while old growth reaches averaged more than five times that -- 29,300 kg/km. The two disturbed reaches averaged 97,500 kg.km of channel, 15 times the average storage of altered reaches, although this number is based on only two reaches, and may be skewed by the fact that the Middle Ouzel reach was burned ~30 years ago and may be experiencing peak wood volume in the stream as a result of that fire [*Bragg*, 2000; *Bragg et al.*, 2000]. Although this is only a rough approximation, it is clear that natural disturbances and human alterations can have order of magnitude differences on the amount of instream carbon storage.

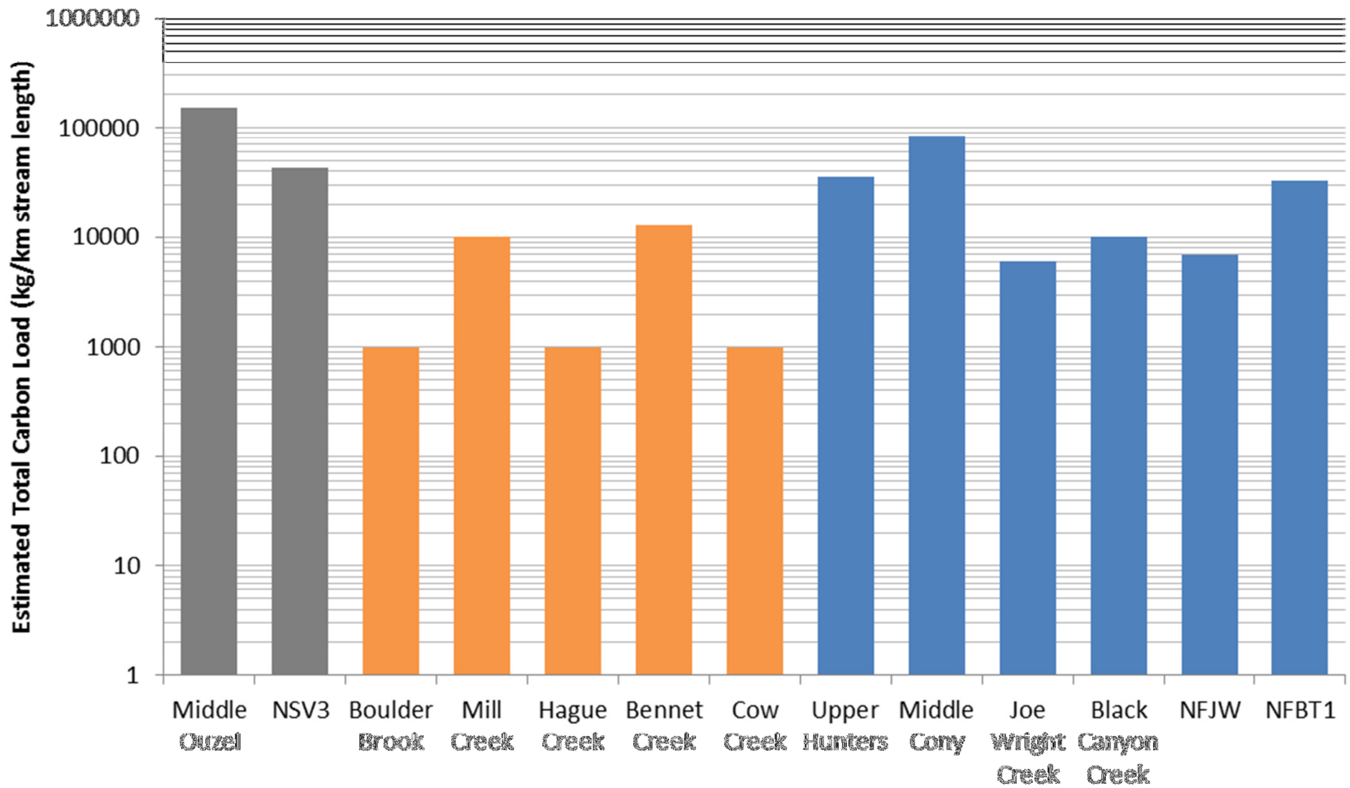


Figure 40: Estimated carbon load (in kg/km of stream) for the reaches which had both jam densities and individual jam surveys. Note that the y-axis is logarithmic. Bar color indicates forest type: altered (orange), disturbed (gray) and old growth (blue).

Table 14: First order estimate of instream carbon loads in kg/km of stream length and Mg/ha of stream surface area. Shaded rows indicate old growth reaches (stand age >200 years). The two bold rows (Middle Ouzel and NSV3) indicate disturbed reaches, where the stand age is less than 200 years due to natural events and no logging occurred. These numbers are assumed to be overestimates because jams counted at the reach level did not have to be channel spanning or retain fine sediment. The Middle Ouzel reach is probably experiencing peak wood loads following a fire in 1978.

Reach name	Estimated Total Carbon Load (kg/km stream length)	Estimated Total Carbon Load (Mg/ha stream surface area)
Middle Ouzel	**152000**	151
NSV3	**43000**	34
Boulder Brook	1000	5
Mill Creek	10000	26
Hague Creek	1000	1
Bennet Creek	13000	9
Cow Creek	1000	7
Upper Hunters	36000	62
Middle Cony	84000	97
Joe Wright Creek	6000	9
Black Canyon Creek	10000	75
NFJW	7000	16
NFBT1	33000	65

In section 2.3.4, I found that jam density within a reach is best predicted based on the stand age, channel width and ramp/bridge spacing. In this section, I showed that total carbon in an individual jam is related to forest age, valley type and forest history. Combined, these two results indicate that forest history and stand age influence the total amount of carbon stored within a reach. First-order estimates show an order of magnitude difference between reaches which have been logged and reaches which have been disturbed by natural events. This supports my third hypothesis, that headwater streams in the Front Range are currently "dam-impoverished" ecosystems with greatly reduced organic matter storage capacity relative to unaltered streams, although the organic matter is stored as wood rather than as CPOM or FPOM as I originally hypothesized.

3.4 DISCUSSION

No significant difference was found in the organic matter content of sediment stored by jams and sediment stored in other areas of the channel, so there was no support for my first hypothesis, that jam sediments would store more organic matter than other areas of the channel. This was an unexpected result, because I observed large amounts of organic matter stored behind jams in the field, and jams have been found to be more efficient at trapping sediment than large clasts and channel margins [*Fisher et al.*, 2010].

There was a significant difference between the proportion of OM in jam sediments and sediment downstream of jams, so jams may be affecting the amount of OM deposited immediately downstream, either by trapping a portion of the OM or by creating additional turbulence downstream that does not allow OM to settle.

The percentage of organic matter in the sediment impounded by a log jam can be explained by forest age (basal area) and volume of wood in the jam. Forest age may be important because it influences the background levels of organic matter in the stream; old growth forests tend to have more biomass [*Ryan and Waring*, 1992; *Luyssaert et al.*, 2008], more trees close to the stream and therefore more opportunity for litter to fall into the stream. Engelmann spruce forests in Colorado produce approximately 170 g m^{-2} $year^{-1}$ of litterfall. This is low for a coniferous forest, but because of the cold environment that litterfall can be stored for 30 years on the forest floor [*Arthur and Fahey*, 1992]. Because large jams can raise water levels and force water onto the floodplain, it is likely that fallen litter washed into the river with returning overbank flow during high flows is a larger source of OM to the stream than direct litterfall.

Wood volume may be an indication not only of the size of the jam, but also the age or permeability of the jam, because larger jams can be more stable and have a longer time in which to trap small pieces that reduce the overall permeability of a jam, therefore increasing the likelihood that organic matter will remain within the sediment pool.

I was unable to identify variables which can predict the volume of sediment behind a dam, although sediment surface area can be weakly related to WSEL slope and WSEL drop. This indicates that the variables measured can explain the area over which sediment is deposited, but not the depths to which sediment is deposited. Sediment wedge volume could reflect a wide variety of variables that were not evaluated in this study, including: age of jam, assuming that jams that remain stable for progressively longer periods accumulate greater sediment volumes; porosity/permeability or retentiveness, assuming that jams with lower porosity and permeability more effectively retain sediment upstream; local sources of fine sediment and OM, or cumulative upstream sources of fine sediment and OM; proximity to an upstream jam, assuming that an upstream jam storing large volumes of sediment and OM limits sources of this material for the next jam downstream; site-specific and complex hydraulics within a pool upstream from a jam; and interannual variability in flow, which influences transport of fine sediment and OM, as well as jam retentiveness of these materials.

Although I was unable to correlate measured variables with sediment volume, I was able to relate the total carbon stored as sediment to stand age and the volume of wood in the jams, most likely because stand age and wood volume influence the percent of organic matter behind a jam. Organic carbon in sediment increases with stand age and wood volume. Because this FPOM and CPOM is a particularly important source of nutrients for aquatic food webs in shaded forest streams [*Tank et al.*, 2010], the existence of significant differences in total carbon within sediment in relation to stand age and wood volume implies that streams with older and unaltered forests and larger jams can be more biologically productive.

Comparison of the different reservoirs of carbon in a jam indicates that more carbon is stored as wood than as sediment. The overall effect on carbon storage in a reach due to large wood is unclear. Carbon stored as large wood is generally less available to stream biota than CPOM and FPOM, but it can be a substrate for biologically active surfaces [*Eggert and Wallace*, 2007], increase flow through the bio-active hyporheic zone [*Fanelli and Lautz*, 2008; *Sawyer et al.*, 2012] and create channel habitat diversity [*Keller and Swanson*, 1979; *Montgomery and Piegay*, 2003], all of which encourage carbon processing. However, larger jams may also encourage higher rates of instream carbon storage, since large wood is more likely to be stored for years to centuries, rather than the hours to years over which CPOM and

FPOM are stored [*Fisher et al.*, 2010]. Complicating the response even further is the finding that increasing wood volume also increases CPOM and FPOM storage in jam sediments.

Using a different dataset collected in the same study area, a previous study found that valley type and confinement was a more important control than stand age on jam formation [*Wohl and Beckman*, 2013]. Because jams were most prevalent in semi-confined valleys, the jam-level surveys conducted for this study necessarily took place in semi-confined valleys. The findings of these two studies imply that within the semi-confined valley type, stand age has an effect, but that overall valley type controls where jams form (and thus where carbon is stored) within the stream network. This has been attributed in the past to hydraulic factors such as the ability of the streams to expand laterally in semi-confined valleys, but based on the results of this study, it may also be because semi-confined valleys provide a local source of key pieces which remain anchored during high flows.

Using data from the reach-level surveys, I found that old growth reaches stored an average of 29,300 kg/km or 54 Mg/ha of carbon, altered reaches stored 5,200 kg/km or 9 Mg/ha and disturbed reaches stored the highest amount of carbon with an average of 97,500 kg/km (93 Mg/ha) of channel. Of note is the fact that there were only two disturbed reaches surveyed, and the average is skewed by the extremely high wood loads on Middle Ouzel, which was burned by the Hourglass fire in 1978 and is expected to currently be experiencing peak post-fire wood recruitment [*Bragg*, 2000; *Bragg et al.*, 2000; *Benda and Sias*, 2003]. Because the definition of a jam at the reach level included non-channel spanning jams as well as CSJs, the first-order approximation of carbon stored in reaches is expected to be high. However, because the method used is the same across all reaches in this study, these estimates can be compared to each other in order to evaluate relative carbon storage rates. Although the total carbon storage in a reach is only a rough approximation, it is clear that natural disturbances and human alterations can have order of magnitude differences on the amount of instream carbon storage.

Previous studies on small streams in the eastern United States have shown a link between instream wood and carbon retention [*Warren et al.*, 2007], and increased transient storage when small accumulations of instream wood are present [*Bilby*, 1981; *Hall et al.*, 2002]. This study supports this finding, and expands it to include larger streams and larger sources of boundary complexity and retentiveness. Previous studies have also linked forest age and logging history to terrestrial carbon storage [*Harmon et al.*, 1990], identified old growth forest as an important carbon sink at the global level [*Dixon et al.*, 1994; *Turner et al.*, 1995; *Pregitzer and Euskirchen*, 2004], and shown that freshwater systems are a key component of carbon processing and transport [*Battin et al.*, 2008, 2009; *Aufdenkampe et al.*, 2011]. The results of this study indicate that old growth forest influences not only terrestrial carbon pools and overall storage, but also riverine storage, and by implication riverine processing of carbon.

Because this is an observational study, there are many confounding factors which could be influencing the results. Perhaps the most important to note is that I selected only channel spanning jams with fine sediment storage for individual surveys, which makes jam selection inherently non-random and may have led to an overestimation of typical jam size and volume of stored sediment. Additionally, logs are recruited from upstream, so adjacent forest age may not be the age of the forest contributing the most logs to a given jam. There are areas of known old growth forest above NSV3, NSV 4, and Coney3, but since forest ages were not available for all upstream reaches, I could not control for upstream forest age.

3.5 CONCLUSIONS

The data did not support my first hypothesis, that log jams have different effects on the channel than other features that result in fine sediment storage. Instead, I found that differences in the percent of OM in sediment behind jams are not significant. I also found that the carbon stored as OM in sediment was not as large as the amount of carbon stored in the actual logs forming the jam. Overall, wood constitutes a larger reservoir of carbon in the stream than organic matter stored as sediment.

There was support for only the first part of my third hypothesis, that jams have a higher overall volume of wood and higher relative organic sediment content in streams draining old growth forests, although the definition of old growth forest has to be expanded to include forest which was old growth prior to a natural disturbance. I also found that sediment organic content was more closely related to total wood volume in a jam than to forest age. In fact, my results indicate that the major impact of logging on instream carbon is probably not to the amount of POM stored with fine sediment (although that may be the most bioavailable form of carbon and therefore have the greatest effect on the local ecosystem), but rather to remove jams –which are the most abundant source of stored organic carbon – from the channel.

The most important implication of this research is that streams through logged forests have an order of magnitude less carbon stored within the channel than streams in forests of equivalent age with natural disturbance. This implies that past and contemporary forest management not only changes terrestrial forest ecology and nutrient cycling [*Harmon et al.*, 1990; *Bradford et al.*, 2008], but also riverine nutrient dynamics and, presumably, aquatic ecology. Previous studies have shown the strong reciprocal links between terrestrial and aquatic biota [*Fausch et al.*, 2002; *Baxter et al.*, 2004, 2005], as well as the role that leaf litter and other allocthonous material can play in subsidizing stream ecosystems [*Eggert and Wallace*, 2007; *Tank et al.*, 2010; *Marcarelli et al.*, 2011]. These effects are not only local, but cascade through the river network as nutrients and organic matter are carried downstream [*Meyer et al.*, 2007; *Wipfli et al.*, 2007]. Since forest age and disturbance history have a major effect on the biomass available to enter the stream [*Chen et al.*, 2005; *Hall et al.*, 2006; *Warren et al.*, 2007], and this study shows that there are quantifiable differences in stored stream carbon in areas of different disturbance history, it follows that forest changes due to age and disturbance may also be apparent in aquatic ecosystems.

It is difficult to predict how long these impacts will persists in forest/stream ecosystems, since there are no streams in this study which have had 200 years to recover after logging, and the naturally disturbed areas were only in the beginning phase of recovery from fire. The implications of this research and the need for key pieces to start jams indicate that there may indeed be a threshold effect which results in alternate stable states of wood-poor and wood-rich streams, and that human activity has pushed these streams into a wood-poor state by removing stream-adjacent trees. There is no coherent trend towards more jams or more closely spaced key pieces as forest age increases (Figure 41), indicating forest age alone is not sufficiently powerful to overwhelm site-specific factors. A study which tracks specific reaches through time would give a much better picture of the dynamics of stream recovery than a space-for-time substitution study such as this one.

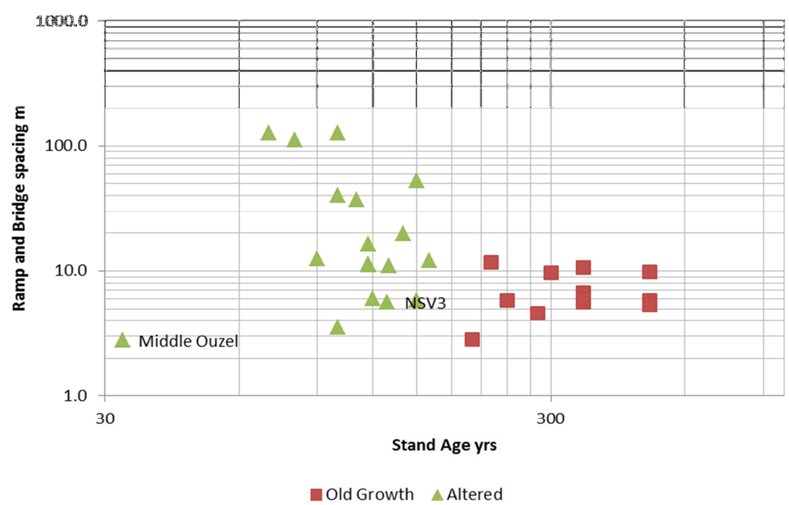


Figure 41: Ramp and bridge spacing (m) versus stand age (yrs) showing a lack of coherent trend over time in the accumulation of key pieces in altered reaches.

At the landscape level, the carbon per hectare stored in streams is on the same order of magnitude, although not as large as the carbon stored per hectare in the terrestrial forest (Table 15). The slightly lower numbers may be because this study did not measure all carbon in the reach. If future studies find that non-jam carbon storage is a significant portion of the carbon pool, then these estimates may be a lower bound for stream storage. More likely, however, is that the difference is due to the differences between the aquatic and terrestrial environments. The carbon in streams is not spread evenly over the surface area as it would be in a forest's duff and leaf litter, making the overall surface area average lower. In addition, biomass in the stream is subjected to abrasion and higher decay rates (through freeze/thaw and wetting and drying cycles) than biomass on the forest floor. The concentration of carbon in backwater areas and jams could create "hot spots" of carbon processing by stream biota which accelerate the flux of carbon out of stored OM and woody biomass. Since stream environments tend to be much more dynamic than terrestrial environments, the average carbon flux (in the absence of a large disturbance) is almost certainly higher in streams and may play a large role in the carbon stored in a reach at any given time. Although this study did not estimate carbon flux, I recommend that future researchers attempt to quantify the inputs and outputs at a reach and network level.

Table 15: Estimated stored carbon in forested landscapes, updated with the estimated values of carbon stored in streams found in this study. The range of values for stored carbon in rivers is on the same order as the ranges for terrestrial storage.

	Estimate of Stored Carbon, Mg/ha		
	low	mid	high
Arthur and Fahey (1990)		70	
Ryan and Waring (1992)	61	78	98
Tinker and Knight (2000)	123		180
Binkley et al (2003)		126.5	
Kueppers et al (2004)	4.7		54
Houghton (2005)		70	
Battaglia et al (2010)	27		54
***Beckman* (2013)**	**1**	**40**	**151**

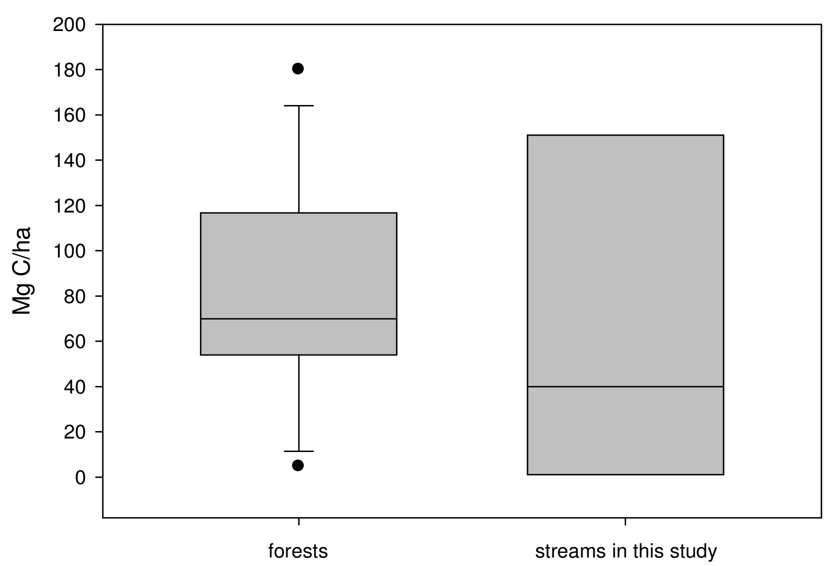


Figure 42: Schematic illustration of range of carbon storage values in forest environments versus those in streams of this study, using the low, mid and high values shown in Table 15.

OVERALL CONCLUSIONS

The results of this study indicate that streams in subalpine forests of the Colorado Front Range may, indeed, have crossed a threshold of resiliency with respect to instream wood loads, channel spanning logjams and associated carbon storage. The streams in areas subject to logging and other human impacts differ in ecologically important ways from relatively undisturbed streams that I used as an analogue for the pre-European forests of the Rocky Mountains. The results of this study indicate that forest age and disturbance history are important to riverine carbon storage (and by extension global carbon storage and transport) through their impact on background OM content of fine sediment and channel spanning log jams which retain carbon as wood and POM in headwater streams. The results summarized here indicate that log jams store smaller pieces of wood that would likely otherwise remain in transport through headwater stream reaches, thus increasing total instream wood load within a reach. The backwater upstream of a log jam also retains larger volumes of POM than other potential storage zones, such as eddies behind a protruding boulder. Previous work also indicates that log jams reduce channel conveyance and facilitate overbank flooding and floodplain storage of POM [*Wohl et al.*, 2012]. Closely spaced ramp and bridge pieces entering a stream from adjacent old growth forest thus interact with downstream fluxes of water, sediment, and OM in complex ways that result in a net increase in riverine carbon storage relative to streams flowing through younger forest that has been altered by human activities.

(H1) The results do not support my hypothesis that log jams have different effects on the proportion of organic matter stored with fine sediments than other features that result in fine sediment storage. There were no statistically significant differences in the organic content of sediment samples taken from the fine sediment directly above log jams and the organic content of samples taken from other fine sediment within the stream, and the dataset was not sufficient to test whether the total volume of fine sediment behind jams is larger than the total volume stored in other areas of the channel. Observations suggest that more sediment is stored behind jams than is stored in other areas of the channel, but this remains to be rigorously evaluated. There was, however, a significant effect based on stand age, with disturbed and old growth reaches having a significantly larger proportion of organic matter than altered reaches for samples taken in all areas of the channel.

(H2) The results indirectly support my hypothesis that local forest age is more important to the quantity and characteristics of instream wood than basin characteristics. Old growth reaches have higher wood loads (as measured by jam density), and more closely spaced key pieces. The differences appear to be driven by both increased wood supply (as measured by basal area) and the increase in locally recruited wood that is more likely to have an anchor point outside the active channel than fluvially transported wood.

(H3) The results support the hypothesis that jams have higher overall volume of wood and higher relative organic sediment content in streams draining old growth forests, although the amount of carbon stored in a stream is influenced more by the volume of wood in a stream than by the OM stored in sediment. A first-order estimate of instream carbon storage confirms that the streams draining altered forests are currently “dam-impoverished” and lacking carbon reservoirs. Altered streams store an order of magnitude less carbon than old growth reaches and streams which have been disturbed by natural events.

Forest age and disturbance history are more important to carbon storage than basin characteristics, and the primary reason seems to be the increased recruitment of local pieces, which have a larger volume and are more likely to act as key pieces for jam formation, as stand age increases. There is a strong threshold of increased jam density and total wood load at 20 m between key pieces, suggesting that managers attempting to increase jam density and instream carbon storage should take steps to ensure both increased wood loads and the recruitment of closely spaced key pieces. This study supports previous findings that increased debris roughness leads to increased carbon retention in small streams, but expands previous work to include larger streams and larger sources of boundary complexity and retentiveness such as channel spanning log jams

Additionally, forest disturbance history was found to have a larger effect on instream carbon storage than stand age alone, since carbon stored as wood is commonly the largest reservoir of carbon within a stream. This implies that past and contemporary forest management not only changes terrestrial forest ecology and nutrient cycling [*Harmon et al.*, 1990; *Bradford et al.*, 2008], but also riverine nutrient dynamics and, presumably, aquatic ecology, and that these effects can persist for decades or centuries.

The results of this study do not support the linear conceptual model described in Section 1.1, in which increased jam density led directly to fine sediment retention and in-stream carbon storage. Instead, the results indicate that jam density and carbon storage are controlled at different scales. Although forest age is important to both jam formation and carbon storage, in general, the mechanisms which increase jam density in a stream act on the reach level (channel width, ramp and bridge spacing), while the factors which can lead to larger carbon storage act at the landscape level (valley confinement, forest disturbance history). The interactions between these different factors at different scales is shown in Figure 43, and is far less linear than the conceptual model envisioned at the start of this work. Additional work may be able to better quantify the relationships, for instance looking at how the percentage and location relative to the stream of different forest cover types in a watershed might affect the total carbon storage within a reach.

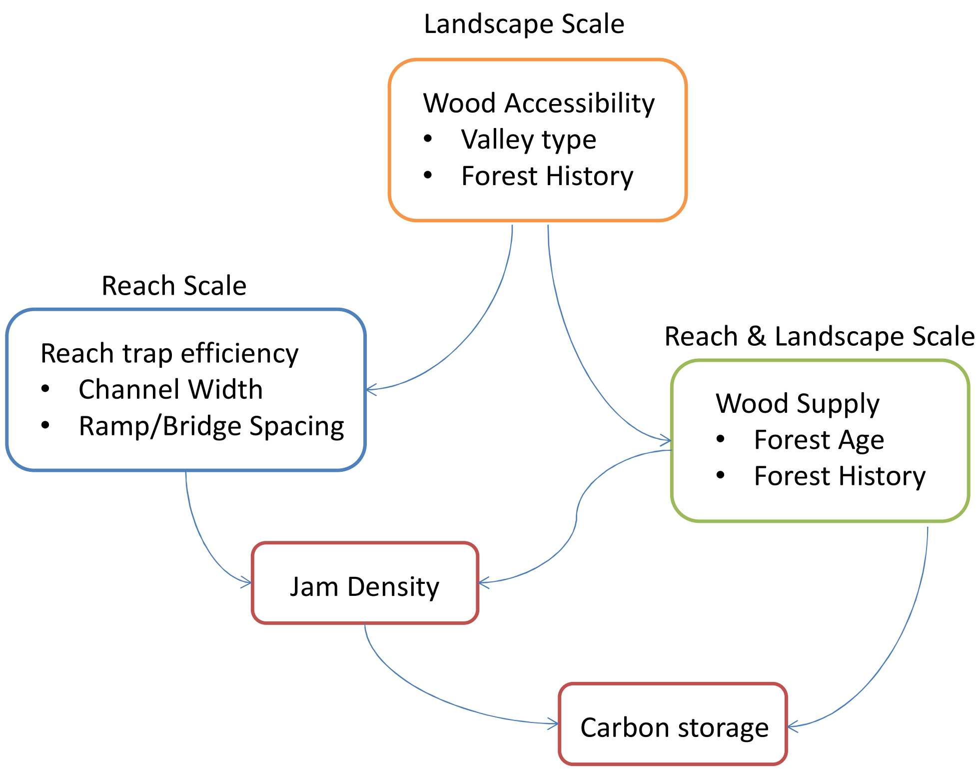


Figure 43: Conceptual model of jam formation and carbon storage within a reach

3.6 RECOMMENDED FUTURE WORK

Future researchers should take care to reduce the influence of spatial and temporal variability in carbon by confining field sites to a single basin, or taking care to sample each basin multiple times in a given year. Interannual variability in discharge can influence short term sediment and OM retention in unpredictable ways. It would also be useful if future studies look at the background OM content across more drainage basins within the Front Range, so that the contribution of background OM levels to the overall variability in OM can be assessed.

An important factor in carbon storage that this study was not able to address is the amount of OM stored as fine sediment in non-jam areas of the channel. Although samples were taken in non-jam areas, the total volume of non-jam fine sediment was not estimated in each reach and therefore it was not possible to compare the total amount of carbon stored in jams to the total amount stored in other areas. Future studies should include longitudinal estimates of non-jam sediment volume, because the cumulative effect of many small non-jam deposits may be important.

Since stream environments tend to be much more dynamic than terrestrial environments, the average carbon flux (in the absence of a large disturbance) is almost certainly higher in streams and may play a large role in the carbon stored in a reach at any given time. Although this study did not estimate carbon flux, it is recommended that future researchers attempt to quantify the inputs and outputs at a reach and network level.

Another important area of research is to identify the factors that influence the volume of sediment stored behind a jam. This study was unable to find a strong link between stored sediment volume and basin, stand age, valley type, wood volume in the jam, water surface slope, height of water surface drop through the jam, or the number of pieces in the jam. The lack of correlations may reflect a sampling design spread across two summer field seasons, or field seasons that coincided with years of unusually large and/or sustained peak snowmelt flows. Future work should focus on jam age, permeability, and the importance of small wood. It is possible that pieces smaller than 10 cm diameter (which were not included in this study) are a major influence on jam permeability and may impact the volume of stored sediment.

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APPENDIX A- REACH SURVEY DATA

Reach name	Date surveyed	Reach length	Basin	Strahler Stream order at 1:24,000	Reach average gradient (measured in field)	Reach average gradient (measured on topo)	Reach Average Slope	Reach Average Channel Width	Drainage Area at Down-stream End
					%	%	%	m	km^2
Middle Ouzel	**2009**	**1000**	**NSV**	**3**	**5%**	**16%**	**5%**	**10.1**	**12.7**
NSV3	**2009**	**1000**	**NSV**	**3**	**--**	**7%**	**7%**	**12.54**	**20.51**
Boulder Brook	2010	1000	BT	2	12%	16%	12%	2.27	10.0
Mill Creek	2010	1000	BT	2	8%	9%	8%	3.95	11.4
La Poudre Pass Creek	2010	1000	Poudre	2	2%	1%	2%	13.24	22.7
Hague Creek	2010	1000	Poudre	3	4%	4%	4%	9.05	35.2
Poudre River South	2010	1000	Poudre	4	2%	2%	2%	14.4	87.8
Corral Creek	2010	1000	Poudre	2	3%	1%	3%	4.2	16.5
Willow Creek	2010	1000	Poudre	2	6%	6%	6%	7.1	15.3
Bennet Creek	2010	1000	Poudre	2	2%	4%	2%	14.69	20.5
Cow Creek	2011	1000	BT	1	12%	12%	12%	2.12	15.3
Glacier Creek	2011	1000	BT	2	5%	6%	5%	6.16	19.7
Pennock Creek	2011	1000	Poudre	3	5%	8%	5%	5.96	32.1
Beaver Brook	2011	1000	BT	1	5%	5%	5%	1.27	6.1
Beaver Creek	2011	1000	Poudre	3	1%	3%	1%	7.71	54.1
Fall River	2011	1000	BT	2	4%	3%	4%	4.7	17.9
Roaring Creek	2011	1000	Poudre	2	1%	2%	1%	4.3	22.9
NFBT2	2011	1000	BT	2	3%	4%	3%	5.16	43.3
Lower Hunters	*2009*	*1000*	*NSV*	*3*	*28%*	*32%*	*28%*	*6.67*	*12.5*
Upper Hunters	*2009*	*1000*	*NSV*	*3*	*14%*	*13%*	*14%*	*5.73*	*11.7*
Upper Cony	*2009*	*1000*	*NSV*	*3*	*4%*	*18%*	*4%*	*8.33*	*14.1*
Middle Cony	*2009*	*1000*	*NSV*	*4*	*7%*	*7%*	*7%*	*8.7*	*19*
Upper Ouzel	*2009*	*630*	*NSV*	*2*	*--*	*15%*	*15%*	*9.95*	*7.25*
NSV1	*2009*	*1000*	*NSV*	*3*	*14%*	*15%*	*14%*	*6.1*	*10.2*
NSV2	*2009*	*1000*	*NSV*	*3*	*4%*	*4%*	*4%*	*8.56*	*16*
Joe Wright Creek	*2010*	*1000*	*Poudre*	*2*	*2%*	*5%*	*2%*	*6.59*	*19.1*
Black Canyon Creek	*2011*	*1000*	*BT*	*2*	*3%*	*5%*	*3%*	*1.3*	*11.8*
NFJW	*2011*	*1000*	*Poudre*	*2*	*4%*	*2%*	*4%*	*4.3*	*9.0*
Fern Creek	*2011*	*640*	*BT*	*2*	*18%*	*18%*	*18%*	*4*	*7.3*
NFBT1	*2011*	*1000*	*BT*	*2*	*4%*	*6%*	*4%*	*5.13*	*45.3*

Reach name	Down-stream Elevation	Up-stream Elevation	Average Elevation	Reservoir Upstream Logical	Number of pieces surveyed	Average Basal Tree Count	Basal Area	Stand Age	Method for stand age	Old Growth logical
	m	m	m	y/n			m^2/ha	yrs		y/n
Middle Ouzel	**2833**	**2991**	**4329**	**n**	**1412**	**3**	**6.9**	**33**	**Sibold**	**n**
NSV3	**2804**	**2870**	**4239**	**n**	**767**	**38**	**87.2**	**129**	**Sibold**	**n**
Boulder Brook	2689	2845	4112	n	176	19	43.6	117	Sibold	n
Mill Creek	2606	2694	3953	n	293	7	16.1	117	Sibold	n
La Poudre Pass Creek	3052	3064	4584	y	58	2	4.6	70	cored	n
Hague Creek	2973	3011	4479	n	58	6	13.8	150	cored	n
Poudre River South	2957	2973	4444	n	31	3	6.9	100	cored	n
Corral Creek	3044	3055	4572	n	31	4	9.2	80	cored	n
Willow Creek	3026	3089	4571	n	89	6	13.8	110	avg	n
Bennet Creek	2467	2505	3720	n	351	13	29.8	150	cored	n
Cow Creek	2571	2688	3915	n	124	5	11.5	130	cored	n
Glacier Creek	2969	3030	4484	n	--	5	11.5	117	Sibold	n
Pennock Creek	2637	2713	3994	n	--	9	20.7	140	cored	n
Beaver Brook	2589	2639	3909	n	--	6	13.8	100	Sibold	n
Beaver Creek	2740	2765	4123	y	--	5.3	12.2	100	cored	n
Fall River	2789	2822	4200	n	--	7.3	16.8	120	Sibold	n
Roaring Creek	2686	2710	4041	n	--	7.6	17.4	90	cored	n
NFBT2	2380	2418	3589	n	--	8	18.4	160	cored	n
Lower Hunters	*2590*	*2912*	*4046*	*n*	*626*	*25*	*57.4*	*355*	*Sibold*	*y*
Upper Hunters	*2918*	*3046*	*4441*	*n*	*632*	*37*	*84.9*	*355*	*Sibold*	*y*
Upper Cony	*2912*	*3088*	*4456*	*n*	*858*	*45*	*103.3*	*500*	*Sibold*	*y*
Middle Cony	*2784*	*2857*	*4213*	*n*	*971*	*47*	*107.9*	*500*	*Sibold*	*y*
Upper Ouzel	*3049*	*3141*	*4620*	*n*	*339*	*35*	*80.3*	*500*	*Sibold*	*y*
NSV1	*3064*	*3210*	*4669*	*n*	*504*	*40*	*91.8*	*355*	*Sibold*	*y*
NSV2	*3021*	*3064*	*4553*	*n*	*621*	*47*	*107.9*	*355*	*Sibold*	*y*
Joe Wright Creek	*2958*	*3003*	*4460*	*y*	*247*	*15*	*34.4*	*220*	*cored*	*y*
Black Canyon Creek	*2730*	*2781*	*4121*	*n*	*--*	*8*	*18.4*	*200*	*cored*	*y*
NFJW	*2948*	*2971*	*4434*	*n*	*--*	*12*	*27.5*	*300*	*cored*	*y*
Fern Creek	*2570*	*2687*	*3914*	*n*	*--*	*6*	*13.8*	*280*	*Sibold*	*y*
NFBT1	*2328*	*2389*	*3523*	*n*	*--*	*4.6*	*10.6*	*240*	*cored*	*y*

Reach name	Total wood load	Total wood volume in jams	Total wood load in jams	Total wood load not in jams	Proportion of wood load in Jams
	m^3/ha channel surface	m^3	m^3/ha channel surface	m^3/ha channel surface	%
Middle Ouzel	**248**	**170.002**	**168.3**	**79.37**	**69%**
NSV3	**91**	**75.80**	**60.4**	**30.95**	**83%**
Boulder Brook	51	2.01	8.9	42.51	4%
Mill Creek	72	11.69	29.6	42.11	16%
La Poudre Pass Creek	5	2.57	1.9	3.04	52%
Hague Creek	13	4.33	4.8	7.98	34%
Poudre River South	3	0.99	0.7	2.04	36%
Corral Creek	5	0	0.0	5.25	0%
Willow Creek	17	4.56	6.4	10.77	27%
Bennet Creek	27	12.81	8.7	18.70	47%
Cow Creek	1	0.04	0.2	1.02	3%
Glacier Creek	--	15.16	24.6	--	--
Pennock Creek	--	0.19	0.3	--	--
Beaver Brook	--	70.95	558.7	--	--
Beaver Creek	--	1.20	1.6	--	--
Fall River	--	38.44	81.8	--	--
Roaring Creek	--	17.45	40.6	--	--
NFBT2	--	21.47	41.6	--	--
Lower Hunters	*100*	*30.348727*	*45.5*	*54.06*	*30%*
Upper Hunters	*151*	*55.55*	*96.9*	*54.49*	*37%*
Upper Cony	*159*	*88.783*	*106.6*	*52.08*	*56%*
Middle Cony	*117*	*65.2874*	*75.0*	*41.68*	*56%*
Upper Ouzel	*133*	*56.40*	*56.7*	*75.87*	*43%*
NSV1	*146*	*36.788*	*60.3*	*85.88*	*25%*
NSV2	*121*	*72.5588*	*84.8*	*36.54*	*60%*
Joe Wright Creek	*79*	*22.10*	*33.5*	*44.99*	*28%*
Black Canyon Creek	--	*102.16*	*785.8*	--	--
NFJW	--	*19.17*	*44.6*	--	--
Fern Creek	--	*81.27*	*203.2*	--	--
NFBT1	--	*80.17*	*156.3*	--	--

Reach name	Ramp and Bridge Spacing	Ramp Spacing	Bridge Spacing	Ramps, non-jam	Ramps, jam	Bridges, non-jam	Bridges, Jam	Jam Density	Jams per average width	Average Pieces/jam
	m	m	m	#/km	#/km	#/km	#/km	#/km	#/m	
Middle Ouzel	**2.8**	**2.9**	**62.5**	**183**	**162**	**7**	**9**	**77**	**8**	**13**
NSV3	**5.6**	**5.8**	**200.0**	**114**	**59**	**3**	**2**	**49**	**4**	**10**
Boulder Brook	11.4	19.6	27.0	40	11	35	2	12	5	4
Mill Creek	11.1	15.6	38.5	44	20	17	9	23	6	6
La Poudre Pass Creek	125.0	125.0	>1000	7	1	0	0	5	0	5
Hague Creek	52.6	52.6	>1000	15	4	0	0	4	0	5
Poudre River South	125.0	125.0	>1000	6	2	0	0	2	0	7
Corral Creek	111.1	166.7	333.3	6	0	3	0	0	0	0
Willow Creek	37.0	38.5	1000.0	18	8	1	0	6	1	6
Bennet Creek	5.8	11.9	11.4	54	30	67	21	22	1	7
Cow Creek	11.0	22.7	21.3	32	12	46	1	9	4	5
Glacier Creek	16.4	22.7	58.8	35	9	11	6	10	2	6
Pennock Creek	19.6	27.8	66.7	32	4	11	4	4	1	6
Beaver Brook	3.5	7.9	6.3	74	52	119	41	34	27	5
Beaver Creek	40.0	40.0	>1000	24	1	0	0	4	1	4
Fall River	6.0	9.8	15.4	66	36	49	16	23	5	8
Roaring Creek	12.5	14.7	83.3	51	17	10	2	11	3	9
NFBT2	12.0	15.2	58.8	41	25	12	5	15	3	9
Lower Hunters	*6.7*	*6.8*	*333.3*	*106*	*40*	*2*	*1*	*47*	*7*	*6*
Upper Hunters	*5.6*	*6.0*	*83.3*	*90*	*76*	*7*	*5*	*49*	*9*	*9*
Upper Cony	*5.8*	*5.8*	*>1000*	*100*	*71*	*0*	*0*	*63*	*8*	*9*
Middle Cony	*5.4*	*5.6*	*142.9*	*109*	*70*	*1*	*6*	*62*	*7*	*10*
Upper Ouzel	*9.8*	*9.8*	*>1000*	*67*	*35*	*0*	*0*	*37*	*4*	*7*
NSV1	*10.6*	*10.6*	*>1000*	*66*	*28*	*0*	*0*	*44*	*7*	*6*
NSV2	*6.0*	*6.3*	*125.0*	*82*	*76*	*3*	*5*	*45*	*5*	*9*
Joe Wright Creek	*11.8*	*14.5*	*62.5*	*57*	*12*	*12*	*4*	*11*	*2*	*11*
Black Canyon Creek	*2.8*	*5.7*	*5.5*	*125*	*50*	*175*	*7*	*26*	*20*	*5*
NFJW	*9.6*	*12.2*	*45.5*	*72*	*10*	*18*	*4*	*9*	*2*	*8*
Fern Creek	*4.6*	*6.5*	*16.0*	*98*	*56*	*34*	*28*	*52*	*13*	*7*
NFBT1	*5.8*	*6.9*	*37.0*	*94*	*51*	*14*	*13*	*35*	*7*	*9*

Reach name	Average mass of carbon in jam sediment	Estimated reach carbon load due to sediment	Average mass total carbon in jams (wood + sediment)	Estimated reach total carbon load
	kg	kg/km	kg	kg/km
Middle Ouzel	**109.45**	**5057**	**1978.2**	**152322**
NSV3	**n/a**	**0**	**880.4**	**43137**
Boulder Brook	20.09	145	85.5	1026
Mill Creek	12.82	177	449.0	10326
La Poudre Pass Creek	--	--	--	--
Hague Creek	78.33	188	188.9	755
Poudre River South	--	--	--	--
Corral Creek	--	--	--	--
Willow Creek	--	--	--	--
Bennet Creek	441.11	5823	601.4	13231
Cow Creek	26.4	143	164.2	1478
Glacier Creek	--	--	--	--
Pennock Creek	--	--	--	--
Beaver Brook	--	--	--	--
Beaver Creek	--	--	--	--
Fall River	--	--	--	--
Roaring Creek	--	--	--	--
NFBT2	--	--	--	--
Lower Hunters	--	--	--	--
Upper Hunters	*n/a*	*0*	*729.8*	*35760*
Upper Cony	--	--	--	--
Middle Cony	*n/a*	*0*	*1356.7*	*84114*
Upper Ouzel	--	--	--	--
NSV1	--	--	--	--
NSV2	--	--	--	--
Joe Wright Creek	*84.09*	*555*	*540.9*	*5950*
Black Canyon Creek	*30.98*	*483*	*372.9*	*9695*
NFJW	*371.47*	*2006*	*757.7*	*6819*
Fern Creek	--	--	--	--
NFBT1	*402.67*	*8456*	*950.7*	*33275*

Reach name	Average Log Diameter (in jams)	Average Log Diameter (reach)	Total Log D16	Total Log D50	Total Log D84	Total Dmax
	cm	cm	cm	cm	cm	cm
Middle Ouzel	**20**	**20**	**12**	**19**	**27**	**66**
NSV3	**21**	**21**	**12**	**19**	**29**	**85**
Boulder Brook	14	14	11	14	17	48
Mill Creek	15	15	11	14	18	41
La Poudre Pass Creek	20	21	13	19	27	42
Hague Creek	20	19	12	17	27	34
Poudre River South	15	16	12	16	19	30
Corral Creek	--	16	13	17	18	25
Willow Creek	18	18	14	16.5	22	43
Bennet Creek	16	16	11	15	23	35
Cow Creek	19	19	13	17	26	48
Glacier Creek	19	--	--	--	--	--
Pennock Creek	19	--	--	--	--	--
Beaver Brook	15	--	--	--	--	--
Beaver Creek	14	--	--	--	--	--
Fall River	17	--	--	--	--	--
Roaring Creek	15	--	--	--	--	--
NFBT2	16	--	--	--	--	--
Lower Hunters	*16*	*16*	*10*	*14*	*22*	*53*
Upper Hunters	*18*	*18*	*11*	*15*	*25*	*66*
Upper Cony	*20*	*20*	*12*	*17*	*28*	*55*
Middle Cony	*17*	*17*	*11*	*15*	*23*	*54*
Upper Ouzel	*25*	*26*	*14*	*24*	*35*	*78*
NSV1	*20*	*22*	*13*	*19*	*31*	*70*
NSV2	*22*	*22*	*14*	*20*	*29*	*70*
Joe Wright Creek	*20*	*21*	*13*	*18*	*30*	*70*
Black Canyon Creek	*18*	--	--	--	--	--
NFJW	*19*	--	--	--	--	--
Fern Creek	*17*	--	--	--	--	--
NFBT1	*19*	--	--	--	--	--

Reach name	Jam Log D16	Jam Log D50	Jam Log D84	Jam Log Dmax	Non-Jam Log D16	Non-Jam Log D50	Non-Jam Log D84	Non-Jam Log Dmax	Avg log length (in jams)	Avg log length (reach)
	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm
Middle Ouzel	**12**	**19**	**27**	**66**	**12**	**20**	**27**	**52**	**329**	**354**
NSV3	**12**	**19**	**30**	**57**	**13**	**20**	**28.5**	**85**	**281**	**273**
Boulder Brook	10	13	15	24	11	14	17	48	311	419
Mill Creek	10	14	18	41	11	14	18	38	369	398
La Poudre Pass Creek	13	19	25	34	13	19	30	42	282	266
Hague Creek	12	17	29	32	13	17	26	34	452	163
Poudre River South	12	13	17	25	14	16	20	30	322	97
Corral Creek	--	--	--	--	--	--	--	--	--	78
Willow Creek	13	16	22	29	14	17	22	43	408	182
Bennet Creek	11	15	22	31	12	15	23	35	299	391
Cow Creek	10	15	19	29	14	18	28	48	523	--
Glacier Creek	15	17	23	39	--	--	--	--	351	--
Pennock Creek	13	16.5	27.5	65	--	--	--	--	488	--
Beaver Brook	13	15	18	27	--	--	--	--	257	--
Beaver Creek	13	14	16	19	--	--	--	--	303	--
Fall River	12.5	16	19	52	--	--	--	--	360	--
Roaring Creek	10	13	21	39	--	--	--	--	251	--
NFBT2	13	15	17.5	58	--	--	--	--	301	--
Lower Hunters	*10*	*13*	*21*	*52*	*10*	*14*	*23*	*53*	*291*	*330*
Upper Hunters	*11*	*15*	*24*	*66*	*10*	*16*	*26*	*52*	*302*	*331*
Upper Cony	*12*	*17*	*28*	*55*	*12*	*17*	*28*	*46*	*299*	*311*
Middle Cony	*11*	*15*	*23*	*54*	*11*	*16*	*24*	*50*	*297*	*307*
Upper Ouzel	*14*	*24*	*34.5*	*78*	*15*	*25*	*36*	*62*	*280*	*322*
NSV1	*12*	*17*	*28*	*70*	*14*	*22*	*33.5*	*70*	*253*	*277*
NSV2	*13*	*20*	*29*	*70*	*14*	*21*	*29*	*64*	*289*	*289*
Joe Wright Creek	*12*	*17*	*28*	*50*	*14*	*20*	*33*	*70*	*441*	*445*
Black Canyon Creek	*13*	*17*	*20*	*64*	--	--	--	--	*337*	--
NFJW	*14*	*17*	*22*	*38*	--	--	--	--	*310*	--
Fern Creek	*11*	*16*	*22*	*54*	--	--	--	--	*303*	--
NFBT1	*14*	*17*	*26*	*43*	--	--	--	--	*325*	--

APPENDIX B- INDIVIDUAL JAM SURVEY DATA

Jam Name	Reach Name	Survey date	Stand age	Stand Age Method	Forest Category	Old Growth Logical	Basal Tree Count	Basal Area	Jam breached by end of data collection (2011)?	Jam on multi channel stream?
			yrs					m^2/ha	y/n	y/n
Bennet 1	**Bennet Creek**	**2011**	**150**	**cored**	**A**	**n**	**13**	**29.8**	**n**	**n**
Boulder 1	**Boulder Brook**	**2011**	**117**	**Sibold**	**A**	**n**	**14**	**32.1**	**n**	**n**
Boulder 2	**Boulder Brook**	**2011**	**117**	**Sibold**	**A**	**n**	**15**	**34.4**	**n**	**n**
Cow Creek 1	**Cow Creek**	**2011**	**130**	**cored**	**A**	**n**	**6**	**13.8**	**n**	**n**
Cow Creek 2	**Cow Creek**	**2011**	**130**	**cored**	**A**	**n**	**9**	**20.7**	**n**	**n**
Cow Creek 3	**--**	**2011**	**130**	**cored**	**A**	**n**	**9**	**20.7**	**n**	**n**
Hauge Creek 1	**Hauge Creek**	**2011**	**150**	**cored**	**A**	**n**	**14**	**32.1**	**n**	**y**
Hauge Creek 2	**Hauge Creek**	**2011**	**150**	**cored**	**A**	**n**	**14**	**32.1**	**n**	**y**
Mill 1	**Mill Creek**	**2011**	**117**	**Sibold**	**A**	**n**	**8**	**18.4**	**n**	**n**
Mill 2	**Mill Creek**	**2011**	**117**	**Sibold**	**A**	**n**	**11**	**25.3**	**n**	**n**
Coney 3	--	2010	130	Sibold	D	n	17	39.0	n	n
NSV 3	NSV3	2011	130	Sibold	D	n	20	45.9	n	y
NSV 4	NSV3	2011	130	Sibold	D	n	9	20.7	y	n
Ouzel 3	Middle Ouzel	2010	35	Sibold	D	n	1	2.3	n	n
Ouzel 4	--	2010	35	Sibold	D	n	6	13.8	n	n
Black Canyon 1	*Black Canyon*	*2011*	*200*	*cored*	*O*	*y*	*8*	*18.4*	*n*	*n*
Black Canyon 2	*Black Canyon*	*2011*	*200*	*cored*	*O*	*y*	*7*	*16.1*	*y*	*n*
Coney 1	*Middle Cony*	*2010*	*340*	*Sibold*	*O*	*y*	*17*	*39.0*	*n*	*y*
Coney 2	*Middle Cony*	*2010*	*340*	*Sibold*	*O*	*y*	*18*	*41.3*	*n*	*y*
Hunter 1	*Upper Hunters*	*2011*	*355*	*Sibold*	*O*	*y*	*21*	*48.2*	*n*	*y*
Hunter 2	*Upper Hunters*	*2011*	*355*	*Sibold*	*O*	*y*	*31*	*71.2*	*n*	*y*
NFBT 1	*NFBT1*	*2011*	*240*	*cored*	*O*	*y*	*8*	*18.4*	*n*	*n*
NFBT 2	*NFBT1*	*2011*	*240*	*cored*	*O*	*y*	*1*	*2.3*	*n*	*n*
NFBT 3	*NFBT1*	*2011*	*240*	*cored*	*O*	*y*	*5*	*11.5*	*n*	*n*
NSV 1	*--*	*2010*	*355*	*Sibold*	*O*	*y*	*17*	*39.0*	*y*	*y*
NSV 2	*--*	*2010*	*355*	*Sibold*	*O*	*y*	*10*	*23.0*	*y*	*y*
Ouzel 1	*--*	*2010*	*355*	*Sibold*	*O*	*y*	*12*	*27.5*	*n*	*n*
Ouzel 2	*--*	*2010*	*355*	*Sibold*	*O*	*y*	*10*	*23.0*	*n*	*n*
JW 1	*Joe Wright*	*2011*	*220*	*cored*	*O*	*y*	*14*	*32.1*	*n*	*n*
NFJW 1	*NFJW*	*2011*	*300*	*cored*	*O*	*y*	*16*	*36.7*	*n*	*n*

Jam Name	Vstar Sediment depth	Sediment Surface Area	Sediment Volume	OM (LOI) for < 2mm fraction	OM (LOI), total sediment including 2mm fraction	Volume OM in sediment	Mass carbon in sediment (bulk density of 1330 kg/m^3)	Wood volume in jam	Volume OM in wood (0.5 x total vol)	Mass OM in wood (@450 kg/m^3)
	cm	m^2	m^3	% g/g	% g/g	m^3	kg	m^3	m^3	kg
Bennet 1	**37.12**	**22.34**	**8.29**	**8.16**	**9.51**	**0.79**	**524.37**	**0.67**	**0.34**	**151.45**
Boulder 1	**--**	**--**	**3.64**	**1.96**	**2.77**	**0.10**	**67.12**	**0.35**	**0.17**	**78.55**
Boulder 2	**34.00**	**2.35**	**0.80**	**0.51**	**0.49**	**0.00**	**2.60**	**0.19**	**0.09**	**42.18**
Cow Creek 1	**34.88**	**5.50**	**1.92**	**0.94**	**0.95**	**0.02**	**12.11**	**0.80**	**0.40**	**180.71**
Cow Creek 2	**39.00**	**7.72**	**3.01**	**1.58**	**1.38**	**0.04**	**27.63**	**0.46**	**0.23**	**104.04**
Cow Creek 3	**32.90**	**8.10**	**2.67**	**1.00**	**1.00**	**0.03**	**17.73**	**1.98**	**0.99**	**444.80**
Hauge Creek 1	**48.75**	**3.21**	**1.91**	**1.74**	**1.62**	**0.03**	**20.62**	**0.44**	**0.22**	**99.40**
Hauge Creek 2	**39.50**	**0.84**	**1.56**	**1.53**	**1.43**	**0.02**	**14.87**	**1.07**	**0.53**	**240.28**
Mill 1	**62.86**	**4.15**	**2.61**	**1.12**	**1.10**	**0.03**	**19.07**	**2.19**	**1.10**	**493.79**
Mill 2	**38.67**	**3.23**	**1.25**	**1.14**	**1.09**	**0.01**	**9.06**	**1.67**	**0.83**	**375.26**
Coney 3	32.58	4.81	1.57	4.66	3.36	0.05	34.99	2.88	1.44	648.73
NSV 3	--	--	2.31	2.04	3.21	0.07	49.39	4.81	2.40	1081.55
NSV 4	27.20	3.36	0.91	3.07	4.24	0.04	25.78	2.80	1.40	629.10
Ouzel 3	26.50	21.61	5.73	3.74	1.80	0.10	68.55	8.2	4.08	1835.78
Ouzel 4	22.09	3.49	0.77	12.81	12.69	0.10	64.98	6.8	3.41	1533.72
Black Canyon 1	*32.50*	*5.89*	*1.91*	*1.16*	*1.12*	*0.02*	*14.26*	*1.4*	*0.71*	*318.70*
Black Canyon 2	*55.54*	*6.43*	*3.57*	*8.61*	*18.63*	*0.67*	*442.61*	*0.9*	*0.46*	*207.78*
Coney 1	*42.33*	*24.13*	*10.21*	*13.18*	*15.57*	*1.59*	*1057.60*	*4.58*	*2.29*	*1031.62*
Coney 2	*45.27*	*13.69*	*6.20*	*7.92*	*9.50*	*0.59*	*391.55*	*2.04*	*1.02*	*460.03*
Hunter 1	*24.60*	*45.92*	*11.30*	*2.90*	*4.95*	*0.56*	*371.84*	*2.91*	*1.45*	*654.06*
Hunter 2	*28.25*	*6.32*	*1.79*	*5.46*	*11.14*	*0.20*	*132.30*	*2.32*	*1.16*	*522.85*
NFBT 1	*34.70*	*8.93*	*3.10*	*2.50*	*3.32*	*0.10*	*68.42*	*3.07*	*1.53*	*689.85*
NFBT 2	*40.00*	*21.87*	*8.75*	*6.08*	*3.02*	*0.26*	*175.72*	*3.60*	*1.80*	*809.97*
NFBT 3	*24.57*	*20.16*	*4.95*	*3.11*	*5.04*	*0.25*	*166.05*	*3.75*	*1.88*	*844.62*
NSV 1	*40.38*	*26.85*	*10.84*	*21.35*	*24.51*	*2.66*	*1767.21*	*9.68*	*4.84*	*2178.00*
NSV 2	*23.71*	*3.89*	*0.92*	*3.16*	*5.47*	*0.05*	*33.52*	*0.96*	*0.48*	*215.57*
Ouzel 1	*29.47*	*7.03*	*2.07*	*20.98*	*21.58*	*0.45*	*297.10*	*5.8*	*2.90*	*1303.37*
Ouzel 2	*20.17*	*3.92*	*0.79*	*19.99*	*17.25*	*0.14*	*90.64*	*4.9*	*2.44*	*1098.12*
JW 1	*28.10*	*15.00*	*4.22*	*3.49*	*2.74*	*0.12*	*76.80*	*1.97*	*0.98*	*443.04*
NFJW 1	*54.90*	*16.96*	*9.31*	*5.81*	*6.59*	*0.61*	*407.99*	*1.77*	*0.88*	*397.98*

Jam Name	Total carbon in jam	Proportion carbon as wood	OM in Non-jam-comparison D/S (LOI, <2mm)	OM in Non-jam-comparison U/S (LOI, <2mm)	Valley type	Total WSEL drop through jam (low flow)	Water surface slope
	kg	kg/kg	%	%		m	m/m
Bennet 1	**675.83**	**0.22**	**--**	**--**	**un**	**0.5**	**0.03**
Boulder 1	**145.67**	**0.54**	**0.56**	**0.87**	**semi**	**0.8**	**0.12**
Boulder 2	**44.79**	**0.94**	**0.67**	**0.56**	**semi**	**0.8**	**0.11**
Cow Creek 1	**192.82**	**0.94**	**--**	**1.36**	**semi**	**0.7**	**0.07**
Cow Creek 2	**131.68**	**0.79**	**0.72**	**1.94**	**semi**	**1.3**	**0.09**
Cow Creek 3	**462.53**	**0.96**	**--**	**--**	**un**	**0.4**	**0.01**
Hauge Creek 1	**120.03**	**0.83**	**--**	**2.31**	**semi**	**0.5**	**0.07**
Hauge Creek 2	**255.15**	**0.94**	**1.69**	**--**	**semi**	**0.2**	**0.07**
Mill 1	**512.86**	**0.96**	**0.95**	**1.71**	**un**	**0.9**	**0.05**
Mill 2	**384.33**	**0.98**	**1.11**	**--**	**un**	**1.2**	**0.13**
Coney 3	683.72	0.95	--	2.60	confined	0.9	0.14
NSV 3	1130.94	0.96	--	--	semi	1.5	0.06
NSV 4	654.88	0.96	--	--	confined	1.1	0.08
Ouzel 3	1904.33	0.96	--	4.37	un	0.9	0.06
Ouzel 4	1598.70	0.96	--	4.88	un	1.3	0.09
Black Canyon 1	*332.95*	*0.96*	*2.79*	*0.73*	*semi*	*0.3*	*0.03*
Black Canyon 2	*650.39*	*0.32*	*--*	*1.05*	*semi*	*0.5*	*0.05*
Coney 1	*2089.22*	*0.49*	*1.72*	*5.06*	*confined*	*0.9*	*0.03*
Coney 2	*851.57*	*0.54*	*1.31*	*2.46*	*confined*	*1.0*	*0.10*
Hunter 1	*1025.89*	*0.64*	*0.63*	*0.58*	*semi*	*1.0*	*0.05*
Hunter 2	*655.15*	*0.80*	*4.25*	*0.78*	*semi*	*0.9*	*0.05*
NFBT 1	*758.27*	*0.91*	*0.76*	*11.16*	*confined*	*1.3*	*0.04*
NFBT 2	*985.69*	*0.82*	*0.92*	*1.62*	*confined*	*1.2*	*0.04*
NFBT 3	*1010.67*	*0.84*	*1.86*	*1.03*	*semi*	*0.8*	*0.02*
NSV 1	*3945.21*	*0.55*	*1.28*	*1.34*	*seme*	*0.7*	*0.04*
NSV 2	*249.09*	*0.87*	*--*	*--*	*semi*	*0.2*	*0.04*
Ouzel 1	*1600.47*	*0.81*	*--*	*7.43*	*confined*	*0.3*	*0.03*
Ouzel 2	*1188.76*	*0.92*	*--*	*4.32*	*semi*	*0.6*	*0.05*
JW 1	*519.84*	*0.85*	*2.06*	*10.14*	*semi*	*1.0*	*0.03*
NFJW 1	*805.97*	*0.49*	*7.13*	*6.54*	*semi*	*1.1*	*0.05*

Jam Name	Number of pieces in jam	Average volume per peice	Volume of max piece	Max piece ratio (max piece/ avg piece)	Average Log Diameter
		m^3	m^3		cm
Bennet 1	**7**	**0.10**	**0.17**	**2**	**21**
Boulder 1	**6**	**0.06**	**0.09**	**2**	**16**
Boulder 2	**7**	**0.03**	**0.05**	**2**	**14**
Cow Creek 1	**6**	**0.13**	**0.48**	**4**	**17**
Cow Creek 2	**7**	**0.07**	**0.36**	**5**	**13**
Cow Creek 3	**8**	**0.25**	**0.79**	**3**	**24**
Hauge Creek 1	**5**	**0.09**	**0.36**	**4**	**17**
Hauge Creek 2	**9**	**0.12**	**0.32**	**3**	**21**
Mill 1	**7**	**0.31**	**1.11**	**4**	**21**
Mill 2	**14**	**0.12**	**1.67**	**14**	**18**
Coney 3	20	0.14	0.54	4	19
NSV 3	29	0.17	1.06	6	22
NSV 4	24	0.12	1.11	10	20
Ouzel 3	63	0.13	0.87	7	20
Ouzel 4	40	0.17	2.04	12	19
Black Canyon 1	*5*	*0.28*	*0.74*	*3*	*18*
Black Canyon 2	*4*	*0.23*	*0.43*	*2*	*24*
Coney 1	*58*	*0.08*	*1.03*	*13*	*18*
Coney 2	*41*	*0.05*	*0.19*	*4*	*15*
Hunter 1	*13*	*0.22*	*0.64*	*3*	*25*
Hunter 2	*13*	*0.18*	*0.91*	*5*	*19*
NFBT 1	*16*	*0.19*	*0.81*	*4*	*22*
NFBT 2	*21*	*0.17*	*1.19*	*7*	*22*
NFBT 3	*30*	*0.13*	*0.97*	*8*	*17*
NSV 1	*59*	*0.16*	*3.27*	*20*	*18*
NSV 2	*5*	*0.19*	*0.76*	*4*	*19*
Ouzel 1	*52*	*0.11*	*0.77*	*7*	*18*
Ouzel 2	*46*	*0.11*	*1.00*	*9*	*17*
JW 1	*17*	*0.12*	*0.41*	*4*	*21*
NFJW 1	*15*	*0.12*	*0.36*	*3*	*20*

APPENDIX C- LOSS ON IGNITION (LOI) DATA

Notes: 1: Drainage basin for stream, either Big Thompson (BT), Cache la Poudre (Poudre) or North Saint Vrain (NSV)
2: Survey type being conducted when sample was taken, either reach or individual jam level
3: Type of sediment sample collected, either in the sediment upstream of the jam (sed) or in a non-jam area of flow seperation (NJC)
4: For individual jam-level surveys, the position (upstream or downstream) of the comparison sample

Stream Name	Jam Number (from U/S to D/S)	Jam Name	Basin[1]	Survey type[2]	Sample type[3]	Position of sample relative to jam[4]	Forest Age	Old growth logical	Sample date	OM in sample (< 2mm fraction only)	OM in sample (including >2mm fraction)
							yrs	y/n		% (g/g)	% (g/g)
Beaver Brook	NA	NA	BT	reach	jam	NA	100	n	2011	1.29	2.35
Beaver Brook	NA	NA	BT	reach	NJC	NA	100	n	2011	1.19	1.06
Beaver Creek	NA	NA	BT	reach	NJC	NA	100	n	2011	1.81	2.81
Bennet Creek	1	Bennet 1	Poudre	individual jam	jam	sed	150	n	2011	1.57	1.57
Bennet Creek	1	Bennet 1	Poudre	individual jam	jam	sed	150	n	2011	16.49	19.33
Bennet Creek	1	Bennet 1	Poudre	individual jam	jam	sed	150	n	2011	6.42	7.63
Bennet Creek	NA	NA	Poudre	reach	jam	NA	150	n	2010	15.57	21.35
Bennet Creek	NA	NA	Poudre	reach	NJC	NA	150	n	2010	1.17	1.18
Black Canyon	1	Black Canyon 1	BT	individual jam	jam	sed	200	y	2011	1.16	1.12
Black Canyon	1	Black Canyon 1	BT	individual jam	NJC	ds	200	y	2011	2.79	2.73
Black Canyon	1	Black Canyon 1	BT	individual jam	NJC	us	200	y	2011	0.73	0.73
Black Canyon	2	Black Canyon 2	BT	individual jam	jam	sed	200	y	2011	13.42	29.18
Black Canyon	2	Black Canyon 2	BT	individual jam	jam	sed	200	y	2011	3.80	8.09
Black Canyon	2	Black Canyon 2	BT	individual jam	NJC	us	200	y	2011	1.05	1.05
Black Canyon	NA	NA	BT	reach	NJC	NA	200	y	2011	3.53	7.19
Black Canyon	NA	NA	BT	reach	jam	NA	200	y	2011	0.97	0.91
Black Canyon	NA	NA	BT	reach	jam	NA	200	y	2011	1.82	4.61
Black Canyon	NA	NA	BT	reach	NJC	NA	200	y	2011	1.54	1.46
Boulder Brook	1	Boulder 1	BT	individual jam	NJC	ds	117	n	2011	0.87	0.32
Boulder Brook	1	Boulder 1	BT	individual jam	NJC	us	117	n	2011	0.56	0.27
Boulder Brook	1	Boulder 1	BT	individual jam	jam	sed	117	n	2011	1.06	1.06
Boulder Brook	1	Boulder 1	BT	individual jam	jam	sed	117	n	2011	0.55	0.55
Boulder Brook	1	Boulder 1	BT	individual jam	jam	sed	117	n	2011	4.27	6.68
Boulder Brook	2	Boulder 2	BT	individual jam	NJC	ds	117	n	2011	0.60	0.37
Boulder Brook	2	Boulder 2	BT	individual jam	jam	ds	117	n	2011	0.74	0.44
Boulder Brook	2	Boulder 2	BT	individual jam	jam	sed	117	n	2011	0.51	0.51
Boulder Brook	2	Boulder 2	BT	individual jam	jam	sed	117	n	2011	0.51	0.51
Boulder Brook	NA	NA	BT	reach	jam	NA	117	n	2010	1.58	1.94
Boulder Brook	NA	NA	BT	reach	NJC	NA	117	n	2010	1.15	0.92
Coney	1	Coney 1	NSV	individual jam	jam	sed	340	y	2010	4.10	3.92
Coney	1	Coney 1	NSV	individual jam	jam	sed	340	y	2010	30.86	35.09
Coney	1	Coney 1	NSV	individual jam	jam	sed	340	y	2010	10.48	14.34
Coney	1	Coney 1	NSV	individual jam	NJC	ds	340	y	2011	1.72	1.47
Coney	1	Coney 1	NSV	individual jam	NJC	us	340	y	2011	5.06	11.14
Coney	1	Coney 1	NSV	individual jam	jam	sed	340	y	2010	2.54	1.65
Coney	1	Coney 1	NSV	individual jam	jam	sed	340	y	2010	28.74	34.36
Coney	1	Coney 1	NSV	individual jam	jam	sed	340	y	2010	2.38	4.06
Coney	2	Coney 2	NSV	individual jam	jam	sed	340	y	2010	1.04	1.04
Coney	2	Coney 2	NSV	individual jam	jam	sed	340	y	2010	1.29	1.52
Coney	2	Coney 2	NSV	individual jam	jam	sed	340	y	2010	15.76	25.10
Coney	2	Coney 2	NSV	individual jam	NJC	ds	340	y	2011	1.31	2.31
Coney	2	Coney 2	NSV	individual jam	NJC	us	340	y	2011	2.46	1.85
Coney	2	Coney 2	NSV	individual jam	jam	sed	340	y	2010	1.40	1.42
Coney	2	Coney 2	NSV	individual jam	jam	sed	340	y	2010	5.74	3.21
Coney	2	Coney 2	NSV	individual jam	jam	sed	340	y	2010	1.76	1.48
Coney	2	Coney 2	NSV	individual jam	jam	sed	340	y	2010	28.47	32.70
Coney	3	Coney 3	NSV	individual jam	NJC	us	130	d	2011	1.26	0.84
Coney	3	Coney 3	NSV	individual jam	NJC	us	130	d	2011	3.94	7.72
Coney	3	Coney 3	NSV	individual jam	jam	sed	130	d	2010	3.27	1.99
Coney	3	Coney 3	NSV	individual jam	jam	sed	130	d	2010	6.05	4.72
Corral Creek	NA	NA	Poudre	reach	NJC	NA	80	n	2010	1.91	0.67
Cow Creek	1	Cow Creek 1	BT	individual jam	NJC	us	130	n	2011	1.36	1.19
Cow Creek	1	Cow Creek 1	BT	individual jam	jam	sed	130	n	2011	1.34	1.36
Cow Creek	1	Cow Creek 1	BT	individual jam	jam	sed	130	n	2011	0.54	0.54
Cow Creek	2	Cow Creek 2	BT	individual jam	NJC	ds	130	n	2011	0.72	0.61
Cow Creek	2	Cow Creek 2	BT	individual jam	NJC	us	130	n	2011	1.94	1.63
Cow Creek	2	Cow Creek 2	BT	individual jam	jam	sed	130	n	2011	0.59	0.56
Cow Creek	2	Cow Creek 2	BT	individual jam	jam	sed	130	n	2011	2.23	1.71
Cow Creek	2	Cow Creek 2	BT	individual jam	jam	sed	130	n	2011	1.93	1.87
Cow Creek	NA	NA	BT	reach	jam	NA	130	n	2011	1.09	1.09
Cow Creek	NA	NA	BT	reach	NJC	NA	130	n	2011	3.07	7.59
Fall River	NA	NA	BT	reach	jam	NA	120	n	2011	1.95	5.61
Fall River	NA	NA	BT	reach	NJC	NA	120	n	2011	8.95	25.57
Glacier	NA	NA	BT	reach	jam	NA	117	n	2011	40.91	13.75
Glacier	NA	NA	BT	reach	NJC	NA	117	n	2011	20.44	4.58

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3: Type of sediment sample collected, either in the sediment upstream of the jam (sed) or in a non-jam area of flow seperation (NJC)
4: For individual jam-level surveys, the position (upstream or downstream) of the comparison sample

Stream Name	Jam Number (from U/S to D/S)	Jam Name	Basin[1]	Survey type[2]	Sample type[3]	Position of sample relative to jam[4]	Forest Age	Old growth logical	Sample date	OM in sample (< 2mm fraction only)	OM in sample (including >2mm fraction)
							yrs	y/n		% (g/g)	% (g/g)
Hague	1	Hauge Creek 1	Poudre	individual jam	jam	sed	150	n	2011	1.25	1.01
Hague	1	Hauge Creek 1	Poudre	individual jam	jam	sed	150	n	2011	2.23	2.22
Hague	1	Hauge Creek 1	Poudre	individual jam	NJC	us	150	n	2011	2.31	2.31
Hague	2	Hauge Creek 2	Poudre	individual jam	NJC	ds	150	n	2011	1.69	1.67
Hague	2	Hauge Creek 2	Poudre	individual jam	jam	sed	150	n	2011	1.42	1.24
Hague	2	Hauge Creek 2	Poudre	individual jam	jam	sed	150	n	2011	1.64	1.62
Hague	NA	NA	Poudre	reach	NJC	NA	150	n	2010	2.31	2.87
Hague	NA	NA	Poudre	reach	NJC	NA	150	n	2010	1.65	1.90
Hunter	1	Hunter 1	NSV	individual jam	NJC	ds	355	y	2011	0.63	0.60
Hunter	1	Hunter 1	NSV	individual jam	jam	us	355	y	2011	0.58	0.49
Hunter	1	Hunter 1	NSV	individual jam	jam	sed	355	y	2011	4.86	7.46
Hunter	1	Hunter 1	NSV	individual jam	jam	sed	355	y	2011	3.46	8.28
Hunter	1	Hunter 1	NSV	individual jam	jam	sed	355	y	2011	1.03	1.03
Hunter	1	Hunter 1	NSV	individual jam	jam	sed	355	y	2011	2.24	3.04
Hunter	2	Hunter 2	NSV	individual jam	NJC	ds	355	y	2011	4.25	7.79
Hunter	2	Hunter 2	NSV	individual jam	jam	us	355	y	2011	0.78	0.56
Hunter	2	Hunter 2	NSV	individual jam	jam	sed	355	y	2011	13.17	29.65
Hunter	2	Hunter 2	NSV	individual jam	jam	sed	355	y	2011	2.10	2.35
Hunter	2	Hunter 2	NSV	individual jam	jam	sed	355	y	2011	1.11	1.41
JW	1	JW 1	Poudre	individual jam	NJC	ds	220	y	2011	2.06	0.42
JW	1	JW 1	Poudre	individual jam	NJC	us	220	y	2011	10.14	0.68
JW	1	JW 1	Poudre	individual jam	jam	sed	220	y	2011	4.21	1.65
JW	1	JW 1	Poudre	individual jam	jam	sed	220	y	2011	3.49	4.14
JW	1	JW 1	Poudre	individual jam	jam	sed	220	y	2011	2.76	2.43
JW	NA	NA	Poudre	reach	jam	NA	220	y	2010	3.89	4.75
JW	NA	NA	Poudre	reach	NJC	NA	220	y	2010	2.24	1.81
LPPC	NA	NA	Poudre	reach	NJC	NA	70	n	2010	1.32	1.22
LPPC	NA	NA	Poudre	reach	NJC	NA	70	n	2010	1.84	1.84
Mill	1	Mill 1	BT	individual jam	jam	sed	117	n	2011	1.12	1.12
Mill	1	Mill 1	BT	individual jam	jam	ds	117	n	2011	0.95	0.58
Mill	1	Mill 1	BT	individual jam	NJC	us	117	n	2011	1.71	1.70
Mill	1	Mill 1	BT	individual jam	jam	sed	117	n	2011	0.73	0.73
Mill	1	Mill 1	BT	individual jam	jam	sed	117	n	2011	1.51	1.47
Mill	2	Mill 2	BT	individual jam	jam	sed	117	n	2011	1.34	1.31
Mill	2	Mill 2	BT	individual jam	jam	sed	117	n	2011	1.25	1.25
Mill	2	Mill 2	BT	individual jam	NJC	ds	117	n	2011	1.11	1.08
Mill	2	Mill 2	BT	individual jam	jam	sed	117	n	2011	0.83	0.71
Mill	NA	NA	BT	reach	jam	NA	117	n	2010	3.97	4.75
Mill	NA	NA	BT	reach	NJC	NA	117	n	2010	0.90	0.58
NFBT	1	NFBT 1	BT	individual jam	NJC	ds	240	y	2011	0.76	0.91
NFBT	1	NFBT 1	BT	individual jam	NJC	us	240	y	2011	11.16	16.04
NFBT	1	NFBT 1	BT	individual jam	jam	sed	240	y	2011	1.95	4.01
NFBT	1	NFBT 1	BT	individual jam	jam	sed	240	y	2011	3.82	2.46
NFBT	1	NFBT 1	BT	individual jam	jam	sed	240	y	2011	1.72	3.48
NFBT	2	NFBT 2	BT	individual jam	NJC	ds	240	y	2011	0.92	0.79
NFBT	2	NFBT 2	BT	individual jam	NJC	us	240	y	2011	1.62	3.23
NFBT	2	NFBT 2	BT	individual jam	jam	sed	240	y	2011	0.76	1.21
NFBT	2	NFBT 2	BT	individual jam	jam	sed	240	y	2011	1.24	2.12
NFBT	2	NFBT 2	BT	individual jam	jam	sed	240	y	2011	16.25	5.74
NFBT	3	NFBT 3	BT	individual jam	NJC	ds	240	y	2011	1.86	1.68
NFBT	3	NFBT 3	BT	individual jam	NJC	us	240	y	2011	1.03	0.96
NFBT	3	NFBT 3	BT	individual jam	jam	sed	240	y	2011	0.58	0.79
NFBT	3	NFBT 3	BT	individual jam	jam	sed	240	y	2011	2.19	2.69
NFBT	3	NFBT 3	BT	individual jam	jam	sed	240	y	2011	6.55	11.64
NFBT	NA	NA	BT	reach	jam	NA	160	n	2011	2.40	3.03
NFBT	NA	NA	BT	reach	NJC	NA	160	n	2011	2.68	7.32
NFJW	1	NFJW 1	Poudre	individual jam	NJC	ds	300	y	2011	7.13	6.67
NFJW	1	NFJW 1	Poudre	individual jam	NJC	us	300	y	2011	6.54	5.67
NFJW	1	NFJW 1	Poudre	individual jam	jam	sed	300	y	2011	3.96	3.79
NFJW	1	NFJW 1	Poudre	individual jam	jam	sed	300	y	2011	5.15	4.82
NFJW	1	NFJW 1	Poudre	individual jam	jam	sed	300	y	2011	8.53	7.93
NFJW	1	NFJW 1	Poudre	individual jam	jam	sed	300	y	2011	5.59	9.84

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4: For individual jam-level surveys, the position (upstream or downstream) of the comparison sample

Stream Name	Jam Number (from U/S to D/S)	Jam Name	Basin[1]	Survey type[2]	Sample type[3]	Position of sample relative to jam[4]	Forest Age	Old growth logical	Sample date	OM in sample (< 2mm fraction only)	OM in sample (including >2mm fraction)
							yrs	y/n		% (g/g)	% (g/g)
NSV	1	NSV 1	NSV	individual jam	jam	sed	355	y	2010	47.47	47.94
NSV	1	NSV 1	NSV	individual jam	jam	sed	355	y	2010	46.21	49.25
NSV	1	NSV 1	NSV	individual jam	jam	sed	355	y	2010	6.45	12.80
NSV	1	NSV 1	NSV	individual jam	jam	sed	355	y	2010	3.49	3.75
NSV	1	NSV 1	NSV	individual jam	jam	sed	355	y	2010	30.60	34.61
NSV	1	NSV 1	NSV	individual jam	jam	sed	355	y	2010	12.97	21.07
NSV	1	NSV 1	NSV	individual jam	jam	sed	355	y	2010	2.27	2.12
NSV	1	NSV 1	NSV	individual jam	NJC	ds	355	y	2011	1.28	1.22
NSV	1	NSV 1	NSV	individual jam	NJC	us	355	y	2011	1.34	2.62
NSV	2	NSV 2	NSV	individual jam	jam	sed	355	y	2010	2.51	2.45
NSV	2	NSV 2	NSV	individual jam	jam	sed	355	y	2010	1.43	1.42
NSV	2	NSV 2	NSV	individual jam	jam	sed	355	y	2010	2.59	2.55
NSV	2	NSV 2	NSV	individual jam	jam	sed	355	y	2010	1.72	1.02
NSV	2	NSV 2	NSV	individual jam	jam	sed	355	y	2010	7.55	19.91
NSV	3	NSV 3	NSV	individual jam	jam	sed	130	d	2011	2.45	2.87
NSV	3	NSV 3	NSV	individual jam	jam	sed	130	d	2011	1.66	1.63
NSV	3	NSV 3	NSV	individual jam	jam	sed	130	d	2011	0.91	0.79
NSV	3	NSV 3	NSV	individual jam	jam	sed	130	d	2011	3.16	7.58
NSV	4	NSV 4	NSV	individual jam	jam	sed	130	d	2011	3.29	2.75
NSV	4	NSV 4	NSV	individual jam	jam	sed	130	d	2011	4.69	8.85
NSV	4	NSV 4	NSV	individual jam	jam	sed	130	d	2011	1.22	1.10
Ouzel	1	Ouzel 1	NSV	individual jam	NJC	us	500	y	2011	13.26	6.21
Ouzel	1	Ouzel 1	NSV	individual jam	NJC	us	500	y	2011	1.60	1.39
Ouzel	1	Ouzel 1	NSV	individual jam	jam	sed	500	y	2010	12.97	15.29
Ouzel	1	Ouzel 1	NSV	individual jam	jam	sed	500	y	2010	1.96	0.94
Ouzel	1	Ouzel 1	NSV	individual jam	jam	sed	500	y	2010	48.00	48.51
Ouzel	2	Ouzel 2	NSV	individual jam	NJC	us	500	y	2011	4.32	4.90
Ouzel	2	Ouzel 2	NSV	individual jam	jam	sed	500	y	2010	38.53	34.36
Ouzel	2	Ouzel 2	NSV	individual jam	jam	sed	500	y	2010	1.28	0.65
Ouzel	2	Ouzel 2	NSV	individual jam	jam	sed	500	y	2010	20.14	16.72
Ouzel	3	Ouzel 3	NSV	individual jam	NJC	us	35	d	2011	4.37	2.92
Ouzel	3	Ouzel 3	NSV	individual jam	jam	sed	35	d	2010	1.25	1.03
Ouzel	3	Ouzel 3	NSV	individual jam	jam	sed	35	d	2010	1.89	2.59
Ouzel	3	Ouzel 3	NSV	individual jam	jam	sed	35	d	2010	8.09	1.79
Ouzel	4	Ouzel 4	NSV	individual jam	NJC	us	35	d	2011	4.88	4.17
Ouzel	4	Ouzel 4	NSV	individual jam	jam	sed	35	d	2010	2.70	1.79
Ouzel	4	Ouzel 4	NSV	individual jam	jam	sed	35	d	2010	1.90	1.63
Ouzel	4	Ouzel 4	NSV	individual jam	jam	sed	35	d	2010	33.82	34.64
Pennock	NA	NA	Poudre	reach	NJC	NA	140	n	2011	1.67	1.64
Pennock	NA	NA	Poudre	reach	NJC	NA	140	n	2011	1.45	1.78
Pennock	NA	NA	Poudre	reach	jam	NA	140	n	2011	16.02	21.16
Poudre River	NA	NA	Poudre	reach	NJC	NA	100	n	2010	1.65	1.26
Roaring Creek	NA	NA	Poudre	reach	jam	NA	90	n	2011	0.98	1.99
Roaring Creek	NA	NA	Poudre	reach	NJC	NA	90	n	2011	0.95	1.47
Willow Creek	NA	NA	Poudre	reach	NJC	NA	110	n	2010	0.97	0.55