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ARTICLE

# Reductions in Instream Wood in Streams near Roads in the Interior Columbia River Basin

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***Abstract***
**Despite the success of recent management efforts to reduce streamside logging, instream wood recovery may be limited by the presence of near-stream roads. We investigated the relationships between the presence of near-stream roads and the frequency and volume of different size-classes of wood in streams in the interior Columbia River basin. We developed models to evaluate the average reduction in instream wood for streams near roads (<30 m or 30–60 m). We compared this with the changes in wood frequency and volume related to changes in environmental conditions such as precipitation, bank-full width, gradient, and forest cover as well as to changes in grazing-related management. In order to extrapolate our findings to the entire study area, we used a GIS approach to determine the distance to roads for randomly selected sites throughout the study area. Sites <30 m from a road had 65 (26%) fewer pieces of total wood, 33 (34%) fewer pieces of coarse wood, 31 (37%) fewer pieces of pool-forming wood, and 37 $m^3$ (42%) less wood volume per kilometer than sites >60 m from a road. We also observed significant reductions at sites 30–60 m from a road, but these were about half those documented for sites <30 m. Changes in environmental conditions and grazing intensity had effects similar to those of being near a road. Based on our GIS analysis, approximately 29% of the sites in the study area are within 60 m of a road, and this percentage is even greater if unroaded catchments are excluded. Our results provide strong evidence that the presence of roads has significantly reduced habitat conditions for salmonids in the interior Columbia River basin and illustrate the need for road removal or relocation projects to increase wood in streams.**

Habitat alteration is one of the foremost factors contributing to declines in salmonid populations (McIntosh et al. 2000; Rieman et al. 2001). The last several decades have seen considerable effort expended on improving habitat conditions for salmonids (Bernhardt et al. 2005), yet these restoration efforts are often hindered by the legacy of past land management decisions. For instance, historical harvest in riparian areas has greatly reduced instream wood in the Columbia River basin (McIntosh et al. 2000). Instream wood is one of the most important components of salmonid habitat, which provides many habitat functions (Gregory et al. 2003; Gurnell et al. 2006). Current management strategies for conserving at-risk populations of Bull Trout *Salvelinus confluentus*, salmon, and steelhead *Oncorhynchus mykiss* now restrict riparian harvest, but recovery of instream wood may be limited in part because of the presence of near-stream roads (USFWS 2004; NOAA 2009).

The majority of streams in the USA are affected by roads. Ritters and Wickham 2003 estimates that 50% of the total land area within the conterminous USA is within 382 m of a road. Public lands also have extensive road networks largely due to historical logging activities. Some of the direct effects of high road density within forested landscapes include adverse effects on hydrology and geomorphology, increased habitat fragmentation, increased invasion by exotic species, degraded water quality, and degraded riparian habitat quality (Gucinski et al. 2001). Many of these effects are a result of the removal or alteration of streamside vegetation. Hydrologic and geomorphic consequences of streamside vegetation removal include increased erosion and channelization, changes in stream flow regime, and the alteration of surface and subsurface flow paths (Jones 2000; Opperman et al. 2005). Much of this is due to the removal of larger, woody vegetation, which occurs during harvest, as part

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of the road construction process, or as trees become a hazard to safety. Reductions in woody vegetation can also occur due to firewood cutting, recreational activities, and infrastructure that occur because of the increased accessibility provided by the road (Johnson and Haight 1984).

Although wood recruitment into streams differs depending upon the characteristics of the landscape (Burnett et al. 2006), in many streams the majority of wood inputs come from the stream's riparian zone (McDade et al. 1990; Van Sickle and Gregory 1990). Therefore, declines in tree density or volume due to near-stream roads result in fewer wood inputs into the stream. In western Washington, for instance, extensive roadside logging resulted in a reduction in the size of large (e.g., >30 cm in diameter) instream wood pieces (Ralph et al. 1994). In western Oregon, the presence of riparian roads was shown to decrease large wood volume and frequency regardless of whether logging was associated with the road (Czarnomski et al. 2008). The presence of a road may also effectively limit channel migration and the connection of the stream to its floodplain, further reducing wood inputs. These effects on lateral migration are potentially greatest in mountainous landscapes with moderately confined alluvial valleys (such as the interior Columbia River basin) because the most convenient place to build roads in these landscapes is near streams (Blanton and Marcus 2009).

Alteration of instream wood inputs can affect multiple life stages of salmonids (Roni and Quinn 2001; MacInnis et al. 2008). Cover provided by instream wood contributes to higher densities of fry and juvenile salmonids (Roni and Quinn 2001) by providing protection from predation and high flow events. Wood stores and sorts sediment important for salmonid spawning (Bilby and Ward 1989; Gurnell et al. 2006). Instream wood shapes channel morphology by creating pool habitats and backwaters (Richmond and Fausch 1995) that are important refugia and feeding locations for adult salmonids. Ultimately, reductions in wood have cascading effects on many aspects of salmonid habitat (Gurnell et al. 2006).

Determining the relative influence of instream wood loss on salmonid populations is particularly challenging, given the presence of other competing stressors (e.g., connectivity, barriers, invasive species, and other aspects of habitat condition; Rieman et al. 2001) that interact with wood loss to negatively affect salmonid populations. Nevertheless, numerous studies illustrate the importance of wood to either abundance or survival for salmonids found throughout the Columbia River basin, including steelhead, Coho Salmon *O. kisutch*, Cutthroat Trout *O. clarkii*, and Bull Trout (Quinn and Peterson 1996; Roni and Quinn 2001; Rich et al. 2003; Rosenfeld et al. 2007). Efforts to restore instream wood and other habitat features have been shown to positively increase densities and survival of these species, particularly age-0 and juvenile fish (Solazzi et al. 2000; Roni et al. 2002). Reduced wood inputs due to historical timber harvest and other management activities has been cited as the primary factor contributing to the loss of pool habitat in the Columbia River basin; approximately 50% of managed streams in the basin have lower large and deep pool frequencies than they did historically. Research also suggests strong links between management practices and instream wood. Using a subset of data used in our analysis, Al-Chokhachy (2010) demonstrated that the mean number of wood pieces (>10 cm diameter, 1 m length) in reference reaches characterized by no logging, grazing, and minimal roads was 388 pieces/km, while the mean number of pieces at managed reaches was 50% of that (197 pieces/km). It can take up to 100 years for instream wood to recover from past riparian logging (Murphy and Koski 1989; Beechie et al. 2000), and roads may further reduce the ability of riparian areas to recover from disturbance. Given the difficulty in removing roads, they represent a nearly permanent and potentially long-term loss of wood inputs.

Despite the potential impacts of roads, many studies of the broad-scale patterns of wood in streams have not investigated how wood frequencies or volumes change in relation to the proximity and density of roads (Bilby and Ward 1991; Richmond and Fausch 1995). Conversely, studies of relationships between the presence of riparian roads and instream wood have generally been focused on small geographic areas (Czarnomski et al. 2008) and have not considered the relative impacts of roads compared to environmental conditions that limit wood inputs to streams across a landscape, including climate and stream size.

We investigated how the volume and frequency of instream wood within the interior Columbia River basin has been impacted by the presence of roads adjacent to streams. We hypothesize that stream reaches near roads will have lower instream wood volumes, frequencies, and pool-forming wood frequencies compared to reaches not near roads. Further, we hypothesize that a large proportion of fish bearing stream segments within the interior Columbia River Basin are near roads.

## METHODS

*Reach selection.*—We used habitat data available for reaches within the interior Columbia River basin sampled by the Pacfish Infish Biological Opinion Effectiveness Monitoring Program (PIBOEMP; Kershner et al. 2004; Archer et al. 2012). These reaches were determined using a spatially balanced random design, were putatively fish-bearing, and were in locations where ≥50% of the watershed upstream of the sampled point was managed by either the U.S. Forest Service (USFS) or Bureau of Land Management (BLM; Figure 1). Reaches exhibited a range of environmental and management characteristics (building and maintenance, timber harvest, livestock grazing, mining, and motorized recreation) and included reference reaches located in wilderness areas or watersheds with minimal road density and no mining or recent grazing or logging (Kershner et al. 2004). From 2003 to 2012 a total of 1,181 unique reaches (207 reference, 974 managed) were evaluated. The PIBOEMP reaches are sampled on a 5-year rotation with a subset of 50 sampled annually. For this analysis we used averaged values for

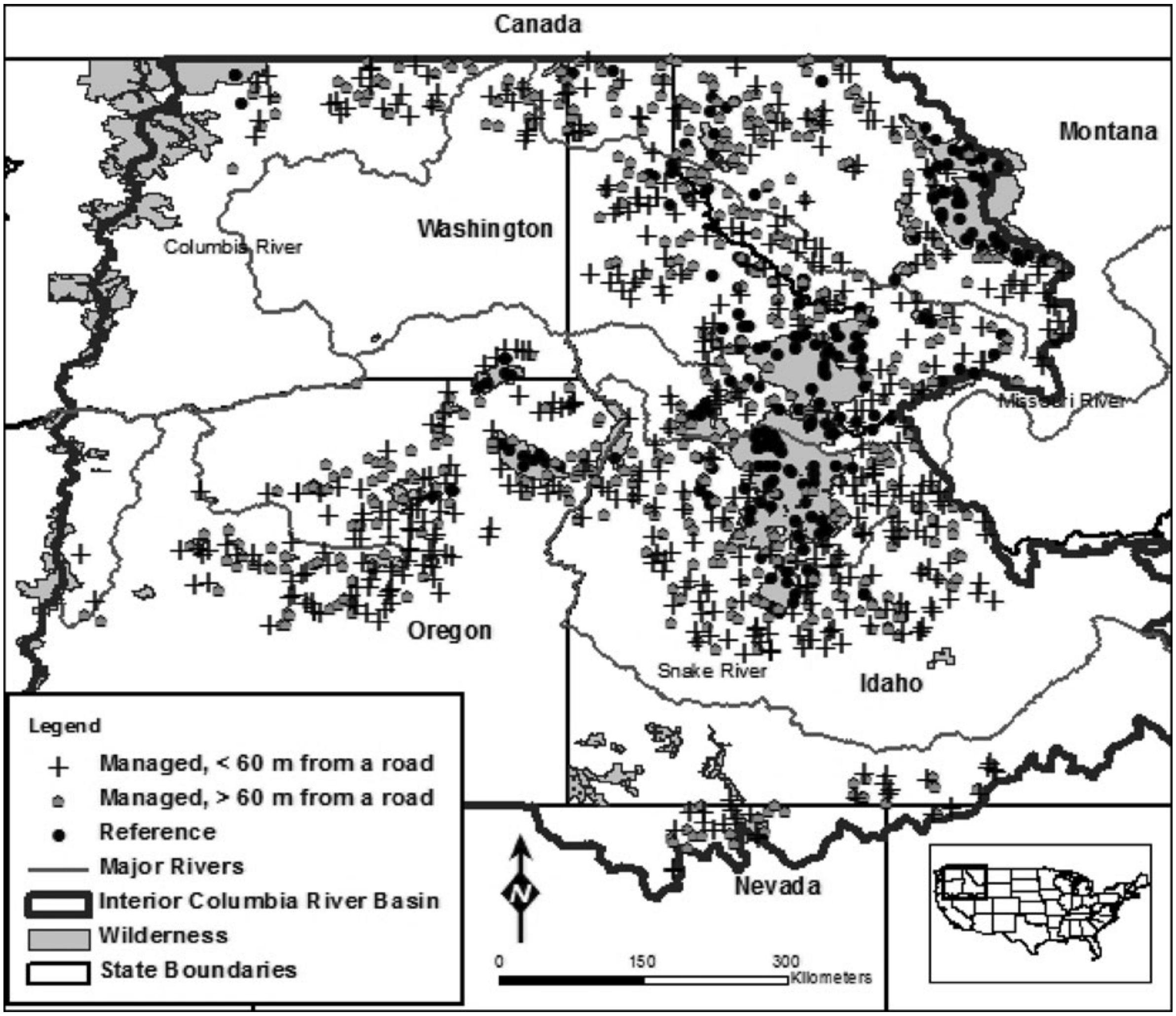


FIGURE 1. Instream wood study reaches in the interior Columbia River basin, including non–reference reaches located 0–60 and >60 m from a road and reference reaches (i.e., reaches defined as >60 m from a road).

predictor and response variables at a reach across all the visits to that reach within the above timeframe.

*Predictor and response variables.*—We developed response metrics (Table 1) describing the amount of instream wood within each reach. As part of the PIBOEMP sampling protocol, every piece of wood within the bank-full channel that was both greater than 10 cm in diameter and one m in length (measured at one-third the distance from the base) was counted and measured (Archer et al. 2012). We used these data to calculate a variety of wood- related metrics including total wood frequency (pieces/km), coarse wood frequency (pieces/km), pool-forming wood frequency (pieces/km), and wood volume ($m^3$/km) for each reach. To determine total wood frequency we used the number of pieces within each reach that exceeded 10 cm in diameter and 1 m in length. To determine coarse wood frequency, we used the number of wood pieces greater than 20 cm in diameter and 2 m in length in the reach. We determined potential pool-forming large wood frequency by using the number of pieces that met our minimum diameter criteria of 10 cm but also had a length that equaled or exceeded that reach's bank-full width (Beechie and Sibley 1997). Finally, to determine wood volume, we applied the formula for the volume of a cylinder (volume $= \pi r^2 h$, in which $r$ was the radius of the piece at one-third of the base and $h$ was the piece's length) to each piece of wood encountered that was $>1$ m long and $>10$ cm in diameter. All metrics were then scaled to number or volume per 1 km of stream length. The low threshold of instream wood size for our volume and total wood frequency estimates were used in this study because small instream wood plays a role in fish cover and other stream processes, not just for pool formation (Bilby and Ward 1991; Dambacher and Jones 1997). Since larger sizes of wood may be more important for certain habitat functions, we included a metric of coarse wood frequency in the size-range often referred to as "large wood" in the literature (Bilby and Ward

TABLE 1. Summary of predictor and response variables used in assessing wood in streams in the Columbia River basin.

| Variable | Mean | Median | SD | Range |
|---|---|---|---|---|
| **Predictor variables** | | | | |
| Average precipitation (m/year) | 0.93 | 0.90 | 0.32 | 0.27–1.97 |
| Percentage of catchment forested | 76 | 84 | 21 | 0–100 |
| Percentage of reach grazed | 51 | 72 | 49 | 0–100 |
| Gradient (%) | 1.93 | 1.74 | 1.19 | 0.01–8.52 |
| Bank-full width (m) | 6.2 | 5.5 | 3.5 | 0.6–24.1 |
| Elevation (m) | 1,406 | 1,380 | 417.14 | 458–2,464 |
| Reach road density (m of road/m$^2$ of buffer) | 2.52 | 0 | 3.27 | 0–16.98 |
| **Response variables** | | | | |
| Total woody debris frequency (pieces/km) | 273 | 180 | 296 | 0–3,123 |
| Coarse woody debris frequency (pieces/km) | 111 | 67 | 129 | 0–1,207 |
| Pool-forming woody debris frequency (pieces/km) | 80 | 45 | 99 | 0–791 |
| Woody debris volume (m$^3$/km) | 97 | 56 | 127 | 0–1,077 |

1991; May and Gresswell 2003; Fox and Bolton 2007). Finally, we chose to include a metric with pieces greater than bank-full width in length because these pieces could potentially span the entire channel and be more likely to form pools (Beechie and Sibley 1997; Abbe and Montgomery 2003). This approach allowed for the evaluation of relationships between the presence of near-stream roads and different sizes of instream wood.

In our analysis we used the distance to the nearest road as our primary measure of potential road effects. As our proxy for distance to road we used the "near" tool in ArcMap 10.0 (ESRI 2011) to measure the distance from the downstream end of each PIBOEMP reach and the nearest road across multiple road layers (internal USFS and BLM road layer and an Open Street Map 2012 layer [www.openstreetmap.org.]). We used multiple roads layers in this step because each road layer contained some unique roads and it increased the likelihood that the nearest road to the evaluated reach was mapped.

Our preliminary analysis suggested that reaches varied in environmental conditions and grazing-related management, which affected the amount of instream wood. For instance, reference reaches with low road densities tended to be located in areas of higher precipitation. Reaches with a higher intensity of grazing generally had lower amounts of instream wood. Because we wanted to evaluate differences in wood due to roads only, we accounted for these variables representing environmental conditions and grazing intensity (Table 1). Environmental conditions included average watershed precipitation (Woodall and Liknes 2008), bank-full width (Richmond and Fausch 1995), gradient (Keller and Swanson 2007), and forest cover. We estimated average precipitation for each watershed upstream of the reach as the weighted average (by area) of all PRISM (Parameter-Elevation Regression on Independent Slopes Models) precipitation grids that intercepted each individual watershed. We used 30-year average precipitation values (1971–2001; PRISM Climate Group 2004). We determined average bank-full width by averaging estimates of bank-full width collected at 20 equally spaced transects in the reach. We assessed gradient using an auto-level and stadia rod to determine the elevation change at each reach divided by reach length. We accounted for variation in forest cover using GIS methods. Forest cover is a product of interactions between multiple factors including watershed management (e.g., past logging activity), climate, disturbance (e.g., fire), and landscape characteristics (Dose and Roper 1994; Hessburg et al. 2000). In our analysis we considered it to be indicative of broad-scale landscape characteristics. We used LANDFIRE imagery within GIS to determine the percent of the watershed above the sampled reach that was forested (LANDFIRE 2001). We designated a pixel as forested if it fell into one of the LANDFIRE categories within the study area that indicated a forest type with the potential to contribute to instream wood (e.g., deciduous open, evergreen closed, and evergreen open), which we verified using aerial imagery. Based on the vegetation height layer in the LANDFIRE data set, we estimated that the average tree height at over 90% of our reaches to be between 10 m to 30 m. This supported our assumption that the classes of forest we chose to incorporated as forested could contribute wood to streams (e.g., were in the size range used for this analysis: $>$10 cm diameter, $>$1 m long). We used a watershed-level estimate of forest cover because we expected streams in forested watersheds to have higher wood frequencies than those in less forested watersheds; we wanted to control for this relationship when assessing relationships between roads and instream wood at the reach scale.

We also accounted for the variation explained by grazing-related management. Grazing has been shown to influence the health of public lands and instream habitat in the western USA (Armour et al. 1994). Although we observed some amount of correlation between forest cover and grazing intensity ($r = -0.29$), we chose to include both in our models because this correlation did not have an observable influence on model coefficients. We observed that reaches with low grazing did not necessarily have high percent forest, and the opposite was also true. We determined grazing intensity as the percent of land adjacent to each reach (within a 90-m buffer) that contained grazing allotments, using GIS layers of those allotments obtained from the BLM and USFS. We chose to estimate grazing intensity near the reach, because grazing adjacent to the stream has been shown to strongly affect instream wood (Beschta et al. 1987; Snyder et al. 2003).

We did not include an explicit estimate of past logging intensity in our models due to the difficulty in getting consistent GIS data layers for timber harvest across multiple forests. We initially considered using riparian or watershed road density, which has been used successfully as an indicator of logging intensity in other research (Dose and Roper 1994; Baxter et al. 1999). We used GIS to determine road density as the length of road (km) divided by the area in the reach or watershed ($km^2$). However, the highly collinear relationship between road density and both percent forest and proximity to roads resulted in regression estimates that were unstable and strongly dependent upon which attributes were included in the model. Each of the approaches for addressing this collinearity has inadequacies when evaluating such highly variable data (Kiers and Smilde 2007). We therefore chose to remove road density at the watershed from our analysis, which had little effect on model outcomes given that road density had low relative importance in our models. Removal of this attribute from consideration in this analysis should not be taken to mean that watershed road density or logging is not associated with reductions in instream wood, but rather that, in order to determine the specific effects, a different study design (factorial) would have been needed.

*Estimating potential distance to road effects.*—We developed models to predict instream wood from environmental conditions and grazing intensity but not proximity to roads (Table 1). We did this to remove the differences among evaluated stream reaches that were not associated with the proximity of roads to the reach. To develop our models, we used a generalized linear modeling framework. Our predictions were based on model-averaged parameters derived from models within 2 units of the highest-AIC (Akaike information criterion) model (Burnham and Anderson 2002). All statistical analyses were performed using the MuMIn package in R (R Development Core Team 2008; Barton 2013). For all analyses, we used a basic Gaussian model because the residuals of the models approached a normal distribution, given the large sample size ($n = 1{,}181$). Although we initially considered a number of transformations of our environmental and grazing variables (including arcsine transformations of proportion grazing and proportion forest), these transformations did not greatly improve model performance or normality and made the results more difficult to interpret; therefore, untransformed values were used in models.

We used model-averaged coefficients to predict instream wood metrics from our suite of environmental conditions (average precipitation, bank-full width, gradient, and percent forested catchment) and our estimate of grazing intensity (percent grazed reach). For each instream wood metric we graphed the residuals (observed and predicted values) from these models against the distance to the nearest road at 10 m increments. A value <0 for residual wood meant that less wood was found than expected. We visually inspected the graphs to identify the distances at which incremental increases in our wood measures occurred with increasing distance from roads. We used these results (Figure 2) and the literature to determine distances at which roads should affect instream wood.

For all of our wood metrics we found that the amounts of instream wood from a stream located <30 m from a road were consistently less than the amounts of instream wood at distances >30 m (Figure 2). This result was consistent with other research on source distances of trees to streams, which has shown that most wood enters streams from distances of <30 m (Murphy and Koski 1989; McDade et al. 1990). Pool-forming frequency and coarse wood frequency values continued to increase to a distance of approximately 60 m. Based on this preliminary information we chose the following three distance classes in our analysis, based on the corresponding distance to the nearest stream in GIS: <30 m, 30–60 m, and >60 m.

*Analysis.*—We evaluated the average reduction in each of our wood metrics for reaches near roads. For each reach within each distance to road class (<30 m, 30–60 m), we used model coefficients to estimate the value of each metric (volume, total frequency, coarse frequency, and pool-formation frequency) predicted if the reach was >60 m from a road. We subtracted the corresponding road proximity factor (0–30 m or 30–60 m) to obtain the value predicted at each reach given the presence of a road. We estimated the percent reduction in mean wood for each wood metric using the following formula:

$$\frac{\text{predicted mean}\,(>60\,\text{m}) - \text{predicted mean}(<30\text{m}\ \textit{or}\ 30\text{–}60\,\text{m})}{\text{predicted mean}(>60\,\text{m})} \times 100.$$

If the percent decrease in wood at reaches near roads was higher for one wood metric than another metric, then we considered this metric to be more strongly correlated with the presence or absence of near-stream roads. Use of this method assured that the observable difference in wood was related to the presence of roads and not related to environmental conditions or grazing intensity.

Using our models, we determined the relative effects of roads versus environmental conditions and grazing-related management on our instream wood metrics. We predicted the mean amount of wood across the range of covariates (environmental conditions and grazing intensity) while holding the other covariates constant at their mean values. We estimated these values both without a road present and if a road was present within 30 m. We used line plots to depict the relative change in the mean, where differences due to roads within 30 m were represented by the *y* distance between the lines, and differences due to the predictors were represented by the change in the *y*

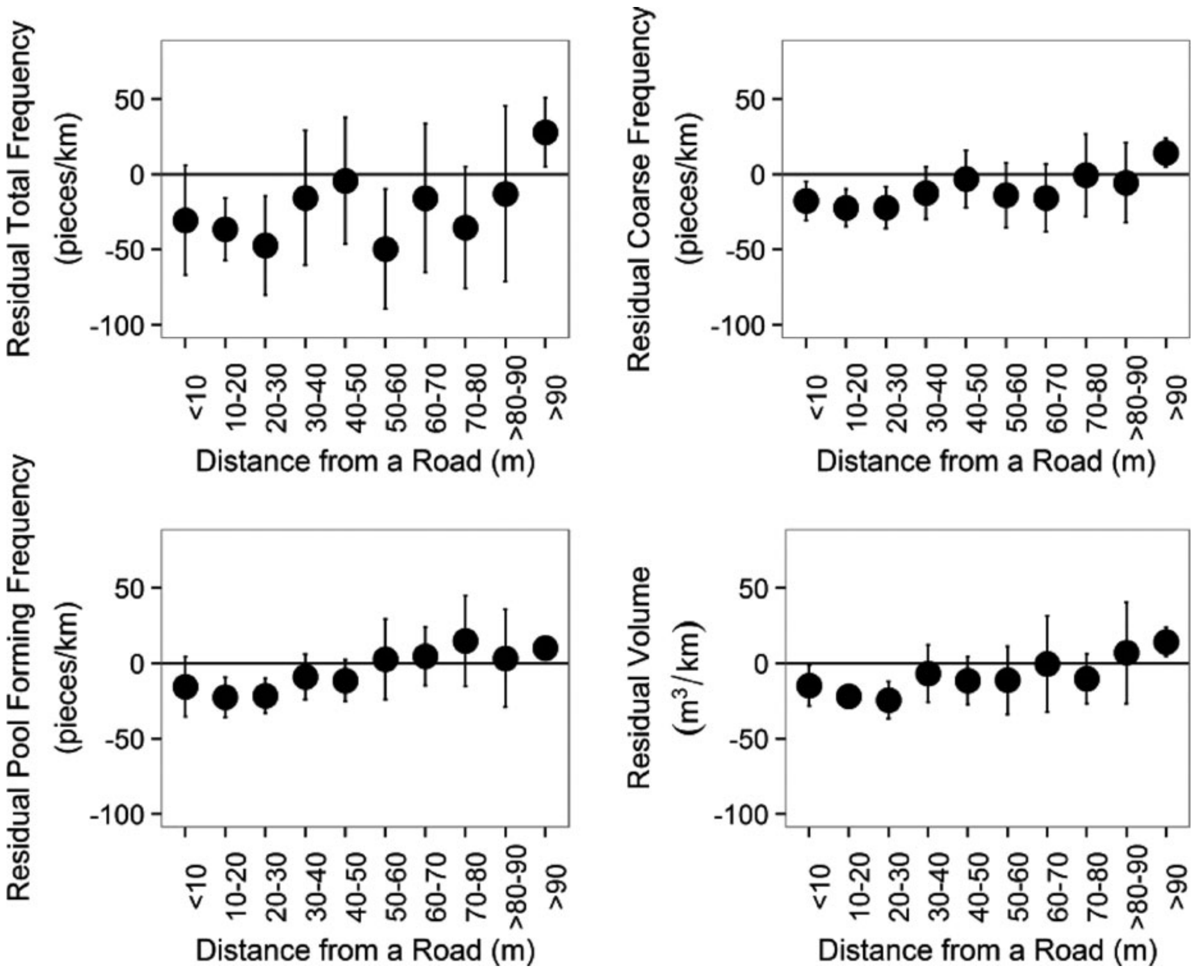


FIGURE 2. Mean residual values of the frequencies for **(A)** total wood, **(B)** coarse wood, and **(C)** pool-forming wood as well as **(D)** wood volume with increasing distance from a road after accounting for environmental conditions and grazing intensity; the error bars represent 10% confidence intervals. A value of 0 on the *y*-axis (solid line) indicates that the amount of wood was equal to that predicted by environmental conditions and grazing intensity, while a value <0 indicates the amount was less than predicted.

value that occurred across the range of the predictor. We recognize the limitations of this method, given that predictors do not change independently. However, this approach allowed us to visualize the amount of change in each predictor that equated to being near a road. We found results for coarse wood frequency were generally similar to those for total wood frequency, and results for wood volume were similar to those for pool formation frequency, in terms of the change in each predictor that equated to being near a road. Because we were most interested in relationships between the presence of riparian roads and both the overall amount of wood and pool-forming wood, we present the results for total frequency and pool formation frequency only.

We scaled our reach-level findings to the interior Columbia River basin by estimating the percent of small to mid-sized streams in the interior basin in close proximity to roads. We used a National Hydrography Dataset Plus shape file (McKay et al. 2012) of streams in the study area to conduct this analysis. We considered a stream segment to be the portion of a stream located between confluences with tributaries. We selected all stream segments in the study area with drainage areas between 5 $km^2$ and 90 $km^2$ because these values represent the range of watershed sizes in the PIBOEMP data set. We placed a random point on each stream segment using ArcGIS Toolbox in ArcMap 10.0 and then estimated the distance to the nearest road for each randomly selected point. We then graphed the cumulative percentage of our random points that are located at increasing 10-m increments from roads. From this we estimated the percent of points located <30 m from a road and 30–60 m from a road (i.e., the distances at which we evaluated instream wood loss). We considered the outcome of this analysis to represent an estimate of the percent of stream locations in the Columbia River basin that are near roads.

We used our estimates of the percentages of reaches in each management (reference/non-reference) and road-proximity category (reference, non-reference and 0–30 m from a road;

non-reference and 30–60 m from a road; and non-reference and >60 m from a road) and the mean amounts of wood in each category to calculate total potential landscape wood loss for the interior Columbia River basin for each wood metric. To estimate the percent of area in reference condition, we assumed that all wilderness areas are in reference condition (even though a small percentage of non–reference reaches were located in wilderness due to grazing at these reaches; Figure 1). The percent of the area in reference condition (25%) was determined by adding the percent of the study area in designated wilderness area (8%) to the nonwilderness portion of the study area estimated in reference conditions (17%). We determined that an additional 17% of the study area was in reference condition based on the fact that the majority of the remaining reference reaches sampled by PIBOEMP were located 40 km from a wilderness area, and this comprised an additional 17% of the study area. We recognize that this is only an approximation, but it is similar to the percent of the Forest Service Lands in the states of Idaho, Oregon, and Washington that were identified as roadless (USFS 2001).

We estimated the percent reduction in wood across the landscape due to roads using an approach similar to that used to determine the percent reductions in wood for the <30-m and 30–60-m road-classes. We accounted for the fact that wood volume and frequency differed by management and distance to road-class. We multiplied the mean value of each of our wood metrics predicted for each management and distance to road category (including reference; >60 m; 30–60 m; <30 m) by the percent that it comprised in the study area, and summed across categories to obtain an estimate of the mean value of each wood metric given roads (roads, <60 m). In order to determine the mean value of wood metrics predicted across the landscape if all streams were >60 m from a road (roads, >60 m), we substituted the amount of wood predicted if reaches were instead >60 m from a road. We determined the percent landscape loss in wood as

$$\frac{\text{landscape wood predicted (roads} > 60\,\text{m}) - \text{landscape wood predicted (roads} < 60\,\text{m})}{\text{landscape wood predicted (roads} > 60\,\text{m})} \times 100.$$

Given the lower amounts of wood at streams near roads, landscape loss of wood will be higher in catchments with few roadless areas (e.g., reference reaches). In order to demonstrate how the absence of roadless areas can influence landscape loss of wood, we also determined the percent landscape loss when reaches in reference catchments were excluded from the analysis.

To illustrate how total wood loss may vary across the landscape due to management, we used the distribution of distance-to-road values obtained using GIS to predict the potential wood loss within two example subbasins characterized by differing amounts of areas in designated wilderness: the John Day subbasin and the Clearwater subbasin. For this analysis, we assumed that mean amounts of wood in each management and road-proximity category were similar to those in the larger study area. Although this is not likely to be true, the purpose of this exercise was to demonstrate how spatially varying road changes in distance to roads, rather than other environmental characteristics, influence wood loss. We used GIS to estimate the percent of reaches in each management and road-proximity category. We estimated that reference areas comprised 5% of the John Day subbasin and 37% of the Clearwater subbasin. Non–reference reaches in the John Day subbasin comprised 49% within the >60-m, 18% within the 30–60-m, and 28% within the <30-m road-proximity categories. Non–reference reaches in the Clearwater subbasin comprised 40% within the >60-m, 10% within the 30–60-m, and 13% within the <30-m road-proximity categories.

## RESULTS

All measures of environmental condition (precipitation, bank-full width, gradient, and percent of the watershed that is forested) and management (grazing intensity) considered in our analysis were important predictors of wood in streams (Table 2). All instream wood metrics showed a positive relationship to percent forested catchment and a negative relationship to percent of the reach grazed. Wood volume, total frequency, and coarse forming frequency were positively related to average precipitation, whereas the frequency of pool-forming wood was negatively related to average precipitation. All wood metrics except total frequency were positively related to gradient. All metrics except pool-forming frequency were positively related to bank-full width. Our models explained 17% of the variation in large wood volume, 15% of the variation in large wood frequency, 18% of the variation in coarse wood frequency, and 17% of the variation in pool-forming frequency.

The frequency and volume of wood in streams was lower at sites near roads after accounting for environmental conditions (Table 2). Reaches <30 m of a road had 65 fewer pieces/km of total wood, 33 fewer pieces/km of coarse wood, and 31 fewer pieces/km of pool-forming wood, and their wood volume was reduced by 37 $m^3$/km compared with sites >60 m from a road. Frequencies and volumes of wood at distances of 30–60 m from a road were also lower than at sites >60 m, but reductions were about half that of sites located 0–30 m from a road (Table 2). Wood metrics that exhibited the strongest decreases were pool-forming frequency and wood volume. While total and coarse wood frequency also exhibited significantly lower values at sites near roads, relative differences due to roads were comparatively less (Table 3). Reference sites had the highest amounts of wood, followed by sites >60 m from a road with no grazing, sites >60 m from a road with grazing, sites 30–60 m from a road, and sites <30 m from a road (Table 3).

Based on model results, environmental conditions exhibited different relationships to pool-forming wood than they did to the other wood metrics. Average precipitation was the dominant environmental variable explaining total wood frequency,

TABLE 2. Model-averaged coefficients, where the value of the road-proximity factor represents the decrease in wood on average at sites 0–30 m and 30–60 m from a road compared with the wood at sites >60 m from a road.

| Variable | Precipitation | Percent forested | Bank-full width | Gradient | Percent grazed | Road-proximity factor |
|---|---|---|---|---|---|---|
| **Stream-to-road distance: 0–30 m** | | | | | | |
| Total frequency | 175.16 | 0.30 | 2.19 | −3.14 | −1.08 | −65.37 |
| Coarse frequency | 64.54 | 0.32 | 5.58 | 0.97 | −0.36 | −33.66 |
| Pool-forming frequency | −1.26 | 0.86 | −8.71 | 13.66 | −0.34 | −31.80 |
| Volume ($m^3$/km) | 34.01 | 0.63 | 7.45 | 11.19 | −0.30 | −37.49 |
| **Stream-to-road distance: 30–60 m** | | | | | | |
| Total frequency | 180.79 | 0.90 | 6.29 | −4.03 | −0.92 | −39.49 |
| Coarse frequency | 74.13 | 0.51 | 6.86 | 7.48 | −0.24 | −20.72 |
| Pool-forming frequency | −3.67 | 0.81 | −8.37 | 17.12 | −0.27 | −19.13 |
| Volume ($m^3$/km) | 46.55 | 0.64 | 7.70 | 14.62 | −0.26 | −22.17 |

coarse frequency, and wood volume (Table 2; Figure 3). In contrast, pool-forming frequency was minimally related to average precipitation but instead was explained by stream planform (bank-full width, gradient) and percent of the catchment that was forested. Each wood metric also showed a negative relationship to grazing intensity. The mean wood count and volume at ungrazed sites was similar to the mean at unroaded areas, but declined by up to 40% as grazing increased (Figure 3).

Lower wood frequencies and volumes were correlated with the presence of roads near streams. In the interior Columbia River basin many of the streams are adjacent to roads (Figure 4). We determined distance to roads for a total of 83,552 randomly selected sites across the basin having watershed areas ranging from 5 to 90 $km^2$. We found that 16% of these sites were <30 m from a road, the distance at which the greatest declines in instream wood were observed. An additional 13% of sites were within distances ranging from 30 to 60 m, the distance over which we documented meaningful but smaller reductions in instream wood. These findings indicate that 29% of the small and mid-sized potentially fish-bearing streams on federal lands in the Columbia River basin are <60 m from a road. Based on the negative relationship between near-stream roads and instream wood, it is likely that a large proportion of wadeable streams in the interior Columbia River basin have reduced wood frequencies and volumes.

We documented a considerable loss of instream wood in the landscape at sites near roads (Table 4). Loss across the study area varied by metric and was lowest for total wood (about 5%) and highest for pool-forming wood (9%). When reference areas were not considered in the analysis, the estimated loss of total wood increased to 7% for total wood frequency and to 12% for pool-forming frequency. Our example subbasins differed greatly in the potential amount of wood loss (Table 1). Predicted wood-loss in the John Day subbasin was nearly twice as high as the average for the PIBOEMP study area. In contrast, the Clearwater subbasin had lower predicted wood loss less than the average for the PIBOEMP study area. Given that a lower proportion of sites in the Clearwater subbasin are near roads and that the Clearwater subbasin contains many wilderness or other roadless areas, this is not a surprise.

TABLE 3. Mean amount of wood predicted for reference sites (watersheds with no mining, recent grazing, or logging and minimal road density) and management sites (>60 m, 30–60m, and 0–30 m from a road). The percent wood loss was determined for managed sites near roads by comparing the predicted amount of wood present if roads were >60 m based on the road-proximity factor; PC stands for the percent of landscape in each management and road-proximity category.

| | Mean amount of wood pieces | | | | Percent wood loss | |
|---|---|---|---|---|---|---|
| Variable | Reference: PC = 25% | >60 m from a road: PC = 46% | 30–60 m from a road: PC = 13% | 0–30 m from a road: PC = 16% | Road at 30–60 m | Road at 0–30 m |
| Total frequency | 398 | 291 | 232 | 184 | 15 | 26 |
| Coarse frequency | 167 | 121 | 91 | 65 | 19 | 34 |
| Pool-forming frequency | 92 | 86 | 60 | 54 | 24 | 37 |
| Volume ($m^3$/km) | 147 | 109 | 78 | 53 | 22 | 42 |

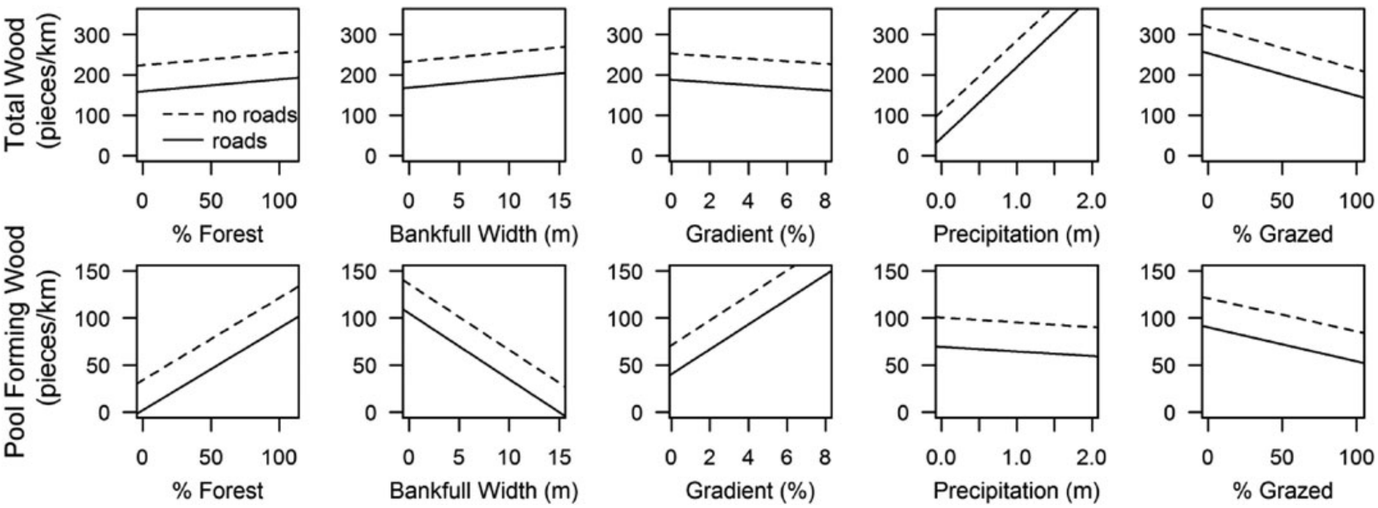


FIGURE 3. Mean changes in total wood frequency (upper panel) and pool-forming wood frequency (lower panel) predicted at sites <30 m from a road (solid lines) and at unroaded site (dotted lines) across the range of five environmental conditions and grazing intensities present in the data set.

## DISCUSSION

Our research demonstrates that even after accounting for the variation in climate, geomorphology, and grazing-related management, streams near roads typically have lower volumes and frequencies of instream wood than streams in unroaded areas of the interior Columbia River basin. Furthermore, a large proportion of small and mid-sized streams on public lands in the basin are near roads. Given the strong influence that instream wood has on salmonid habitat, these lower amounts of wood probably contribute to widespread reductions in habitat condition.

We observed that streams <30 m from a road had lower wood volumes and frequencies than streams 30–60 m from a road, which also had lower wood frequencies and volumes than sites not near roads. However, reductions in wood at a 30–60 m distance were lower in magnitude and more variable than roads closer to the streams. Since research has indicated much of the wood that falls into streams comes from <30 m of the stream edge (Murphy and Koski 1989; McDade et al. 1990), the direct effects of removing wood to build these roads could account for most of the decrease. In contrast, loss of instream wood at distances of 30–60 m probably not only reflects the effects of the road itself but past logging, infrastructure, and recreational uses, which are facilitated by the road. Because the presence of these indirect effects probably differs by reach, we observed increased variation in instream wood with additional distance from roads.

The strong relationships between fluvial processes and terrestrial conditions on the amount and volume of wood in streams

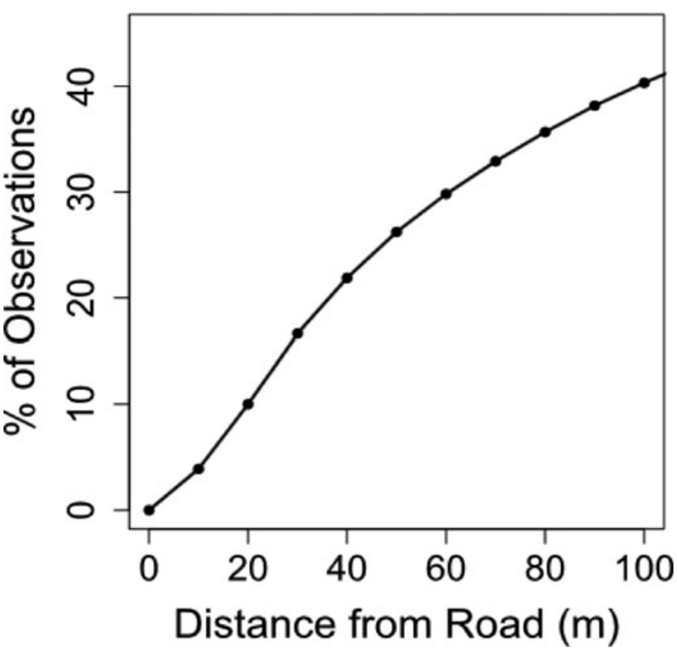


FIGURE 4. Cumulative frequency distribution of the proportion of randomly selected sites within the Columbia River basin located at increasing distances from a road.

TABLE 4. Estimated percent landscape wood loss for different portions of the Columbia River study area based on the distribution of distances to roads in each management category.

| Variable | Frequency for Total | Coarse | Pool-forming | Volume ($m^3$/km) |
|---|---|---|---|---|
| Entire study area | 5 | 6 | 9 | 8 |
| Non–reference areas | 7 | 9 | 12 | 11 |
| John Day subbasin | 9 | 12 | 14 | 14 |
| Clearwater subbasin | 4 | 5 | 7 | 6 |

demonstrate the need to control for these factors when evaluating wood debris in streams. By controlling for these conditions in our analysis, we were able to isolate the relationship between roads and wood across a broad spectrum of stream and environmental conditions while minimizing the chance of spurious correlations (Kershner et al. 2004). If we had just compared the amount of wood in roaded areas with that of reference sites without roads, we would have overestimated the loss of wood at sites near roads because these basins do not have the exact same environmental conditions or management histories. All of the nonroad environmental variables we included in our analysis were important predictors of instream wood.

Even though some of our evaluated reaches have large amounts of instream wood, the average amounts of instream wood in our study area are considerably less than in other studies conducted in the Pacific Northwest (Fox and Bolton 2007; Czarnomski et al. 2008). We attribute this to the low average precipitation found across much of our study area, which does not include the portion of the Columbia River basin west of the Cascade mountain range. Most of our study area lies mainly in the dry Snake River Plateau, but extends into northern Idaho and western Montana (PRISM Climate Group 2004). The relationships between our environmental condition covariates and wood were similar to literature reports (Richmond and Fausch 1995; Hassan et al. 2005; Fox and Bolton 2007). An exception was the negative relationship between average precipitation and the frequency of wood that was most likely to form pools. We initially considered that this negative relationship could be related to strong covariance between average precipitation and either bank-full width or percent forest, but including these interactions did not affect the performance of the model or sign of the relationship. We therefore hypothesize this negative relationship is related to selective harvest of the larger pool-forming wood sizes at our more productive, high-precipitation sites; that was not captured by the variables used in our analysis or ice-jam break-ups, which occur more often in high-precipitation areas and can cause scouring of wood from channels (White 2003; Keeton et al. 2007)

Despite the overarching influence of nonroad environmental and management variables in predicting instream wood, our results illustrate that riparian roads contribute as much to the reduction in the amount of wood in channels as large changes in climate, watershed position, and grazing intensities. For instance, a 0.4-m decrease in precipitation is comparable to the decrease in total wood frequency that occurs for sites <30 m from a road. This is over half the difference in precipitation between the wet northern Rocky Mountains (north Idaho) and the dry Snake River Plateau (southeast Idaho), which is approximately 0.7 m (PRISM Climate Group 2004). Further, an increase in bank-full width of 4 m is comparable to the decrease in pool-forming frequency that occurs for sites <30 m from a road. We estimate that such an increase in bank-full width occurs with an increase in watershed area from 50 $km^2$ to 200 $km^2$ for streams in the Snake River Plateau (Castro and Jackson 2001). Finally, being <30 m from a road essentially had a similar relationship to our metrics of instream wood as did presence of grazing. These findings suggest that when stream reaches are near roads, the conditions of those reaches are greatly altered. The presence of roads has changed some of the broad-scale spatial patterns in instream wood and resulting habitat that we would expect to find in river networks (Ebersole et al. 1997).

We documented lower values of all instream wood metrics at sites near roads. However, compared with the other metrics, the greatest decrease was for the wood most likely to form pools. Roads or roadside logging may have a lesser effect on smaller wood pieces because they regrow more quickly following disturbance. In contrast, the quantity of pool-forming pieces may take decades to recover (Murphy and Koski 1989). The presence of roads may therefore cause disproportionate reductions of wood that forms pools and large habitat features. Road maintenance activities may also compound these effects as large, dying trees are often targeted for removal (Sedell et al. 1988).

We speculate that environmental conditions offset some of this loss of wood due to roads. The presence of pool-forming wood is highly correlated with geomorphic factors (Richmond and Fausch 1995). For instance, the decrease in pool-forming wood that we estimated due to roads is smaller than the average decrease in pool-forming wood that occurs between high and low gradient streams. Further, the relationship with stream size is illustrative of the fact that smaller sizes of wood are required in order to span bank-full width and be retained in small streams (Bilby and Ward 1989). As a result, small streams may recover wood faster than large streams. We observed great variation in pool-forming wood, including some sites with high wood amounts. In large streams <60 m from roads, wood >8 m averaged 32 pieces (SD, 34), while in small streams <60 m from roads, wood <4 m averaged 92 pieces (SD, 113). Some of the reduction in pool-forming wood pieces may also be offset if the upstream catchment is forested. Our estimate of percent forest specifically included forest classes with larger pieces of wood. Therefore, the importance of this predictor may reflect that sites in more forested settings have more large wood to contribute or that more pieces are contributed from upstream if the catchment is highly forested. The total wood frequency could also be offset to some degree by percent forest, but this metric was strongly correlated to average precipitation. The total wood frequency metric includes smaller pieces and forest types not included in our percent forest estimate (e.g., willow, alder), which may regrow in a short time span with higher precipitation, regardless of forest type. In general, these results highlight that geomorphic, climate, and landscape factors may play a role in increasing availability of wood so as to compensate for some of the loss due to roads. Conversely, if these environmental conditions result in less wood potential, then the presence of a road could result in wood amounts lower than thresholds needed to produce salmonid habitats (Kershner and Roper 2010) and less capacity to replace wood in the future.

Other management activities may also exacerbate the loss of wood related to roads. We found that the presence of grazing-related management was negatively correlated with each of our wood metrics. Sites without grazing had mean amounts of wood similar to sites without roads, while sites with permitted grazing had wood amounts equal or less than sites with roads. The decrease in multiple size-classes of wood suggests that grazing may not only influence the number of smaller stems within the riparian area, which includes more pieces in the range of sizes that can be consumed by livestock, but also what is recruited into larger size-classes. We do not know whether this relationship to grazing is a legacy of past grazing practices or a reflection of current grazing activity (Ripple and Beschta 2007). However, this finding suggests that the impacts of roads near streams may be partially mitigated by reducing grazing pressure in these areas as well.

Our analysis of the potential landscapewide effects of roads on wood illustrates the importance of preventing road construction in designated wilderness and other high-quality roadless areas (e.g., reference areas in our analysis), which has been suggested by other scientists who examined the manifold impacts of roads (Trombulak and Frissell 2000). Based on our analysis, these reference areas comprise 25% or less of the landscape but contain as much as 34% of the total wood present. Many portions of the study area have a low percentage of reference areas (e.g., Figure 1) to augment loss of wood. For instance, we showed that wood loss due to roads may be twice as high in portions of the landscape (e.g., the John Day subbasin) than it is in the average for the PIBOEMP study area. Negative effects of roads may also be exacerbated by the fact that they can affect multiple habitat attributes in addition to instream wood. High road density in the basin can increase the amount of fine sediment in streams (Opperman et al. 2005). The loss of woody vegetation can increase stream temperature, reducing salmonid survival in systems where temperatures are already high (Beschta et al. 1987). Riparian roads can alter stream hydrology by altering the routing of surface and subsurface flow and the timing and magnitude of flow events (Moore and Wondzell 2005). Previous research suggests that there can be direct, indirect, and cumulative impacts of roads (Gucinski et al. 2001).

The survey protocol used by PIBOEMP allowed us to evaluate how the presence of roads and other factors explained the frequency and volume of different size-classes of wood. Many studies consider only the large pieces of wood, without consideration of stream size. However, what may be large in one stream may not be large in another stream of greater width (Richmond and Fausch 1995). Smaller pieces are more important to habitat-formation in smaller streams (Bilby and Ward 1989; Beechie and Sibley 1997). Therefore, the large decrease in pool-forming wood that we observed may have larger ramifications for instream habitat than decreases in other wood measures. We suggest that future efforts to explain patterns and abundance of instream wood would benefit from measuring a broad range of wood sizes in the field and not using size bins. This approach allows for an increased ability to evaluate relationships between environmental and management conditions, different size-classes of wood, and salmonid habitat characteristics and to make comparisons with other research.

Despite accounting for environmental conditions, grazing, and proximity to roads, we observed considerable unexplained variation in the amount of wood predicted to be in streams. Our findings support other research demonstrating much spatial variation in instream wood due to stochastic factors, as well as the spacing of geomorphic features (Kraft and Warren 2003). Our reaches were 20 channel widths in length, which may not be adequate to capture this spatial variation. We did not account for interactions between covariates that may have explained additional variation in instream wood. While we recognize interactions may explain additional variation in instream wood, we found that that including some of these interactions (e.g., bank-full width by gradient by average precipitation by percent forest) had little influence on model AIC and lowered our ability to interpret model outcomes. Finally, we acknowledge many environmental and management covariates not included in our models influence instream wood. For instance, instream wood may vary by forest type and age (Evans et al. 1993). By including average precipitation, we accounted for only some of this variation (Marcus et al. 2002). Given the complexity of these relationships, it is unlikely we would ever include all attributes that explained variation in wood counts; therefore, we focused on those already established in the literature.

Our findings have important ramifications given the strong relationship between instream wood, habitat conditions, and salmonid populations (Rosenfeld et al. 2000; Roni and Quinn 2001). While only a few studies (both focusing on Bull Trout) have investigated the levels of wood that support salmonid populations in this region, they highlight the potential importance of instream wood. In a study of factors correlated with Bull Trout distributions in Montana streams, the value of large instream wood (diameter > 10 cm, length > 3 m) above which Bull Trout occurred was 150 pieces/ km (Rich et al. 2003). We estimate the mean value of coarse wood (diameter >10 cm, length >2 m) at reaches >60 m from a road to be about 121 pieces/km; near-stream roads would reduce coarse instream wood at these reaches to 88–101 pieces/km (given wood-proximity factor; Table 2). Additionally, juvenile Bull Trout are most typically found in streams with instream wood volumes ranging from 90 to 280 $m^3$/km (Dambacher and Jones 1997). We estimated mean wood volume at reaches >60 m from roads to be 109 $m^3$/km; near-stream roads would reduce wood volume at these sites to 72–87 $m^3$/km; (given wood-proximity factor; Table 2). Therefore, frequencies and volumes of instream wood in the study area are at or near values considered suitable for Bull Trout. Roads may further reduce wood amounts below these thresholds and may explain why Bull Trout are not found in areas with high road densities (Dunham and Rieman 1999).

Although our study was purely correlative, the relationships between near-stream roads and instream wood that we documented are unlikely to have occurred by chance, given our random sampling design and large sample size. Our approach allowed us to consider relationships between roads and instream wood across a broad spatial scale and to account for climate, geomorphology, and management variation, which would not have been possible with a smaller-scale experimental study. Our study design did not allow us to directly address the mechanisms by which roads limit wood in streams, such as by removing trees, acting as a barrier to larger riparian forests, reducing stream-floodplain connectivity, and facilitating other land uses (Johnson and Haight 1984; Gucinski et al. 2001; Blanton and Marcus 2009). Experiments are needed to study how these additional factors affect instream wood within different climate, geomorphic, and management settings. These experiments could be conducted in conjunction with restoration projects (e.g., road removal and wood additions) and be used to inform future efforts to restore wood in streams (Switalski et al. 2004). Such experiments could also investigate upstream factors, such as crossings and culverts that act as barriers to downstream transport and accumulation of wood (Flanagan 2004), and relationships between road type and the amount of instream wood (Switalski et al. 2004). Although we acknowledge this need, economic, logistical and bureaucratic complications make large-scale land management experiments difficult to implement. Furthermore, due to the time necessary to grow large trees, potential results are decades in the future. We therefore think the best path forward is large-scale monitoring programs, combined with longer-term experiments that can eventually help explain processes (Lovett et al. 2007).

Our findings illustrate that roads can have the same effect on wood in streams as large changes in climate, geomorphology, and management. The potential loss of habitat due to roads is high because most roads are a permanent feature of the landscape. Nonetheless, wood inputs are one the few aspects of habitat that can be easily manipulated by land managers, partly through changes in riparian management practices and placement of wood into streams (Roni et al. 2002; Lester et al. 2007). If managers invest the necessary restoration resources to reduce road impacts, the ecological gains from such actions could more than compensate for some of the potential losses due to factors such as climate change and past habitat degradation. Common management actions to restore wood include road removal, road relocation, wood additions, and changes in land use adjacent to the streams (e.g., grazing and harvest; USFWS 2004; NOAA 2009). Because streams differ in their ability to retain and accumulate wood, the most appropriate management strategy will vary by location (Czarnomski et al. 2008). Viewing road restoration projects in the context of large landscapes would allow for the identification of the most suitable areas for road restoration projects, and the maximum benefit given funding and other limitations.

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