Restoration Ecology
THE JOURNAL OF THE SOCIETY FOR ECOLOGICAL RESTORATION

REVIEW ARTICLE

Linkages between unpaved forest roads and streambed sediment: why context matters in directing road restoration

Robert Al-Chokhachy[1,2], Tom A. Black[3], Cameron Thomas[4], Charles H. Luce[3], Bruce Rieman[5], Richard Cissel[3], Anne Carlson[6], Shane Hendrickson[7], Eric K. Archer[8], Jeff L. Kershner[1]

Unpaved forest roads remain a pervasive disturbance on public lands and mitigating sediment from road networks remains a priority for management agencies. Restoring roaded landscapes is becoming increasingly important for many native coldwater fishes that disproportionately rely on public lands for persistence. However, effectively targeting restoration opportunities requires a comprehensive understanding of the effects of roads across different ecosystems. Here, we combine a review and a field study to evaluate the status of knowledge supporting the conceptual framework linking unpaved forest roads with streambed sediment. Through our review, we specifically focused on those studies linking measures of the density of forest roads or sediment delivery with empirical streambed sediment measures. Our field study provides an example of a targeted effort of linking spatially explicit estimates of sediment production with measures of streambed sediment. Surprisingly, our review uncovered few studies ($n = 8$) that empirically tested the conceptual framework linking unpaved forest roads and streambed sediment, and the results varied considerably. Field results generally supported the conceptual model that unpaved forest roads can control streambed sediment quality, but demonstrated high-spatial variability in the effects of forest roads on streambed sediment and the need to address hotspots of sediment sources. The importance of context in the effects of forest roads is apparent in both our review and field data, suggesting the need for in situ studies to avoid misdirected restoration actions.

Key words: restoration, road density, sediment production, streambed sediment

Implications for Practice

- Limited empirical evidence exists to specifically quantify the effects of forest roads on aquatic ecosystems and effectively target restoration.
- Sediment production from roads and delivery to streams varies substantially within and across landscape settings.
- The conceptual model linking roads to streambed sediment is supported by field data, but the contribution from different road segments can vary substantially, highlighting the importance of context in prescribing restoration actions as a means to reduce sediment contributions.

Introduction: The Need for Road Restoration

Public lands remain a critical component of large landscape conservation within western North America (Noss et al. 2002; Hauer & Muhlfeld 2010). Such public lands, however, are culturally and socioeconomically valuable to adjacent communities (Naylor et al. 2009), rendering a wide range of current and historical land use practices. Historically, unpaved roads have been constructed across the public lands of western North America to facilitate forest management, as well as associated land use practices such as timber harvest and grazing. The total extent of unpaved forest roads in Idaho, Montana, Oregon, and Washington alone is seven times the length of interstate highways across the contiguous United States. Many of these roads have been identified as causing significant impacts to streams and riparian systems through changes in hydrology, mass wasting and sediment delivery, and riparian degradation (Jones et al. 2000; Trombulak & Frissell 2000). Because there are hundreds of thousands of miles of existing unpaved roads, prioritization of restoration actions is an imperative step in effectively recovering ecosystems.

Author contributions: RA, TAB, CT, CHL, BR, AC, SH, EKA, JLK conceived and designed the research; RA, TAB, RC, SH, EKA collected field data; RA, TAB, RC, CHL analyzed the data; RA, TAB, CT, CHL, BR, AC, JLK wrote and edited the manuscript.

[1]U.S. Geological Survey, Northern Rocky Mountain Science Center, 2327 University Way, Suite 2, Bozeman, MT 59715, U.S.A.
[2]Address correspondence to R. Al-Chokhachy, email ral-chokhachy@usgs.gov
[3]USDA Forest Service, 322 East Front Street, Suite 401, Boise, ID 83702, U.S.A.
[4]USDA Forest Service, 200 E. Broadway, PO Box 7669, Missoula, MT 59807-7669, U.S.A.
[5]Clearwater Resources Council, PO Box 1471, Seeley Lake, MT 59868, U.S.A.
[6]The Wilderness Society, 503 W. Mendenhall, Bozeman, MT 59715, U.S.A.
[7]USDA Forest Service, Building 24a, Fort Missoula, Missoula, MT 59804, U.S.A.
[8]USDA Forest Service, 860 N 1200 E, Logan, UT 84321, U.S.A.

doi: 10.1111/rec.12365
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.12365/suppinfo

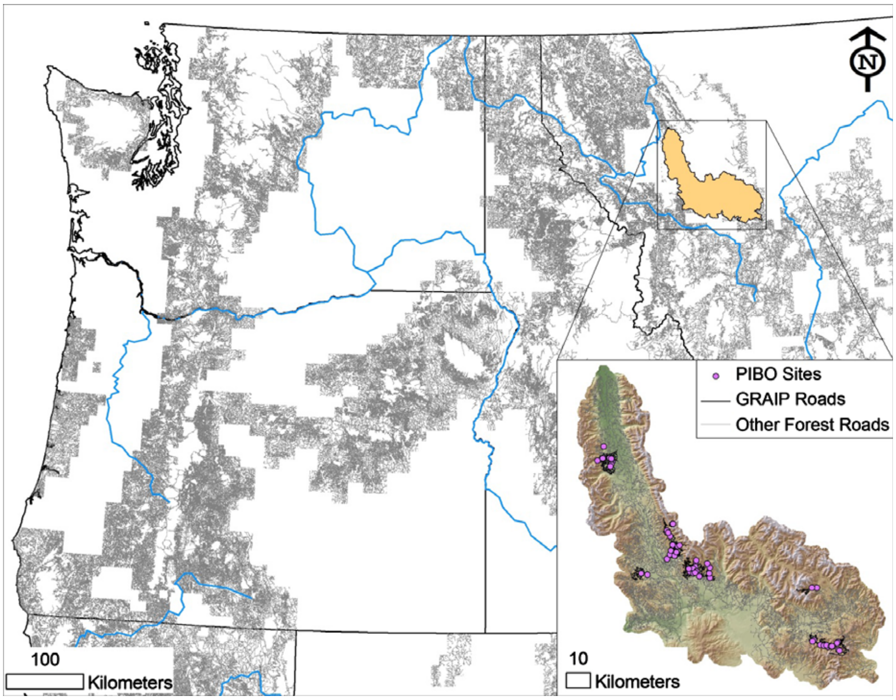

Figure 1. The majority of forest road networks (gray) and major rivers (blue) throughout the Pacific Northwest (gray), the location of the *Southwest Crown of the Continent (inset), forest roads included in the GRAIP inventory (black), and habitat sampling locations (i.e. PIBO sites).

Removing or restoring unpaved roads remains an option for mitigating ecosystem effects (Lloyd et al. 2013), but this is a daunting task given the extent of the current road network (Fig. 1), the high cost of either maintenance, relocation, or obliteration of roads, and the restrictive nature of available funding. Furthermore, there remains considerable resistance from the public to closing forest roads that have historically been open for recreation and management.

Mitigating the effects of unpaved forest roads is an important component of native salmonid (e.g. salmon and trout) conservation, a group of fishes with high ecological, socioeconomic, and culture value (Naiman et al. 2002; Stapp & Hayward 2002; Loomis 2006) that has experienced significant declines in distribution and abundance across the Rocky Mountains (Thurow et al. 1997). Headwater streams within and immediately downstream of public lands are critical for supporting multiple stages of salmonid life cycles (Northcote 1997). Anticipated changes in climate suggest that montane ecosystems are likely to be disproportionately important as areas of coldwater refugia (Wenger et al. 2011), and yet these areas contain a large portion of the existing, unpaved roads. Although roads may not represent a large portion of the total sediment budget in these areas (Goode et al. 2012), they can have a disproportionate effect on streambed sediment (Maturana et al. 2014). A key question for managers remains how and what can be done (i.e. climate adaptation) to increase species resilience to climate change through alleviating land management activities that potentially limit populations (Lawler et al. 2010).

In response to the need for forest restoration, the U.S. Congress established the Collaborative Forest Landscape Restoration Program (CFLRP) in 2009 to initiate science and community-based, large-scale restoration on public lands. The CFLRP is part of the Omnibus Public Land Management Act and encourages collaborative, science-based ecosystem restoration while specifically incorporating ecological, economic, and social sustainability components. A key component in initiating landscape restoration is science-based justification of specific locations for restoration (sensu Luce et al. 2001; Rieman et al. 2010), as well as monitoring the long-term effectiveness of such actions (e.g. ecosystem response to road restoration). Providing empirically-based rationale for the need for road restoration will likely facilitate socially and economically acceptable restoration under the CFLRP.

Effectively targeting road restoration opportunities in montane ecosystems requires spatially explicit disturbance information (i.e. road effects) and an understanding of how different disturbance processes, intensities, routing, and locations affect important attributes of aquatic ecosystems. The general understanding of road effects on aquatic ecosystems has been based largely on varied measures of road density and their associations with in-stream habitat or species/population status (e.g. Thurow et al. 1997; Hughes et al. 2004), but often lacks resolution on specific processes driving the apparent response.

Here, we refine our understanding of forest roads and their effects on streams by combining a review of existing literature linking unpaved forest roads with streambed sediment and a targeted study that integrates field data with mechanistic models of the processes thought to link roads to streams. We specifically focused on road-related sediment delivery and consequently, streambed sediment habitat attributes, as sediment

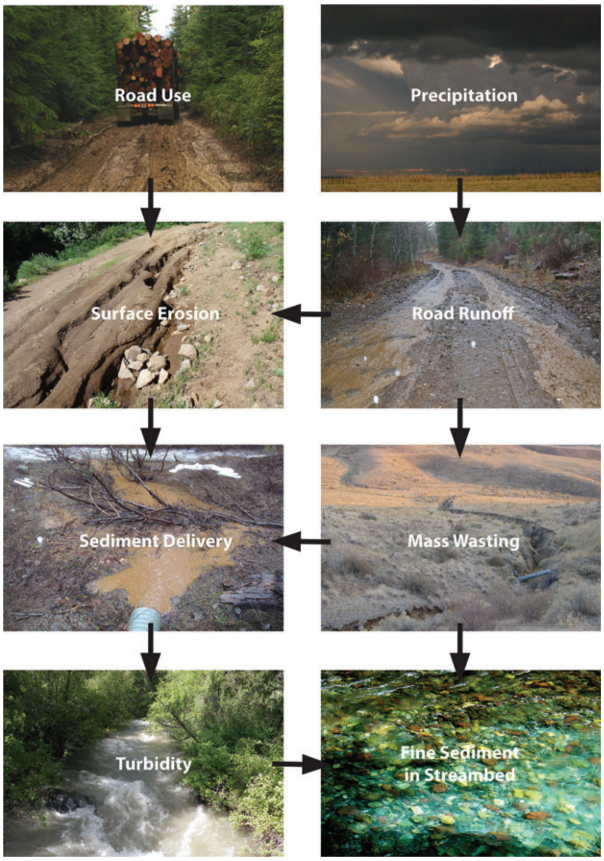

Figure 2. The conceptual model linking different sources of sediment from forest road surfaces and road networks to streambed sediment (Photos by T. Black).

strongly affects salmonid egg survival and habitat use (Tappel & Bjornn 1983; Suttle et al. 2004) and aquatic ecosystems (Wood & Armitage 1997; Allan 2004). Furthermore, the general assumption under the CFLRP is that road-related sediment is a major source of disruption of streams (Fig. 2). We merge the results from the review and the field study to address our specific objectives to evaluate: (1) the variability in sediment production across road networks; (2) the delivery of sediment from road networks to stream networks; and (3) the conceptual model (e.g. Trombulak & Frissell 2000) linking sediment production from unpaved roads to in-stream habitat characteristics (Fig. 2). Collectively, our review, which is largely driven by studies aimed at reducing the effects of roads on streams within the historical range of salmon species (*Oncorhunchus* spp.) currently listed on the U.S. Endangered Species Act list, and our case study serves to guide restoration in similar situations around the world.

Review of Current Literature

A number of reviews exist concerning the ecological effects of roads (Forman & Alexander 1998; Jones et al. 2000; Trombulak & Frissell 2000) and the delivery of sediment from mountain roads (Croke & Hairsine 2006). Here, we concentrated our efforts on peer-reviewed studies that specifically evaluated empirical relationships between sediment delivery from unpaved road surfaces and road density estimates with streambed sediment composition. We were interested in sediment from unpaved, forest roads—typically characterized as “fine” sediments (i.e. <6 mm)—as it can be mobilized by rain and melting snow, aggrade in-stream habitats and in some cases restrict the development of embryos or other life stages of fishes (Jensen et al. 2009). Our focus on these specific linkages is driven by the common and pervasive use of streambed sediment metrics to evaluate the effects of management activities on aquatic habitat (Kershner et al. 2004).

We used Web of Science to search for articles matching these criteria. We performed searches that iteratively used “forest road AND sediment or substrate” and “road density AND sediment or substrate.” Subsequently, we used literature-cited references within relevant publications to identify other applicable research. In addition, we used Google Scholar to examine all publications that cited each applicable article.

What We Found; Literature Review

Focusing specifically on the effects of unpaved, forest roads on streambed sediment, our review uncovered only eight studies that specifically linked measures of sediment delivery or density of unpaved forest roads with streambed sediment metrics (Table 1). Bilby (1985) found considerably differences in turbidity levels above and below a sediment source (i.e. ditch) but no significant difference in streambed sediment characteristics. Instead of road density, Schnackenberg and Macdonald (1998) used the amount of road segments greater than 400 m within 60 m of a stream channel, and found no significant relationships between this surrogate for road density and fine sediment across catchments dominated by granitic or sedimentary geologic formations. Despite different response metrics, three of the four studies that included density of unpaved roads found significant, positive relationships between road density and measures of fine sediment. Yet, the strength of these relationships was variable and sometimes weak (e.g. $r = 0.36$; McCaffery et al. 2007). Together, these results indicate considerable variability in associations found between roads and road density and streambed sediment. At least part of this variability may be due to the anthropogenic disturbances related to roads (see below), which are not captured in road-density analyses.

Sediment delivery from locations where forest roads intersect streams (i.e. road crossings) can be particularly acute (Pechenick et al. 2014) and can comprise a large proportion of sediment production for road networks (Coe 2006). The three studies that specifically evaluated linkages between road-stream crossings and streambed sediment found significant correlations (Table 1); however, Schnackenberg and Macdonald (1998) also found the significance of the relationship varied across watershed geologies, suggesting that the effects of road crossings are context-specific. Only Cover et al. (2008) have demonstrated strong positive correlations between streambed sediments with sediment delivery from roads. Overall, given the extensive network of unpaved forest roads (Fig. 1), we consider the paucity

Table 1. Studies from a literature review that evaluated linkages between different road-related metrics and streambed sediment metrics, the location of the studies, the road metric considered, the sediment metric considered, and the correlation direction (ns, nonsignificant). [a]Relationships differed by geologic composition; nonsignificant in sedimentary-volcanic geology, significant in granitic geology. [b]Canada.

Study	*Location*	*Metric*	*Sediment Metric*	*Correlation*
Cederholm et al. (1980)	WA	Road density	Subsurface fine sediment	+
Bilby (1985)	WA	Turbidity from roads	Subsurface fine sediment	ns
Lisle and Hilton (1992)	CA	Road density	Fine sediment volume in pools	+
Eaglin and Hubert (1993)	WY	Road density, density of culverts	Surface fines and embeddedness	ns, road density; + culverts
Schnackenberg and Macdonald (1998)	CO	Density of culverts, extent of road network near channel	Surface fines	ns, +[a] culverts; ns extent of road network near channel
Kreutzweiser et al. (2005)	ON[b]	Stream crossing	Subsurface fine sediment	+
McCaffery et al. (2007)	MT	Road density, crossings	Subsurface fine sediment	+
Cover et al. (2008)	OR	Sediment supply	Surface fines, volume of fines, permeability of streambed	+, +, −

of existing literature linking observed sediment production and road density with streambed sediment surprising.

Measuring Sediment Delivery: A Case Study

We synthesized data from a field study within the 6,070 km^2 Southwestern Crown of the Continent CFLRP project in western Montana (SWCC). The SWCC is set in three adjoining National Forests (Flathead, Helena, and Lolo) and currently contains greater than 7,200 km of roads. Climate within the study area is characterized by relatively cold, wet winter and spring months and relatively warm, dry summers. Streamflows are typical of the northern Rocky Mountains with highest spring flows during May and June, which taper throughout the summer and early winter.

We selected six individual 12-digit subwatersheds in the SWCC (Hydrologic Unit Code [HUC]; http://water.usgs.gov/GIS/huc.html) to conduct field sampling based on the need and potential (i.e. logistically feasible) for road restoration. Reducing sediment contributions to aquatic ecosystems via restoration has been deemed a priority in the SWCC by State and Federal agencies and local communities. A major component of the justification for restoration is to alleviate stressors to rare and threatened species such as bull trout (*Salvelinus confluentus*), a species listed under the Endangered Species Act with specialist habitat requirements (Al-Chokhachy et al. 2010*b*).

Road Inventory and Sediment Modeling

We conducted a detailed inventory of all of the identifiable roads within the watersheds using the Geomorphic Roads Analysis and Inventory Package (GRAIP) methodology (Black et al. 2012). Through a GPS-based inventory we documented the locations of water flow along the road (i.e. ditches) and drain points where that water discharges to the hillslope or stream network (Appendix S1, Supporting Information). We recorded the volumes of gullies, landslides, and fill material that was eroded by runoff from the road and if it delivered to the stream. Next, we measured surface erosion rates for the roads in the study area at eight sediment plots between 2011 and 2014, a period ranging from below to above average precipitation (http://ncdc.noaa.gov; station ID GHCND:USC00247448). Briefly, we located 80-m plots on typical unsurfaced roads that were open ($n = 4$) and closed ($n = 4$) to public traffic. We collected runoff and sediment from the plots into settling tanks and the outflow from the tanks was connected to a filter to retain sediment (Appendix S1). Coarse sediment deposited in settling tanks was then removed and weighed wet at the site with a portable hanging scale each June and October (Black & Luce 2013). Tipping bucket rain gages were deployed near the sediment plot locations to measure liquid precipitation depth and intensity. We integrated the detailed road inventory data and erosion rates from sediment plots with 30-m elevation data (ned.usgs.gov) in the GRAIP model (Version 1.0.8, http://neng.usu.edu/cee/faculty/dtarb/graip; Cissel et al. 2012) resampled to 5 m to estimate road sediment production (E) for each road segment (Luce & Black 1999):

$$E = B \times L \times S \times V \times R$$

where B is the average erosion rate from the sediment plots (kg/m elevation), L is the road length (m), S is the slope of the road (m/m), V is the vegetation cover factor for the flow path, and R is the road surfacing factor. We employed GRAIP to route sediment from the road drain points to the downslope stream using a flow direction grid (Taudem 4, http://hydrology.usu.edu/taudem/taudem4.0/, Tarboton 1997) and the field observations of stream connection (Appendix S1). Finally, we used GRAIP to accumulate delivered road sediment in a downstream direction and normalized the total mass by watershed area to provide a specific road sediment value (mg/km^2), which allows sediment impacts to be compared between watersheds of different sizes (Cissel et al. 2012).

Streambed Sediment

Our initial sampling frame included all perennial streams in the selected SWCC subwatersheds that occurred on public lands. We used the National Elevation Dataset (30 m; http://ned.usgs.gov) to initially screen for streams with low (<6%) gradients to focus on areas most sensitive to changes in watershed conditions (e.g. Montgomery & Macdonald 2002). We then categorized the existing road densities of catchments for streams based on existing forest road information (1:24,000 scale; USDA 2014), and used a spatially balanced, stratified sampling design (generalized random tessellation stratified; Stevens & Olsen 2004) with road density categories as our strata (spsurvey package; R Development Core Team 2012) to identify specific sites for sampling (Appendix S2).

We sampled stream habitat at sites during baseflow conditions in late August and September when sediment transport is minimized (2012–2014; Kershner et al. 2004). At each sample site, we measured sediment and physical attributes that can moderate sediment characteristics (e.g. large woody debris). We sampled sediment metrics that have been demonstrated to have strong linkages with salmonid survival during the early life-history stages and are commonly used in land management monitoring programs (Al-Chokhachy et al. 2010*b*; Bryce et al. 2010). Our sediment sampling included: (1) the measures of median particle size (d_{50}) of all surface substrate particles; (2) the percent of surface fine sediment (<6 mm) in pool tails; and (3) the percentage of fine sediment (<6 mm) in subsurface sediment determined from a shovel–core sampling approach (Sutherland et al. 2010).

Quantifying Road-stream Habitat Linkages

At each of the randomly selected sites, we delineated catchments upstream of each site which encompassed all existing road information from the GRAIP surveys. We then summarized landscape-level covariates including an index of stream power (Flores et al. 2006), catchment-level estimates of drainage density, average precipitation and proportion of the catchment with less erosive Belt Series geology (i.e. sedimentary; Sugden & Woods 2007), and site-level estimates of large woody debris, and sinuosity (Appendix S3). We constrained our analyses to sample sites with field estimates of gradient (Appendix S3) less than 3.5% to align with regional monitoring programs (Kershner et al. 2004). We then developed multiple linear regression (MLR) models to evaluate relationships between road density and sediment delivery from GRAIP and streambed sediment in sites after accounting for covariates. To avoid any potential effects on model structure arising from the order in which explanatory variables entered the MLR models (i.e. spatial scales, landscape factors, and so on), we used an all-subsets modeling approach (R Development Core Team 2012).

Sediment Delivery from Roads in the SWCC

Our detailed inventory in the SWCC subwatersheds included 896 km of forest roads and 13,125 drain points. In our study, only 4–5% of the forest road network was found to be hydrologically connected to stream networks, which is dramatically different than 57% estimated in western Oregon by Wemple et al. (1996). Localized hotspots of sediment production were apparent and typically included road crossings and culverts (Fig. 3A & 3B), and only 2% of the drain points were estimated to deliver 90% of the sediment in our study watersheds. We estimated that over time road surface erosion delivered 44% of the total sediment from the road to streams, while episodic contributions from gullies, landslides, and fill erosion delivered 22%, 18% and 15%, respectively (Cissel et al. 2014).

On average roads open to travel (0.40 kg/m^2) were estimated to produce over an order of magnitude more sediment than roads closed to travel (0.03 kg/ m^2). A substantial difference with road use is consistent across studies, but the effects of use can vary considerably (e.g. Reid & Dunne 1984; Luce & Black 2001).

Road Density, Sediment Delivery, and Streambed Sediment

Estimated sediment delivered to streams varied by over an order of magnitude (Fig. 3C) and catchment-level measures of road density and sediment delivery were significantly correlated ($r = 0.43$, $p = 0.002$; Fig. 4A). Measures of streambed sediment differed across sites and we observed a range of sediment values for a given road density and sediment delivery (Fig. 4B & 4C; Fig. S2). Considering sediment criteria for bull trout, 22% of the sites exceeded what has been suggested as an optimum level for surface fines for bull trout spawning and egg incubation (Bryce et al. 2010).

After controlling for covariates, we found significant relationships between d_{50} (−), pool tail fines <6 mm (+), and percent subsurface fines (+) with road density ($p < 0.05$; Fig. 4D; Fig. S1). Although the pattern was still supportive of the conceptual model, our multimodel approach indicated less support in our data for models linking sediment production from road networks with streambed sediment than those based on simple road density (Table S1; Fig. 4C). Unfortunately, this leaves more questions than clarity, likely as sediment delivery from roads varied across a small range in the SWCC (e.g. Fig. 5 and contrast with the study of Goode et al. 2012).

Rethinking the Relationship of Roads and In-stream Sediment Effects in the SWCC

Our study clearly demonstrated a negative relationship between field-measured densities of forest roads and the quality of streambed sediment (i.e. proportion of fines, d_{50}). Data linking sediment production and streambed sediment suggest that sediment production serves as a constraint on streambed sediment (i.e. limits the possible range of conditions; Fig. 4C); indeed post hoc quantile regression analysis (0.9 quantile) supports this notion (d_{50}; $\beta = -0.09$; SE = 0.02). In other words, streams with the highest road densities or estimated sediment production and delivery rates are likely to dramatically reduce the upper range of possibilities for d_{50} (i.e. maximum possible median particle size). In concordance with this general pattern, we found an increasing range for attributes such as the percent of surface fine sediment in pool tails and percent subsurface fine sediment

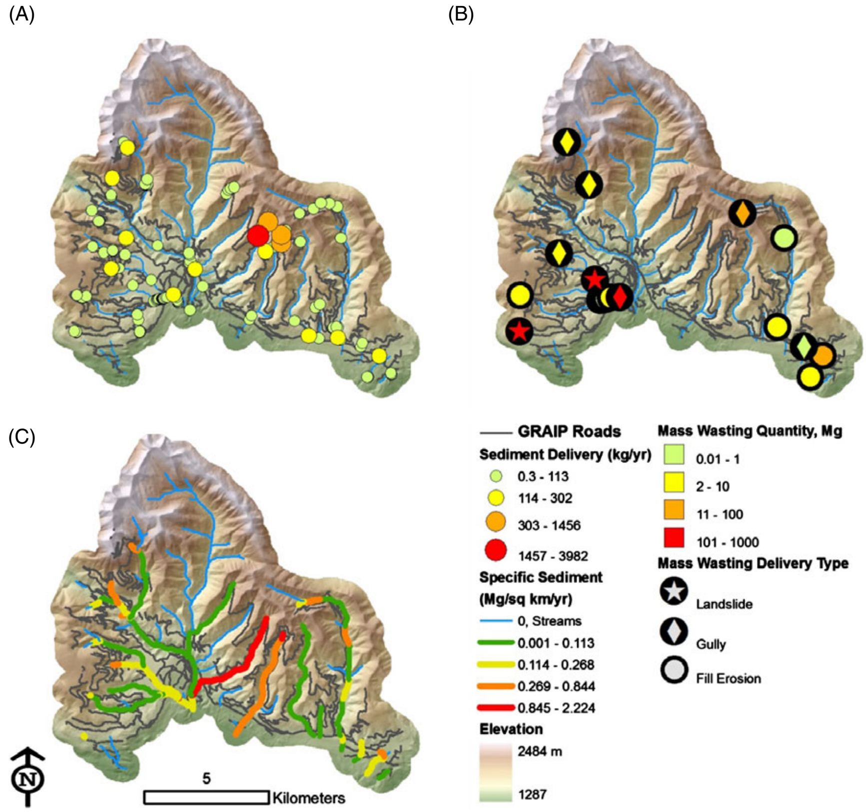

Figure 3. Spatial variability in sediment delivery from road surfaces for locations where road networks are connected to stream networks (A), locations and quantity of sediment from mass wasting (B), and the specific sediment production to stream from road networks (C) for a subwatershed in the SWCC study area.

with increasing road density but less clarity in such relationships with sediment delivery (Fig. S2). Our data support a model that natural disturbances and variability in hydrologic and geomorphic processes lead to a wide range of variability in streambed sediment that can be more and more constrained with intensive road development within a watershed.

The Importance of Context

The variability in the relationships we observed and comparisons to that of other studies (e.g. Cover et al. 2008) imply that all roads are not equal in their effects, and that topographic and geologic contexts matter. This is not surprising across inherent differences in geology, which control the characteristics of the material and the erosion rates. The SWCC is largely dominated by Belt Series metasedimentary parent materials that result in relatively low erosion rates (e.g. Sugden & Woods 2007), while the inference by Cover et al. (2008) is from a far more weathered granitic geology. But even within our study, the variability in sediment production and delivery with simple road density is substantial (Fig. 4A). Certainly, our results do not suggest that forest roads have limited effects on sediment delivery to streams everywhere in Belt Series geology but understanding the geologic as well as landscape, climatic, and so on (Pechenick et al. 2014) context matters. Borrowing inference from previous studies to justify action (i.e. road construction or restoration) or no-action may not be judicious.

Concomitantly, sediment that enters streams comes from a variety of both land management and natural sources and this complicates our ability to identify the effect on streambed sediments from just one source. For example, off road vehicle trails, cattle grazing, and forest management may also create sediment that eventually ends up in streams. Potential legacy effects (e.g. Harding et al. 1998) from past disturbances or even episodic events from road networks (e.g. mass wasting) may represent further contributions to streambed sediment that are difficult to measure with a single snapshot of existing watershed conditions. However, data identifying management intensity (e.g. livestock grazing) and legacy effects are extremely limited (Al-Chokhachy et al. 2010*a*). Isolating these sources from current road sediment contributions continues to be a major challenge but necessary to help managers prioritize where restoration of roads might be most effective.

Issues of Scale in Monitoring to Guide Road Restoration

The majority of existing stream habitat data within roaded (i.e. unpaved roads) and managed landscapes has been collected through large-scale monitoring programs by agencies

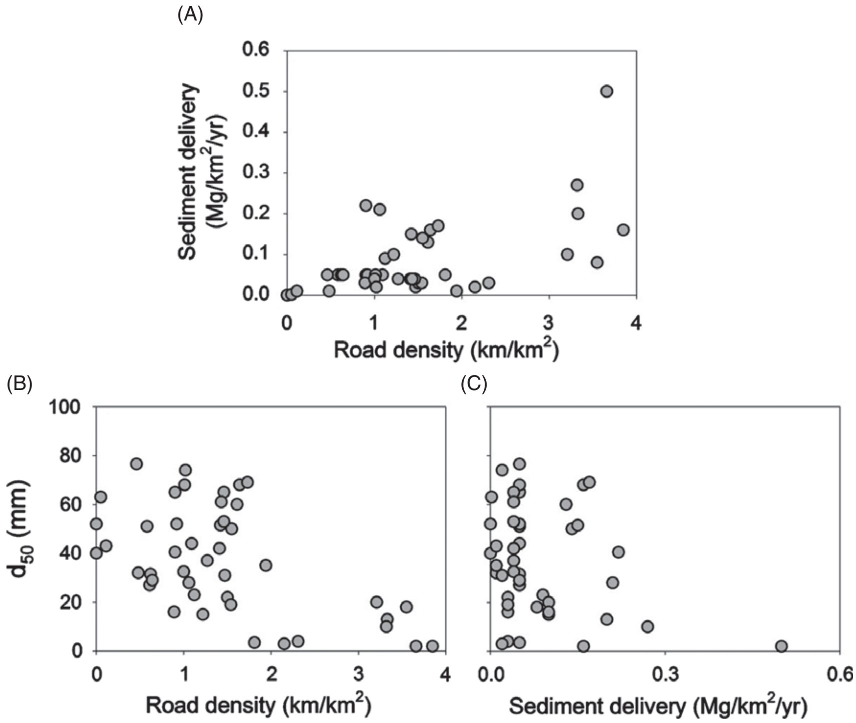

Figure 4. The relationship between estimates of sediment delivery estimated from GRAIP and road density in catchments upstream of streambed habitat sampling sites ($r=0.43$; A) and median particle size (d_{50}) from low-gradient sites (<3.5% gradient) plotted against catchment-level estimates of road density ($r=-0.53$; B) and sediment delivery estimated from GRAIP ($r=-0.23$; C) for sampling locations in the Southwest Crown of the Continent in Montana.

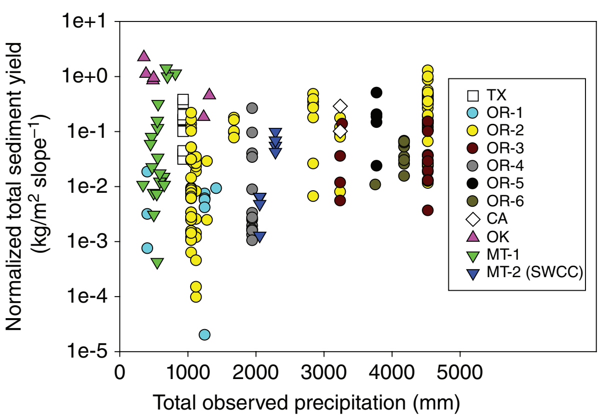

Figure 5. Estimates of sediment yield (normalized for road area and slope; log scale) across different precipitation regimes (measured in situ at individual plots) from studies in different regions of the United States. The locations of studies are indicated by U.S. state symbols; where multiple studies occurred within any given state, a number is used to denote a separate study.

including the U.S. Forest Service, U.S. Environmental Protection Agency, and so on designed specifically to monitor the effectiveness of management actions. While such programs may be essential in identifying landscape disturbance patterns across large landscapes (e.g. Kershner et al. 2004), there remains a paucity of applications where such data are aligned with detailed management disturbance information such as sediment production and delivery. This monitoring mismatch makes it challenging to accurately identify and prioritize hotspots of sediment sources, particularly through the use of office-mapped road density data alone (Fig. 1). Furthermore, in many cases road density provides an index of overall human disturbance, not the specific effects of sediment contributions from roads.

At first glance, labor intensive, in situ studies of sediment production, connectivity to stream networks, and measures of streambed sediment as demonstrated herein may seem cost prohibitive. Alternatively, the costs associated with naïve road restoration ($10,000–100,000/mile; Robinson et al. 2010) may not only have little effect on changing the conditions of streambed sediment but also detract from locations where resources could be used more effectively. For areas where streambed sediment may be limiting ecosystem processes, the costs of a detailed study that refines effective restoration choices and specifically develops defensible, sediment mitigation plans (e.g. Lisle et al. 2015) are likely to fall well below the costs of a broadly applied naïve road restoration program. Indeed the costs of a targeted study as opposed to the uncertainty of the benefits of restoration should be considered.

Understanding the Benefits of Road Restoration: Management Considerations

Part of the challenge in quantifying the benefits of road restoration to aquatic ecosystems is because of the limited number of studies that have monitored the results in a statistically rigorous manner (Bernhardt et al. 2005). Detailed studies have examined sediment production from road segments (Reid & Dunne 1984; Sugden & Woods 2007, among others), and changes in sediment production through restoration actions (e.g. Switalski et al. 2004). However, few efforts have quantified how restoration actions (e.g. surfacing, obliteration and culvert removal) translate into changes in streambed sediment at the scale of an entire watershed.

Sediment production from road surfaces varies dramatically within and across ecological settings (Macdonald & Coe 2008; Dube et al. 2011), with over three orders of magnitude differences within similar ecoregions and precipitation regimes (Fig. 5). Differences in sediment production coupled with landscape-influenced differences in connectivity to stream networks and streambed sediment highlight the challenges in understanding the benefits of road restoration (Benda & Dunne 1997).

Although the results of our field study represent only a snapshot of time, they support management priorities that include addressing sediment sources at road crossings and closing roads to travel as options for reducing sediment risks in the SWCC. Infrastructure upgrades, best management practices, and removal/restoration provide mitigation opportunities at stream crossings (McCaffery et al. 2007). Promoting revegetation of roads through closure can dramatically reduce sediment production while still allowing some maintenance of infrastructure for future management and avoiding the high costs of complete road obliteration (Foltz et al. 2009). Ultimately, we suggest that cost-benefit analyses that explicitly consider ecological effects and financial obligations associated with different management approaches are warranted.

A Systematic Approach to Identifying Problem Roads

In some cases, road sediments that are related to culvert failures, landslides, and gullies present obvious locations for road rehabilitation or restoration. When these obvious problems are not present, a systematic approach that is more informative for identifying the need and means for remedying road-related issues may be warranted. An initial step in this approach would be to quantify if and where sediment levels (e.g. suspended sediment, streambed sediment) are exceeding regional baseline levels and/or are limiting biota (e.g. Shaw & Richardson 2001). This step is imperative, particularly where sediment effects on aquatic ecosystems are the justification for restoration. A logical next step would be to quantify road density information from readily available Geographic Information System (GIS) layers as well as potential other sources of sediment contribution (e.g. recreation) as measures of potential risk; however, the extent of forest roads may need to be verified as we documented greater than 30% more roads than reported in GIS layers. Where road networks exist upstream of sediment-impaired ecosystems, information regarding chronic and episodic source locations (e.g. mass wasting) may be necessary to identify hotspots of sediment production and effectively target restoration options (Luce et al. 2001). Region-specific measures of sediment production may be warranted given inherent differences in geology, soil types, precipitation, and the design, aggregation, and use of roads (Pechenick et al. 2014). Accumulation of studies will ultimately improve our understanding of the differences in sediment production from road networks, and concomitantly delivery to streams, across parent geology and soil types. Once refined, developing hybrid field-GIS-based approaches (e.g. Benda et al. 2007) that would allow platforms such as GRAIP to be regionally calibrated can allow managers to identify and prioritize locations for restoration activities (Fig. 3). Within this framework, we suggest that it may be imperative to incorporate monitoring approaches (Bernhardt et al. 2005) that will allow for robust assessments of the effectiveness of restoration opportunities.

Conclusions

Here, we specifically focused our review and analyses on linkages between sediment production and delivery from unpaved forest roads and streambed sediment metrics, but not changes in hydrology, fragmentation, or other alterations of terrestrial and aquatic ecosystems because of roads. The influence of forest roads on streambed sediment is often a major justification for restoration under programs such as the CFLRP.

Commonly, there is intense disagreement among biologists, hydrologists, foresters, and supervisors about the relevance of road derived sediment in streams. We find support for the conceptual model linking forest roads and streambed sediment, yet the severity of the effects of roads is highly variable—likely fostering such contention. Although we acknowledge that the inference from our review and case study mainly focused on montane areas of Northwestern United States, sediment from unpaved roads remains a global issue (e.g. Croke et al. 1999; Gruszowski et al. 2003; Sidle et al. 2006) and we consider our results germane in directing restoration efforts. Identifying hotspots of sediment delivery provides a framework for cost-effective and ecologically relevant restoration and evidence to garner public support where the closure/restoration of roads meets resistance from local residents.

Acknowledgments

We would like to thank the PIBO Effectiveness Monitoring Program for logistical support and field data collection and C. A. Dolloff (USFS/Virginia Tech), A. Switalski (InRoads), J. Buffington (USFS), and G. Reeves (USFS) for providing critical reviews of earlier drafts of this manuscript. Funding was supplied in part by the Great Northern Landscape Conservation Cooperative, the U.S. Forest Service, and the CFLRP. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Supporting Information

The following information may be found in the online version of this article:

Appendix S1. Road inventory and sediment modeling.
Appendix S2. Streambed sediment.
Appendix S3. Quantifying road-stream habitat linkages.
Table S1. Multimodel results from multiple linear regression analyses linking road density and sediment production estimates from GRAIP with different measures of streambed sediment.
Figure S1. An example of a settling tank and outflow filter used in sediment plots for calibrating the GRAIP model.
Figure S2. The relationships between site-level estimates of percentage of fine sediment in pool tails (A, B) and percentage of subsurface fine sediment (C, D) with estimates of road density in catchments and sediment delivery estimated from GRAIP, respectively, for sampling locations in the Southwest Crown of the Continent in Montana.

Received: 8 November, 2015; First decision: 17 December, 2015; Revised: 7 March, 2016; Accepted: 9 March, 2016