Resource Roads in British Columbia:
Environmental challenges at the site level

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1. *Inventory and Modeling the Hydro-geomorphic Impacts of Forest Roads on the Middle Fork of the Payette River, Idaho*

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Forest roads have been shown to cause damage to aquatic resources in many environments. High quality road inventory data can provide an economical way to efficiently address the environmental risks created by roads. The Geomorphic Road Analysis and Inventory Package (GRAIP), can be applied for about $250 per mile, and is relatively simple for field crews to implement and for a hydrologist to analyze. GRAIP combines a detailed field inventory with GIS modeling tools to analyze the impacts that forest roads have on watershed resources. The model predicts fine sediment production and delivery, hydrologic integration of the roads and stream, gully and landslide risks, and stream channel diversions. This data can free up scarce road maintenance dollars and improve effectiveness by specifically targeting treatments towards areas in the road system that maximize the benefits to the watershed.

The road-related risks to the Middle Fork of the Payette (MFP) watershed were captured by a detailed inventory and modeling effort conducted by the US Forest Service with support from the Environmental Protection Agency. The total amount of fine sediment from mapped roads delivered to the MFP River and its tributaries was modeled to be 1,691Mg/yr, or 20% of total production on the roads. The average GRAIP predicted sediment delivery rate from roads in the study area was 2 Mg/km^2 (5.5 ton/mi^2) although the values for sub-watershed range from zero to 5.3 Mg/km^2 (0–15.0 ton/mi^2). The average sediment delivery was modeled to be 10% of the natural background stream sediment mass observed locally, with a range from zero to

22%. Road-stream hydrologic connectivity was observed to be 163 km (101 mi) or 17% of all road length surveyed. Much of the road impact was focused on a small fraction of the landscape. We found that 90% of the sediment delivery occurs from 10% of the road length and is routed to streams through 7% of the drainage features.

Introduction

Roads can have a variety of impacts on managed watersheds that include sediment delivery, gully and landslide initiation, stream channel diversion, and changes to the timing of small storm hydrographs. Roads can also impact wood recruitment to streams and affect the aquatic and terrestrial habitat. Some of these impacts can be observed directly while other effects play out infrequently in time and space, particularly following large weather events.

The United States Forest Service manages a land base of 780,000 km^2 and administers over 603,000 km of forest roads. Much of this road system was constructed over 30 years ago when timber harvest was more extensive and under a different road engineering paradigm. This results in the present challenge to the US Forest Service of managing an extensive and aging road system using limited resources.

In order to begin to understand the hydrologic and geomorphic impacts of forest roads on watersheds, we developed a road inventory and modeling system called *The Geomorphic Road Analysis and Inventory Package* (GRAIP). The output of this system allows managers to better understand the various types of road-related risk that exist in their watersheds and provides the basis for managing and prioritizing restoration work to address these risks.

GRAIP is used to inventory and model the risk profile of each of the road segments and drain point features included in the study. The GRAIP system consists of a detailed, field-based road inventory protocol combined with a suite of Geographic Information System (GIS) models. The inventory is used to systematically describe the hydrology and condition of a road system with Global Positioning System (GPS) technology and automated data forms (Black et al. 2012). The GIS applications couple field data with terrain analysis tools to analyze road-stream hydrologic connectivity, fine sediment production and delivery, downstream sediment accumulation, stream sediment input, shallow landslide risk potential with and without road drainage, gully initiation risk, and the potential for and consequences of stream crossing failures (Cissel et al. 2012). Detailed information about the performance and condition of the road drainage infrastructure is also supplied.

The study area

The MFP River is a tributary to the Snake River and is located 80 km north of Boise, Idaho. The main stem of the MFP is listed under the Clean Water Act as impaired by sediment and temperature. The basin is composed of late Cretaceous granodiorites of the Idaho Batholith. The 12 sub-watersheds cover an area of 877 km^2. The watershed is in the snow zone between 900 and 2,650 m in elevation and receives an average annual precipitation of between 50 cm and 150 cm per year depending on the elevation. The dominant forest cover is ponderosa pine at the lower elevation and sub-alpine fir at the upper elevation. Much of the basin is managed timber land with 85% public ownership. Three survey crews inventoried all of the roads on public land but not all private roads; 938 km of road and 17,203 drain points (of which 14,016 were active) were documented over portions of three field seasons.

Road–stream hydrologic connectivity

Roads can intercept shallow groundwater and convert it to surface runoff, resulting in local hydrological impacts when that water is discharged directly to channels (Wemple et al. 1996). Additional runoff is also produced from the compacted road surface. Basin-scale studies in the Oregon Cascades suggest that a high degree of integration between the road drainage system and the channel network can increase peak flows (Jones and Grant 1996).

The hydrologically connected portion of the road system is calculated in GRAIP using field observations of connection at each drain point and a road segment flow routing system. The flow path below each drain point is followed until evidence of overland flow ceases or the flow path reaches a channel. In the MFP, 163 km or 17% of the total road length was hydrologically connected to the channel (Table 1). There was substantial variability in the connectivity within the 12 sub-watersheds; from 0% to 44% were hydrologically connected. This is in part due to the large difference in the length and locations of road within the sub-watersheds. Much of the road is located in the southwestern portion of the study area where many stream side roads were built in a steep dissected landscape. In the northeastern portion of the study area, little timber harvest and road development has occurred and fewer stream side roads exist. Thirty four percent of the road is associated with diffuse drainage, which is most common on outsloped roads. These roads delivered very little sediment (2% of the total). Ditch relief culverts drained 19% of the road length and were associated with 34% of the total sediment delivery.

Fine sediment production and delivery

Fine sediment production at a drain point (*E*) is estimated with a base erosion rate and the properties of two flow paths along the road (Luce and Black 1999, Cissel et al. 2012, Prasad 2007), as shown below.

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

B is the base erosion rate (kg/m)
L is the road length (m) contributing to the drain point
S is the slope of the road contributing to the drain point (m/m)
V is the vegetation cover factor for the flow path
R is the road surfacing factor.

Sediment production on 938 km of road surface was associated with 14,016 active drainpoints and totaled 8,388 Mg/yr. Of these, 11,881 drain points delivered water and sediment back to the hillslope and did not have evidence of surface flow path connection to an active channel. Total sediment delivery from the 2,135 hydrologically connected points was 1,691 Mg/yr. Twenty percent of the material eroded from the road surface and ditch was predicted to deliver to the channel.

Table 1. *GRAIP modeled sediment production, sediment delivery and observed hydrologic connection by drain point type for the MFP, Idaho.*

Drain Point Type	Count	Sediment Production (Mg/yr)	Sediment Delivery (Mg/yr)	% Drain Point Delivery	% of Total Production	% of Total Delivery	Total Road length (m)	% Length	Connected Road length (m)	% connected length
Broad Based Dip	2,086	2,132	219	10%	25%	13%	155,603	17%	16,604	11%
Diffuse Drain	4,546	790	28	4%	9%	2%	314,942	34%	4,913	2%
Ditch Relief Culvert	1,869	1,509	570	38%	18%	34%	177,804	19%	64,958	37%
Lead Off Ditch	125	84	21	24%	1%	1%	9,070	1%	3,116	34%
Non-Engineered	1,712	1,358	254	19%	16%	15%	95,831	10%	19,975	21%
Stream Crossing	369	282	282	100%	3%	17%	34,884	4%	34,884	100%
Sump	127	104	-	0%	1%	0%	9,782	1%	-	0%
Water Bar	3,182	2,127	318	15%	25%	19%	140,483	15%	18,320	13%
All Drains	**14,016**	**8,388**	**1,691**	**20%**	**100%**	**100%**	**938,398**	**100%**	**162,771**	**17%**

The sediment delivery from all drain points was ranked by magnitude to examine the cumulative sediment delivery (Figure 1). Seven percent of all drain points, (967 points) deliver 90% of the sediment, and 2% deliver 50% of sediment at 276 points. This finding that a few drain points and roads are causing the majority of the sediment delivery allows managers to target restoration treatments at the largest sediment sources first. This Pareto relationship has been found in all of the watersheds where we investigated road sediment delivery patterns.

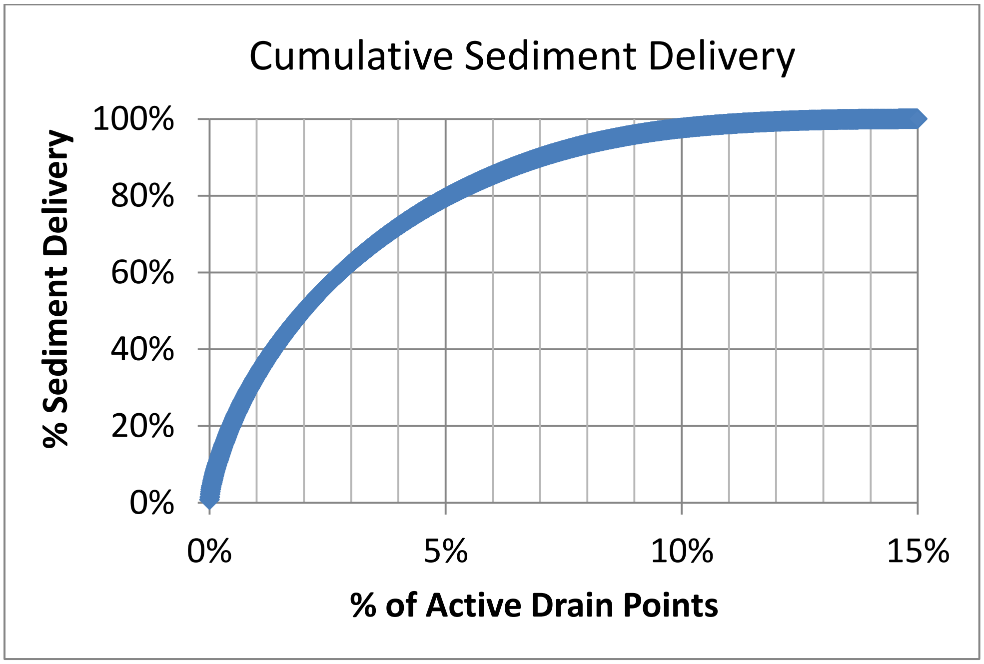

Figure 1. *The fraction of the 14,016 active drainage locations ranked as a cumulative function of their sediment delivery.*

Once we have an accurate map of sediment delivery it is relatively easy to target the top delivering road segments for treatment: 450 Mg of sediment was modeled to deliver at the top 100 drain points, representing 27% of total delivery.

Figure 2 illustrates the pattern of sediment delivery found in the MFP. The main system roads were built along streams and have relatively high sediment delivery. Seventeen of the 100 highest sediment delivery drainpoints are shown here in Anderson Creek accounting for 79 Mg/yr of sediment delivery.

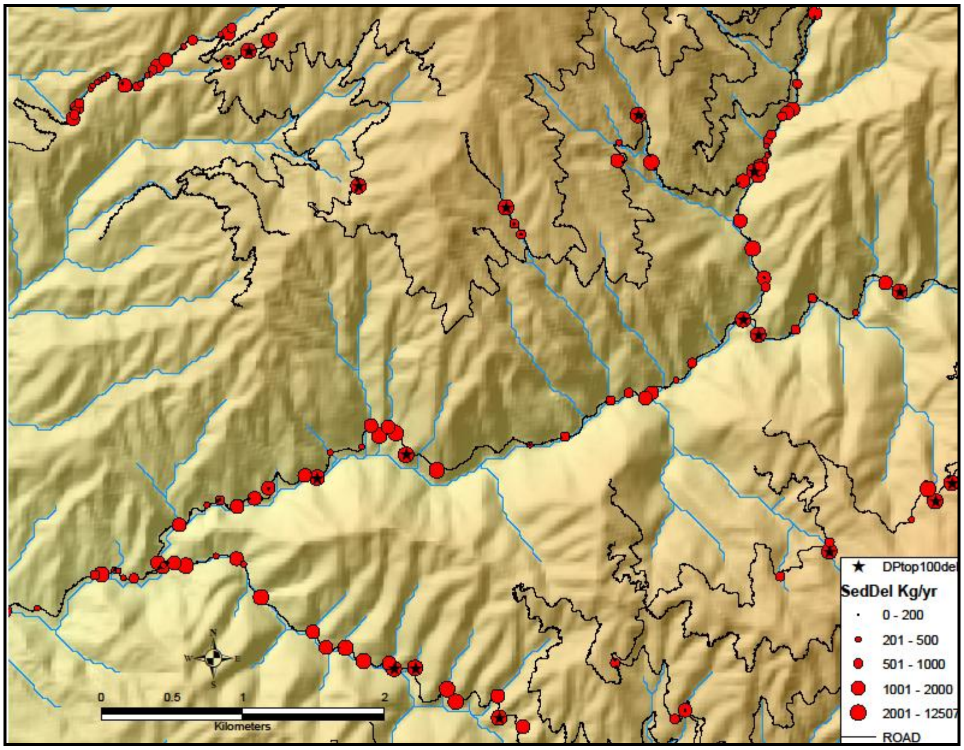

Figure 2. *Sediment delivery from drain points in Anderson Creek. The red circles are scaled to illustrate sediment delivery. Black stars indicate the location of the top 100 sediment delivery points in the MFP watershed.*

We examined the relationship between sediment delivery and several landscape metrics and found that distance to stream, hillslope position, and local ground slope had the best relationship. Seventy-three percent of the total sediment delivery from drains occurs within 100 m of the channel. Drainage locations that were less than 30 meters from the channel had a probability of stream connection of 60% while locations that were in excess of 300 m from the channel had a probability of about 5%. Hillslope position and local ground slope were also closely related to probability of sediment delivery. The highest probability of stream connection occurs on the lower third of the hillslope where local slope was less than 20%.

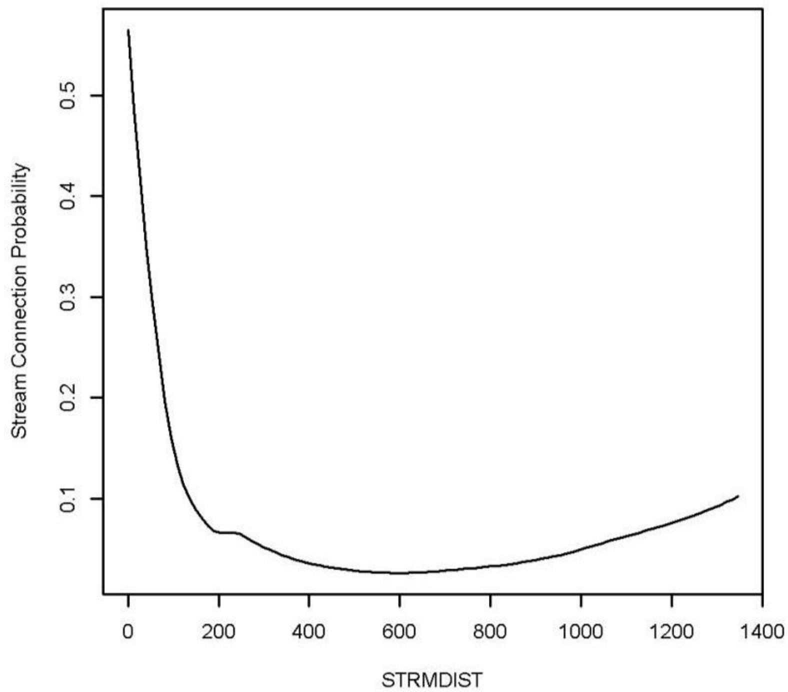

Figure 3. *Local fit to the drain point data showing the probability of stream connection as a function of distance to stream in meters.*

Road surface derived fine sediment enters the stream network below connected drain points. Road-related sediment accumulates in streams and is routed through the network. GRAIP calculates two measures of sediment accumulation for each stream segment. The first measure, sediment accumulation (Figure 4), is the mass of road-related sediment that passes through each stream segment per year. The second measure, specific sediment accumulation, is the mass of road-related sediment normalized by the contributing area. In this metric, area is used as a proxy for discharge, allowing us to compare the sediment impacts to channel segments with differing contributing areas.

Road-related sediment at the mouth of the MFP totaled 1,691 Mg/yr or 1.9 $Mg/km^2/yr$. Specific sediment accumulation in highly impacted channel segments is as high as 6.5 $Mg/km^2/yr$. Three sub-watersheds (Anderson, Scriver and Plye) have sediment accumulation above 5 $Mg/km^2/yr$. Previous work on unmanaged watersheds in Silver Creek measured an annual average erosion rate of 20 Mg/km^2. The most heavily impacted sub-watersheds have road sediment delivery that is 25% above this undisturbed rate, and short channel segments may exceed this.

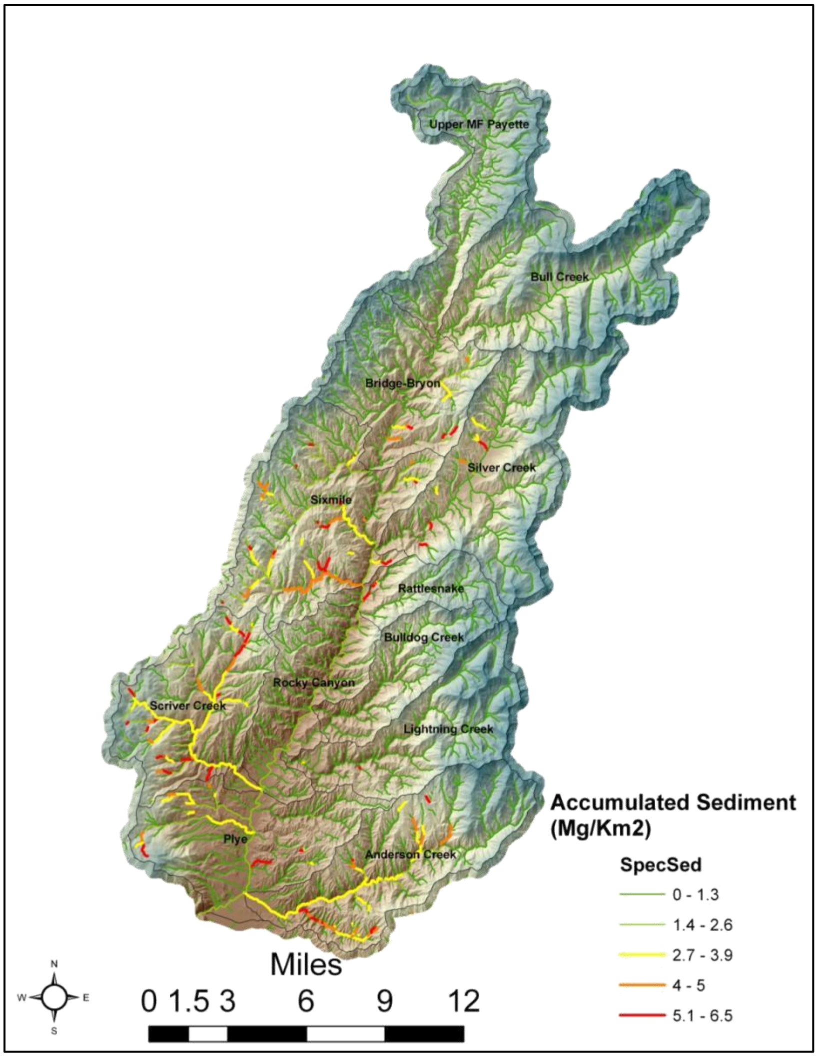

Figure 4. *Road sediment in tonnes per square kilometer accumulated in stream segments.*

Drain points

Not all road drainage systems are equal. Table 1 shows total sediment production and sediment delivery grouped by drain point type. Overall, 20% of all the erosion from the road is delivered to the stream. Half of the total sediment is produced on roads drained with water bars and broad-based dips. These two drain points combined deliver only 32% of the sediment that they receive. Stream crossings receive 3% of the sediment produced but deliver 17% of the total. Likewise, ditch relief culverts deliver sediment at almost twice their proportional share from a sediment production or road length basis.

We can also use this data to assess the effectiveness of our best management practices (BMPs). We examined which drain types were likely to deliver the sediment that was routed to them. Stream crossings were most likely to deliver followed by ditch relief culverts, lead off ditches, and non-engineered drains. Diffuse drainage (outsloped roads) and broad-based dips were least likely to deliver.
Another way of looking at our BMP effectiveness is to examine the condition of the drain points. If a drainpoint has more than .14 m^3 (5 ft^3) of erosion or other specific failure types, it is classified as a problem that warrants a follow up. For example, pipes that are significantly rusted, or have greater than 20% occlusion are considered problems. Overall problems were observed at 10% of drains, and 5% had excessive fill erosion. Ditch relief culverts and sumps had the highest failure rate.

In addition to contributing fine sediment to streams through surface erosion, stream crossings may fail catastrophically when blocked and deliver large sediment pulses to stream channels. Stream crossing failure risks were assessed using the Stream Blocking Index (SBI) (Flanagan et al. 1998). The SBI characterizes the risk of plugging by woody debris by calculating the ratio of the culvert diameter to the upstream channel width and the skew angle between the channel and the pipe inlet. Forty-eight of 369 non-bridge stream crossings were considered at high risk of blocking by SBI, and the fill volume at risk above these pipes was about 4,000 m^3.

A second, and perhaps greater, consequence of concern at compromised stream crossings is the diversion of stream flow onto road surfaces or ditches that allow drainage on to unchannelled hillslopes. Once a stream crossing becomes occluded and begins to act as a dam, failure can occur in several ways. If the road grade dips into and rises out of the crossing, the failure is likely to be limited to a localized overtopping of the stream crossing. However, if the road grades away from the stream crossing in one or more directions, the flow may be diverted down the road and ditch and onto adjacent hillslopes, where it can cause gullying and/or landslide (Furniss et al. 1997, Best et al. 1995). In these situations, large volumes of sediment far exceeding those at the crossing can be at risk. Pipe overtopping or flow diversion down the road was recorded at 17 stream crossings.

A total of 199 gullies were mapped and their volumes measured. Gullies occurred at 187 drain points. Most of these gullies occurred below ditch relief culverts and non-engineered features. The volumes were converted to a mass of 24,435 Mg or 490 Mg/yr assuming an average life of 50 years for the road.

To investigate the risk of gully initiation we calibrated the Erosion Sensitivity Index (ESI), based on the length of the road drainage and square of the hillslope below the drain location. The average probability of a gully occurring below a drain location was about 1%. However, when the ESI value exceeded 30 the gully risk rose to about 6%.

We investigated the potential cost savings available from having the detailed GRAIP road inventory information that allows a precise targeting of sediment delivery problems. We used the Scriver Creek integrated restoration plan to help us look at the planned restoration expenditures. The plan for work in one of the sub-watersheds of the MFP calls for 1.2 million dollars in road -based watershed improvement work over a number of years. We used this as a typical case for a large integrated restoration project.

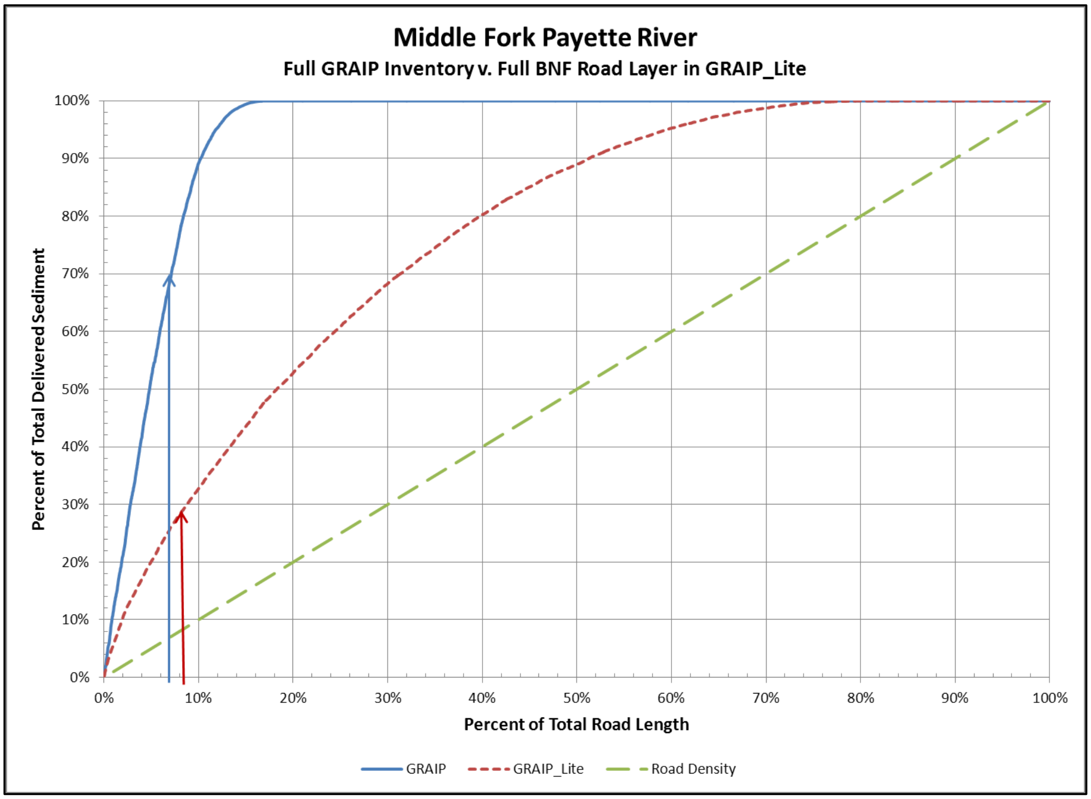

Figure 5. *This figure shows percentage of sediment delivery as a function of cumulative road length for the MFP. The blue line shows the relationship observed with the GRAIP inventory and model. The red dashed line illustrates general relationship found from GIS analysis of the road lines, stream lines and the digital elevation model without local information about sediment delivery at specific drainage locations. The green line shows the relationship between sediment delivery and road length when no data are available, often known as the road density approach.*

First consider the case where we have the detailed inventory dataset. The GRAIP inventory cost was about $135,000, leaving $1,065,000 for treatments. The figure of $25,000/mile was used as an average value for road decommissioning and aggressive restoration treatment. This would support 43 miles of road treatment. Using the blue GRAIP prioritization curve (Figure 5), we would achieve a 71% reduction in sediment delivery from this amount of work, assuming complete elimination of sediment delivery. To simulate the standard approach that does not have a detailed inventory to predict sediment delivery, we used the road line data and the digital elevation model to predict sediment production and the slope position to predict sediment delivery (Figure 5, red line). There was no inventory cost so 48 miles of road was available for treatment. However the efficiency of treating a mile of road was degraded significantly due to a lack of local stream connection data, so roads were not treated in the optimal order. This case resulted in a 29% reduction in sediment delivery versus a 71% reduction for the GRAIP scenario.

Conclusions

The road related risks to the MFP watershed were captured by a detailed inventory and modeling effort conducted by the US Forest Service. Road sediment delivery below drains, gullying below drains, and flow diversions at stream crossings were the mechanisms most likely to result in water quality degradation. Seventeen percent of the road length was able to deliver water and 1,691 Mg of sediment per year to the fluvial system. GRAIP can aid prioritization and improve the efficiency of restoration work by narrowing the focus to the places that really matter in the watershed, for a variety of processes.

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