PRIORITIZING ROAD RESTORATION FOR AQUATIC ECOSYSTEMS USING INVENTORIES AND MODELS

Tom Black, Charlie Luce, and Nathan Nelson

Boise Aquatic Sciences Lab, USDA Forest Service Rocky Mountain Research Station, Boise, ID USA

INTRODUCTION

People have built roads and trails over the millennia to connect communities, facilitate commerce, enhance defense, and access resources. In the western United States, the United States Forest Service (USFS) has constructed and maintained a system of forest trails and roads since it's inception in 1905, at first to provide access to remote locations to manage fires and later to provide access for timber harvest and other uses. Road construction over the last century has resulted in a network of over 380,000 miles on USFS lands. While these roads provide valuable access to remote areas, the extensive road system also creates a diversity of negative impacts on the natural environment.

Concerns first arose about the environmental consequences of forest roads in the western US following widespread road related landslide failures after the historically large winter storms of 1964 (Megahan and Kidd 1972). We've since learned that roads can have a variety of negative environmental impacts on both terrestrial and aquatic ecosystems, but in this article we will focus on the aquatic impacts. As shown in Figure 1, roads generate and deliver fine sediment to streams (Reid and Dunne 1984, Luce and Black 1999), increase mass wasting processes such as landslides (Montgomery 1994) gullies and debris flows (Wemple et al 1996, Croke and Mockler 2001), and cause local hydrologic changes (Wemple and Jones 2003, Luce 2002). Roads also impede or block access to migratory fish species (Dunham and Rieman 1999) and facilitate the dispersal of non-native species and pathogens (Parendes and Jones 2000). These sedimentation and hydrologic impacts are particularly problematic in the 11 western United States where 51% of the surface water originates on USFS lands (Brown et al 2008).

Figure 1: Road surface sediment production, ditch erosion, road fill failure (landslide), and road sediment delivery to a stream. Clockwise from top left.

Many USFS roads are no longer needed or used, and due to budgetary limitations, no longer maintained. But as long as they remain on the land, the impacts to aquatic resources, fisheries, and drinking water continue. Not all roads are equally impactful, however. In our experience measuring, mapping, and modeling road impacts to aquatic systems in the western US, we have observed three important facts about roads that are relevant to prioritizing road treatments for watershed restoration:

- Not all roads are equivalent, and differences in road location, construction, maintenance and use result in substantially different impacts on the environment.
- The types and magnitudes of road impacts vary through time, so road age is important.
- Using maps of roads in concert with topographic information can yield useful screening information for prioritization.

There are several robust options for treating the roads most damaging to streams, including infrastructure upgrades, removal or decommissioning. Well located roads that serve long term needs can be improved using storm damage risk reduction methods. Because this is a topic unfamiliar to many people outside the western US, we will first review some of our findings from investigations of the hydro-geomorphic impacts of forest roads on public lands to illustrate these three main points, and then describe how we are now using models and data to prioritize investment in road treatments to drastically improve watershed restoration outcomes.

ALL ROADS ARE NOT THE SAME

Forest roads are typically built for a specific purpose, and their engineering and road location dictate much of the road impact. Road sediment production is sensitive to the road slope, length, surfacing material, vegetative cover, and vehicle use (Luce and Black 1999, 2001a). Where the road is located relative to streams and convergent topography and how the drainage is designed influences how much of the sediment from the road reaches nearby streams. Taken together, these factors mean certain stretches of roads present very high risks and can deliver hundreds of times more sediment to streams compared to a stretch even just short distance away.

The good news is that by quantifying these variables with models such as GRAIP (Figure 2a) (Black et al 2012a) and GRAIP_Lite (Nelson et al 2019; Figure 2b), we can effectively predict the road sediment delivery to streams at multiple scales.

A metric that has historically been used to quantify road impact is road density, or the sum of miles of road in a particular area of land (Potyondy and Geier 2011). Road density has been shown to relate to terrestrial wildlife distribution as well as fish abundance (Lee et al, 1997) and occurrence

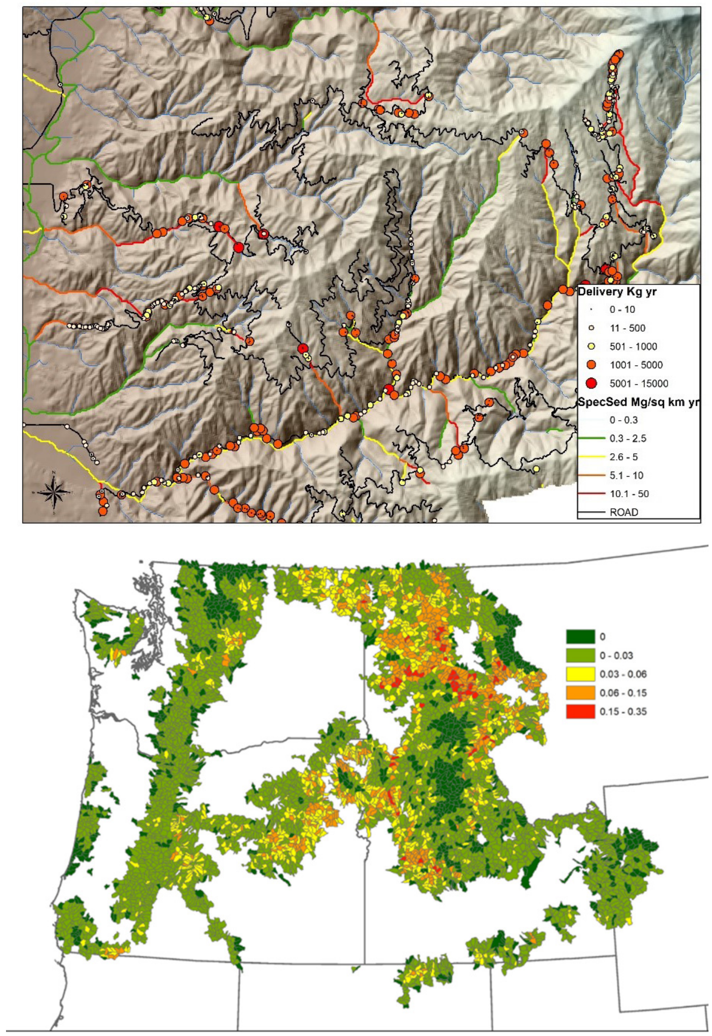
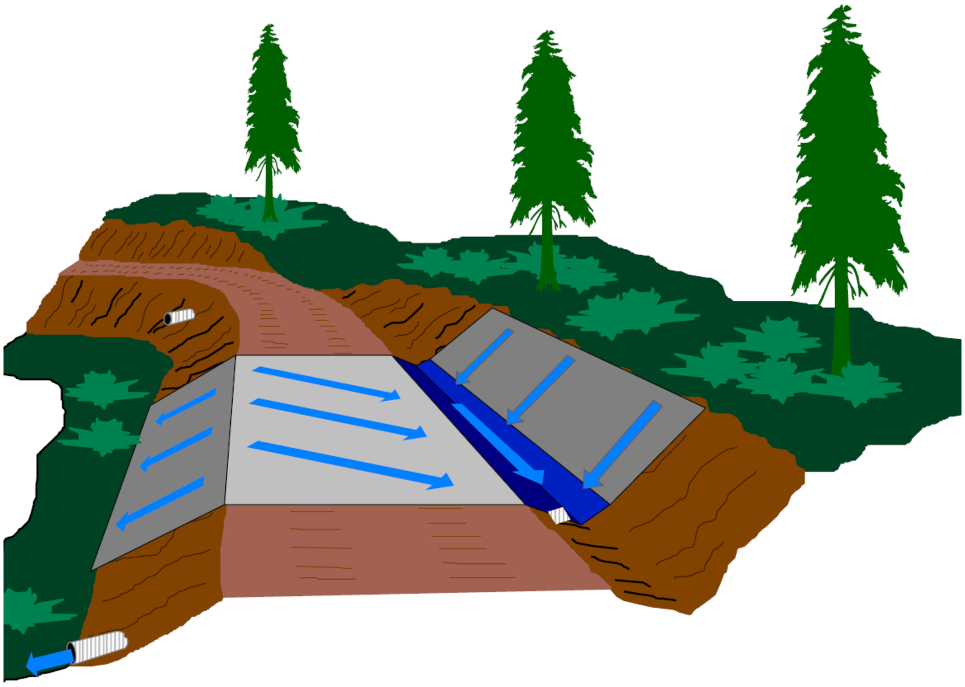


Figure 2a: Mass of road sediment delivery to streams predicted by the GRAIP model from inventoried drainage locations in Anderson Creek, ID. The red circles are drainage locations scaled to illustrate sediment delivery in Kg per year.

2b: Road fine sediment delivery risk to streams in the Pacific Northwest US, predicted using a unit base erosion rate in the GRAIP_Lite model. Data aggregated by sub-watershed.



Typical forest road section showing a road surface and cutslope draining water to a ditch. The ditch is periodically drained to the hillslope with a culvert pipe under the road.

(Dunham and Reiman 1999). While this metric has been useful at the broad scale for predicting some impacts of roads on wildlife such as vehicle mortality, road density may miss much of the complexity, variability, and the process interactions that allow us to effectively manage road impacts on aquatic ecosystems. Using road density as the only measure of road impact may cause us to treat roads that are not degrading the aquatic environment, in large part because this metric treats all roads as essentially equivalent in their impact.

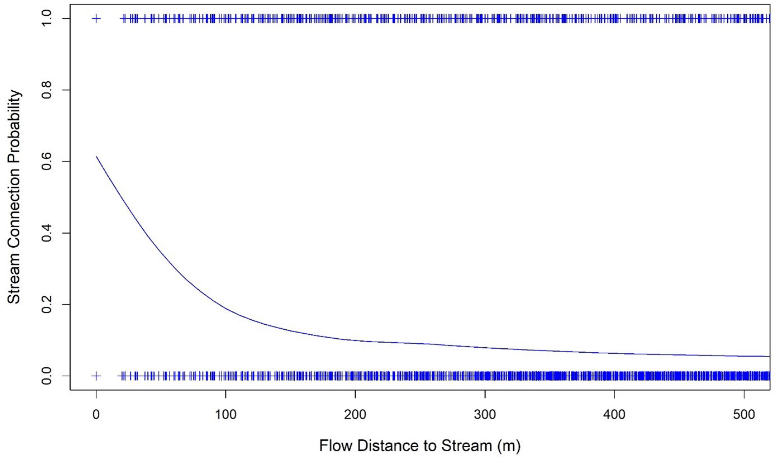
Many of the environmental impacts of roads originate from how the road drainage system (designed to keep roads stable and passable in wet weather) directs and concentrates rainfall and shallow groundwater (Luce and Wemple, 2001). Roads are designed to shed rainfall and to route runoff away from the road surface to prevent surface erosion and the saturation of road fills. Thus, areas with low precipitation and rainfall intensity tend to cause less sediment discharge, while areas with higher annual precipitation and intensity cause more sediment impacts (Luce and Black 2001b, Dube et al 2011, Van Meerveld 2014). Wetter areas have more streams, streamside roads, and stream crossings, and therefore more potential for sediment delivery to the channel. Road stream crossings can cause aquatic organism passage issues (e.g., fish trying to move through culverts) and increased stream flow diversion risk when culverts become plugged by sediment, wood, or high flows. The steep-wet forests of northwestern North America have the additional risk of debris flows that may be initiated by failing road fills and stream channel diversions that can occur when stream crossing structures are blocked (Furniss et al 1997).

Road Location Matters

Road location on the landscape is one of the primary predictors of road interaction with the aquatic system. In our surveys of roads across the western US, the probability of sediment delivery to a stream was strongly related to the downslope distance between the road and the stream (Figure 3). Therefore, streamside and mid-slope roads that have frequent stream crossings and shorter distances to streams can have higher sediment delivery probability and a bigger impact on water quality than roads built along ridgetops. Mid-slope roads are also unique since they are constructed to quickly traverse from valley bottom to ridgeline, often resulting in steeper roads that can cross multiple small streams and unstable slopes. Road slope is a primary control on sediment production, with steeper road grades providing more energy to rapidly transport runoff water and sediment.

Road Use and Cosure

Road use is an important factor influencing the amount of fine sediment that washes off of road surfaces (Reid and Dunne 1984). Actively used roads typically have high levels of fine sediment at the surface that is generated by vehicle passage (Luce and Black 2001a). This fine sediment can be quickly washed from the road and into hillslopes and streams during storms. As an example, using an existing gravel surfaced road to move log trucks during runoff events can increase sediment



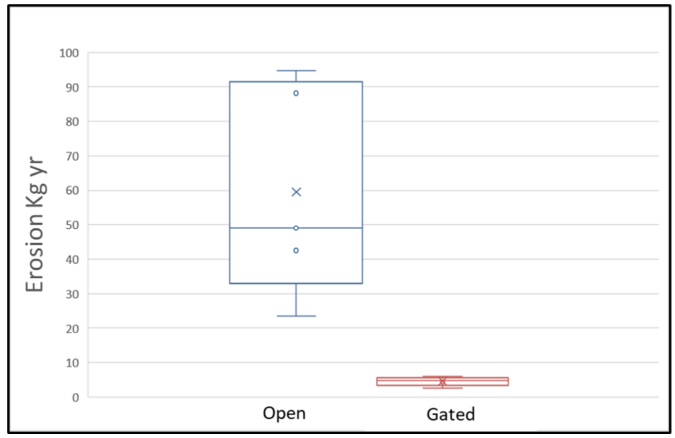


Figure 3 (left): The observed probability of sediment delivery to streams based on the distance between the road drain and the stream.

Figure 4 (right): Average annual sediment production from four plots over four years on roads open to summer recreational traffic compared to those behind administrative gates on the Lolo National Forest, Montana.

production and delivery substantially depending on the local conditions and road engineering (Luce and Black 2001a, Van Meerveld 2014).

The amount of chronic sediment produced by a road often decreases as road use declines. Many roads in the USFS network are inactive or gated for much of the time, and these roads often have stabilized and vegetated surfaces with little available sediment. We found that gated roads near Seeley Lake, Montana produced less than 10% of the sediment as similar roads that had summer recreational and administrative traffic (Figure 4).

Road Maintenance

Periodic road maintenance such as cleaning culverts is critical to ensure the function of the road drainage system in wet locations to minimize catastrophic failures during large runoff events. However, routine road grading and aggressive ditch cleaning can generate as much or more sediment than use by heavy vehicles (Luce and Black 2001a).

ROAD IMPACTS VARY THROUGH TIME

Modeling the hydro-geomorphic effects of roads is helpful because of the wide variation in the impacts that roads can have at different times following their construction. Roads constructed for timber harvest on public lands in the US are not as static as they first appear. Like every built structure, forest roads are engineered to serve a purpose for a finite period, although with proper construction and maintenance they can serve their intended purpose for many years.

When roads are first built in anticipation of timber harvest, they have a suite of impacts due to the exposure of fresh soil surfaces near streams and the routing of water and sediment in new locations. In steep terrain, new roads have been more likely to cause landslides in the first large storms and in the first decade post-construction rather than decades later, as the weakest spots tend to fail first. It is not clear how long the large sediment impacts associated with initial road building and landslides may persist in the aquatic system, but sediment from elevated mass wasting can persist in low gradient streams for decades (Platts et al 1989).

After initial construction and dedicated use (e.g., for timber harvest), the environmental impacts of roads vary by their ongoing level of use. During periods between management activity when roads are unused, they may be gated or closed and treated with additional drainage features according to national best management practices (USFS 2012) to minimize erosion. Depending on the forest management activity, a minor road may remain unused for a decade or more before there is another need for access to the area, at which point there may be another spike in use and sediment producing activity. Some larger roads continue to be used for public or management access, and in these cases the ongoing activity and maintenance may cause them to continue to erode fine sediment. Of course, anytime there is intense precipitation or runoff, the function of the road drainage system and the stability of the fill material can be stressed, leading to large sedimentation consequences if the drainage is inadequate.

While sediment loss can decrease as a road ages and falls out of use, other negative impacts can increase as a result of aging road infrastructure. Stream crossings and culverts become rusted and can cause significant damage to streams when they leak or fail. Drainage structures on unmaintained roads can also become blocked by debris and no longer route water and sediment to the desired locations.

Age of Road Construction

Besides the basic changes over time as roads age, road construction design and techniques have changed so the age of the road is also relevant to understanding its environmental impacts. Many of the roads on public lands in the western US were built in the period of 1950-1990, when road building practices were less oriented towards potential environmental concerns. As new environmental priorities, transportation, engineering, and logging technology evolves, new roads are built with different characteristics and in different locations on the landscape. Roads built in recent years are often designed to avoid streams and unstable hillslope locations, to minimize disturbance from large cuts and fills, and to use more robust design practices in steeper landscapes.

Over time, roads that cause environmental degradation or are expensive to maintain may be prioritized for removal or improvement (Figure 5). Some progress has been made to remove barriers to aquatic organism passage and to improve or restore some of the high-risk roads under the 2008-2017 Legacy Roads and Trails Remediation Program. However, a typical road system in a watershed often consists of a mix of older legacy roads, reconstructed roads, and new construction; because roads are expensive to build, improve, or remove, their total extent changes slowly.

IT IS HARD TO MANAGE WITHOUT INFORMATION

Good decisions about road management and restoration are informed by relevant data. This may be obtained from an inventory of road risks and impacts or it may take the form of a model that is used to predict the risks and impacts (GRAIP and GRAIP_Lite). Work by our group in the western US has found that over 90% of the sediment delivery

Figure 5: Road decommissioning by fully recontouring an unstable road above critical salmon spawning habitat in the Dollar Creek drainage of the Boise National Forest. Image thanks to USFS GTAC/ Red Castle Resources.

from roads is typically sourced from less than 10% of the road length (Figure 6, blue line). Similar patterns have been found in the distribution of road related landslide risk (Allison et al 2000). Knowing the location of the roads with the highest risk of sediment delivery in the watersheds that contain our highest aquatic values (e.g., municipal drinking water supplies, threatened and endangered fish habitat) allows for a cost-effective prioritization approach. Allocating watershed restoration efforts where they will have the largest benefit for the environmental management objectives should be the goal, although there may be funding and logistical reasons why this may not always be possible.

The Payette River Sediment Modeling

In the Middle Fork of the Payette River in central Idaho (US), the USFS used the GRAIP road inventory and model (https://www.fs.fed.us/GRAIP/index.shtml) to quantify the hydrologic and geomorphic impacts on the aquatic system from forest roads (Black et al 2012b). This included the direct field observation of 583 miles of roads in 12 sub-watersheds. This project documented the fine sediment production and delivery to streams as well as predicting risks and impacts of landslides, gullies, and stream crossing failures. The cost of this multi-year effort was about $135,000 and the total budget allocated for an integrated watershed restoration through road reclamation/storm damage risk reduction effort in this area was $1,200,000. We compared three prioritization approaches with different level of effort and information to estimate how efficiently fine sediment delivery could be targeted and remediated.

After applying the GRAIP inventory to collect the highest level of information, the USFS still had $1,065,000 available for the actual watershed restoration work, largely through full road removal and recontour which was then estimated to cost $25,000/ mile. The restoration funds, therefore, allowed for treatment of 42.6 miles of road. Figure 6 shows the ranking of road segments by their sediment delivery to streams as the percentage of

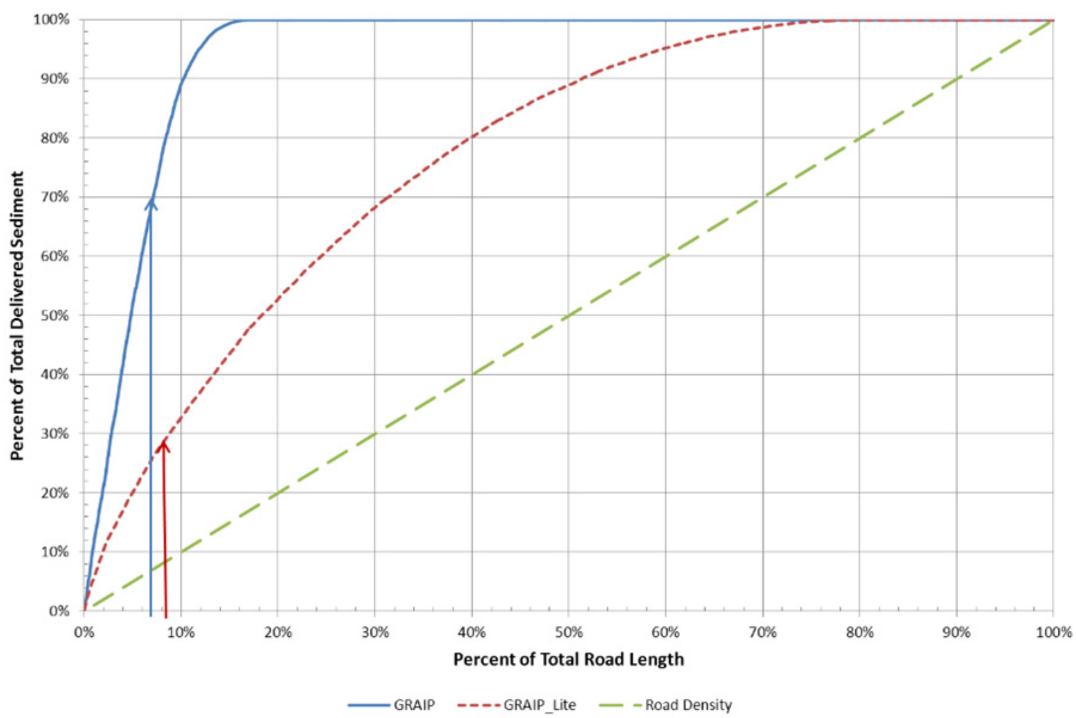


Figure 6: This figure shows percentage of sediment delivery ranked as a function of cumulative road length for the Middle Fork of the Payette River. The blue line shows the relationship observed with the GRAIP road inventory and model. The red dashed line illustrates general relationship found from GIS analysis of the road lines, streams, and the digital elevation model without local information about sediment delivery at specific drainage locations (GRAIP_Light). The green line shows the relationship between sediment delivery and road length when no additional data are available, often known as the road density approach.

total road length. The blue line indicates that using this highest level of information (GRAIP) to select restoration priorities would reduce the sediment delivered to the stream system by 71% if the projects were completely successful.

For the second approach, we used a model similar to the GRAIP_Lite tool (https://www.fs.fed.us/GRAIP/GRAIP_Lite.html; Nelson et al 2019) to estimate the impacts of roads based on topography, road and stream locations, and an estimate of the average road surface erosion rate for the area and typical sediment delivery distances below roads. The predicted sediment delivery to the Middle Fork of the Payette is shown by the red line in Figure 6. This simplified approach saves money and time as it had no field component. It would allow us to allocate nearly the full budget of $1,200,00 to restoration, resulting in more roads treated than the first scenario (48 miles vs 42.6 miles). However, because the predictions were made based on the average conditions of the roads without the benefit of actual road drainage locations or local sediment delivery data, the predictions were not as successful in identifying the specific high sediment delivery locations, and this prioritization work would only reduce the sediment delivery by 29% despite treating more road area. While the advantage is that it is quicker and more road miles are treated, the restoration outcome is significantly lower in this example.

The third approach we considered was the commonly used road density method of prioritization, which uses only the road presence information and places equal risk on each road segment. Results from this approach are illustrated by the green line in Figure 6. Like the second approach, the entire project budget can be allocated to restoration under this scenario, but the treatment of 48 miles of road would result in only an 8% reduction in sediment delivery as there was no priority placed on selecting the road segments with the greatest impact on sediment delivery.

When road density reduction is the sole objective of restoration plans (which is sometimes the focus to restore terrestrial species habitat, such as for elk or grizzly bears), many roads with negligible sediment delivery may be treated to reach the desired result. As a practical matter, this could result in a focus on minor roads that are easily treated in an attempt to treat more miles while avoiding expensive projects that resolve issues near streams. If the goal is to identify and reduce the hydro-geomorphic impacts of roads, it is clear that more local information about the road and local geomorphology will lead to better prioritization of work and more efficient use of restoration resources. Additional research by our team has shown that watershed restoration through road decommissioning, full road recontouring, or storm-damage risk reduction is highly successful at reducing sediment delivery to streams, and that these benefits are maintained even after severe storms that cause damage and erosion in untreated control roads (https://www.fs.fed.us/GRAIP/LegacyRoadsMonitoringStudies.shtml).

Applications of models to prioritize road treatment on the National Forests

Roads are the largest investment of capital on USFS managed lands and are considered in many levels of management discussions. Broad scale road modeling is used in long-range forest planning to prioritize among sub-watersheds for future restoration work. Models such as GRAIP_Lite are also used to understand how widespread changes in road management and extent over decades can yield improvement in water quality and watershed condition (Potyondy and Geier 2011, AREMP 2021).

At the project or sub-watershed scale, road models are used to prioritize among potential restoration projects and to choose between groups of roads. Models such as GRAIP_Lite are well suited to disclose the likely impacts of changes to the properties and extent of the road network as required in the National Environmental Policy Act (NEPA) and to compare the costs and benefits of alternative road treatment options.

Yet more efficiency could be realized by hierarchically applying a broad scale tool like GRAIP_Lite to prioritize where to conduct a detailed survey (like GRAIP) to focus efforts. This will also reduce the cost of using the detailed survey and increase the amount of funds available for watershed restoration. At the finer scale, road inventory-based models such as GRAIP can be used in priority areas to quantify and evaluate the multiple hydro-geomorphic impacts of roads on the aquatic system. Models can be locally calibrated to report results in units of mass in order to relate them to the local water quality conditions and standards and address regulatory questions in streams with Total Maximum Daily Load issues or other areas with heightened concern over road sediment.

CONCLUSIONS

Forest roads come in many varieties due to their design, location, maintenance, and use. These inherent differences, combined with the effects of age on the infrastructure, result in different kinds and degrees of environmental impacts. Because of the strong influence of road-stream proximity on sediment delivery, road density alone may not be the best metric for prioritizing road treatments for water quality improvement. Our ability to effectively model the hydrologic and geomorphic impacts of roads is improving due to increased understanding and better basic data. Broad-scale models such as GRAIP_Lite can be used to identify sub-watersheds with high risks. These results can guide inventory-based efforts to focus on identifying specific locations within those sub-watersheds where the risks can be effectively mitigated. Road inventories and spatial models provide a useful framework for locating and understanding road impacts. When local impacts are quantified and mapped, it is easier to efficiently prioritize hydro-geographic restoration work to mitigate the impacts of roads in the places that we value the most.

REFERENCES

Allison C, Sidle RC, Tait D (2004). Application of decision analysis to forest road deactivation in unstable terrain. *Environmental Management* 33: 173-185

AREMP (2021) The Northwest Forest Plan, The first 25 Years. PNW-GTR, USDA Forest Service - *in press*

Black TA, Cissel R, Luce CH (2012) The Geomorphic Road Analysis and Inventory Package(GRAIP) Volume 1: Data Collection Method. Gen. Tech. Rep. RMRS-GTR-280WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station

Black TA, Luce CH, Cissel CR, Nelson NA, Thornton (2012) Inventory and Modeling the Hydro-geomorphic Impacts of Forest Roads on the Middle Fork of the Payette River, Idaho, in Resource Roads in British Columbia, Challenges at the Site Level. Proceedings pp19-30. Columbia Mountains Institute of Applied Ecology

Brown TC, Hobbins MT, Ramirez JA (2008) Spatial Distribution of Water Supply in the Coterminous United States. *Journal of the American Water Resources Association* 44:1474-1487

Cissel R, Black T, Schreuders KAT, Prasad A, Luce C, Tarboton DG, Nelson N (2012) The Geomorphic Roads Analysis and Inventory Package (GRAIP) Volume 2: Office Procedures. RMRS-GTR-281. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Boise, ID. 162 pp

Croke J, Mockler S (2001) Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. *Earth Surface Processes and Landforms* 26: 205-217

Dubé K, Black T, Luce C, and Riedel M (2011) Comparison of Road Surface Erosion Models with Measured Road Surface Erosion Rates. Technical Bulletin No. 0988. National Council for Air and Stream Improvement, Inc. Research Triangle Park, NC

Dunham JB, Rieman BE (1999) Metapopulation structure of bull trout: Influences of physical, biotic, and geometrical landscape characteristics. *Ecological Applications* 9:642-655

Furniss MJ, Love M, Flanagan SA (1997) Diversion potential at road-stream crossings. Water/Road Interaction Technology Series 9777 1814-SDTDC. San Dimas CA: US Department of Agriculture, Forest Service. Technology and Development Program

Lee D, Sedell J, Rieman B, Thurow R, Williams J, and others (1997) A broad-scale assessment of aquatic species and habitats. In: Quigley, T. and S. Arbelbide, Tech. Eds. An assessment of ecosystem components of the interior Columbia River Basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-GTR-405. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station

Luce CH, Black TA (1999) Sediment Production from Forest Roads in Western Oregon. *Water Resources Research* 35:2561-2570

Luce CH, Black TA (2001a) Effects of traffic and ditch maintenance on forest road sediment production. In: Proceedings of the Seventh Federal Interagency Sedimentation Conference, March 25-29, 2001, Reno, NV. pp. V67-V74

Luce CH, Black TA (2001b). Spatial and temporal Patterns in erosion from forest roads. Land Use and Watersheds: *Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*: 165-178

Luce CH, Rieman BE, Dunham JB, Clayton JL, King JG, Black TA (2001). Incorporating aquatic ecology into decisions on prioritization of road decommissioning. *Water Resources Impact* 3: 8-14

Luce CH, Wemple BC (2001). Introduction to special issue on hydrologic and geomorphic effects of forest roads. *Earth Surface Processes and Landforms* 26: 111-113

Luce CH (2002) Hydrological processes and pathways affected by forest roads: What do we still need to learn? *Hydrological Processes* 16: 2901-2904

Montgomery DR (1994). Road surface drainage, channel initiation, and slope instability. *Water Resources Research* 30: 1925-1932

Nelson N, Luce C, and Black T (2019) GRAIP_Lite: A System for Road Impact Assessment. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Boise, ID. 145 pp

Parendes LA, Jones JA (2000) Role of light availability and dispersal in exotic plant invasion along roads and streams in the HJ Andrews Experimental Forest, Oregon. *Conservation Biology* 14: 64-75

Platts W S, Torquemada RJ, McHenry ML, Graham CK (1989). Changes in salmon spawning and rearing habitat from increased delivery of fine sediment to the South Fork Salmon River, Idaho. *Transactions of the American Fisheries Society* 118: 274-283

Potyondy JP, Geier TW (2011) Watershed condition classification technical guide, FS-978. Washington, DC: United States Department of Agriculture, Forest Service

Reid LM, Dunne T (1984) Sediment Production from Forest Road Surfaces. *Water Resources Research* 20: 1753-1761

United States Dept. of Agriculture, Forest Service (2012) National Best Management Practices for Water Quality Management on National Forest System Lands. FS-990a

Van Meerveld H, Baird E, Floyd W (2014) Controls on sediment production from an unpaved resource road in a Pacific maritime watershed. *Water Resources Research* 50: 4803-4820

Wemple BC, Jones JA, Grant GE (1996) Channel network extension by logging roads in two basins, western Cascades, Oregon. *Water Resources Bulletin* 32: 1195-1207

Wemple BC, Jones JA (2003). Runoff production on forest roads in a steep, mountain catchment. *Water Resources Research,* 39: 1220. doi: doi 10.1029/2002WR001744