Road BMP Effectiveness Best Available Science And Research Alternatives

Context

Washington State Forest Practices are regulated by means of the Forest Practices Act (Title 222 WAC) and Forest Practices Rules adopted by the Washington Forest Practices Board (WFPB). The WFPB is charged with developing rules that protect the state's public resources while maintaining a viable timber industry. Since much of the land regulated under the act contains habitat for aquatic and riparian-dependent species that have been, or may be, listed under the Federal Endangered Species Act (ESA), the Washington Department of Natural Resources (WADNR) has developed a Forest Practices Habitat Conservation Plan (FPHCP) to provide Federal Assurances that the rules will meet the requirements of the ESA.

The WFPB has set up a formal science-based Adaptive Management Program (AMP) to provide technical information and science-based recommendations that will assist the WFPB in determining when it is necessary or advisable to adjust rules and guidance to achieve the Forests & Fish Report resource objectives. The resource objectives are to ensure that forest practices will not significantly impair the capacity of aquatic habitat to: a) support harvestable levels of salmonids; b) support the long-term viability of other covered species; or c) meet or exceed water quality standards, including protection of beneficial uses, narrative and numeric criteria, and anti-degradation (WAC 222-12-045).

The WFPB has empowered the Cooperative Monitoring Evaluation and Research committee (CMER) and the T/F/W Policy Committee (Policy) to participate in the AMP (WAC 222-12-045(2)). In 2012, the WFPB directed CMER to pilot a Lean process for developing a research alternatives document and study design for the Road Prescription-Scale Effectiveness Monitoring Project. Per the new 'pilot' process, a Technical Writing and Implementation Group (TWIG) was formed to develop options for addressing questions related to the effectiveness of road prescriptions and best management practices (BMP).

As stated in the 2015 CMER Work Plan, the objectives of monitoring forest roads at the prescription-scale are to:

1) Evaluate the effectiveness of road maintenance categories in meeting road performance targets; and
2) Identify sensitive situations where prescriptions are not effective.

This project will study surface erosion sediment production and delivery reductions from site-specific BMP.

It is anticipated the results of this project will inform the forest practices AMP about the effectiveness of BMP in common use, including those used for Road Maintenance and Abandonment Plans (RMAP). These BMP are potentially critical in achieving the FPHCP goals. Should the common BMP used on forest roads prove to be ineffective, Policy and the WFPB may have to revisit the rules and the Forest Practices Board Manual to refine the BMP requirements and application.

The Road BMP Effectiveness Project TWIG:

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Rule Group:	Roads	
Rule Context:	WAC 222-24 and Forest Practices Board Manual, Section 3	
Research and Monitoring Program	Road Prescription-Scale Effectiveness Monitoring	
2016 Budget	$25,000 (study design development)	

Statement of the Problem[1]

Scientific knowledge of road BMP and prescription effectiveness is insufficient to make sound recommendations. This leads to the potential for:

1) Landowners wasting money on ineffective treatments;
2) Rule and BMP implementations being inadequate to achieve functional objectives and performance targets (Schedule L-1);
3) Overconfidence about the degree of protection landowners can attain (with implications for road construction and maintenance standards); and
4) Treatments creating additional environmental risks (e.g., landslides and gullies).

General Background

Roads play an important role in our society, providing vital links for transportation of people and materials quickly and efficiently. There are hundreds of thousands of miles of roads in Washington State. Many of these roads are unpaved forest roads, used to access lands managed primarily for timber harvest. Forest roads provide many useful functions such as allowing timber products to be transported efficiently to mills, providing access for recreationalists, hunters and fishermen, and even giving wildlife travel corridors.

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[1] It should be noted that the statement of the problem, project purpose, and the critical research questions may be refined during the development of the study design.

However, roads influence a variety of watershed processes, including sediment production (Megahan and Kidd 1972; Reid and Dunne 1984; Bilby et al. 1989; Luce and Black 1999, 2001a; MacDonald et al. 2001), hydrologic event timing (Wemple et al. 1996; Jones and Grant 1996), and slope stability (Sessions et al. 1987; Montgomery 1994). Of particular concern is road erosion and the locations where it is delivered to streams and rivers. Road erosion can be a large source of anthropogenic sediment in watersheds managed for forest production (Megahan and Kidd 1972; Swanson and Dyrness 1975; Reid and Dunne 1984; Megahan and Ketcheson 1996). The fine-grained sediment produced by road surface erosion has the potential to adversely affect water quality and aquatic resources at the site-scale (e.g., the water quality at a culvert outlet), the reach scale of a channel, and the watershed scale. As noted by Black and Luce (2013): "Forest road runoff and fine sediment delivery are widely acknowledged to have serious impacts on aquatic ecosystems (Cederholm et al. 1981; Platts et al. 1989; Thurow and Burns 1992; Lee et al. 1997; Luce and Wemple 2001)." With rare exception (e.g., Martin 2009 found some square miles of land with forest roads and NO delivery), the potential for adverse effects from forest roads exists across the roaded, forested landscape. As a consequence, water quality regulations and cumulative effects modeling of forest management have frequently focused on forest roads.

Excessive sedimentation is the most important cause of lotic ecosystem degradation in the United States in terms of stream distance impacted (USEPA 2000). This is a concern to environmental managers because increased inorganic sediment loads alter the natural biotic community (algae, macrophytes, invertebrates and fishes) in streams (Tebo 1955; Cordone and Kelley 1961; Waters 1995; Wood and Armitage 1997; Kaller and Hartman 2004; Suttle et al. 2004; Fudge et al. 2008). Increased inorganic sediment loads, beyond quantities or frequencies that occur naturally, can influence the stream biota in a number of ways. Turbidity increased by sediments can reduce stream primary production by reducing photosynthesis, physically abrading algae and other plants, and preventing attachment of autotrophs to substrate surfaces (Van Nieuwenhuyse and LaPerriere 1986; Brookes 1986). Decreasing primary production can affect many other organisms in the stream food web (Izagirre et al. 2009). Sedimentation has been shown to be a major factor in the loss of habitat for mussels worldwide (Poole and Downing 2004; Geist and Auerswald 2007). Minshall (1984) examined the importance of substratum size to aquatic insects and found that substratum is a primary factor influencing the abundance and distribution of aquatic insects. Aquatic macroinvertebrates are adversely affected by habitat reduction and/or habitat change resulting in increased drift, lowered respiration capacity (by physically blocking gill surfaces or lowering dissolved oxygen concentrations), and reducing the efficiency of certain feeding activities especially filter feeding and visual predation (Lemly 1982; Waters 1995; Runde and Hellenthal 2000; Suren and Jowett 2001). Macroinvertebrate grazers are particularly affected as their food supply either is buried under sediments or diluted by increased inorganic sediment load thus increasing search time for food (Suren 2005; Kent and Stelzer 2008). Deposited sediments affect fish directly by smothering eggs in redds (Fudge et al. 2008), altering spawning habitat, and reducing overwintering habitat for fry (Cordone and Kelley 1961), and indirectly by altering invertebrate species composition, thereby decreasing abundance of preferred prey (Suttle et al. 2004). Declines in salamander abundance also were seen with increases in fine sediment inputs (Lowe and Bolger 2002).

Specific Statement of the Problem

Roads are persistent sources of fine sediment to forest streams, which otherwise have characteristically clear water except during significant storm events. While substantial improvements in water quality have been secured in recent decades through diligent application of mitigation measures (usually called best management practices or "BMP") for sediment from forest roads, there are still some locations where noticeable loading occurs related to forest roads (Dubé et al. 2010). Recent work has demonstrated that sediment delivery from forest roads is focused in a small fraction of the road network. Two Washington studies found that only 10-11% of the forested road length is delivering sediment to the channel network (Dubé et al. 2010; Martin 2009). Similar work in Oregon and Idaho, summarized in Figure 1, shows that 90% of the delivered sediment comes from 9.2% of the drainage points (Black et al. 2013). That fraction is primarily comprised of larger, more heavily travelled roads in proximity to streams. Mitigation for these locations has proven more challenging than in other places, and better information is needed to hone our capacity to efficiently handle sediment from these high-traffic, near-stream (HTNS) road segments.

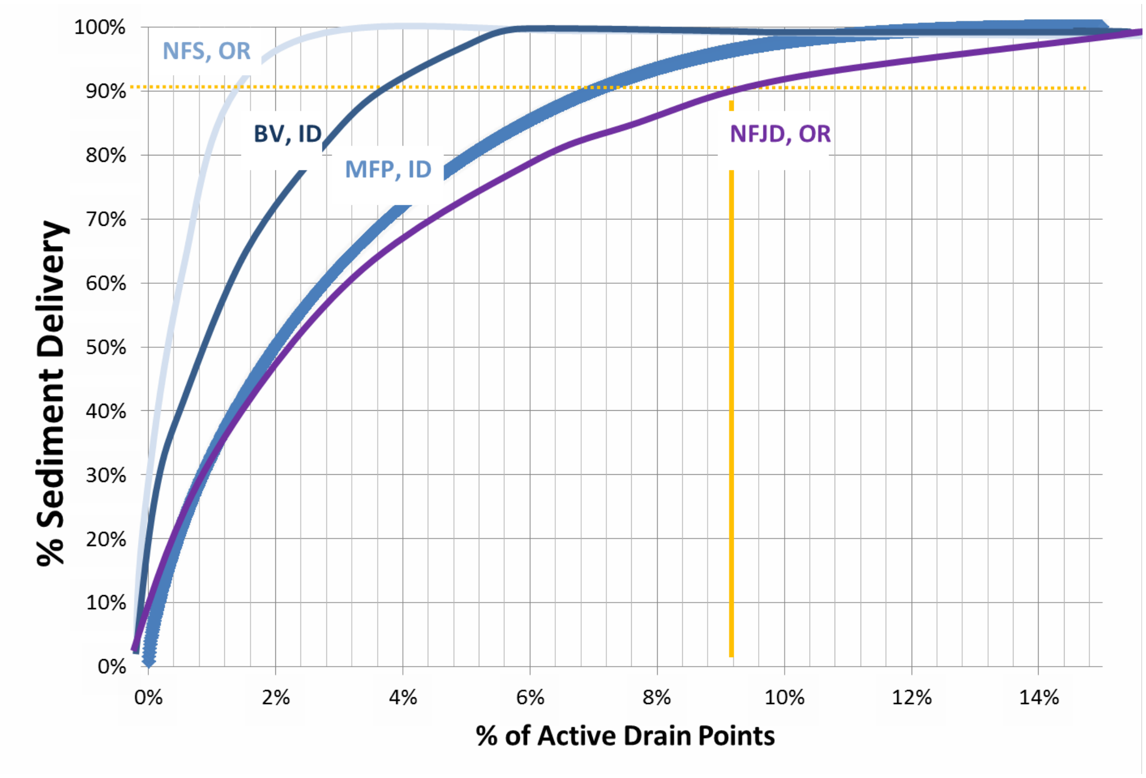

Figure 1: Pareto analysis of sediment production from four GRAIP watershed surveys (Black et al. 2013).

There are several reasons why HTNS road segments are particularly challenging for sediment control. Frequent heavy traffic decreases the effectiveness of surfacing roads with quality rock by the crushing of the rock and pumping of fines from the substrate. Drainage modifications that limit delivery are also compromised when water bars are worn and ruts form (e.g., Burroughs and King 1989; Black et al. 2013). Segments carrying frequent heavy traffic may be the most difficult to restrict traffic on during wet weather, increasing the severity of these effects. These roads also need frequent maintenance of the surface (e.g., frequent grading to reduce pot hole development) to maintain their ability to handle traffic. The close proximity to streams makes it difficult to rely on infiltration into the forest floor to disconnect road discharges from streams. The proximity to streams or stream crossings also means that these roads will be the wettest and most affected by groundwater and exfiltration from the hillslope. In technical parlance, these are high production (detachment of sediment from the road surface and ditch), high delivery (greater fraction of produced sediment carried to stream) road segments.

These HTNS roads present strong technical challenges. Since excessive fine sediment in fish-bearing streams is perhaps the single largest, management-related factor impacting instream biota, including listed fish species, reducing road surface erosion and delivery to stream is of critical importance. Not only are HTNS roads more likely to deliver sediment to streams, they are typically critical to the transportation network as key mainline roads. Therefore, HTNS roads may warrant additional investment by landowners to use enhanced BMP not only to meet stewardship goals, but for operational needs as well. Improved mitigation for erosion of HTNS forest roads may allow better operational flexibility so forest operations can be conducted in a wider range of weather, with improved vehicle-use capacity and potentially reduced maintenance. However, road upgrades and enhanced BMP are a significant cost; therefore, improved knowledge of individual and in-combination BMP is essential for understanding the return on BMP investments.

Whether from the landowner or regulatory perspective, a central question is what <u>combinations</u> of surfacing, ditch line management, traffic control, and drainage management will most efficiently and effectively mitigate sediment yields and hydraulic effects from HTNS roads? The question pivots on combinations because there is already significant information on what individual treatments such as rocking or traffic changes can do to mitigate sedimentation (e.g., as summarized by Burroughs and King 1989). Such information has been formulated into simple empirical approaches that estimate sediment yield from a road surface based on a number of empirical multipliers similar to the Universal Soil Loss Equation (USLE) (e.g., Dubé et al. 2010; Luce and Black 2001a). These efforts predicate on two assumptions: 1) That the implementation of multiple BMP has the expected positive benefits; and 2) That those positive benefits are multiplicative. Luce and Black (2001a) experimented with BMP combinations and their results do not support these two assumptions.

BMP treatments are rarely used alone and it is the combination of activities that has been inadequately studied. Some combinations work well together while others may produce little additive improvement at a greater cost. Under certain circumstances, one BMP may even reduce the effectiveness of another one; for example, paving a road reduces production of sediment from the surface, but contributes more water to the ditch line, and if the ditch is bare soil, erosion can increase relative to that expected from a gravel road. Furthermore, safety and operational constraints imposed by one part of a design can impair another part. For example, rocking with high value rock sometimes encourages use of a road grader to retrieve lost rock from the ditch line, which in turn renews the availability of sediment in the ditch (where stream power is high) potentially negating much of the benefit of the rocking.

Furthermore, these simple models based on empirical, site-specific studies may have very little applicability to locations other than where they were developed (e.g., WARSEM) as they are not process-based representations of the effects of BMP. Therefore, there is a strong need for joint development of extensive field studies and process-based numerical modeling approaches using physical principles to study the effects of single and multiple BMP on water and sediment transport across roads. Models should provide the physical framework for the different pathways of BMP influence on water and sediment flows, while field observations would provide the data to further refine models, and can be used as model input parameters.

Project Objectives

The forest practices road rules are designed to protect water quality and riparian/aquatic habitats through road prescriptions (WAC 222-24) and best management practices (BMP – Forest Practices Board Manual, Section 3, 2013)[2]. These prescriptions and BMP, also called "treatments" in this document, are broadly intended to minimize: 1) sediment production and delivery from the road prism; 2) hydrologic connection between roads and the stream network; and 3) the risk of road-related landslides caused by inadequately built and maintained roads and culverts. This project will specifically focus on 1) and 2) – it will take a different study design to evaluate the treatment effectiveness of 3).

Although an extensive body of research of the performance of individual BMP already exists (e.g., as summarized in Burroughs and King 1989 and Dubé et al. 2004), some individual BMP are not well studied and substantial gaps exist in our understanding of the collective performance of road BMP at the site scale in reducing sediment production, sediment delivery and hydrologic connectivity. Of particular concern is that conceptual models used in the design of road BMP field studies in the literature assume a multiplicative approach such that data collection is focused on observing and measuring factors that are used in multiplicative models. This limits the scalability of those observations using different, more process-based models.

As landowners work to complete implementation of their RMAP and to meet road sediment performance targets and water quality standards, it is important to provide them and other stakeholders with a more confident technical foundation for determining which BMP are most effective and cost effective at minimizing the discharge of sediment to the stream network and the practical and operational limitations of what can be achieved in certain sensitive environmental settings.

In summary, our understanding of BMP effectiveness is too incomplete to make sound recommendations based on existing scientific evidence. Therefore, we may not be achieving resource objectives, nor applying BMP in the most cost effective manner with the best risk trade-offs.

Critical Questions

CMER Work Plan Critical Question

- *Are road prescriptions effective at meeting site-scale water quality standards and performance targets for sediment and water? (Exclusive of mass wasting prescriptions, which are covered in the Unstable Slopes Rule Group.)*

Study Design Critical Questions

1) How effective are road sediment BMP, individually and in combination, at minimizing production and delivery of coarse and suspended sediments from forest roads to streams?

2) What is the comparative effectiveness of BMP in minimizing the production, routing, and delivery of sediment to streams? And what are the comparative installation cost effectiveness, and maintenance cost effectiveness and frequency, of these BMP?

3) Are combinations of individual BMP for the roads and ditches additive, multiplicative, synergistic, or antagonistic?

4) For individual or combinations of BMP, are increases in turbidity minimized? If turbidity increases, at what stream length below the stream crossing does it abate?

5) To what extent do road BMP affect water storage and erosion potential at site-scale road segments?

6) How do different characteristics of topography and lithology effect the selection and design of road BMP?

7) How quickly after installation or removal of BMP does the post-construction disturbance that temporarily increases sediment production and delivery abate?

Best Available Science Summary

Empirical Research

The generation of fine sediment from road networks in the forested environment has been investigated for more than forty years. The largely unpaved road networks are geographically extensive and therefore cross or lie parallel to many streams across the landscape. Early logging limitations led to high road densities; high rainfall in the coastal region causes high stream density and numerous stream crossings and, thus, road impacts are unusually high. In addition, early engineers largely took a pragmatic approach to railroad and road building by placing the larger "mainline roads" along the mainstem of the principal river and the larger tributaries in a watershed. So, it became clear to the early researchers that this juxtaposition had the potential to deliver substantial loads of eroded material to river networks (e.g., Megahan and Kidd 1972; Beschta 1978; Reid and Dunne 1984; Bilby 1985).

The earliest research was conducted in the 1970's and 1980's (e.g., Megahan and Kidd 1972; Reid and Dunne 1984) and served to illuminate how much sediment was being produced from different parts of the road prism under a variety of circumstances. In particular, Walt Megahan and colleagues made numerous contributions to the body of science relating to road prism sediment sources. One of their important contributions was the 1972 effort evaluating the role of subsurface storm flow interception (SSSFF) - SSSFF produced 7.3 times more water than the road's surface; this result fundamentally changed our understanding of roads and their impact on the landscape.

Subsequent efforts focused on traffic levels (e.g., Luce and Black 2001a and references therein), tread configuration (e.g., Burroughs and King 1989), tread surfacing (e.g., Swift 1984) and cutslope vegetation (e.g., Luce and Black 2001b). The effectiveness of cross-drain spacing has been extensively studied (e.g., Montgomery 1994; Wemple 1996; Croke and Mockler 2001; Luce et al. 2014) as has the benefit of quality rock surfaces (e.g., Foltz and Truebe 1995). It has, in fact, been common to measure sediment production across a variety of situations. Most of this research has focused on the measurement of sediment production or delivery with and without a single BMP application.

The work by Luce and Black (1999) is particularly important to western Washington because it was conducted in the same ecoregion – the Oregon Coast range. In an intensive study, they examined road design and maintenance at 74 plots where they measured sediment production and road features. Looking at distance from culverts, road slope, soil characteristics, and cutslope height as well as the vegetation condition of cutslopes and ditches, they were able to develop relationships among variables which greatly improve erosion estimates. In both of Megahan and Kidd (1972) and Luce and Black (1999), there was an extensive field program of replicated treatments allowing reasonably powerful statistical tests among site characteristics and treatments. These are only examples of some of the profound work previously completed, but these examples allow us to consider what is still needed, how previously completed work can be built on, and the effort necessary to collect the meaningful data.

A variety of useful methods for quantifying surface erosion has been described in the literature (Megahan and Kidd 1972; Reid and Dunne 1984; Ice 1986; Bilby et al. 1989; Foltz and Trube 1995; Luce and Black 1999; Kahklen 2001; MacDonald et al. 2001 and 2004). This information was briefly summarized in Black and Luce (2013) who point out that "the methods require a range of effort and expense and vary substantially in accuracy." Black and Luce (2013) provide a settling basin and tipping bucket design that measures both water and sediment discharge for individual road plots which can be systematically applied to road sediment and road hydrology studies in the future.

The sum of the research had grown enough by the early part of this century that researchers could review the combined findings. In 2004 in a CMER-funded project, Drew Coe did a review of the published literature – 35 studies. The review examined projects that looked at both site and basin level responses. While the individual studies focused on specific topics to meet their project's objectives, the body of the science could be summarized into several key findings. Many researchers documented how site-specific conditions dramatically change runoff processes. A few studies highlighted the importance of the interception of surface flow by cutslopes as a dominant mechanism. The magnitude of that interception is dependent on lithological features. Another theme in the reviewed work was the extent of connectivity between the road and stream network and the factors exerting influence on connectivity. The document also provided insights from studies on the hydrologic effects streams have on runoff generation. Much of this work was the basis of the early generations of road models, particularly another CMER-funded project, WARSEM (Dubé et al. 2004).

In a subsequent publication, MacDonald and Coe (2008) compared sediment delivery from roads in 11 studies from across the world. The work compared research from across the US and other locales such at New Zealand and the US Virgin Islands with a wide range of estimated production rates both within and between studies. They segregated the studies by road prism feature and were able to estimate sediment production by road surface, and cutslopes and fillslopes. In addition, they compared road erosion fine sediment inputs to landslide delivery of fine sediment. When they scaled the road studies to the work focused on landslides, the values were similar and in some cases larger in the road-related erosion. One difference was that road-related delivery was primarily at stream crossings.

Model Development

Efforts to develop models of road erosion that could be applied at larger scales has resulted in numerous summaries of the existing body of empirical research (e.g., Dubé et al. 2004; MacDonald and Coe 2008). The development of models became imperative as scientists and managers recognized that given the extent of road networks, tools needed to be developed to better understand potential cumulative impacts and how they might prioritize remediation efforts.

Road erosion models can be grouped into two categories, empirical and physically-based. Empirical models are based on statistically significant relationships between erosional response (road surface, ditch, cutslope) and independent site variables or factors (e.g., geology, road surfacing and length, rainfall). Effects of independent site variables are incorporated as multipliers to predict total erosion from a road segment, which is then multiplied by a sediment delivery ratio (SDR) to estimate sediment delivered to a nearby stream. Empirical models are used to predict mean annual sediment contribution from roads often at the catchment scale. Physically-based models incorporate conservation equations that describe sediment detachment, transport and delivery processes from road segments which are driven by rainfall and overland flow. Models typically share a relatively standard road surface hydrology component for modeling infiltration and runoff generation, driven by rainfall events, although they disregard interception of surface and subsurface flow from hillslopes by roads.

Empirical Models

Washington Department of Natural Resources (WADNR) developed Watershed Analysis methods (WFPB 1995), which included a series of empirical relationships to estimate road surface erosion based on empirical modeling concepts developed by Megahan and Kidd (1972) and Megahan (1974) and the R1-R4 model (Cline et al. 1981; Ketcheson et al. 1999). A number of similar watershed modeling tools that employ different software have evolved from the Watershed Analysis methods of WADNR to assess impacts of roads on annual sediment yields. The models estimate annual road surface, ditch, and cutslope erosion based on multiplicative empirical site-specific factors (geology, surfacing, traffic, rainfall, sediment delivery), sum them up, and multiply by a road age factor. Among these models, Washington Road Surface Erosion Model (WARSEM) was developed as a Microsoft Access database application. Boise Cascade developed a GIS-based program (SEDMODL) to automate the WADNR road erosion calculations used in WARSEM for landowners with extensive road networks. Version 2 of this model (SEDMODL2) was developed by NCASI in collaboration with Boise Cascade (NCASI 2003). The model uses an elevation grid combined with road and stream information layers to produce a GIS version of WARSEM. WARSEM and its interface with SEDMODL2 is a spatially distributed model by road segment, including features for estimating ditch, cutslope, and road surface erosion. WARSEM can be applied at large catchment scales and the effects of a variety of Best Management Practices (BMP) enable the model to be used to aid catchment decision-making (Dubé et al. 2004; Fu et al. 2010).

GRAIP is a distributed watershed-scale tool that analyzes risks from multiple erosion processes for forest roads, including surface erosion, gullying, landslides, and stream crossing failure, in a GIS environment based on road inventory and terrain data (Prasad et al. 2005). As input, GRAIP requires GIS coverages of road lines and drain points to represent the continuity of water flow paths along and off of the road. The model uses a base erosion rate (A), scales that with multipliers for topographic factors of flow path length (L) and slope (S), a vegetation factor (V), and a road surface factor (R), and estimates mean annual sediment yield from a watershed, SY=A*L*S*V*R (kg/yr) based on the formula of Luce and Black (1999). Sediment production from road segments can be mapped using GIS. The model uses simple rules to route sediment to drain points such as culverts, estimates sediment delivery to streams from culvert outlets, and routes accumulated sediment from culverts through the channel network. The routed sediment gives a long-term average of sediment yield sourced from road surfaces. Sediment delivery from sub-catchments within a watershed can be analyzed and compared in relation to road density and other factors. GRAIP includes a landslide risk component that estimates an index of stability (SI). SI increases in the model at culvert locations where water concentrates at a point outlet. While the representation of roads in GRAIP is based on an empirical equation which needs a baseline erosion rate, the range of integrated processes represented in GRAIP makes it an effective tool to examine relative impacts of road conditions holistically across a watershed.

Physically Based Models

Two physically based models have been applied to modeling road erosion: WEPP and Kineros. Of these, WEPP has a specific module intended to assist users in inputting parameters for roads. That version – WEPP Road – is limited to modeling road segments (Elliot and Hall 1997). WEPP Road is a fairly generic tool that is run online using site and road conditions selected from a menu of default choices developed largely based on empirical observations. Site conditions include climate (obtained from weather stations), soil textural type, rock cover %, and inputs to characterize road geometry such as gradient, length and width of road, fill and buffer, as well as road design conditions. The Road version does not require any site-specific field observations and, therefore, it is relatively easy to implement and can be used directly from the web (http://forest.moscowfsl.wsu.edu/fswepp/). Another interface, WEPP Road Batch, predicts erosion for multiple road segments, currently up to 200 segments in a batch. Both interfaces predict average annual erosion only.

Site-specific data can be incorporated in the WINDOWS version of the model, which allows users to run both hillslope and ‘watershed’ configurations (Elliot and Hall 1997; Elliot et al. 1999a), where the ‘watershed’ configuration allows for using shapes beyond the single-plane representation in WEPP Road. However, the generic WINDOWS version requires a large number of data inputs which are often difficult to obtain in the field and are highly uncertain. WEPP was designed around BMP for farmer's fields, and adaptation to roads has required ad-hoc adjustments to create a road-like simulation. Consequently the web-based version offers a simpler application option for roads. A strong aspect of WEPP is its capacity to develop continuous simulations driven by sequences of rainfall events. While this model can be useful to characterize relative rates of sediment production from different road surfaces for initial design and maintenance purposes, it does not include functionality for road sediment BMP. In addition, the high data intensity makes its implementation difficult and introduces a high degree of uncertainty on model results.

Another physically-based model that has shown some predictive capability for road erosion is KINEROS2. However this model does not have an explicit road component, and was used in a single study that used a road surface hydrology and sediment yield measurements in Thailand (Ziegler et al. 2001).

Model Limitations

Several studies evaluated and reviewed the performance of empirical and physically-based road models against observations (Elliot et al. 2009; Fu et al. 2010; Dubé et al. 2011). Studies that used WEPP Road have shown varying levels of model performance against observed storm runoff and sediment yields from roads. At different sites, both under (e.g., Peranich 2005) and over estimations (e.g., Amann 2004) of runoff and erosion have been reported in studies that used WEPP Road. Busteed (2004) had success with model predictions in large storms, and under predicted response driven by small storms.

Dubé et al. (2011) compared SEDMODL2/WARSEM, GRAIP, WEPP Road and WEPP watershed models against a large data set of road erosion observations at 9 sites across the US that had sufficient data to run and test the models. The WEPP (PC interface) model which has the ability to predict runoff and erosion from individual storms produced relatively better results for individual storms than for long-term averages. The GRAIP and SEDMODL2 models predicted between-segment variations generally well and were found suitable for relative comparisons of different management conditions. Overall, none of the models showed good performance in predicting actual values of average annual runoff and erosion at all sites. The two main points of the analysis are that the models were reasonably good at discerning relative differences among locations, but poor at predicting actual amounts of sediment delivered. This is both encouraging and disappointing. Encouraging, because they should allow prioritizations of road segments for remediation and possibly be useful in evaluating improvements. Disappointing because with the regulatory process it is necessary to have a reasonable estimate of how much sediment is delivered. Dubé et al. (2011) recommended the use of local data from field observations to calibrate the surface erosion models if estimates of actual values are needed. Therefore, more extensive information could both improve actual modelling estimates in a region and allow enhancements to the model(s).

In summary, while simple models are thought to be more useful and easily applied for land management purposes, more complex models can conceptually provide a basis for building improved understanding and scientific knowledge. However, both approaches provided in the literature have shown significant deficiencies and have very limited utility especially for evaluating the impact of road BMP. Some of the most pronounced limitations of existing models are:

- Empirical models are driven by data and work best in regions where they were developed.
- Spatial and temporal dynamics in the climate are not included in inputs of empirical models.
- The effect of each factor on sediment yield is assumed to be multiplicative, following the USLE equation idea, without much physical justification. One publication, Luce and Black (2001a), notes that the multiplicative interaction is in error for independently derived empirical effects of traffic and ditch grading. That documents a need for a better theoretical foundation for mixed BMP effect modeling.
- Among models, only WARSEM considers the effects of BMP from a list of 70 different BMP choices. In the WARSEM manual, each BMP is described qualitatively and a deterministic multiplier is assigned to introduce the influence of BMP in the calculated sediment yield (Table C-1, WARSEM manual, Dubé et al. 2004). These multipliers were based on very limited data, and were not systematically obtained by holding other conditions constant while changing one BMP. Because multipliers were obtained from limited sites, inference beyond the local setting is not validated. Nor is there a guarantee that one BMP is not redundant with another. The model does not build physical causalities between BMP and the hydrologic and erosional responses of the road setting.
- The WEPP runoff generation component poorly predicts runoff responses in most data sets collected at a range of study sites as reviewed by Dubé et al. (2011). Natural hydrology of a road site, such as base flow and surface flow contributions to ditches and culverts from hillslopes, was not incorporated in the existing physically-based models for roads.
- Both physically based models only work on assemblages of planes, so water cannot accumulate in ruts or ditches unless they are explicitly input by the user (they do not exist at all in WEPP Road). Concentrated flow erosion in WEPP is not physically based but essentially input as a parameter by the user. This is an important factor in evaluating rut development and ditch line erosion in forest roads.

Alternative Research Approaches

Overview

Alternatives developed by the TWIG show tradeoffs between doing new empirical research or trying to improve existing models with existing data without doing additional empirical research, between concentrating new empirical research on HTNS roads or doing a wider suite of forest road types, and between doing new empirical research with or without a modeling component. Our preferred alternative, #4 below, proposes empirical research focused on HTNS roads with a modeling component. For each of the five alternatives, we provide details about the approach, a list of products, assessment of benefits and limitations, and estimations of relative time and cost.

This is step 4 in the TWIG process. If Policy approves follow-up work on one or more of the following alternatives, a study design will be developed. The study design will contain detailed methods for site selection and layout, data collection, and analysis.

The alternatives we propose are:

Alternative #1 – Empirical Research of BMP on HTNS Roads

Alternative #2 – Empirical Research of BMP on HTNS and non-HTNS Roads

Alternative #3 – Utilize Existing Data to Improve Existing, Segment-Scale Models

Alternative #4 – Do Empirical Research of BMP on HTNS Roads (Alternative #1) and Utilize New and Existing Data to Improve Existing Models

Alternative #5 – Do Empirical Research of BMP on HTNS and non-HTNS Roads (Alternative #2) and Utilize New and Existing Data to Improve Existing Models

Discussion of Alternatives

Alternative #1 –Empirical Research of BMP on HTNS Roads

Proposal

Alternative #1 comprises measurements of road sediment production from road prisms and delivery below roads. We propose to research road surface erosion by observation and measurement of sediment production from a sample of individual road segments using sediment traps. We propose to research delivery below roads by observing delivery versus non-delivery (success or failure) from a large number of segments. For Alternative #1, we propose to do detailed empirical research on individual BMP and combinations of BMP targeting specifically HTNS roads.

Details of Approach

Opportunities to reduce both sediment production and sediment delivery will be studied. Study sites will be placed in 2-4 distinct regions of climate, lithology and topography in Washington State to address relative effectiveness as a function of regional contexts. During the study design phase, the TWIG will identify potential opportunities to evaluate aquatic effects from differing volumes of road inputs while conducting empirical research on BMP.

The sampling frame for the sediment production field studies will apply a basic conceptual understanding of the physics of sediment detachment and transport from/through the road tread, cutslope, ditch line, and fill slope to facilitate the exploration of the influences of BMP on sediment production and transport in these different domains. Conceptually, the cutslope and tread generate runoff and sediment, which is then fed to the ditch (or a rut) where concentrated flow transports the sediment. The primary sources of water are the components of the road prism with large areas, the tread and cutslope. The tread generates runoff during relatively intense precipitation events (see Luce and Cundy 1992 and 1994; Luce 2004), whereas the cutslopes produce more runoff from long precipitation events or snowmelt in the Pacific

Northwest (Luce 2002). Runoff from both of these sources will carry some fine sediment depending on the characteristics of their surfaces and sediment detachment by raindrops and traffic. Runoff from these areas is generally shallow and diffuse in nature, but when that runoff is accumulated along the ditch line or in ruts, it becomes concentrated flow, and the more powerful flowing water can more actively detach sediment where the soil is exposed. Alternatively, a well vegetated ditch can promote settling of fine sediments from the cutslope or tread. We can think about parallel processes when water runs off of a crowned or rutted surface over the fillslope, as well.

Empirical Research on Sediment Production Reduction

The first approach would use sediment trap technology developed by the USFS (Black and Luce, 2013 - see Figure 2 below) to test sediment production differences from several plots applying a few prescribed combinations of BMP, as much to demonstrate the effectiveness of a "best" design as to determine how far it is necessary to go to achieve substantial reductions in production.

Figure 2: A sediment trap installed below a road segment.

Testing of BMP combinations will be done for mixed tread, ditch line, and cutslope treatments in a way that isolates tread and cutslope treatment effects from the concentrated flow treatment effects (see Burroughs and King 1989 for examples of individual effects) as well as how the presence or lack of treatment in the concentrated flow road-element can enhance or limit the effectiveness of tread and cutslope treatments. For example, a graded ditch line can undo sediment reductions from the tread simply because the clean water from a paved road can detach sediment from the bare ditch line to satisfy transport capacity (e.g., Luce and Black 2001a). Although the subject has been approached before for a specific combination (e.g., Luce and Black 2001a), it has not been systematically applied toward the particular end of understanding the general effects of multiple BMP.

The sediment production tests of BMP will ultimately be stratified by geology and climate, but will initially be applied in a single area with relatively consistent base geology and climate. A sample of about 80 plots was used in the Oregon Coast Range (Tyee Sandstone and weathered volcanics) in the 1990s using a small crew; it offered a reasonable sample size for a number of alternative treatment combinations. The number of suitable sites (HTNS) may be the limiting factor on getting a large sample size; for Alternative #2, obtaining suitable sites for other road types is not expected to be a limitation.

Empirical Research on Sediment Delivery Reduction

The second approach would use a sediment delivery survey like that used in GRAIP (Black et al. 2012), a simple sampling approach to estimate short-scale delivery reductions when careful drainage design is applied in these hydrologically challenging locations. The basic question to address is the relationship of sediment transport distances below drainage features with the contributing road length/area. Related survey work on stream connectivity shows an effect of the contributing length or area of road and the probability of delivery at different distances (Luce et al. 2014, Figure 3). There is also a suggestion from analysis of those data (not shown in Figure 3) that the effect of distance is more pronounced for smaller contributing areas, which would be relevant to the use of crowning or water bars to reduce the area of roads contributing to stream crossings. A few surveys during wet weather conditions may be the most efficient approach for this study component.

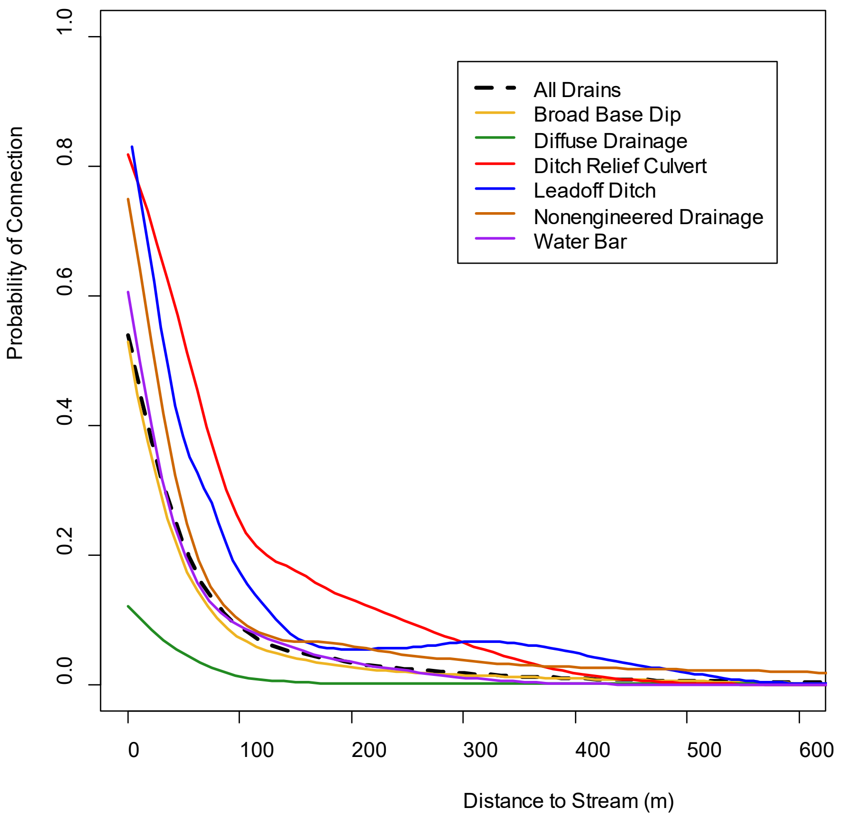

Figure 3: Probability of hydraulic connection between a road drainage diversion and a stream as a function of the drain type and distance to stream (Luce et al. 2014).

Products

- Detailed data about individual and combinations of BMP on HTNS roads in the contexts of lithology and topography.
- An analysis of the data.
- A report about same, including implementation recommendations (i.e., both where and how).

Benefits and Limitations

Alternative #1 will provide information to improve our understanding of road surface erosion and delivery. Doing research across distinct regions of climate, lithology and topography will help develop a better understanding of lithological and topographic controls. That will allow a better understanding of BMP effectiveness for HTNS Roads. In particular, a better understanding of the relationships among BMP and how combinations of BMP relate to each other (e.g., may not be multiplicative as applied in existing operational models). With a focus of HTNS roads, potential gains at the roads most likely to contribute will be evaluated. Not doing research on non-HTNS roads does not mean that these results cannot be applied to non-HTNS roads. Results about lithologic and topographic controls and how BMP interact will be applicable to the rest of the road network, although some special designs for HTNS roads may not be necessary for other road types.

Modeling is a logical extension of empirical research because of the need to apply expensive, detailed, site-specific results to the landscape. NOT doing modeling, as is proposed in Alternative #1, limits the use of these new data and precludes broader landscape application. In particular, local topographic, geologic, and climatological contexts are important. We have gained considerable knowledge from road surface erosion and delivery field studies. Those studies have been conducted throughout the US and elsewhere and, as detailed in Dubé et al. (2011), the field studies have led to the development of models providing reasonably good estimates on relative amounts of material eroded. However, they are only fair to poor in predicting actual amounts of eroded material unless local calibration data are used. Improvement in the existing models is to a large degree limited by available data. Much of the modeling efforts have been using “best available data’ which may not be appropriate for many of the road segments where the models may be used (Dubé et al. 2011). Since empirical work cannot be done across all possible scenarios, additional work needs to focus on data collection that will provide the most useful new information to operational prediction of actual amounts. And not proceeding with a modeling effort begs the question: How do we demonstrate meeting WQ standards or TMDL requirements if we don’t model?

While detailed field work is impractical for all roads, a large enough sample size of well replicated treatments across 2-4 regions will improve the inferential capacity of the data set. A primary limitation to gaining more information is the cost associated with such an effort. Treatments will need to be designed to address the various processes and mechanisms for erosion with the treatments and their distribution designed so individual as well as cumulative processes can be quantified. These sampling requirements will drive cost as sites will require both equipment and labor over time. The design will also need substantial site selection effort.

Depending on the details of the sampling design, Alternative #1 will answer Critical Questions 1-7 for HTNS roads for those specific situations included in the sample (e.g., regions, lithologies, topographic positions) and, to a lesser extent, will answer Critical Questions 1-7 for non-HTNS roads for those specific situations included in the sample. However, extrapolation of these results to other situations and stronger answers to Critical Questions 2-4 and 6 will be possible with modeling (Alternative #4).

Relative Cost/Time Estimates

- Mobilization to Each Region – $4,000
- Estimate of Site Selection – Unknown
- Equipment, Installation – $3,500
- Monitoring per Site – $1500 each year
- Estimate of Number of Sites / Region – 40
- Estimate of Number of Regions – 2-4
- Total (minimum estimate) - $768,000 (assumes only 2 regions; assumes 4 years of sampling; does not include site selection and maintenance; could be expanded by using results to drive changes to design or factors tested)

Alternative #1 is approximately 1/3rd the cost of Alternative #2 for the same number of regions, and less than 1/3rd the cost of Alternative #5. It is somewhat less expensive than Alternative #4 which proposes an equivalent field effort and incorporates a modeling component. It is much more expensive than Alternative #3.

Alternative #2 – Empirical Research of BMP on HTNS and non-HTNS Roads

Proposal

Alternative #2 comprises measurements of road sediment production from road prisms and delivery below roads. We propose to research road surface erosion by observation and measurement of sediment production from a sample of individual road segments using sediment traps. We propose to research delivery below roads by observing delivery versus non-delivery (success or failure) from a large number of segments. For Alternative #2, we propose to do detailed empirical research on individual BMP and combinations of BMP on both HTNS roads and other forest roads.

Details of Approach

See above in Alternative #1 – research efforts would be extended to additional road types, but techniques would be the same. The minimum cost estimate has tripled (see below) because three traffic levels would be sampled in each region.

Products

- Detailed data about individual and combinations of BMP on both HTNS roads and other forest roads in the contexts of lithology and topography.
- An analysis of the data.
- A report about same, including implementation recommendations (i.e., both where and how).

Benefits and Limitations

Alternative #2 will provide information to improve our understanding of road surface erosion and delivery. Doing research across distinct regions of climate, lithology and topography will help develop a better understanding of lithological and topographic controls. As with Alternative #1, this alternative will improve our understanding of BMP effectiveness for HTNS Roads. Of particular importance in both Alternative #1 and #2, we will develop a better understanding of the relationships among BMP and how combinations of BMP relate to each other (e.g., may not be multiplicative as applied in existing operational models). Doing both HTNS and non-HTNS roads would incrementally improve our knowledge of the entire road network (i.e., relative sediment production and delivery between road types).

Modeling is a logical extension of empirical research because of the need to apply expensive, detailed, site-specific results to the landscape. NOT doing modeling, as is proposed in Alternative #2, limits the use of these new data and precludes broader landscape application. In particular, local topographic, geologic, and climatological contexts are important. We have gained considerable knowledge from road surface erosion and delivery field studies. Those studies have been conducted throughout the US and elsewhere and, as detailed in Dubé et al. (2011), the field studies have led to the development of models providing reasonably good estimates on relative amounts of material eroded. However, they are only fair to poor in predicting actual amounts of eroded material unless local calibration data are used. Improvement in the existing models is to a large degree limited by available data. Much of the modeling efforts have been using "best available data' which may not be appropriate for many of the road segments where the models may be used (Dubé et al. 2011). Since empirical work cannot be done across all possible scenarios, additional work needs to focus on data collection that will provide the most useful new information to operational prediction of actual amounts. And not proceeding with a modeling effort begs the question: How do we demonstrate meeting WQ standards or TMDL requirements if we don't model?

While detailed field work is impractical for all roads, a large enough sample size of well replicated treatments across 2-4 regions will improve the inferential capacity of the data set. A primary limitation to gaining more information is the cost associated with such an effort. Treatments will need to be designed to address the various processes and mechanisms for erosion with the treatments and their distribution designed so individual as well as cumulative processes can be quantified. These sampling requirements will drive cost as sites will require both equipment and labor over time. The design will also need substantial site selection effort.

Depending on the details of the sampling design, Alternative #2 will answer Critical Questions 1-7 for HTNS roads and for other traffic levels for those specific situations included in the sample (e.g., regions, lithologies, topographic positions). However, extrapolation of these results to other situations and stronger answers to Critical Questions 2-4 and 6 will be possible with modeling (Alternative #4).

Relative Cost/Time Estimates

- Mobilization to Each Region – $4,000
- Estimate of Site Selection – Unknown
- Equipment, Installation per Site – $3,500

- Monitoring per Site – $1500 each year
- Estimate of Number of Sites / Region – 120
- Estimate of Number of Regions – 2-4
- Total (minimum estimate) - $2,304,000 (assumes only 2 regions; assumes 4 years of sampling; does not include site selection and maintenance; could be expanded by using results to drive changes to design or factors tested)

Alternative #2 is approximately three times the cost of Alternative #1 for the same number of regions, and almost three times the cost of Alternative #4. It is somewhat less expensive than Alternative #5 which proposes an equivalent field effort and incorporates a modeling component. It is much, much more expensive than Alternative #3.

Alternative #3 – Utilize Existing Data to Improve Existing, Segment-Scale Models

Proposal

We present a modest proposal to apply a geomorphic model to understand road prism erosion in the context of multiple contributing and transporting elements. The proposed model is not intended as an operational tool, rather as a theoretical support tool to place new and existing empirical information into a context that can better be incorporated into the existing operation tools such as WARSEM and GRAIP. This model will be developed at the scale of road segments, and it will include the hillslope hydrologic processes that contribute to road cutslopes. While the model will be capable of predicting water and sediment dynamics in the road prism (tread, cutslope, ditches, and fillslope) under the influence of single and combined BMP, it will also provide capability to conceptually interface with existing operational empirical models to extrapolate their estimates to different environments (topography, lithology, soils) and time scales.

Details of Approach

Substantial modeling capacity of road erosion already exists. A review of models available for road erosion estimation is provided above in the Best Available Science Summary. However, these models do not provide a robust theoretical framework to merge information from multiple empirical studies done in different environments. There is no existing model that embodies the necessary features to study the impacts of road BMP alternatives. Empirical models focus on mean annual response using simple linear equations based on multipliers and neglect physical processes, nonlinearity, and climatic variability, while physical models are often over parameterized, adapted from agricultural literature. Representation of hillslope hydrology and lithologic and topographic controls on runoff generation are not included in any model. Models lack proper representations of the continuum of water and sediment generation, transport and storage dynamics across the road prism and the influence of BMP on these processes.

We propose a model to contextually place and extend existing and planned empirical studies into a valid framework for applications using combinations of BMP in operational models like WARSEM or GRAIP. Existing physically based models are too constrained in topology and hydrology to reasonably represent many road BMP. However, a combination of existing software applications can lead to a theoretically rigorous tool to evaluate combinations of BMP and design smaller empirical studies to provide local calibration parameters for physically-based relationships.

We envision a modular and component-based numerical model that can be used to investigate the effectiveness of individual and collective uses of a range of forest road BMP within road segments integrated to watershed flow paths. A new landscape modeling framework called Landlab is suitable for this purpose (http://landlab.readthedocs.org/en/latest/index.html). Landlab is a Python software package that supports numerical modeling in earth science, and especially those fields that deal with earth-surface dynamics including geomorphology, hydrology, glaciology, stratigraphy, and related areas. Landlab is actively being developed by collaborations among University of Colorado, University of Washington (Istanbulluoglu), and Tulane University.

Landlab is a modeling environment in which scientist can build a numerical landscape model without having to code all of the individual parts (e.g., Tucker et al., 2015). Landlab provides four main resources and capabilities:

1) A library of *code resources* for building two-dimensional numerical models from scratch. The Landlab library includes a powerful "gridding engine" for creating, managing, and iteratively updating data on structured or unstructured grids. The library also includes support for input and output, including input of digital elevation models (DEM) in ArcInfo ASCII format, handling of parameter inputs using formatted text files, and netCDF-format input and output.
2) A set of pre-built *components*, each of which implements a numerical representation of a particular process.
3) A *framework for building models* by assembling and linking process components.
4) A *library of models* that have already been created from component(s).

In this project we would use Landlab functionalities of spatial representation of model domains and flow generation and routing. Our modeling efforts would initially focus on processes within a road segment while representing incoming flows of water and sediment from the defined boundaries of the road segment (i.e., hillslope contribution and flows from upslope road segments) as external inputs from other models, linking models, or as specified contexts. Such a model will support the planning of experimental field studies by means of developing what-if scenarios and hypothesis testing of BMP design alternatives to note where results of a given empirical study likely depend strongly on other contexts; this powerful model result is only realized by this project if one of Alternatives #4 or #5 is chosen.

Representation of hillslope hydrology and long-term (seasonal to annual) hydrologic memory is critical in the PNW to obtain realistic hillslope runoff contribution into ditches. For this purpose we would delineate catchment areas that contribute flows into a road segment and use a separate hydrology model to represent hydrological dynamics on slopes (see Figure 4). We envision using an existing watershed hydrology model suitable for the PNW conditions, such as the Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al., 1994), and feed off-line DHSVM predictions as input to the road model. The watershed model predictions will provide surface runoff and subsurface flow input in the upper boundary of a road cutslope over sub-daily or daily time scales throughout simulations.

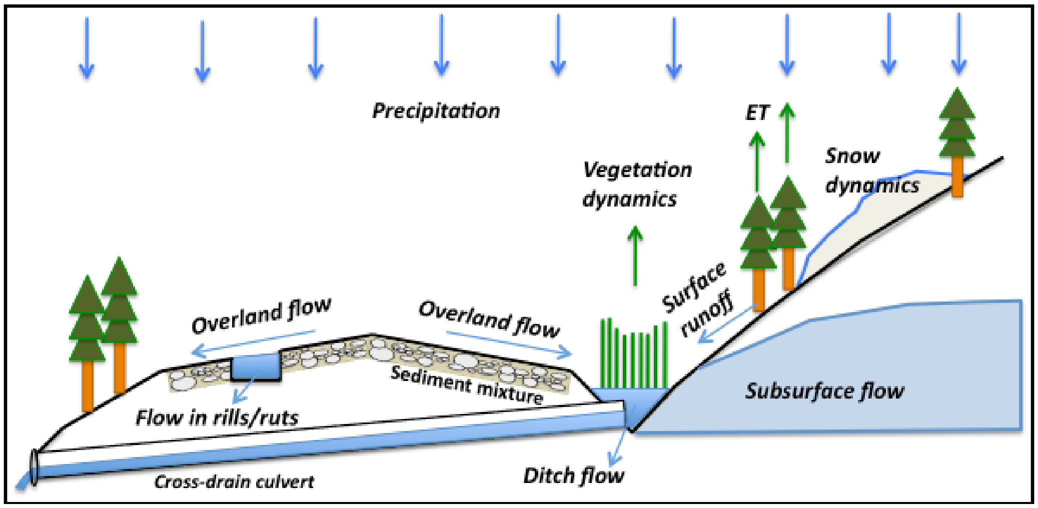

Figure 4. Forest road cross-section with some of the proposed model components indicated in text.

Rainfall-driven infiltration, runoff generation and overland flow routing will be represented on the road surface, ditches and cutslopes, following the model of Luce and Cundy (1994). Overland flow will be routed as diffused or concentrated depending on the flow lines dictated by the surface topography. In the ditches, flow will always be in the form of channel flow. The model will be built to allow for sediment detachment, transport, and deposition using fixed and dynamic grid representations. The latter will deform the initial elevation field as rills form. Because runoff erosion is highly nonlinear to concentrated discharge, representation of surface dynamics will improve predictions. Routing flows on the road surface will show the implications of the evolving nature of road surface on the contribution of runoff overland flow on fillslopes. In the ditch slopes, we will also represent the influence of vegetation (e.g., grass, shrub, bush, etc.) on flow depth, velocity, shear stress, detachment and transport. Storm processes will be modeled in hourly or sub hourly time scales, which will depend on model stability conditions and intensity of rainfall input. Such short time scales will allow developing hydrographs at culvert outlets and ditches. Continuous hydrological processes will be simulated on contributing cutslopes at daily or sub daily time scales as needed. Model forcing can be obtained from gridded climate data used for regional hydrologic models (e.g., Livneh et al. 2013) or local weather stations as available.

Each BMP will be coded as an individual module. BMP will be geographically placed on the desired location on the road surface, cutslopes, ditches or fillslopes, and will use flows of water and sediment as inputs. Storage dynamics of water and sediment will be represented in each BMP, and BMP will provide outflows at their outlets (either point or as continuous boundary). The modular structure of the proposed model will allow testing of BMP off-line of the road model, using necessary inputs and outputs as time series. When multiple BMP are used, the influence of each BMP on runoff and sediment discharge and storage will be linked along the flow paths of integrated hillslope and road prism domains. All BMP will provide outputs to the road segment. Simulations using a combination of BMP will illustrate their cumulative effects on or downstream of the road prism.

Products

This project will deliver a forest roads BMP component in Landlab with applications and a users' manual. The tools will be made available to public through the Landlab web-based model repository (http://landlab.readthedocs.org/en/latest/).

Benefits and Limitations

The proposed modeling approaches in Alternative #3 may be able to improve our use and interpretation of existing data sets and thereby lead to better understanding of road surface erosion and delivery. For example, using improved DEM, considering hillslope hydrology above road cutslopes in HTNS roads, and forcing the road surface processes with actual climatologic input will lead to improved interpretation of existing data and models.

An important advantage of using the Landlab modeling framework in this project will be that the proposed forest roads component will be readily compatible with other processes in Landlab, such as landslides, and hillslope and stream erosion and transport processes. This will facilitate watershed and regional scale evaluations of the impacts of roads on watershed hydrologic and geomorphic processes and the potential improvements that can be achieved by road BMP.

There will be a number critical limitations of developing new model components without new field studies designed consistent with model theory. Several important drawbacks in relying only on existing data will include differences and inconsistencies in the qualitative and quantitative data and descriptions of site conditions such as climate, topography and lithology, as well as differences in data collection methods and instrumentation among sites. As models become more process-based there is a need for detailed characterization of experimental conditions at field sites where models are evaluated, and have a good representation of model forcing conditions as well as hillslope hydrology. Lack of empirical data systematically collected by focusing single and collective effects of BMP over similar space and time scales would hamper the level of fundamental understanding that can be achieved from this modeling effort.

Relative Cost/Time Estimates

- Estimated Cost of Literature Review for Existing Data, gathering data in different formats and geo-referencing the data – $25,000
- Estimated Cost of Model Development – $ 300,000 (assumes 3 years of graduate student time)

Alternative #4 – Do Empirical Research of BMP on HTNS Roads (Alternative #1) and Utilize New and Existing Data to Improve Existing Models (preferred alternative of the TWIG)

Proposal

Alternative #4 will combine Alternatives #1 and #3 and synthesize co-developed data from field observations and model applications to recommend regional BMP alternatives and suggest approximate relative changes in sediment and water yield predictions in space and time.

Details of Approach

See above in Alternative #1 for details of the proposed field work on HTNS roads. For the remainder of this section, we present this alternative from the perspective of combined field and modeling effort.

The road surface model inter-comparison study of Dubé et al. (2011) showed large uncertainties in model predictions and suggested that most models can only be used at best for relative comparisons of model scenarios for decision making. Among the models they used, only WARSEM included an empirical BMP component. Datasets obtained from field measurements used to develop and evaluate such models focused on quantifying the effects of single BMP at a time and, therefore, are not suitable for testing and evaluating models that can simulate multiple BMP. There is need for developing a theoretical modeling framework for road hydrology and sediment yield modeling with functionality for BMP which could guide the design of empirical field studies in different regions; those results could then be used improve model theory. Figure 5 below illustrates how a theoretical model and fieldwork design can be used in a feed-back loop to improve our understanding of road BMP effectiveness in a region and develop targeted recommendations for stakeholders.

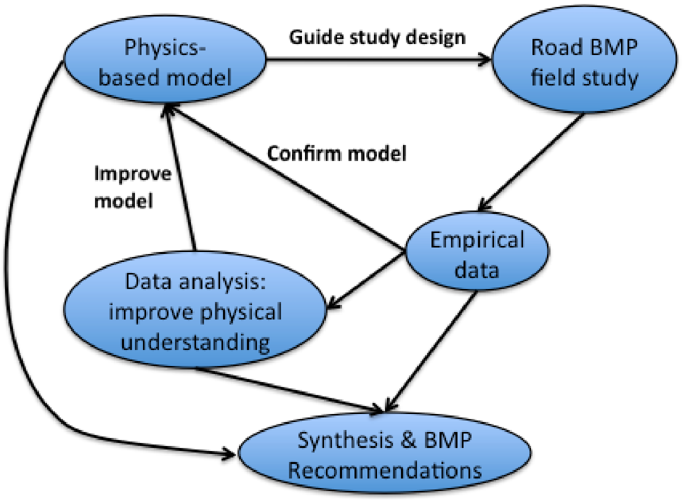

Figure 5. Conceptual framework to improve understanding of the effects of road BMP through the feedback loop of physically-based modeling, field work design, empirical measurements and use of field data.

For example, the model we outlined in Alternative #3 can aid in the planning of field instrumentation, such as sediment traps and flow measurement, by providing runoff hydrographs with estimated contributions of hillslope runoff, subsurface flow and road surface runoff. Preliminary model runs showing active erosion and deposition areas can be used for identifying monitoring sites. Field data will also be used to: 1) Identify the relative roles of local (road features and design) and global (lithology and geomorphology of contributing areas) controls at a field site; 2) Reevaluate model conceptualization and theory to improve the representations of such controls; 3) Update model parameter values; 4) Regionalize model performance; and 5) Identify model limitations in relation to local and global controls. At each field site, other existing modeling tools will be evaluated as potentials for improving existing tools, and interfacing them with Landlab will be considered. In the final year of the project, field data and modeling at all sites will be synthesized, and BMP recommendations will be developed in different regions and with examples of model implementation. We expect that this modeling tool, based on a component-based Landlab landscape modeling framework, can dramatically reduce model coding and development time and costs for future improvements. A graphical user interface (GUI) can be developed in the future to facilitate both research and operational use of the modeling framework.

Products

- Detailed data about individual and combinations of BMP on HTNS roads in the contexts of lithology and topography.
- An analysis of the data.
- A report about same, including implementation recommendations (i.e., both where and how).
- This project will deliver a forest roads BMP component in Landlab with applications and a users' manual. The tools will be made available to public through the Landlab web-based model repository (http://landlab.readthedocs.org/en/latest/).

Benefits and Limitations

Alternative #4 will provide information to improve our understanding of road surface erosion and delivery. Doing research across distinct regions of climate, lithology and topography will help develop a better understanding of lithological and topographic controls. That will allow a better understanding of BMP effectiveness for HTNS Roads. In particular, a better understanding of the relationships among BMP and how combinations of BMP relate to each other (e.g., may not be multiplicative as applied in existing operational models). With a focus of HTNS roads, potential gains at the roads most likely to contribute will be evaluated. Not doing research on non-HTNS roads does not mean that these results cannot be applied to non-HTNS roads. Results about lithologic and topographic controls and how BMP interact will be applicable to the rest of the road network, although some special designs for HTNS roads may not be necessary for other road types.

Modeling is a logical extension of empirical research because of the need to apply expensive, detailed, site-specific results to the landscape. In particular, local topographic, geologic, and climatological contexts are important. We have gained considerable knowledge from road surface erosion and delivery field studies. Those studies have been conducted throughout the US and elsewhere and, as detailed in Dubé et al. (2011), the field studies have led to the development of models providing reasonably good estimates on relative amounts of material eroded. However, they are only fair to poor in predicting actual amounts of eroded material unless local calibration data are used. Improvement in the existing models is to a large degree limited by available data. Much of the modeling efforts have been using "best available data' which may not be appropriate for many of the road segments where the models may be used (Dubé et al. 2011). Since empirical work cannot be done across all possible scenarios, additional work needs to focus on data collection that will provide the most useful new information to operational prediction of actual amounts.

While detailed field work is impractical for all roads, a large enough sample size of well replicated treatments across 2-4 regions will improve the inferential capacity of the data set. A primary limitation to gaining more information is the cost associated with such an effort. Treatments will need to be designed to address the various processes and mechanisms for erosion with the treatments and their distribution designed so individual as well as cumulative processes can be quantified. These sampling requirements will drive cost as sites will require both equipment and labor over time. The design will also need substantial site selection effort.

Depending on the details of the sampling design, Alternative #4 will answer Critical Questions 1-7 for HTNS roads for those specific situations included in the sample (e.g., regions, lithologies, topographic positions) and, to a lesser extent, will answer Critical Questions 1-7 for non-HTNS roads for those specific situations included in the sample. Extrapolation of these results to other situations and stronger answers to Critical Questions 2-4 and 6 will be possible with the modeling effort proposed in this alternative.

<u>Relative Cost/Time Estimates</u>

- Alternative # 3 Lit Review and Modeling Effort for Existing Data – $325,000
- Additional Modeling Efforts for New Data, Data Analysis and Synthesis – $100,000 (assumes another year of graduate student time)
- Mobilization to Each Region – $4,000
- Estimate of Site Selection – Unknown
- Equipment, Installation – $3,500
- Monitoring per Site – $1500 each year
- Estimate of Number of Sites / Region – 40
- Estimate of Number of Regions – 2-4
- Total (minimum estimate) - $1,193,000 (assumes only 2 regions; assumes 4 years of sampling; does not include site selection and maintenance; could be expanded by using results to drive changes to design or factors tested)

Alternative #4 is approximately 1/3rd the cost of Alternative #5 for the same number of regions. It is approximately the cost of Alternatives #1 and #3 combined because it is the combination of those two alternatives. It is much more expensive than Alternative #3.

Alternative #5 – Do Empirical Research of BMP on HTNS and non-HTNS Roads (Alternative #2) and Utilize New and Existing Data to Improve Existing Models

Proposal

Alternative #5 will combine Alternatives #2 and #3 and synthesize co-developed data from field observations and model applications to recommend regional BMP alternatives and suggest approximate relative changes in sediment and water yield predictions in space and time.

Details of Approach

Details of the field sampling are discussed above in Alternative #1; this alternative also samples non-HTNS roads as discussed in Alternative #2. Modeling efforts are described in Alternative #3 and the power of combining field and modeling efforts is described in Alternative #4.

Products

- Detailed data about individual and combinations of BMP on both HTNS roads and other forest roads in the contexts of lithology and topography.
- An analysis of the data.
- A report about same, including implementation recommendations (i.e., both where and how).
- This project will deliver a forest roads BMP component in Landlab with applications and a users' manual. The tools will be made available to public through the Landlab web-based model repository (http://landlab.readthedocs.org/en/latest/).

Benefits and Limitations

Alternative #5 will provide information to improve our understanding of road surface erosion and delivery. Doing research across distinct regions of climate, lithology and topography will help develop a better understanding of lithological and topographic controls. That will allow a better understanding of BMP effectiveness for HTNS roads and for other traffic levels. In particular, a better understanding of the relationships among BMP and how combinations of BMP relate to each other (e.g., may not be multiplicative as applied in existing operational models).

Modeling is a logical extension of empirical research because of the need to apply expensive, detailed, site-specific results to the landscape. In particular, local topographic, geologic, and climatological contexts are important. We have gained considerable knowledge from road surface erosion and delivery field studies. Those studies have been conducted throughout the US and elsewhere and, as detailed in Dubé et al. (2011), the field studies have led to the development of models providing reasonably good estimates on relative amounts of material eroded. However, they are only fair to poor in predicting actual amounts of eroded material unless local calibration data are used. Improvement in the existing models is to a large degree limited by available data. Much of the modeling efforts have been using "best available data' which may not be appropriate for many of the road segments where the models may be used (Dubé et al. 2011). Since empirical work cannot be done across all possible scenarios, additional work needs to focus on data collection that will provide the most useful new information to operational prediction of actual amounts.

While detailed field work is impractical for all roads, a large enough sample size of well replicated treatments across 2-4 regions will improve the inferential capacity of the data set. A primary limitation to gaining more information is the cost associated with such an effort. Treatments will need to be designed to address the various processes and mechanisms for erosion with the treatments and their distribution designed so individual as well as cumulative processes can be quantified. These sampling requirements will drive cost as sites will require both equipment and labor over time. The design will also need substantial site selection effort.

Depending on the details of the sampling design, Alternative #5 will answer Critical Questions 1-7 for HTNS roads and for other traffic levels for those specific situations included in the sample (e.g., regions, lithologies, topographic positions). Stronger answers to Critical Questions 2-4 and 6 will be possible with the modeling effort proposed in this alternative.

<u>Relative Cost/Time Estimates</u>

- Alternative # 3 Lit Review and Modeling Effort for Existing Data – $325,000
- Additional Modeling Efforts for New Data – $100,000+ (expect more $ than for Alternative #4)
- Mobilization to Each Region – $4,000
- Estimate of Site Selection – Unknown
- Equipment, Installation per Site – $3,500
- Monitoring per Site – $1500 each year
- Estimate of Number of Sites / Region – 120
- Estimate of Number of Regions – 2-4
- Total (minimum estimate) - $2,729,000 (assumes only 2 regions; assumes 4 years of sampling; does not include site selection and maintenance; could be expanded by using results to drive changes to design or factors tested)

Alternative #5 is approximately three times the cost of Alternative #4 for the same number of regions. It is approximately the cost of Alternatives #2 and #3 combined because it is the combination of those two alternatives. It is much, much more expensive than Alternative #3.

References

Adams, J. M., S. S. Nudurupati, N. M. Gasparini, D. E. J. Hobley, E. W. H. Hutton, G. E. Tucker, and E. Istanbulluoglu, 2014. Landlab: Sustainable Software Development in Practice. http://dx.doi.org/10.6084/m9.figshare.1097629. 2nd Workshop on Sustainable Software for Science: Practice and Experiences (WSSSPE2). New Orleans Convention Center on Sunday, 16 November 2014

Amann, J. R., 2004. Sediment production from forest roads in the upper Oak Creek watershed of the Oregon Coast Range. Master's Thesis. Corvallis, OR: Oregon State University.

Beschta, R. L., 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14: 1011-1016.

Bilby, R. E., 1985. Contributions of road sediment to a western Washington stream. Forest Science 31(4): 827-838.

Bilby, R.E., K. Sullivan and S.H. Duncan, 1989. The Generation and Fate of Road-surface Sediment in Forested Watersheds in Southwestern Washington. Forest Science 35(2):453-468.

Black, T. A., R. M. Cissel, and C. Luce, 2012. The Geomorphic Roads Analysis and Inventory Package (GRAIP) Volume 1: data collection method. RMRS-GTR-280Rep., 115 pp, USDA Forest Service, Rocky Mountain Research Station, Boise, ID.

Black, T. A., N. Nelson, R. Cissel and C. Luce, 2013. Prediction of erosion from forest road networks. Presentation at European Geophysical Union, Vienna, Austria. April 7, 2013.

Black, T. A. and C. H. Luce, 2013. Measuring water and sediment discharge from a road plot with a settling basin and tipping bucket. Gen. Tech. Rep. RMRS-GTR-287, 38 pp, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.

Brookes, A., 1986. Response of aquatic vegetation to sedimentation downstream from river channelization works in England and Wales. Biological Conservation 38:352–267.

Busteed, P., 2004. Quantifying forest road erosion in the Ouachita Mountains of Oklahoma. Master's Thesis: Oklahoma State University.

Burroughs, E. R. and J. G. King, 1989. Reduction of soil erosion of forest roads. Gen. Tech. Rep. INT-264. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 24 p.

Cedarholm, C. J., L. M. Reid and E. O. Salo, 1981. Cumulative effects of logging and road sediment on Salmonid populations in the Clearwater River, Jefferson County, Washington. In: Proceedings of the Conference on Salmon Spawning Gravel: A

Renewable Resource in the Pacific Northwest? Pullman: Washington State University, Water Research Center: 38-74.

Cline, R., G. Cole, W. Megahan, R. Patten and J. Potyondy, 1981. Guide for predicting sediment yield from forested watersheds. Missoula, MT and Ogden, UT: United States Department of Agriculture Forest Service Northern Region and Intermountain Region.

Coe, D. 2004. The hydrologic impacts of roads at varying spatial and temporal scales: A review of published literature as of April 2004. UPSAG, Cooperative, Monitoring, Evaluation and Research (CMER).

Cordone, A. J. and D. W. Kelley, 1961. Influences of inorganic sediment on the aquatic life of streams. California Fish and Game 47:189–228.

Croke, J. and S. Mockler, 2001. Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. *Earth Surface Processes and Landforms*, *26*(2): 205-217.

Dubé, K., W. Megahan and M. McCalmon, 2004. Washington Road Surface Erosion Model, Manual and Appendices. For: Cooperative Monitoring, Evaluation and Research (CMER) Committee, Adaptive Management Program of the Forests & Fish Habitat Conservation Plan, Washington State. 56 p. Appendices A-E.

Dubé, K., A. Shelly, J. Black and K. Kuzis. 2010. Washington road sub-basin scale effectiveness monitoring first sampling event (2006-2008) report. Cooperative Monitoring, Evaluation and Research Report CMER 08-801. Washington Department of Natural Resources. Olympia, Washington.

Dubé, K, T. Black, C. Luce and M. Riedel, 2011. Comparison of road surface erosion models with measured road surface erosion rates. Tech. Bull. No. 0988. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc.

Elliot, W. J., D. E. Hall and D. L Scheele, 1999a. FS WEPP, Forest Service interfaces for the Water Erosion Prediction Project computer model. United States Department of Agriculture Forest Service, Rocky Mountain Research Station and San Dimas Technology and Development Center.

Elliot, W. J. and D. E. Hall, 1997. Water Erosion Prediction Project (WEPP) forest applications. Gen. Tech. Rep. INT-GTR-365. United States Department of Agriculture Forest Service, Rocky Mountain Research Station.

Elliot, W. J., R. B. Foltz and P. R. Robichaud, 2009. Recent findings to measuring and modeling forest road erosion. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009.

Foltz, R. B. and M. A. Truebe, 1995. Effect of Aggregate Quality on Sediment Production from a Forest Road. Conference Proceedings of the Sixth International Conference on Low-Volume Roads, 1: 57.

Fu, B., T. H. Lachlan and C. E. Ramos-Sharrón, 2010. A review of surface erosion and sediment delivery models for unsealed roads. Environmental Modelling and Software 25: 1-14.

Fudge, T. S., K. G. Wautier, R. E. Evans and V. P. Palace, 2008. Effect of different levels of fine-sediment loading on the escapement success of rainbow trout from artificial redds. North American Journal of Fisheries and Management 28:758–765.

Geist J. and K. Auerswald, 2007. Physicochemical stream bed characteristics and recruitment of the freshwater pearl mussel (*Margaritifera margaritifera*). Freshwater Biology 52: 2299–2316.

Ice, G., 1986. A study of the effectiveness of sediment traps for the collection of sediment from small forest plot studies. Tech. Bull. No. 483. Research Trangle Park, NC: National Council for Air and Stream Improvement Inc.

Izagirre, O., A. Serra, H. Guasch and A. Elosegi, 2009. Effects of sediment deposition on periphytic biomass, photosynthetic activity and algal community structure. Science of the Total Environment 407:5694–5700.

Jones, J. A. and G. E. Grant, 1996. Peak flow responses to clear-cutting and roads in small and large basins, Western Cascades, Oregon. Water Resources Research 32(4): 959-974.

Kahklen, K., 2001. A method for measuring sediment production from forest roads. Res. Note PNW-RN-529. Portland, OR: United States Department of Agriculture Forest Service, Pacific Northwest Research Station. 18 p.

Kaller, M. D. and K. J. Hartman, 2004. Evidence of a threshold of fine sediment accumulation for altering benthic macroinvertebrate communities. Hydrobiologia 518:95–104.

Kent, T. R. and R. S. Stelzer, 2008. Effects of deposited fine sediment on life history traits of *Physa integra* snails. Hydrobiologia 596:329–340.

Lee, D., J. Sedell, B. Rieman, R. Thurow, J. Williams 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.

Lemly, A. D., 1982. Modification of benthic insect communities in polluted streams: combined effects of sedimentation and nutrient enrichment. Hydrobiologia 87:229–245.

Lowe, W. H. and D. T. Bolger, 2002. Local and landscape-scale predictors of salamander abundance in New Hampshire headwater streams. Conservation Biology 16:183–93.

Livneh, B., E. A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K. M. Andreadis, E. P. Maurer and D. P. Lettenmaier, 2013. A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: Update and Extensions. J. Climate, **26**.

Luce, C. H., 2002. Hydrological processes and pathways affected by forest roads: What do we still need to learn? Hydrol. Process. 16: 2901-2904.

Luce, C. H. and T. A. Black, 2001b. Spatial and temporal patterns in erosion from forest roads. In: *Influence of Urban and Forest Land Uses on the Hydrologic-Geomorphic Responses of Watersheds*, edited by M. W. Wigmosta and S. J. Burges, pp. 165-178, American Geophysical Union, Washington, DC.

Luce, C. H., and T. W. Cundy, 1992. Modification of the Kinematic Wave-Philip Infiltration Overland Flow Model. Water Resour. Res. *28*(4): 1179-1186.

Luce, C. H. and T. A. Black, 1999. Sediment Production from Forest Roads in Western Oregon. Water Resources Research 35(8): 2561-2570.

Luce, C. H. and T. A. Black, 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, C. H. and T. W. Cundy, 1992. Modification of the Kinematic Wave-Philip Infiltration Overland Flow Model. Water Resour. Res. *28*(4): 1179-1186.

Luce, C. H. and T. W. Cundy, 1994. Parameter identification for a runoff model for forest roads. Water Resources Research 30(4): 1057-1069.

Luce, C. H. and B. C. Wemple, 2001. Introduction to the special issue on hydrologic and geomorphic effects of forest roads. Earth Surface Processes and Landforms 26: 111-113.

Luce, C. H., T. A. Black, R. Cissel and N. Nelson, 2014. Assessing Controls on Sediment Delivery from Forest Roads, Presentation at International Union of Forestry Research Organizations (IUFRO) World Congress, Oct. 5-11 2014, Salt Lake City, UT.

MacDonald, L. H., R. W. Sampson and D. M. Anderson, 2001. Runoff and road erosion of the plot and segment scales, St John, US Virgin Islands. Earth Surface Processes and Landforms 26: 251-272.

MacDonald, L. H., D. Coe and S. Litschert, 2004. Assessing cumulative watershed effects in the Central Sierra Nevada: Hillslope measurements and catchment-scale modeling. In: Proceedings of the Sierra Nevada Science Symposium: Science for Management and

Conservation. Gen. Tech. Rep. PSW-GTR-193. Portland, OR: United States Department of Agriculture Forest Service, Pacific Southwest Research Station: 149-157.

MacDonald, L. H., R. W. Sampson and D. M. Anderson, 2011. Runoff and road erosion at the plot and segment scales, St John, U.S. Virgin Islands. Earth Surface Processes and Landforms 26(3): 251-272.

MacDonald, L. H. and D. B. R. Coe, 2008. Road sediment production and delivery: processes and management. In: Proceedings of the First World Landslide Forum, United Nations University, Tokyo, Japan. International Consortium on Landslides, Japan, pp. 385-388. http://coast.noaa.gov/czm/pollutioncontrol/media/Technical/D20%20-%20MacDonald%20and%20Coe%202008%20Road%20Sediment%20Production%20and%20Delivery.pdf

Martin, D., 2009. Forest Road Runoff Disconnection Survey of Private Timberlands in Washington. Washington Forest Protection Association, 724 Columbia Street NW, Suite 250, Olympia, WA 98501.

Megahan, W.F. and W. J. Kidd, 1972. Effects of Logging and Logging Roads on Erosion and Sediment Deposition from Steep Terrain. Journal of Forestry 70(3):136-141.

Megahan, W. F., 1974. Erosion over time on severely disturbed granitic soils: A model. Research Paper INT-156. Ogden, UT: United States Department of Agriculture Forest Service, Intermountain Research Station.

Megahan, W. F. and G. L. Ketcheson, 1996. Predicting downslope travel of granitic sediments from forest roads in Idaho. Water Resources Bulletin 32(2): 371-382.

Minshall, G. W., 1984. Aquatic insect-substratum relationships. In: Resh and Rosenberg (Eds.) The Ecology of Aquatic Insects. Praeger Publishers, New York, NY, pp. 358-400.

Montgomery, D. R., 1994. Road surface drainage, channel initiation and slope instability. Water Resources Research 30(6): 1925-1932.

National Council for Air and Stream Improvement, Inc. (NCASI), 2003. SEDMODL Release Ver. 2.0, User's manual and technical documentation. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc. http://www.ncasi.org/support/downloads/Detail.aspx?id=5.

Peranich, C. M., 2005. Measurement and modeling of erosion from four rural unpaved road segments in the Stillwater Creek Watershed. Master's Thesis: Oklahoma State University.

Platts, W. S., R. J. Torquemada, M. L. McHenry and C. K. Graham, 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(3): 274-283.

Poole, K. E. and J. A. Downing, 2004. Relationship of declining mussel biodiversity to stream-reach and watershed characteristics in an agricultural landscape. Journal of the North American Benthological Society 23: 114–125.

Prasad, A., D. G. Tarboton, C. H. Luce and T. A. Black, 2005. A GIS tool to analyze forest road sediment production and stream impacts. In: 2005 ESRI International User Conference Proceedings. July 25-29, San Diego, CA. Redlands, CA: Environmental Systems Research Institute.

Reid, L.M. and T. Dunne, 1984. Sediment Production from Forest Road Surfaces. Water Resources Research 20(11): 1753-1761.

Runde, J. M. and R. A. Hellenthal, 2000. Effects of suspended particles on net-tending behaviors for *Hydropsyche sparna* (Trichoptera: Hydropsychidae) and related species. Annals of the Entomological Society of America 93: 678–683.

Sessions, J., J. Balcom and K. Boston, 1987. Road location and construction practices: Effects on landslide frequency and size in the Oregon Coast Range. Western Journal of Applied Forestry 2(4): 119-124.

Suren, A. M. and I. G. Jowett, 2001**.** Effects of deposited sediment on invertebrate drift: An experimental study. New Zealand Journal of Marine and Freshwater Research 35: 725-737.

Suren, A. M., 2005. Effects of deposited sediment on patch selection by two grazing stream invertebrates. Hydrobiologia 549: 205–218.

Suttle, K. B., M. E. Power, J. M. Levine and C. McNeely, 2004. How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. Ecological Applications 14: 969–974.

Swanson, F. J. and C. T. Dyrness, 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3: 393-396.

Swift, L.W. Jr., 1984. Gravel and grass surfacing reduces soil loss from mountain roads. Forestry Science 30: 657-670.

Tebo, L. B., 1955, Effects of siltation, resulting from improper logging on the bottom fauna of a small trout stream in the southern Appalachians. Progressive Fish Culturist 17: 64–70.

Thurow, R. F. and D. C. Burns, 1992. Fish response to fine sediment deposition in the Idaho Batholith. In: Sommarstrom, Sari, Ed. Proceedings of the Conference on Decomposed Granitic Soils: Problems and Solutions. Davis, CA: University of California, University Extension. 130 p.

Tucker, G. E., D. E. J Hobley, E. Hutton, N. M. Gasparini, E. Istanbulluoglu, J. M. Adams and

S. S. Nudurupati. CellLab-CTS 2015: a Python library for continuous-time stochastic cellular automaton modeling using Landlab, Geosci. Model Dev. Discuss., 8, 9507-9552, doi:10.5194/gmdd-8-9507-2015, 2015.

U.S. Environmental Protection Agency, 2000. Atlas of America’s polluted waters. EPA Report 840-B-00-002. Office of Water, U.S. Environmental Protection Agency, Washington, DC.

Van Nieuwenhuyse, E. E. and J. D. LaPerriere, 1986. Effects of placer gold mining on primary production in subarctic streams of Alaska. Water Resources Bulletin 22: 91–99.

Waters, T. F., 1995. Sediment in streams: sources, biological effects and control. American Fisheries Society Monograph 7. Bethesda, Maryland.

Wemple, B. C., J. A. Jones and G. E. Grant, 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. Water Resources Bulletin 32(6):1195-1207.

Washington Forest Practices Board, 1995. Standard methodology for conducting watershed analysis under Chapter 222-22 WAC, Ver. 3. Timber/Fish/Wildlife Agreement and WFPB, Olympia, Washington.

Wood. P. J. and P. D. Armitage, 1997. Biological effects of fine sediment in the lotic environment. Environmental Management 21: 203–217.

Wigmosta, M. S., L. W. Vail and D. P. Lettenmaier, 1994. A distributed hydrology-vegetation model for complex terrain. Water Resources Research, *30*(6): 1665-1679.

Ziegler, A.D., T.W. Giambelluca and R.A. Sutherland, 2001. Erosion prediction on unpaved mountain roads in northern Thailand: validation of dynamic erodibility modelling using KINEROS2. Hydrological Processes 15(3): 337-358.