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How does traffic affect erosion of unpaved forest roads?

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Abstract

The relationship between traffic and forest road erosion has been studied for decades, and the answer to the question "what happens when traffic is present on unpaved forest roads?" is simple: erosion increases. However, the answer to the question "why does it increase?" is complex and requires us to consider forest road erosion through an integrated lens. Fully understanding how traffic affects forest road erosion will allow us to control forest road erosion effectively. In this synthesis, we look at forest road erosion literature and focus the discussion on the interactions between traffic and erosion. Specifically, we explore four main hypotheses that have been proposed to explain how traffic affects erosion. These hypotheses are discussed in detail, including what data and information are required to evaluate them. In addition to the specific traffic-erosion interactions, we review important factors that interact with traffic to enhance erosion. Finally, we propose a framework that describes forest road erosion as a combination of all limiting factors. This framework can help guide future data collection needs, allow us to form a more holistic understanding of forest road erosion, and ultimately improve predictions of erosion from forest roads.

Key words: Resource roads, erosion, traffic, sediment, rut, runoff

1. Introduction

Erosion from forest roads is a long-standing environmental problem (e.g., Trimble and Sartz 1957; Trimble 1959; Packer 1967; Kochenderfer 1970; Megahan and Kidd 1972; Bilby, Sullivan and Duncan 1989; Lane and Sheridan 2002; Sheridan and Noske 2007), with ongoing contention over how best to prevent road-derived sediments from entering streams (e.g., Boston 2012; Aust, Bolding and Barrett 2015; Brown et al. 2015). Forest streams are generally cleaner than their counterparts in urban, suburban, and agricultural settings, making the impacts of turbid water from forest roads readily apparent. The set of standard best practices for managing sediment from roads includes protecting ditches with vegetation, placing sturdier rock on road surfaces, limiting traffic, and placing roads as far from streams as practical. Even so, locations exist where roads must cross or are located close to streams, and some of these near-stream roads carry substantial traffic. In these locations, options for erosion control are more limited, resulting in impacts that, from a practical standpoint, seem unavoidable. However, where protected fish species are affected, this unavoidability is better framed as an issue of economics and tradeoffs.

Erosion control solutions are commonly presented as two potential options: paving the road surface and limiting traffic on the road. These solutions have been applied to varying locations where the value of both timber and fisheries are high (e.g., Cederholm and Reid 1987). However, these two practices are expensive for forest land managers (e.g., Edwards, Wood and Quinlivan 2016). Framing the management choices as stopping traffic or paving roads is too coarse, and more gradations in treatment choices need to be articulated. Certainly, we could express degrees of traffic limitation, such as an acceptable number of loaded trucks per unit time (e.g., Croke and Hairsine 2006) or condition traffic on other factors, such as precipitation (e.g., Dent, Mills and Robben 2003). Similarly, engineering approaches like reduced tire pressure (e.g., Foltz 1994; Foltz and Elliot 1997), geotextiles placed in the subgrade (e.g., Visser, Brown and Tinnelly 2017), and harder rock (e.g., De Witt, Boston and Leshchinsky 2020) have all been shown to help reduce sediment production and erosion on forest roads.

Unfortunately, the substantial literature covering the interactions between traffic and erosion lacks a holistic treatment of the various ways in which traffic influences sediment and runoff production from forest roads. Research does indicate that the presence of traffic increases forest road erosion (e.g., Reid and Dunne 1984; Luce and Black 2001; Ziegler, Sutherland and Giambelluca 2001; Sheridan et al. 2006; Sugden and Woods 2007) though in a broad sense and with little quantitative accounting for context. Multiple hypotheses have been put forth regarding what traffic-induced processes are driving sediment production and erosion, including pumping, scattering, rutting, and crushing. However, these hypotheses are typically invoked—often individually—as potential explanations of erosion (e.g., Reid and Dunne 1984; Swift, Jr. 1984; Foltz, Evans and Truebe 2000), sometimes without a detailed mechanism being defined or providing quantitative expectations of effect. Some authors have gone further than others, but research is still missing how these mechanisms interact with one another and how they are affected by other treatments for sediment reduction. If we want to address sediment production from high traffic roads in a more fine-tuned and efficient way, it is necessary to advance our understanding of these different effects on roads. The hypotheses that have been put forth require more specific definition, particularly so that quantitative models can be constructed to guide the data collection needed to test the models and hypotheses.

In this synthesis, we focus on the relationship between traffic and erosion by examining the current state of the literature and including a discussion of hypotheses and knowledge gaps. Additionally, we present a potential contextual framing for the erosion process with respect to traffic and other factors and discuss how we can further our understanding of erosion on unpaved forest roads. We begin by focusing on the specific ways in which traffic affects erosion from roads; we then discuss the ways in which erosion is enhanced by the interactions between traffic and contextual climate, topographic, and road characteristics; and we complete the discussion with a conceptualization that generalizes forest road erosion in terms of sediment supply and transport energy to quantify contextual interactions and expectations for treatments.

2. Traffic-induced, erosion-enhancing processes

Traffic is one of the most frequently cited drivers of erosion on unpaved forest roads. Disturbance of the road surface by heavy vehicles—leading to an increase in fine sediment supply and changes in the energy available for sediment transport—has been observed in many studies (e.g., Reid 1981; Swift, Jr. 1984; Bilby, Sullivan and Duncan 1989; Coker, Fahey and Payne 1993; Luce and Black 2001; MacDonald, Sampson and Anderson 2001; Ziegler, Sutherland and Giambelluca 2001; Van Meerveld, Baird and Floyd 2014; Reid, Hassan and Floyd 2016). These studies investigate the effects of traffic on erosion from a broad perspective, generally noting that erosion is highly correlated with the presence of traffic. This general understanding has motivated the development of hypotheses regarding the mechanics of traffic-induced erosion processes.

Observations and anecdotal evidence of the influence of traffic on erosion are multitudinous, but more information is needed to understand how and why traffic has such an influence, particularly if erosion caused by traffic is to be accurately represented in a model. Researchers have hypothesized multiple traffic-induced erosion processes: (1) crushing, (2) pumping, (3) scattering, and (4) flow rerouting. However, available data sets to evaluate these hypotheses are limited. In the next few sections, we address these processes in more depth and present a discussion of what we know and what we have yet to learn.

2.1. Crushing

Crushing occurs when a heavy vehicle, such as a loaded logging truck, drives over an aggregate-covered road surface, and the aggregate breaks down. The downward force exerted by the vehicle onto a brittle material causes breakage, increasing the supply of fine sediment available for transport (Fig. 1A). Shifting of grains against one another under heavy loading causes chipping and abrasion of particles, which we lump conceptually in the term crushing. Crushing is posited to be influenced by aggregate quality, as well as frequency and type of traffic. Because of its relation to other factors and plentiful anecdotal evidence (Fig. 1B), crushing is one of the most cited traffic-induced erosion mechanisms in the literature (e.g., Reid and Dunne 1984; Foltz and Truebe 1995, 2003; Luce and Black 2001; Ziegler, Sutherland and Giambelluca 2001; Dawson and Kolisoja 2006; Dubé et al. 2010; Toman and Skaugset 2011; Kemp, Leshchinsky and Boston 2016; Rhee, Fridley and Page-Dumroese 2018).

Crushing is so closely connected with other factors affecting erosion that few data regarding the process of crushing—why and how it occurs—have been collected. Most field studies related to crushing focus on aggregate strength rather than the role that traffic plays with respect to aggregate. However, in a recent paper, De Witt et al. (2020) describe a field experiment in which they isolated different qualities of road surface aggregate in cylindrical geotextile bags to observe degradation after traffic had driven over the segment. The cylindrical geotextile parcels of aggregate were placed within the road surface and were subject to a different number of truck passes. The authors looked at the aggregate after 500, 950, and 1500 passes of a loaded dump truck and found that most of the degradation occurred within the first 500 truck passes for all aggregate qualities.

The results of this study confirm that crushing relates to traffic volume and frequency, but the observation resolution is still too low to capture the nonlinearities in the crushing rate. The authors recommend a future experiment with earlier and more frequent observations (i.e., check the aggregates after 100, 250, and 350 truck passes) to capture the initial aggregate degradation rate and how it changes. Such an understanding would allow us to represent this diminishing rate process more accurately in a model.

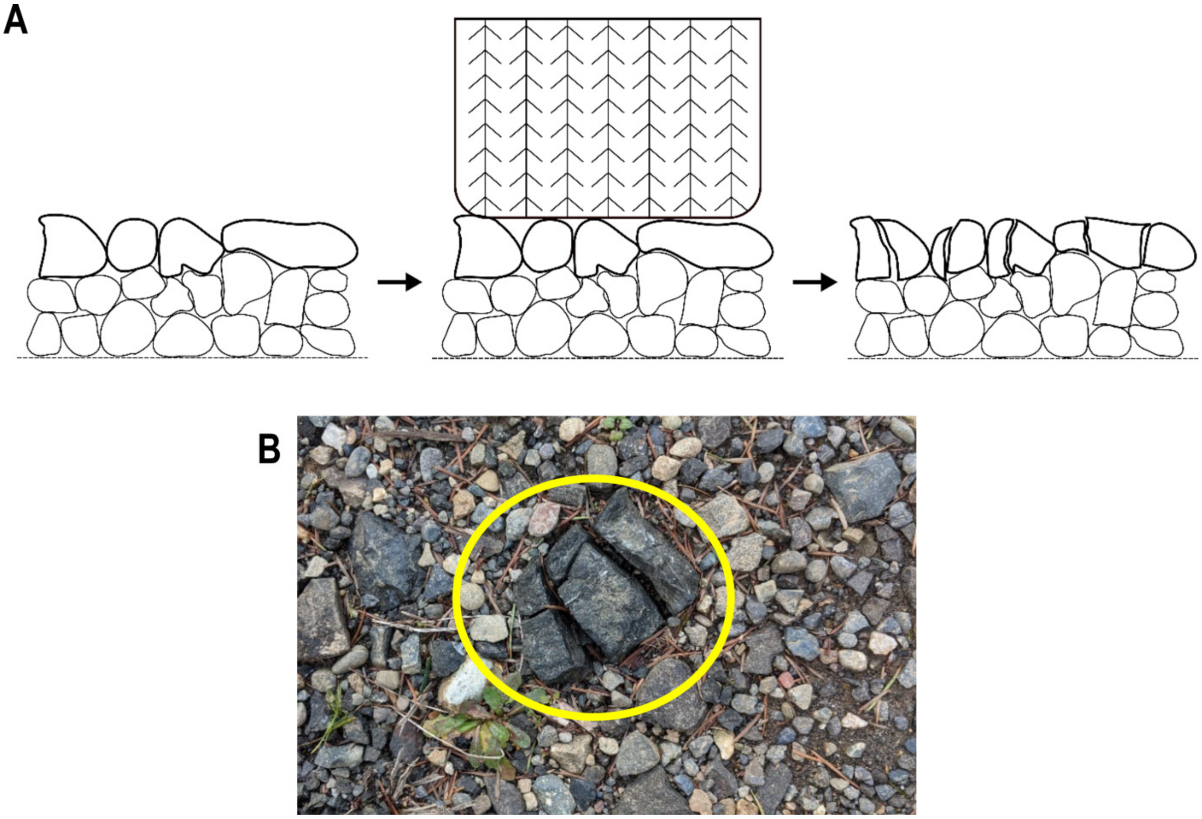
2.2. Pumping

Pumping is the process by which fine sediment is forced upwards toward the surface of the road. When a vehicle passes over a gravel road surface, larger sediment is pushed down, which, in turn, displaces fine sediment, moving it upwards (Fig. 2A). As this process is repeated, fine sediment makes its way to the surface of the road where it is readily available for sediment transport, thus increasing the supply. Pumping has been suggested as a traffic-induced erosion process in many studies (e.g., Reid 1981; Swift, Jr. 1984; Luce and Black 2001; Ziegler, Sutherland and Giambelluca 2001; Foltz and Truebe 2003; Ramos-Scharrón and Macdonald 2005; Dawson and Kolisoja 2006) and anecdotal evidence is abundant (Fig. 2B).

Fig. 1. (A) Schematic of the crushing process. On a typical road surface aggregate (left) when vehicles drive over the road (center), the larger sediment breaks down into finer sediment (right). Image not to scale. (B) Image of forest road with evidence of crushing (circled in yellow).

A

B



Because pumping is a difficult process to isolate, only a few studies investigated the process further than qualitative field observations and conjecture. One study attempted to investigate pumping by examining the utility of three different treatments to reduce fine sediment production, which was hypothesized to be caused by pumping at the surfacing-subgrade interface (Toman and Skaugset 2011). The three different treatments included: (1) placing geotextile between the subgrade and road surfacing; (2) increasing the depth of the road surfacing; and (3) installing a geocell pavement structure. All three treatments were meant to hinder the pumping process at the surfacing-subgrade interface and were compared to control segments.

This study was carried out on recently built spur roads designed for short-term use in three locations. Measurements of sediment runoff were made over a single winter haul season. The authors concluded that pumping was not a significant source of fine material on the roads they tested based on the fact that sediment production did not differ significantly between treated and control road segments. Rather, they concluded that the fine material was either already present in the new road surface aggregate or was generated by crushing of the surface aggregate.

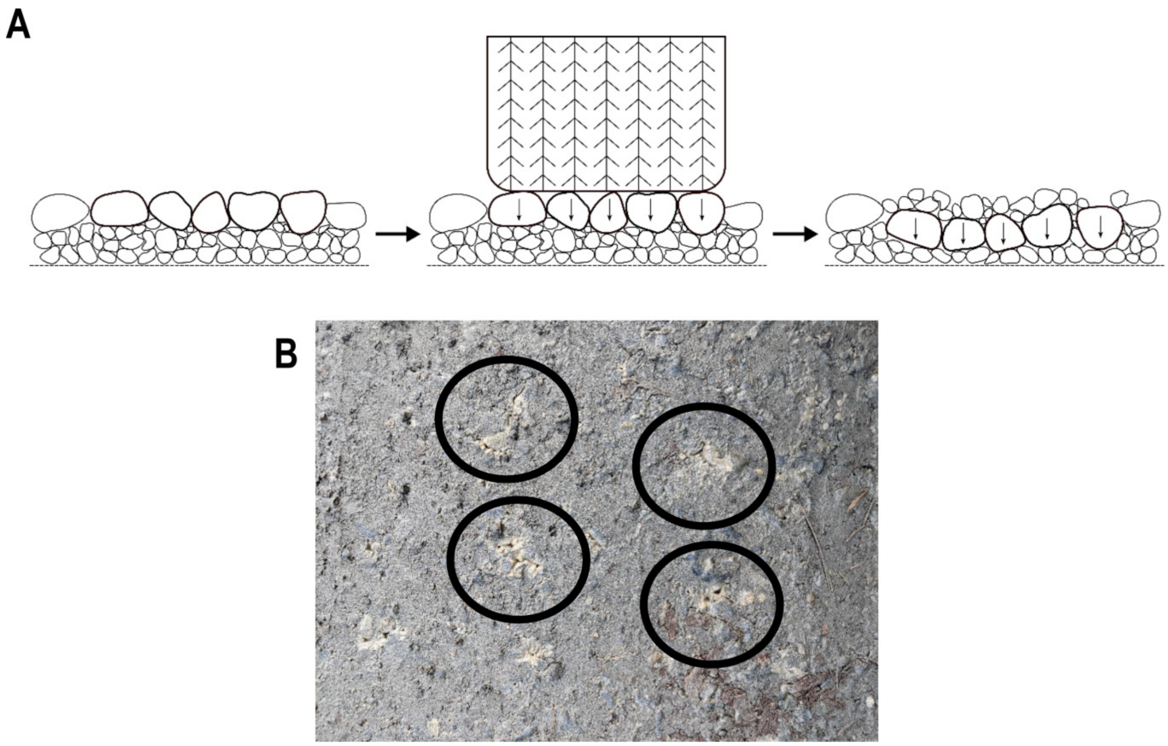
Extrapolation of these findings to more established roads may not be applicable because the study focused on short-term use roads that were recently built and were monitored for only one winter season. Recently built roads have a settling period in which existing fine sediment is flushed away, armoring the road surface (Megahan 1974). This armoring phenomenon is also observed in roads that have been disturbed by other means, such as road maintenance (Luce and Black 2001). As such, the study's findings—that the road surface aggregate was the main source of fine material—may well be a feature of the newly-built road's settling period.

Experimental evidence for pumping has been demonstrated on more established unpaved forest roads. Rhee et al. (2018) carried out a study in Clearwater National Forest, Idaho in which they inferred different processes (i.e., crushing, pumping, and scattering) from changes in the particle size distribution of different vertical layers of the road after varying amounts of traffic (i.e., none, light, and heavy). Coarsening of the middle and bottom layers of these roads provides evidence of pumping, while fining provides evidence of crushing. Significant evidence of pumping (i.e., a coarsened particle size distribution) was found in the bottom layer of the heavy traffic road. Further investigation is warranted to help us understand the rate at which pumping occurs under different conditions.

2.3. Scattering

Road surface armoring occurs when readily available fine sediment is flushed away, leaving only larger sediment that forms a protective layer (Megahan 1974). Scattering is the displacement of the larger sediments that have armored the

Fig. 2. (A) Schematic of the pumping process. Larger sediment over finer sediment (left) gets pushed down due to the weight of the vehicles (center), which forces the finer sediment upwards (right). Image not to scale. (B) Image of forest road with evidence of pumping, light colored deposits of fine sediments around edges of holes (circled in black).



road surface and is caused by a disturbance thereof, such as traffic. Disturbing this armor layer exposes the fine sediments below, increasing the amount of sediment that is readily available for transport (Fig. 3).

This process has been both posited by researchers and observed in the field (e.g., Gnanendran and Beaulieu 1999; Foltz, Evans and Truebe 2000; Johnson 2003). Rhee et al. (2018) is one of the few studies that demonstrated the scattering process in a field study—referred to as "sweeping" in their study. They were able to infer that scattering was a dominant process on the shoulder section of the light traffic road in their study based on an increase in the particle size distribution (i.e., coarsening) at that location on the road. They note that evidence of scattering outside of the tire tracks (i.e., the coarsening of material outside the tire tracks) is more significant than evidence of scattering inside the tire tracks (i.e., the fining of material inside the tire tracks). This suggests that reduced erosion of medians and shoulders can be attributed to traffic but that increased erosion in tire tracks—caused by reduced rock cover therein—might be less clearly attributable to scattering of an armor layer by traffic.

Most other evidence of scattering is largely anecdotal (Fig. 4). More empirical evidence of scattering, as well as quantification thereof, is required if we are to separate the effects of different processes on the supply of fine sediments and to prescribe treatments to mitigate traffic effects. Quantification of scattering under different circumstances (e.g., weather, traffic speed, tire pressure) will help us further understand the process and potential solutions.

2.4. Flow rerouting

Flow rerouting occurs when traffic deforms a road surface and diverts the flow pathways. On a non-deformed road, runoff leaves the road as sheet flow and flows either into a roadside ditch line or onto the fill slope below the road. Traffic-induced road deformation, however, reroutes the flow and changes its hydraulics. One specific traffic-induced road surface deformation is the development of wheel ruts. Ruts are small channels—like rills on a hillslope—that form on an unpaved road surface due to traffic. The formation of ruts is posited to be caused by a combination of factors, including, but not limited to, scattering, compaction, and plastic deformation of the surface (Dawson 1997). Ruts tend to develop on either side of the crown of the road due to traffic straddling the center of the road (Fig. 5A).

Once a rut has formed, a feedback loop begins where concentrated water flows in the rut (Fig. 5B), leading to higher shear stress and, thus, more erosion and further channelization. This advective process would typically produce deep rill- or gully-like features in a strongly consolidated material, but on heavily trafficked roads, the traffic acts as a diffusive process due to its spatially stochastic nature, which allows the ruts to maintain a relatively hydraulically wide shape. Even with the diffusive nature of traffic, the ruts that develop still have a greater capacity and competence to move sediment. This feedback loop of a dominant advective process and an ancillary diffusive process causes the hydraulically wide ruts to persist and deepen unless an outside force, such as grading of the road surface, occurs.

Fig. 3. The road surface develops an armor layer of larger sediments (left). Once the road is disturbed by traffic (center), the armor layer is scattered, exposing fine sediments below (right). Image not to scale.

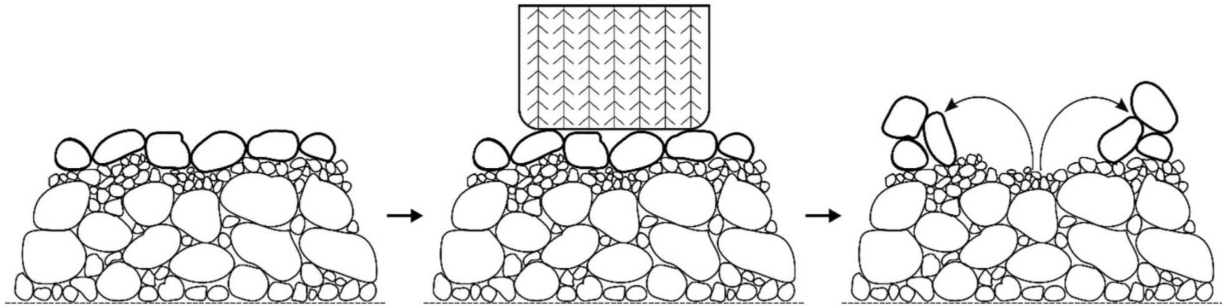


Fig. 4. Image of a forest road with evidence of scattering.

The presence of wheel ruts can cause an effective increase in the supply of fine sediment available to be transported and an effective increase in the energy available to transport the sediment. This traffic-driven change in topology tends to route flow along the road surface instead of to the sides, which has its own implications for erosion. Where wheel ruts prevent out-slope drainage, they directly add to potential delivery through concentration of flow along the road instead of diffuse flow. Where wheel ruts capture flow bound for a ditch, they prevent the potential utility of ditchline best management practices (BMPs)—such as grass lining, wattles, or rock lining—that could reduce transport capacity and potentially yield less erosion.

The presence of ruts and their influence on erosion are anecdotally abundant (Fig. 6). Additionally, empirical studies have found that roads with ruts can produce anywhere from 2 to 5 times more sediment than freshly graded roads (Foltz and Burroughs 1990). However, distributing the weight of logging vehicles over a larger surface area (i.e., reducing tire pressure) can decrease rut development and, thus, erosion (Bradley 1994; Foltz 1994). Additionally, consistent maintenance of roads can minimize the impacts of ruts (Sheridan et al. 2006). Though we have some knowledge about how to decrease rut development, additional information is needed about the formation of wheel ruts and other road surface deformations. Learning the rate at which the road deforms and the conditions under which the road deforms can give us more insight into how to prevent these deformations.

3. Important contextual covariates for traffic effects

Other factors that influence the erosion of unpaved forest roads include rainfall intensity, road topography and topology, aggregate quality, and subgrade strength. These factors can fall into one of two categories: supply-related or energy-related. As discussed in Section 2, traffic is one of the most-cited and least-understood factors affecting the erosion of forest roads that is both supply- and energy-related. Many other processes and characteristics of roads that influence forest road erosion exist and can be either supply-related or energy-related, but these factors also affect how traffic affects erosion. These additional factors are largely related to traffic and each other, and as such, a discussion of all factors and their interaction is warranted to fully frame a discussion of unpaved forest road erosion and the dominant role of traffic therein.

3.1. Rainfall intensity

Rainfall initiates sediment transport on forest roads because it quickly turns into runoff due to low infiltration rates (e.g., Luce and Cundy 1994; Ziegler, Sutherland and Giambelluca 2000). The energy from the rain can contribute to displacement of sediment on the road through rain splash erosion as well. Thus, erosion caused by rainfall can be partitioned into two interconnected processes: hydraulic erosion and rain splash erosion.

Hydraulic erosion is largely energy-related and occurs due to Hortonian overland flow, which is frequently seen on unpaved forest roads. As these roads are used, they can become heavily compacted, allowing for less infiltration, and thus increasing the amount of overland flow (Ziegler and Giambelluca 1997). Hydraulic erosion is the agent through which sediment is transported away from the road prism. For areas in which sediment is readily available prior to a storm—through traffic, road maintenance, or other means—hydraulic erosion tends to be the dominant process at the beginning of a storm (Ziegler, Sutherland and Giambelluca 2000).

Fig. 5. (A) Image of a rutted forest road. (B) Image of a rutted forest road with water flowing in one of the ruts rather than off to the ditch line.

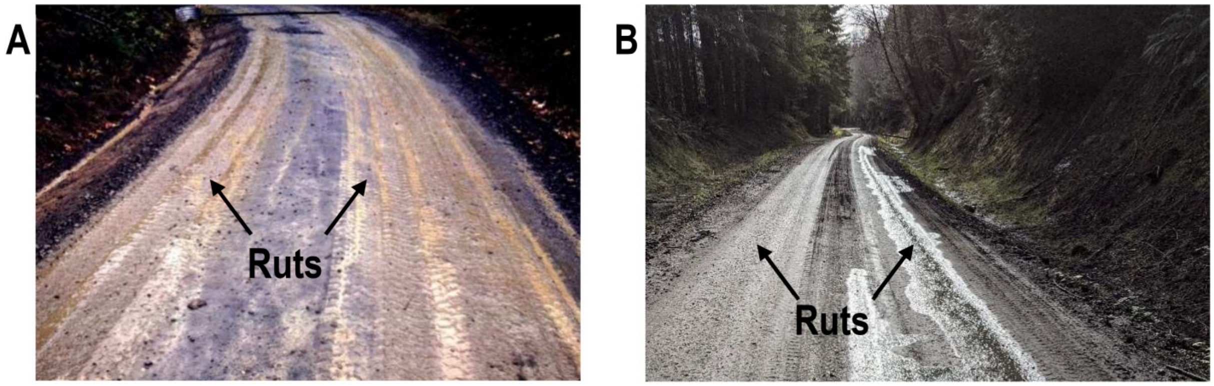
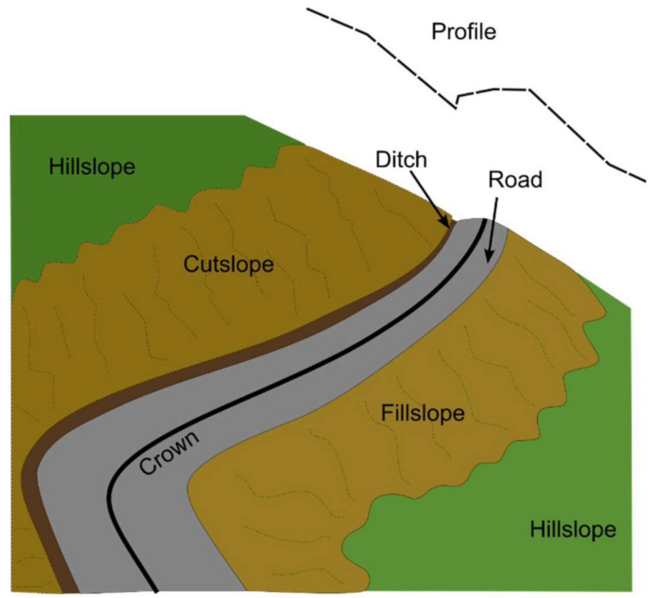


Fig. 6. Image of an extremely rutted road that receives little traffic.

Fig. 7. Schematic of a typical forest road and its surroundings.



Though hydraulic erosion is the transporter of sediment, rain splash erosion is another important supply-related piece in the rainfall-driven erosion process. Rain splash erosion increases the sediment supply that is readily available to be transported due to sediment displacement via rain drop impact, and once sediment is available for transport, hydraulic erosion occurs. For areas in which sediment is not immediately loose enough for overland flow transport alone (i.e., roads that have not been disturbed) rain splash erosion tends to dominate at the beginning of a storm (Ziegler, Sutherland and Giambelluca 2000).

3.2. Road topography and topology

Road topography refers to the geometry, slope, and other spatial characteristics of the road (Fig. 7). Topographical features such as road length and gradient are among the most cited and studied influences on road surface erosion and largely impact erosion from an energy perspective. Road length and gradient are interconnected topographical features that represent the space over which erosion can occur. Assuming a constant road length, increasing the road gradient significantly increases erosion (Arnáez, Larrea and Ortigosa 2004). The interaction between road length and gradient leads to different effects on erosion. For example, increasing the length of a low gradient road has a smaller impact on erosion than increasing the length of a high gradient road. This relationship has been observed on established mainline logging roads (Luce and Black 1999) and less-used unpaved forest roads (Ramos-Scharrón and Macdonald 2005).

Related to topography is the topology of the road. We can think of topology as how water navigates the topography of the road (e.g., across the road vs. along the road). Some roads are out-sloped, where sheet flow that forms during rainfall events is directed primarily toward the fillslope, with some along-road movement that depends on the road's slope. Similarly, some roads are in-sloped, where the water flows toward an inboard ditch that runs alongside the road until a drainage feature, like a culvert, relieves the ditch. For maintenance and traffic reasons, many roads are crowned, with half of the road draining to the fillslope and half to the inboard ditch. A point of special interest discussed in Section 2.4 is that traffic can form wheel ruts that favor flow along the road surface before it reaches either the outer edge or the inboard ditch. Flow coming off out-sloped roads does not travel far because the road contributing area per unit discharge width is small. In contrast, runoff travelling along a road in a ditch or wheel rut becomes concentrated. When this concentrated runoff is discharged from a drainage feature, the likelihood of delivery to a stream increases (Wemple, Jones and Grant 1996).

In addition to water flow along and off of the road, cutslopes along the side of the road and their spatial characteristics have also been shown to affect erosion. Arnáez, Larrea and Ortigosa, (2004) point to mass-wasting and freeze-thaw cycles as being important processes that provide transportable sediment from cut slopes. Additionally, an increase in the cut slope gradient causes erosion to increase (e.g., Jordán and Martínez-Zavala 2008; Jordán-López, Martínez-Zavala and Bellinfante 2009). However, cutslope height is not necessarily a significant influence on sediment yield from roads in some areas, perhaps because of vertical heterogeneity in cutslope material (Luce and Black 1999; Megahan, Wilson and Monsen 2001). Cutslopes are also often sources of water, either as direct overland flow during high rainfall intensity events or through interception of subsurface flow (Ziegler, Sutherland and Giambelluca 2000; Luce 2002; Wemple and Jones 2003). This water flows along the ditch when one is present, which lends itself to carrying sediment towards drainage features.

Some topographical and topological features of roads are commonly used to model road erosion because the features are easily obtained, either through field measurements or GIS software computations, and their relations to erosion are computationally simple. Modeling studies most often incorporate road drainage area and gradient, which are closely related to the concept of the slope-area product in geomorphology (e.g., Istanbulluoglu et al. 2002, 2003). Because these features are easily extracted using GIS technologies and are shown to be correlated with road erosion, they are the basis of multiple models that use empirically based equations to estimate such erosion (e.g., Anderson and Macdonald 1998; Akay et al. 2008). Coefficients for these relationships can be empirically determined using existing data and, with additional experimentation, can be tied to climate, soil, and level of road disturbance.

3.3. Aggregate quality

Aggregate refers to the material used to surface an unpaved forest road (see surfacing in Fig. 8A). This surfacing aggregate provides a layer of protection to the native material underneath and decreases the amount of erosion that would otherwise be present without such protection (e.g., Kochenderfer and Helvey 1987; Brown, Aust and McGuire 2013). Though the presence of surfacing aggregate decreases erosion, aggregate quality must also be considered where traffic occurs. In general, aggregate quality is defined by how much the aggregate breaks down when it is exposed to different stressors, such as water, air, or traffic. The quality of surfacing aggregates is an important factor influencing erosion via the supply of fine sediment. Studies have observed that lower quality aggregate leads to more erosion because of its susceptibility to breakdown (e.g., Foltz and Truebe 1995; Foltz, Evans and Truebe 2000).

What aggregate is used to surface a forest road depends on the landowner's main goal—cost reduction or erosion reduction—though that goal may change based on local availability of material. Generally, lower quality aggregates will be used to decrease cost, whereas higher quality aggregates will be used to reduce sediment loss. The quality of aggregate can be determined via either road managers' recommendations based on experience or physical tests of the aggregate. However, Hanna and Boston (2018) carried out a series of physical tests on aggregate obtained from quarries that road managers were also asked to classify as good or marginal sources of material. Results showed that road manager-recommended aggregates rarely met quality thresholds as established based on literature review, emphasizing the importance of testing aggregate prior to placing it on roads.

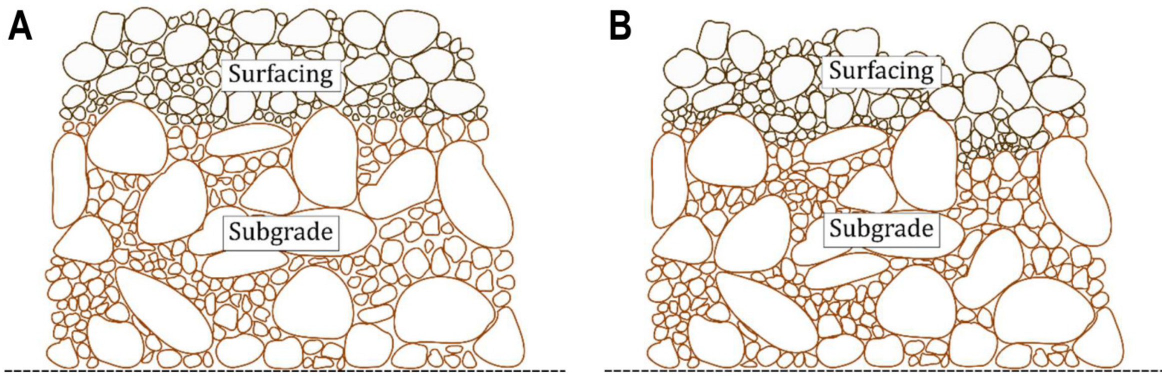
Two of the best tests to predict aggregate quality are the P20 portion of the Oregon air degradation test and the sand equivalent test (Foltz and Truebe 2003). The P20 portion of the Oregon air degradation test assigns an index indicating the breakage resistance of the aggregate when exposed to both water and a jet of air, and the sand equivalent test assigns an index to the aggregate based on the amount of fine material present. The sand equivalent test is more common as it is less time- and equipment-intensive and is therefore easier to carry out in the field.

3.4. Subgrade strength

The subgrade is the base upon which forest roads are built and is generally composed of native soil and rock (see subgrade in Fig. 8A). Multiple studies have looked at the importance of subgrade strength with respect to the durability of the road. Overall, these studies have found that deformation of the road surface—poor aggregate performance and quality aside—can occur when the integrity of the subgrade is compromised (Fig. 8B) and that road surface deformation is positively correlated with erosion. Therefore, lower subgrade strength can lead to increased erosion (e.g., Bloser and Scheetz 2012). As such, subgrade strength influences erosion from a supply perspective.

The strength of the subgrade is highly dependent on both the level of compaction during road construction and the durability of the materials therein. Different levels of compaction can lead to different levels of material breakage, with an optimal range of compaction existing to minimize material degradation (e.g., Indraratna, Lackenby and Christie 2005; Lackenby et al. 2007). Additionally, proper compaction of the subgrade can optimize subgrade strength and

Fig. 8. (A) Schematic of a road cross section. The surfacing (top layer) is the aggregate used to cover the forest road, and the subgrade (bottom layer) is the packed excess fill material from road excavation as well as the native material. (B) Schematic of a road cross section where the integrity of the subgrade has been compromised, causing surfacing deformation. This example demonstrates a case where the subgrade was improperly compacted (i.e., weak) when the road was installed, and repeated outside stressors (traffic) caused further subgrade compaction that deformed the road surface. Images not to scale.



decrease the required amount of surface aggregate—and, therefore, cost—without compromising the integrity of the road (Boston, Pyles and Bord 2008). Easy field measurements of subgrade strength in tandem with a simple correlation model can aid in the proper compaction of the road subgrade (Pattison, Boston and Pyles 2010).

In addition to compaction of the subgrade, other reinforcements—such as geogrids or geotextiles—can be installed in or on the subgrade to increase road strength while decreasing the required amount of road surface aggregate (Giroud and Han 2004). Geotextiles are permeable textiles placed at the subgrade-aggregate interface to increase soil stability; geogrids are synthetic materials that reinforce the subgrade. Visser, Brown and Tinnelly (2017) looked at the cost-benefit of using geogrids with less road surface aggregate and found that doing so may be viable, specifically in cases which would otherwise require expensive or exorbitant amounts of road surface aggregate to maintain similar road strength.

4. A framework for future research

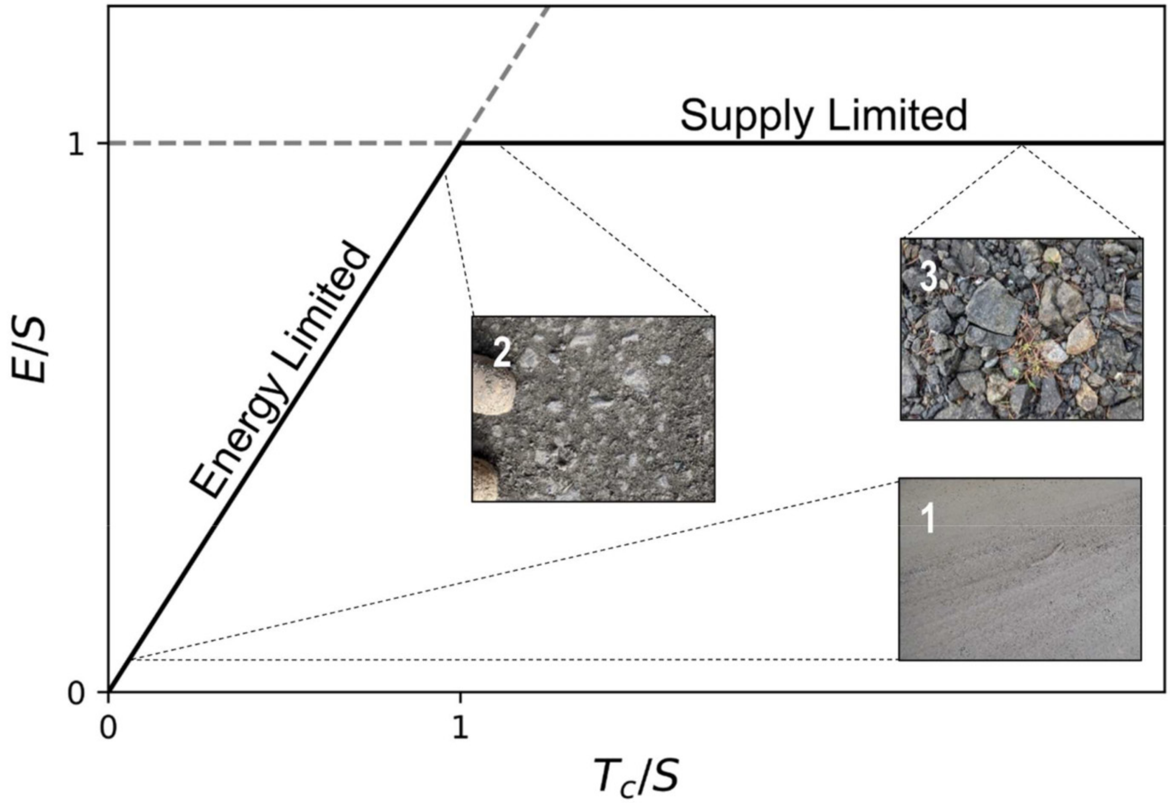
The role of traffic in forest road erosion is still poorly understood, which limits our ability to efficiently reduce its effects on erosion. The studies discussed in previous sections have given us tantalizing individual hints that further our understanding, but they are poorly integrated with one another and form a fragmented field of knowledge. As a result, we are left with many fundamental questions: How does the rate of traffic affect these erosion processes? Which of these traffic-induced erosion processes is the most dominant under different field and climate conditions? Why do some heavily trafficked roads accumulate fine sediment on the surface while others do not? What is the role of compaction in traffic-induced erosion processes? Is the pumping process solely a function of traffic, or are time and moisture variables to be considered as well? What other factors contribute to the importance of these traffic-induced erosion processes? In other words, we want to know how much sediment is coming from which mechanisms under what circumstances—a three-fold problem. To answer these questions, we need an efficient path forward.

We can think of forest road erosion through the lens of supply and energy limitations, a framework commonly used in geomorphology. In the classic geomorphological sense and a very long time perspective, this framework would characterize forest roads as energy limited only. However, if we view a forest road as a closed system that exists under specific conditions, we can characterize the system as either supply or energy limited. Supply limiting factors include traffic (Section 2), aggregate quality (Section 3.3), and subgrade strength (Section 3.4), while energy limiting factors include traffic (Section 2), road topography (Section 3.2), and rainfall (Section 3.1), and all these factors are markedly interconnected. These factors, both individually and combined, determine where a forest road falls on an energy- vs. supply-limited spectrum.

At any point in time, depending on the context, a forest road, even the same segment of forest road, can be considered either a supply-limited or an energy-limited system, and under different contexts, the state of the system may change. As such, we posit that the relationship between erosion, supply, and energy can be described using the concept of limiting factors (Fig. 9). If the energy is less than the supply, the erosion of the system will be dependent on energy, making the erosion process energy limited (e.g., a muddy road storing fine sediment on the surface that has not yet been transported off the road). However, once the energy surpasses the supply, the erosion of the system will be equal to the supply available, making the erosion process supply limited (e.g., a rocky road).

A subset of this relationship can be seen in preliminary sediment and flow data collected in Washington state (Fig. 10) as part of an ongoing study conducted by the Cooperative Monitoring Evaluation and Research Committee within the Washington Department of Natural Resources Adaptive

Fig. 9. A limiting factor diagram for conceptualizing the relationship between erosion, energy, and supply. When the energy (T_c) is less than the supply (S), the erosion (E) depends on energy, and data from this road would plot along the energy limited line. When T_c surpasses S, E is equal to the supply, and data would fall along the supply limited line. Three examples of a forest road in different states are shown: (1) an energy limited road surface; (2) a road surface that is on the cusp between energy and supply limited; and (3) a supply limited road surface.

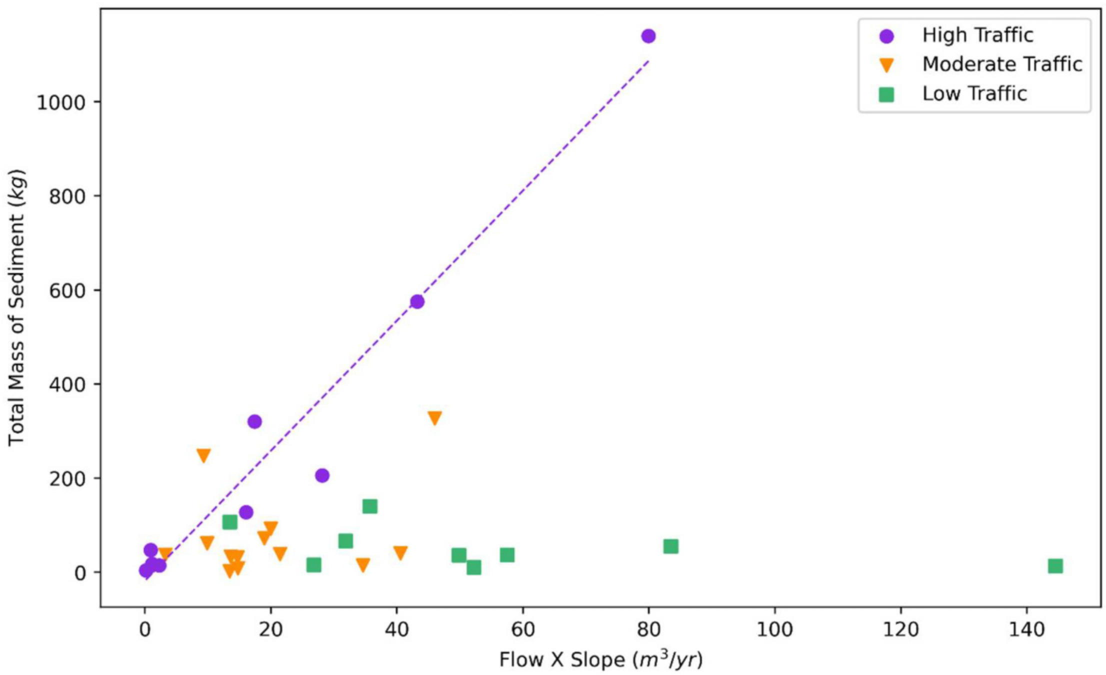


Management Program. In this ongoing study, a number of covariates are being measured. These covariates include the total annual flow of a road segment, which is measured using tipping buckets, and the total annual sediment mass, which is collected in settling basins connected to the same road segment. These preliminary data show the relationship between average annual flow × slope (a surrogate for transport capacity or "energy", T_c) and total annual mass of sediment (a measure of erosion, E) as a function of traffic level (a surrogate for supply, S). At field sites where traffic levels are high (purple circles in Fig. 10), sediment supply is also high and the data show that E depends on T_c. These locations would plot near the energy-limited line in the limiting factor space presented above. In contrast, the low traffic field sites (green squares in Fig. 10) have a lower supply and the data show that E does not depend on T_c. These locations would plot close to the supply-limited line in the limiting factor space. In this limiting factor space—where the response variable (i.e., erosion) is affected by multiple factors (i.e., the energy-supply balance and level of traffic)—quantile regression would be helpful to examine these data (Cade and Noon 2003).

The framing of forest road erosion as a function of both supply and energy can help us focus further research, specifically with respect to the influence of traffic. As discussed above, we know that the role of traffic in this framework can be found in both the supply and energy limitations. For example, pumping and crushing can increase the available supply explicitly, while scattering can affect the available supply implicitly by either revealing or covering existing fine sediment on the road surface. Additionally, scattering can affect the available energy through road surface deformation, similar to rutting. Both rutting and scattering lead to flow rerouting, which effectively increases the energy directed to transporting fine sediments. Rerouted flow will not necessarily reach the roadside ditches, which tend to offer more resistance to flow—through installation of grass or other ditch line BMPs—and, therefore, sediment transport. However, these effects depend on context, such as surfacing quality; subgrade strength; underlying geology; spatial characteristics of the road; wet weather; or freeze-thaw processes.

Thinking of traffic-induced erosion as a function of supply and energy and remembering context dependencies allows for interpretation and synthesis of targeted experiments to test hypotheses regarding these processes. One example experiment could include looking at short-time-scale interactions between traffic and an established mainline road to measure the magnitude of the pumping process. Another segment-scale experiment could include looking at changes in the hydraulics of flow in roadside ditch lines and road

Fig. 10. Preliminary data from western Washington field study showing the total annual mass of sediment (kg) vs. total annual flow x slope (m^3) for three different traffic levels. These data show that for high traffic sites (i.e., high supply sites; purple circles in figure), total annual mass of sediment (surrogate for erosion) is linearly related to total annual flow x slope (surrogate for transport capacity), whereas low traffic sites (i.e., low supply sites; green squares) show no significant dependence.



surface ruts to help characterize the effects of rutting on flow rerouting and, ultimately, erosion.

An important next step would be to use our current understanding and hypotheses to develop a process-based model that incorporates mathematical conceptualizations for the aforementioned processes. The development of such a model can, in turn, help us develop field studies to further understand these processes and parameterize our models. Currently, no model exists that looks at the multiple specific traffic-induced erosion processes. Some previous models incorporate the role of traffic via a traffic factor that changes erosion based on average road use (e.g., Dubé, Megahan and McCalmon 2004; Akay et al. 2008) or via increasing road "erodibility" with traffic over time (Ziegler, Giambelluca and Sutherland 2001), while other models note the importance of traffic but do not consider it quantitatively. Therefore, a process-based unpaved forest road erosion model incorporating the four different traffic-driven processes (Section 2) and their context dependencies (Section 3) is warranted to guide data collection and analysis needs.

Advancing research regarding traffic-induced road erosion has multiple implications. Understanding how much supply is increased by pumping or crushing, and their dependencies on aggregate quality and subgrade integrity, can improve guidelines for traffic levels under particular conditions. Additionally, understanding how much energy increases by scattering or flow rerouting, and their dependencies on spatial road characteristics and weather, can allow for more informed recommendations regarding road maintenance. Overall, increased knowledge of traffic-specific processes and related factors will enable us to determine the most cost-effective steps to take to reduce forest road erosion.

5. Conclusion

The influence of traffic on forest road erosion has been studied from a broad and somewhat qualitative perspective, with the literature commonly focusing on increased erosion due to traffic and the effects thereof, without detailing and quantifying underlying mechanisms. Current research lacks comprehensive consideration of these mechanisms and related contextual covariates, but this research has provided the groundwork for development of quantitative hypotheses regarding four main traffic-induced erosion-enhancing processes: crushing, pumping, scattering, and flow rerouting. Quantifying these processes, and their relation to other important contextual covariates, is integral to furthering our understanding of forest road erosion. To quantify these processes and covariates, we should start framing traffic and other influencing factors in terms of their roles in supply- and energy-limitations. If we focus future research using this framework, our capacity to evaluate the current hypotheses of traffic-induced erosion-enhancing processes will increase, and we will be able to establish the most effective and efficient ways to control forest road erosion.

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Data availability

The data shown in Fig. 10 of this manuscript are not publicly available due to an agreement with the authors' funding agency but are available from the corresponding author upon reasonable request and approval from the funding agency.

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The authors declare there are no competing interests.

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