Toward modeling traffic-induced forest road erosion: field investigations and process-based model conceptualization

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Abstract

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Though abundant anecdotal and empirical evidence of increased erosion on forest roads due to traffic exists, the literature lacks a holistic treatment of the ways in which traffic and other important contextual covariates influence runoff and erosion on forest roads. The main goal of my dissertation is to examine the relationship between forest road erosion, traffic, and potential erosion control treatments through literature synthesis, small-scale field experiments, and the conceptualization of a comprehensive process-based model. In Chapter 2, I discuss current hypotheses of how traffic affects forest road erosion, what data are required to validate those hypotheses, and present the motivation for developing a process-based model of forest road erosion. In Chapter 3, I evaluate the efficiency of multiple roadside ditch line erosion control treatments using ditch line roughness, discuss the theory behind using roughness as an efficiency metric, describe the methodology of the experiment, and present results from the experiment. In Chapter 4, I use unoccupied aerial vehicle (UAV) structure-from-

motion (SfM) technology to examine how wheel ruts evolve on mainline logging forest roads following maintenance of the road surface. The implications of said rut formation on the road surface drainage system and erosion potential are discussed in detail. Finally, in Chapter 5, I lay the theoretical foundation for a process-based model that includes mathematical conceptualizations of traffic-induced local sediment production as well as road-segment-scale sediment transport.

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DEDICATION

To everyone who took the road less traveled by.

Chapter 1

INTRODUCTION

1.1 Background and motivation

Erosion of unpaved forest roads, and the relative impacts thereof, has been a topic of research for decades (*Bilby et al.*, 1989; *Boston*, 2016; *Dubé et al.*, 2010; *Foltz and Burroughs*, 1990; *Luce and Black*, 1999; *Megahan and Kidd*, 1972b; *Ramos-Scharrón and Macdonald*, 2005; *Reid*, 1981; *Reinhart et al.*, 1963; *Sheridan and Noske*, 2007; *Trimble and Sartz*, 1957; *Ziegler et al.*, 2001a). Throughout the years, we have learned that the majority of forest road erosion occurs on high-traffic, near-stream (HTNS) forest roads, specifically those associated with timber production. In Oregon and Idaho, *Black et al.* (2013) found that 90% of sediment delivered to nearby streams came from less than 10% of drainage points, with the majority of those drainage points existing on HTNS roads.

Though abundant anecdotal and empirical evidence of increased erosion of forest roads due to traffic exists (e.g., *Luce and Black*, 2001a; *Reid and Dunne*, 1984; *Sheridan et al.*, 2006; *Sugden and Woods*, 2007; *Ziegler et al.*, 2001b), the substantial literature lacks a comprehensive treatment of the ways in which traffic and other important contextual covariates influence erosion and runoff. To address sediment production from forest roads in a more efficient way, we need to advance our understanding of the erosion processes and potential mitigation strategies.

One way to do this is to improve upon the current collection of forest road erosion models. Most forest road erosion models rely on empirical equations based on limited field data and require a more objective and process-based incorporation of traffic and other important contextual covariates. The main goal of this dissertation is to examine the relationship between forest road erosion, traffic, and potential erosion control treatments to help inform future models through literature synthesis, small-scale field experiments, and the conceptualization of a comprehensive process-based model.

1.2 Organization of dissertation

The chapters outlined below are part of a continuing collaborative effort funded by the Cooperative Monitoring, Evaluation, and Research (CMER) Committee within the Washington State Department of Natural Resources Adaptive Management Program to examine the effectiveness of forest road best management practices in western Washington.

Chapter 2 provides the extensive underlying motivation for Chapters 3, 4, and 5. In this chapter, I and my collaborators review the existing literature regarding interactions between traffic and road erosion, including a discussion of knowledge gaps, and we propose the need for a process-based modeling framework. We also present a limited factor framing that relates the ratios of erosion-sediment supply and transport capacity-sediment supply, similar to the Budyko hypothesis used in hydrometeorology.

Chapter 3 discusses using roughness as a metric to evaluate roadside ditch line erosion control treatment efficiency. We present a small-scale field experiment that measured various hydraulic parameters of roadside ditch lines to examine roughness as an efficiency metric. This chapter provides the basis for the parameterization of a roadside ditch line in future versions of a process-based model presented in Chapter 5.

Chapter 4 discusses using unoccupied aerial vehicle (UAV) structure-from-motion (SfM) technology to examine how wheel ruts evolve on mainline logging roads following road grading and the implications of said rut formation on the road surface drainage system and erosion potential. This chapter provides potential parameterization information for the road surface in future versions of a process-based model presented in Chapter 5.

Chapter 5 lays the theoretical foundation for a process-based model that incorporates local processes of sediment production, as well as road-segment-scale sediment transport. Sediment production is proposed to be driven by four traffic-induced erosion-enhancing processes: crushing, pumping, scattering, and rutting. This chapter includes proof-of-concept examples and a discussion of future model versions.

Chapter 2

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 these 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.

2.1 Introduction

Erosion from forest roads is a long-standing environmental problem (e.g., *Bilby et al.*, 1989; *Kochenderfer*, 1970; *Lane and Sheridan*, 2002; *Megahan and Kidd*, 1972a; *Packer*, 1967; *Sheridan and Noske*, 2007; *Trimble*, 1959; *Trimble and Sartz*, 1957), with ongoing contention over how best to prevent road-derived sediments from entering streams (e.g., *Aust et al.*, 2015; *Boston*, 2012; *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 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 et al.*, 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 et al.*, 2003). Similarly, engineering approaches like reduced tire pressure (e.g., *Foltz*, 1994; *Foltz and Elliot*, 1997), geotextiles placed in the subgrade (e.g., *Visser et al.*, 2017), and harder rock (e.g., *De Witt et al.*, 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., *Luce and Black*, 2001a; *Reid and Dunne*, 1984; *Sheridan et al.*, 2006; *Sugden and Woods*, 2007; *Ziegler et al.*, 2001a) 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—often individually—invoked as a potential explanation of erosion (e.g., *Foltz et al.*, 2000; *Reid and Dunne*, 1984; *Swift*, 1984a), 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 need 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.

2.2 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., *Bilby et al.*, 1989; *Coker et al.*, 1993; *Luce and Black*, 2001a; *MacDonald et al.*, 2001; *Reid et al.*, 2016; *Reid*, 1981; *Swift*, 1984a; *Van Meerveld et al.*, 2014; *Ziegler et al.*, 2001b). 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 datasets 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.

2.2.1 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 (Figure 2.1a). 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