ROADS IN FOREST WATERSHEDS - ASSESSING EFFECTS FROM A LANDSCAPE PERSPECTIVE[1]

Fred Swanson[2], Julia Jones[3], Beverley Wemple[4], and Kai Snyder[5]

Abstract. *Road networks have a great variety of effects on forest watersheds. The type, strength, and location of these effects depends strongly on the interactions of roads with forest landscape structure and topography. A landscape perspective provides a useful basis for examining effects of roads on terrestrial and stream ecosystems. A landscape approach considers lateral effects of roads on adjacent terrestrial systems and also effects of road networks on stream and riparian networks. From a watershed viewpoint, it is useful to emphasize movement of water, sediment, woody debris, debris slides, and debris flows—all of which follow gravitational flow paths. Results of an assessment of erosion features resulting from a major flood reveal the great influence of hillslope position on the effects of roads on sediment routing. An assessment of the watershed effects of roads can incorporate: (1) broad-scale consideration of road and stream network densities—areas with high densities of both networks have highest potential for interaction, (2) propagation of road effects through stream and riparian networks, and (3) site-scale analysis of potential problems.*

INTRODUCTION

We offer some landscape perspectives for examining effects of roads on terrestrial and stream ecosystems. Historically, much of the analysis of effects of roads on ecosystems has been based on site-level investigations or views restricted to road rights-of-way. More recently, particularly in Europe, effects of roads have been addressed with a landscape approach emphasizing the zone of influences of roads extending laterally into terrestrial ecosystems. This approach can be supplemented by consideration of effects of road networks on stream and riparian networks.

In this paper, we consider how landscape structure affects road influences on terrestrial and stream systems. In the realm of stream networks, we emphasize movement of water, sediment, and debris flows—all of which follow gravitational flow paths and are major issues in watershed management. Road-related movement of exotic plants into forest landscapes is also considered briefly to offer an example of transfer processes that do not follow gravitational paths. We close with some consideration of implications for assessment procedures.

These landscape perspectives derive in part from a series of studies centered on the H.J. Andrews Experimental Forest in the Oregon Cascades directed at understanding effects of roads on surface (Jones and Grant, 1996; Wemple et al., 1996; Wemple, 1999) and subsurface (Wemple and Dutton, in progress) water fluxes, road-associated erosion and deposition events during the February 1996 flood (Swanson et al., 1998; Wemple, 1999), debris flows (Wallenstein and Swanson, 1996, in prep.; Snyder, in prep.), and exotic plants (Parendes, 1997). We also draw on findings of European research. A general treatment of interactions of road networks and stream networks is presented in Jones et al. (submitted).

LANDSCAPE STRUCTURES AND FLOWS

For our purposes, it is convenient to view landscapes as composed of interacting vegetation patchworks and networks of streams, riparian zones, and ridges (Swanson et al., 1997). Patchworks are created by substrate contrasts and disturbance processes, such as fire, windthrow, and patch clearcutting. Segments of networks may penetrate or border vegetation patches. Networks function as pathways for accumulation or dispersal of materials (such as stream water), animals (such as game using ridge trails or anadromous fish migrating through stream systems), and plant parts (such as seeds dispersed on the gentle breezes of cool air drainage patterns).

Energy, organisms, and material may move between patches and network segments (Fig. 1). Traffic along roads, for example, may be vectors for movement of exotic plant species into forest landscapes; and under favorable circumstances, those organisms may move into adjacent areas, such as clearcut patches (path 2 in Fig. 1). Runoff and associated sediment from recently disturbed patches of vegetation may move downslope to be intercepted by a road (a patch to network interaction, as show by path 1 in Fig. 1) and then routed down a ditch to the native stream network (a network-network interaction, path 3 in Fig. 1).

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[2]*Research Geologist, USDA Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, Oregon 97331*
[3]*Associate Professor, Department of Geosciences, Oregon State University, Corvallis, Oregon 97332*
[4]*Department of Forest Science, Oregon State University, Corvallis, Oregon*
[5]*Department of Forest Science, Oregon State University, Corvallis, Oregon*

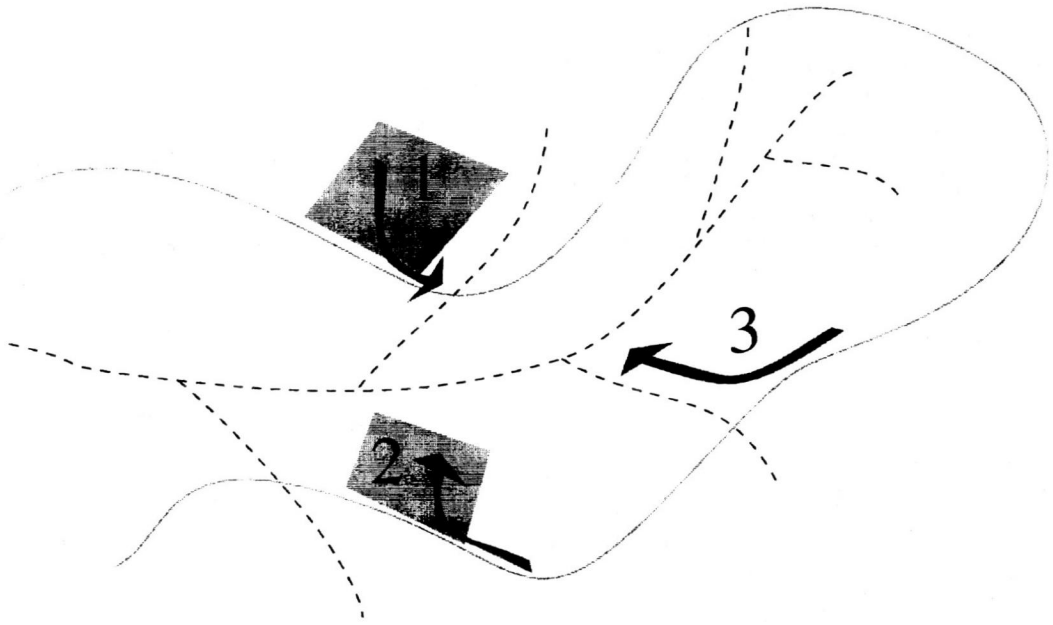

Figure 1. Types of network-patchwork interactions involving roads. Material (e.g., water, sediment), organisms (including propagules), and energy can move from vegetation patches to segments of a road network (1), from road segments to vegetation patches (2), and between road and stream networks (3).

Much of the literature in landscape ecology has been by terrestrial ecologists who tend to see the world as composed of vegetation patches which serve as habitat for wildlife. Studies of the significance of the network structure of streams and roads are uncommon. Many management issues in forested watersheds, especially issues concerning roads, involve understanding of interactions of patchwork and network structures within the landscape.

ZONES OF ROAD INFLUENCE

Ecologists have identified a wide array of road influences on adjacent ecosystems, which can be broadly grouped into the roles of roads as sources (e.g., traffic noise and road dust), sinks (e.g., road kill which results in reduced population size in the vicinity of roads), corridors (e.g., paths for movement of some species along roads), and barriers (e.g., impeding movement of some species, but without necessarily functioning as a sink in terms of mortality) (Fig. 2). Roads form exotic networks in landscapes that exert a variety of influences on the neighboring, native, terrestrial ecosystem patchworks and intersecting stream networks. Roads may have exotic functions in landscapes in the senses of involving non-native, compacted surfaces and drainage structures that carry water across hillslopes and potentially from one natural drainage basin to another. Vehicle traffic can alter the road itself (such as producing fine sediment and dust), directly affect neighboring ecosystems (such as through effects of traffic noise on animal movement), and introduce exotic species into a landscape—species that may eventually affect adjacent terrestrial and aquatic systems.

The influences of roads on terrestrial and stream ecosystems is contingent on the processes perpetrating the influence and the terrain over which that influence is exercised. Topographic factors, such as the hillslope position of a road segment, can strongly affect the type and extent of road effects. Steep hillslopes, for example, can extend road influences greater distances downslope from a road, but a nearby ridge may limit the lateral extent of a road influence. Approaches to examining road effects on ecosystems differ between terrestrial patchworks and stream/riparian networks.

Interaction of Road Networks and Terrestrial Systems

The source and sink types of influences of roads on terrestrial ecosystems have distinctive zones of influence that vary in width, depending on many factors. For example, the impact of road kill on populations of organisms in neighboring areas will depend on dimensions of the home range and on traffic intensity, among many factors.

Complexities of road networks as corridors for dispersal and for interaction with adjacent vegetation patches are represented by recent work on exotic plants in a Cascade Mountain forest landscapes (Parendes, 1997). Some exotic species are widely distributed along forest road networks, while others exhibit a quite spotty distribution. There may be some interaction of the road-side environment (seedbed) and the adjacent vegetation patch (light environment) that determines favorable sites for establishment. However, statistical relations are weak, especially for species with very limited dispersal capabilities; hence, chance plays a big role in determining their distribution. Most exotic species have limited potential for dispersal into adjacent vegetation patches in the Cascade study site, but elsewhere, problem species seem to spread inexorably. These cases include gorse and Port Orford cedar root rot in southern, coastal Oregon, and Himalaya blackberry more widely.

A common approach to assessing the extent of the road influence on a landscape (Fig. 3) has been to multiply road length (or density) by the width of the zone of influence and divide by the overall area of analysis. This gives a measure of the percent of landscape area affected by roads. Using this approach, Richard Forman (Harvard University, personal communication) has estimated that 25% of the United States is influenced by roads. At the present time, such analyses are subject to debate, but it is striking to note that the geographic extent of road impact may be an order of magnitude greater than the extent of the road network itself.

Interaction of Road and Stream Networks

The geometry and interaction of different networks, such as roads and streams, have received scant attention in published studies. We expect that steep hillslopes create a tendency for high densities of road-stream intersections and, hence, interactions (Fig. 4). The gradient of roads is constrained by maximum grades for safe vehicle movement (commonly <10%), so on steep slopes, roads have high angles of intersection with streams, thus favoring high densities of road-stream intersections. Along valley floors of larger channels, roads typically parallel the main stream (Fig. 4) and may encroach on the floodplain and even the channel area itself. These valley floor roads also intersect tributary streams at high angles of intersection (Fig. 4). We hypothesize that these geometric relations strongly influence the types of road-stream interactions in various parts of a landscape.

The dominant effects of road networks on stream and riparian networks involve alteration of routing of water, water-born chemicals, sediment, and mass movements to and through native stream networks. Recent work in the Oregon Cascades provides examples of some of these interactions. Wemple et al. (1996) observed that segments of roads can act as extensions of the native stream network, thus increasing the drainage density of watersheds, which may alter the ability of watersheds to produce peak

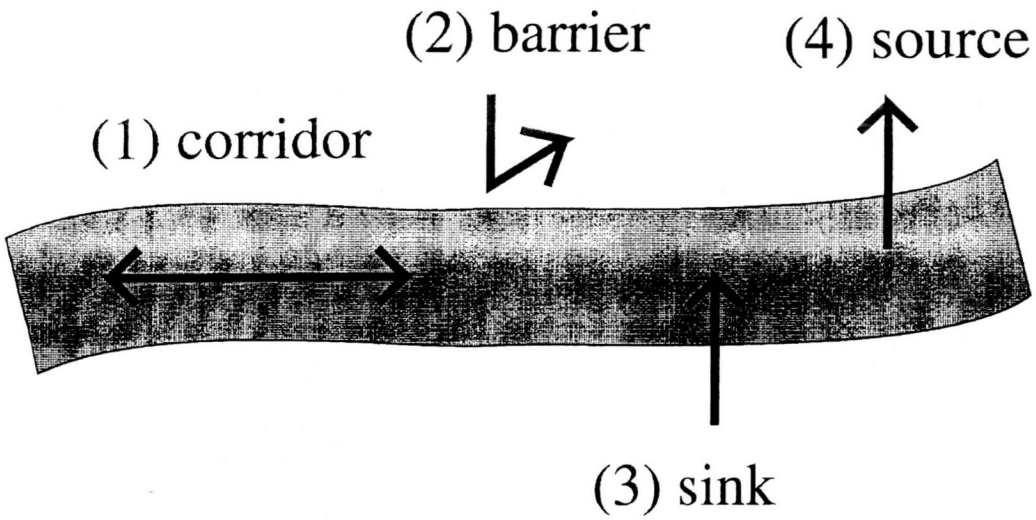

Figure 2. Roads can function as sources, sinks, corridors, or barriers for movement of material, organisms, and energy through landscapes.

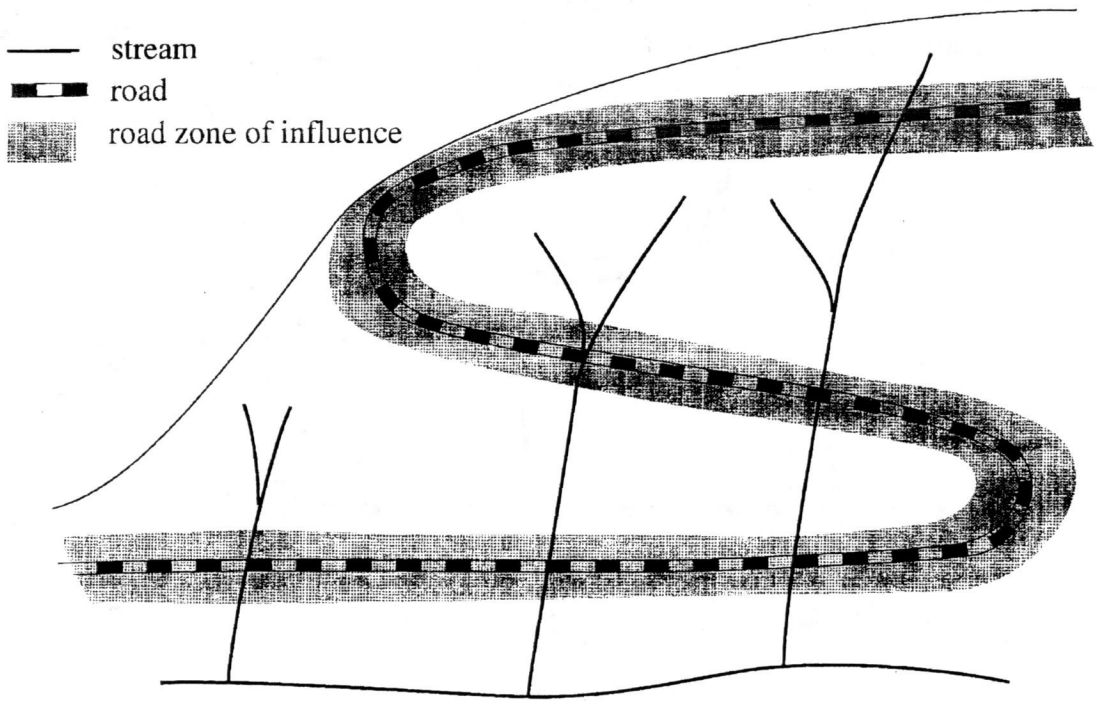

Figure 3. Zones of road influence on terrestrial ecosystems can be represented in the simplest way as a zone extending laterally from the road. A simple estimate of extent of road influence in area of road influence zone divided by area of landscape or watershed assessed.

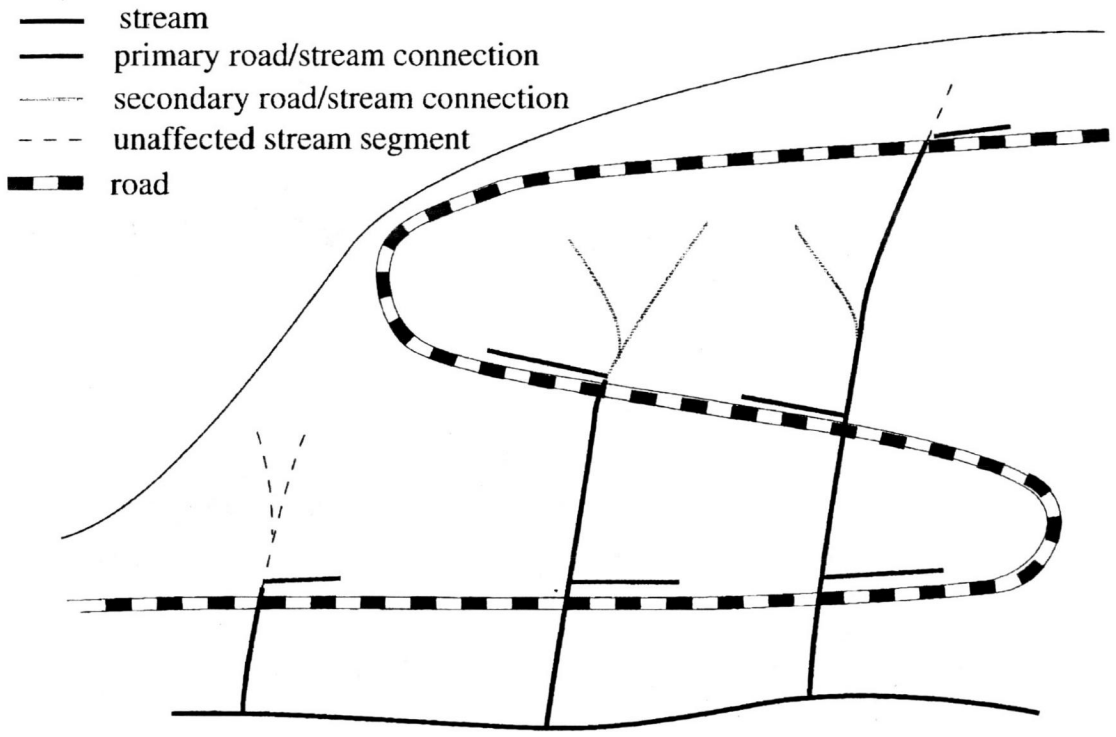

Figure 4. Effects of roads on stream and riparian networks include road ditches serving as extensions of the stream network and effects of streams and associated materials (e.g., sediment) on road segments encountered along the flowpath. The extent of stream network potentially affected by road influences can be expressed in terms of direct and potential influences and in terms of percent of network length affected and in terms of percent extension of drainage network density.

flow events (Jones and Grant, 1996). Wemple (1999) conducted an inventory of more than 100 erosion/deposition features affecting the road system in the upper Blue River drainage in the Cascades. She distinguished seven types of features involving both mass movement (e.g., cutslope or hillslope slides, debris flows from upstream areas) and fluvial processes (e.g., gullying resulting from culvert blockage by excess bedload). The density of the various types of road-related, erosion/deposition features varied strongly with hillslope position. Road segments within 100 m of ridges had a relatively low frequency of such features, and they all originated from the road as fillslope failures. Road segments on steep hillslopes below the near-ridge zone experienced high frequency and diversity of erosion/deposition features, and these roads were net sources of sediment to downslope and downstream areas. Valley floor roads located on floodplains, terraces, and alluvial fans had 10 times the frequency of features of the near-ridge roads and were net storage sites (sinks) for sediment coming from up slope areas.

Analysis of the extent of road influence on stream and riparian networks is most usefully expressed in terms of the percent of stream network length affected in various ways by road influences (Fig. 4). For example, segments of roads draining to native streams (Fig. 4) increase drainage density by definable amounts (Wemple et al., 1996). It is useful to stratify the analysis by stream order, since some processes may be restricted to certain orders. Debris flows, for example, are largely limited to first- through third-order streams where they may affect more than 10% of channel length. However, a much higher percentage of larger channels in debris-flow-affected watersheds experience elevated sediment loads from these headwater events (Jones et al., submitted).

We hypothesize that the greatest effects of roads on stream and riparian networks occur where the densities (length of network per unit of overall landscape area) of both types of network are highest (Fig. 5). For some processes, the degree of this interaction might be indexed by the density of road-stream intersections per unit of watershed area. One important area of future work is to assess stream geomorphic and ecologic characteristics of watershed areas representing different parts of the field of road and stream densities (Fig. 5) to see if a response surface can be defined for key watershed conditions. We could also try to identify thresholds of stream and road densities above which undesired conditions tend to develop. Such analyses need to be placed in the context of capabilities of particular watersheds to show responses, such as their inherent hydrologic and sediment production regimes.

MANAGEMENT IMPLICATIONS

These observations and general concepts suggest several implications for assessment and mitigation of road effects in watersheds. We have been impressed by the strong influence of slope position on the watershed functions of roads in terms of water and sediment routing during floods. Analysis of how hillslope position affects road erosion and damage during floods, such as Wemple s (1999) work, gives a strong quantitative basis for estimating the payoff from modifying roads with objectives of reducing maintenance costs or restoring watershed conditions. Such quantitative analysis of road effects on water and sediment routing can target specific functions of roads, such as sediment or debris flow sources and sinks. Engineering design can then be set in both site and larger watershed contexts.

Assessment of road influences on stream ecosystems can be approached at a series of related scales. At a broad scale, the highest levels of interaction between road and stream networks can be expected to occur where both types of networks occur in high densities. Geographic Information Systems procedures can be used to map and analyze the density of each network type in units of length per unit area and to identify areas with high densities of both types. At a finer scale, the patterns of road-stream intersections can be examined through the stream network to identify areas of high densities of intersections where management action might reduce adverse effects. At the finest scale, traditional, site-level analysis is employed to identify problems and site-scale engineering solutions, but can be set in the contexts of hillslope position, network location, and likelihood of various processes affecting the site or being translated to downslope and downstream areas.

In summary, we believe that a landscape perspective is essential to assessing and managing effects of roads in landscapes and in stream and riparian networks. A landscape approach complements the more traditional approach of assessing roads by simply considering the road right-of-way. Roads are an integral, multi-faceted part of any watershed they occupy.

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REFERENCES

Jones, J. A., and G. E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, west-

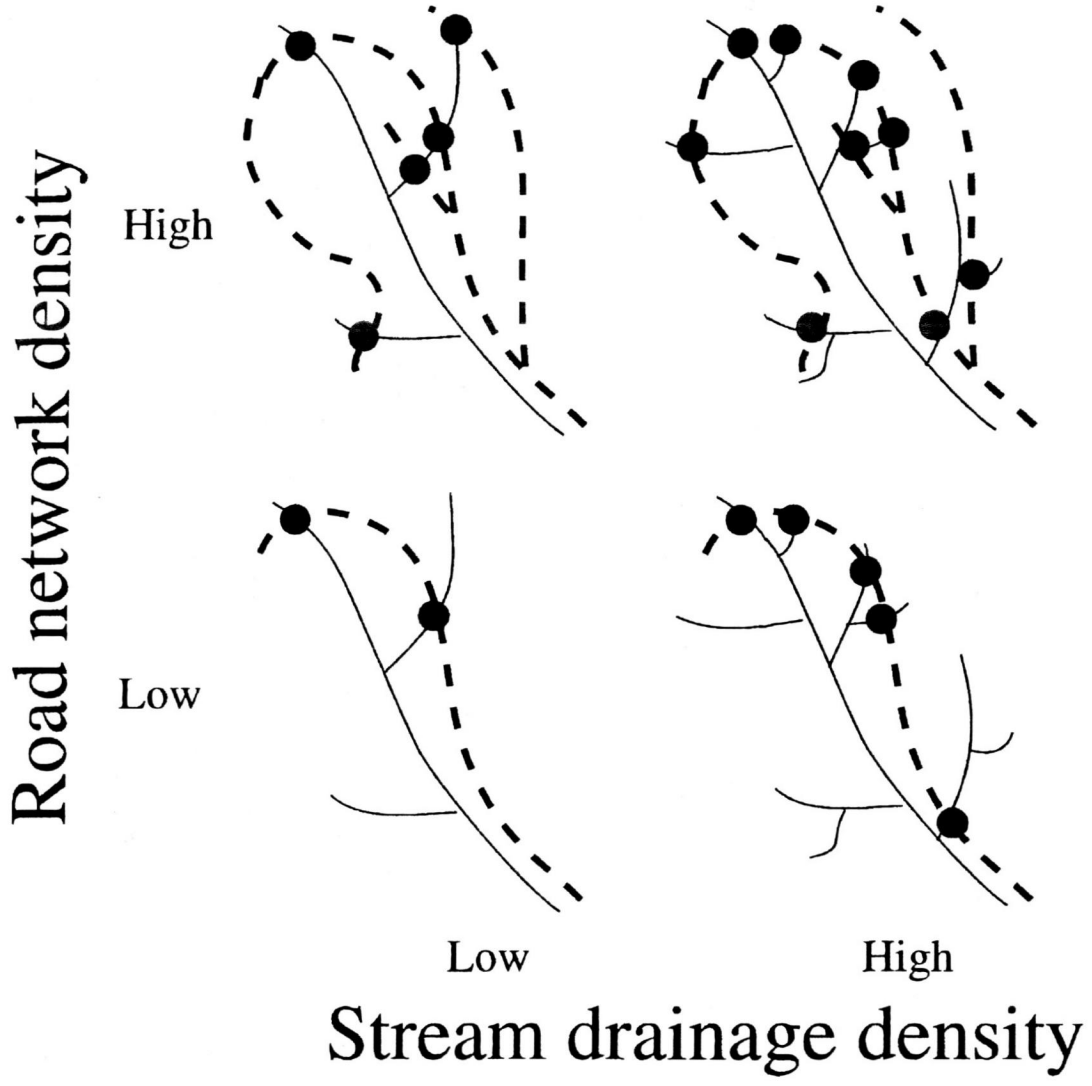

Figure 5. Schematic examples of road (dashed line) and stream (solid line) networks of high and low densities, showing highest density of road-stream intersections (dots) and, therefore, potential interactions in watersheds with high densities of both roads and streams.

ern Cascades, Oregon. *Water Resources Research* 32(4): 959-974.

Jones, J. A., F. J. Swanson, B. C. Wemple, and K.U. Snyder. [Submitted]. Road and stream network interactive effects on hydrology and geomorphology in western Oregon. *Conservation Biology*.

Parendes, L. A. 1997. *Spatial patterns of invasion by exotic plants in a forested landscape.* Ph.D. dissertation. Oregon State University, Corvallis, Oregon. 208 p.

Swanson, F. J., J. A. Jones, and G. E. Grant. 1997. The physical environment as a basis for managing ecosystems. pp. 229-238 In: Kohm, K. A., and J. F. Franklin (editors) *Creating a Forestry for the 21st century: The Science of Ecosystem Management.* Island Press, Washington, DC; Covelo, California.

Wallenstein, M. D., and F. J. Swanson. 1996. Mass movement response to major floods: a western Oregon example [Abstract]. Page F259 in Abstract supplement to *EOS, Transactions, American Geophysical Union.* American Geophysical Union fall meeting 15-19 December. San Francisco, California

Wemple, B. C. 1999. *Investigations of runoff production and sedimentation on forest roads.* Ph.D. dissertation. Oregon State University, Corvallis, Oregon.

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.

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