

**Aquatic and Other Environmental Impacts of Roads:
The Case for Road Density as Indicator of Human Disturbance and Road-
Density Reduction as Restoration Target;
A Concise Review**

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by

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Abstract

Roads have well-documented, significant and widespread ecological impacts across multiple scales, often far beyond the area of the road “footprint”. Such impacts often create large and extensive departures from the natural conditions to which organisms are adapted, which increase with the extent and/or density of the road network. Road density is a useful metric or indicator of human impact at all scales broader than a single local site because it integrates impacts of human disturbance from activities that are associated with roads and their use (e.g., timber harvest, mining, human wildfire ignitions, invasive species introduction and spread, etc.) with direct road impacts. Multiple, convergent lines of empirical evidence summarized herein support two robust conclusions: 1) no truly “safe” threshold road density exists, but rather negative impacts begin to accrue and be expressed with incursion of the very first road segment; and 2) highly significant impacts (e.g., threat of extirpation of sensitive species) are already apparent at road densities on the order of 0.6 km per square km (1 mile per square mile) or less. Therefore, restoration strategies prioritized to reduce road densities in areas of high aquatic resource value from low-to-moderately-low levels to zero-to-low densities (e.g., <1 mile per square mile, lower if attainable) are likely to be most efficient and effective in terms of both economic cost and ecological benefit. By strong inference from these empirical studies of systems and species sensitive to humans’ environmental impact, with limited exceptions, investments that only reduce high road density to moderate road density are unlikely to produce any but small incremental improvements in abundance, and will not result in robust populations of sensitive species.

Aquatic and other environmental impacts of roads

Roads have well-documented, significant and widespread ecological impacts across multiple scales, often far beyond the area of the road “footprint”, with negative effects on biological integrity in both terrestrial and aquatic ecosystems (Forman & Alexander 1998; Gucinski et al. 2001; Trombulak & Frissell 2000).

These include direct mortality from road construction and vehicle collisions, modification of animal behavior, alteration of the physical environment, alteration of the chemical environment, spread of exotic species and increased human use of areas (Forman 2004; Forman & Alexander 1998; Gucinski et al. 2001; Trombulak & Frissell 2000). Road construction kills stationary and slow-moving organisms, injures organisms adjacent to a road and alters physical conditions beneath a road (Trombulak & Frissell 2000), often including direct conversion of habitat to non-habitat within the road and roadside corridor “footprint” (Forman 2004). Behavior modification depends on species and road size/type, but ranges from road corridor use to avoidance to complete blockage of movement, which fragments or isolates populations, often with negative demographic and genetic effects, and with potential consequences up to and including local population or species extinction and biodiversity loss (Forman 2004; Gucinski et al. 2001; Trombulak & Frissell 2000). Additional behavior modification includes changes in home range, reproductive success, escape response and physiological state (Forman & Alexander 1998; Trombulak & Frissell 2000).

Roads change soil density, temperature, water content, light levels, dust, surface waters, patterns of runoff, erosion and sedimentation, as well as adding heavy metals (especially lead), salts, organic molecules, ozone, and nutrients to roadside environments (Forman 2004; Gucinski et al. 2001; Trombulak & Frissell 2000). When delivered to streams, these road-derived contaminants reduce water quality (Gucinski et al. 2001). Increased road-derived fine sediments in stream gravel have been linked to decreased fry emergence, decreased juvenile densities, loss of winter carrying capacity, increased predation of fishes, and reduced benthic organism populations and algal production (Gucinski et al. 2001). Roads greatly increase the frequency of landslides, debris flow, and other mass movement (Gucinski et al. 2001). Roads promote the dispersal of exotic species and pathogens by altering habitats, stressing native species, and providing corridors and vehicle transport for seed/organism dispersal (Forman 2004; Gucinski et al. 2001; Trombulak & Frissell 2000). Roads also promote increased hunting, fishing, poaching, passive harassment of animals, use conflicts, lost solitude, lost soil productivity, fires, and landscape modifications (Forman 2004; Gucinski et al. 2001; Trombulak & Frissell 2000). Presence of roads is highly correlated with changes in species composition, population sizes, and hydrologic and geomorphic processes that shape aquatic and riparian systems and habitat (Gucinski et al. 2001; Trombulak & Frissell 2000), including severing connections between streams and adjacent floodplain networks, converting subsurface to surface flow by intercepting groundwater flowpaths and diverting flow to streams, thereby increasing run-off, “flashiness” and erosion (Forman 2004; Gucinski et al. 2001).

In particular, roads have been consistently singled out as a primary cause of the reduced range and abundance of many aquatic species, not only in the West but also across the continent (CWWR, 1996; USFS and USBLM, 1997a; Trombulak and Frissell, 2000; Kessler et al., 2001; Angermeier et

al., 2004). Czech et al. (2000) estimated that roads in the U.S. contribute to the endangerment of some 94 aquatic species. [Rhodes 2007, p. 7]

Road density as indicator of human disturbance to natural systems

Species and biological communities evolve through co-adapting to each other and the physical environment of their native ecosystems. The broad suite of significant road impacts just described often creates large and extensive departures from the natural processes, interactions and conditions to which organisms are adapted, which increase with the extent and/or density of the road network. Road density is also a useful metric or indicator of human impact at all scales broader than a single site because it integrates impacts of human disturbance from activities that are associated with roads and their use (e.g., timber harvest, mining, human wildfire ignitions, invasive species introduction and spread, hunting, fishing, poaching, etc.) along with direct road impacts (Lee et al. 1997; Quigley et al. 2001; Trombulak & Frissell 2000). Thus, an expectation that environmental degradation and associated biological impacts would increase with road density and, conversely, that remaining areas with very few or no roads would be strongholds of imperiled species and native biodiversity (in addition to providing other important ecosystem services such as clean water sources, carbon sequestration, recreation, and solitude) is both logical and obvious.

Objections have sometimes been raised to use of road density as an indicator of disturbance (or reductions in road density as a target for restoration) on grounds that all roads are not equal in ecological impact. However, while the latter is certainly true, validity and utility of road density as a robust indicator for watershed condition and aquatic impact – because of its integration of non-direct road-specific impacts as noted above – has been repeatedly demonstrated and is strongly confirmed by its extensive and repeated recommendation in the Forest Service's guidance for Roads Analysis (USDA Forest Service 1999).

Expectation that road density would be associated with environmental degradation or species declines is further confirmed by empirical evidence finding significant correlations between population/community strength of Threatened, Endangered, Sensitive or other native species or other measures of ecological integrity and roadless proportion or road density. Together, this evidence strongly indicates that significant negative impacts can be detectable beginning with even the first one-tenth-mile of road per square mile of watershed (Lee et al. 1997). Multiple lines of evidence further indicate that substantial water quality declines, watershed degradation, and aquatic species impact must be expected at road densities higher than about 1 mile per square mile (0.6 km per square km) or less. This in turn suggests that – with limited, generally site-specific exceptions – because adverse impacts become evident even at quite low road densities, the greatest restoration efficiency with limited resources will result

from targeting road reduction to high-value watersheds where low-to-moderately-low road densities can be brought below a mile per square mile or less, rather than where moderate-to-high road density would be reduced, but still remain moderate-to-high (exceptions might include a particular high-risk or high-impact road segment directly impacting a specific, high-value population or highly productive habitat of an at-risk species). These lines of evidence include:

- At the landscape scale, increasing road densities and their attendant effects are correlated with declines in the status of some non-anadromous salmonid species (Gucinski et al. 2001).
- For example, Frissell and Carnefix (2007) found a significant relationship between bull trout spawner abundance and proportion of subwatershed area within designated Wilderness or Inventoried Roadless Areas (IRAs) for 19 subwatersheds in the Rock Creek drainage, Granite and Missoula Counties, Montana, and disproportionately high occurrence of native salmonids, including genetically pure populations, associated with IRAs statewide.

- Ripley et al. (2005) surveyed 172 stream reaches located throughout the majority of the lower two-thirds (where industrial activities, mainly timber harvest and roads, are most predominant) of the Kakwa River basin in central western Alberta, Canada, and modeled relationships of bull trout presence and abundance with environmental factors. Bull trout were observed only at road densities (in the subbasin draining to the sampling reach) ranging from 0 to 0.6 km per square km (1 mile per square mile). Road density was generally related

significantly and negatively to both bull trout occurrence and abundance in logistic and zero-inflated Poisson (ZIP) regression models. Notably, consistent, steepest decline in the modeled probability of bull trout occurrence fell between 0 and 0.4 km per square km (\approx 0.6 miles per square mile; see their Fig. 2 at right). This is consistent with other

evidence (e.g., Lee et al. 1997, see below) that no truly “safe” threshold road density exists, but rather negative impacts begin to accrue and be expressed with incursion of the first road segment. Ripley et al. (2005) further used the modeled negative relation between bull trout occurrence

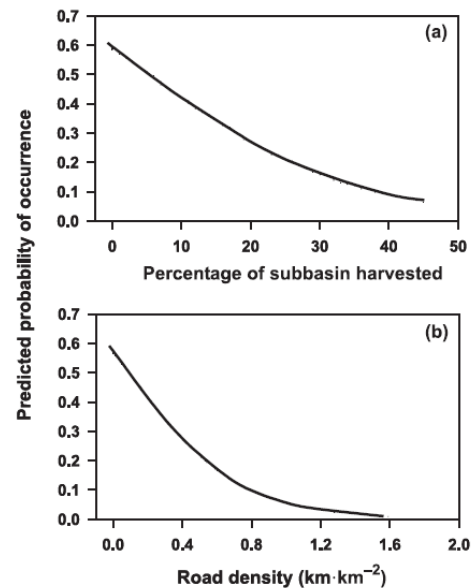


Fig. 2. Logistic regression models of the predicted probability of bull trout (*Salvelinus confluentus*) occurrence and (a) percentage of the subbasin subjected to forest harvesting and (b) density of roads in the Kakwa River basin. [Ripley et al. 2005]

- and percentage of subbasin harvested (a primary driver of road construction) to forecast that forest harvesting over the next 20 years is projected to result in the local extirpation of bull trout from 24% to 43% of stream reaches that currently support the species in the basin.
- Similarly, bull trout redd numbers and changes in redd numbers with time were negatively correlated with density of logging roads in spawning tributary catchments in Montana's Swan River drainage (Baxter et al. 1999).
 - U.S. Fish and Wildlife Service's Final Rule listing bull trout as threatened (USFWS 1999) states:

A recent assessment of the interior Columbia Basin ecosystem revealed that increasing road densities were associated with declines in four non-anadromous salmonid species (bull trout, Yellowstone cutthroat trout, westslope cutthroat trout, and redband trout) within the Columbia River Basin, likely through a variety of factors associated with roads (Quigley & Arbelbide 1997). Bull trout were less likely to use highly roaded basins for spawning and rearing, and if present, were likely to be at lower population levels (Quigley and Arbelbide 1997). Quigley et al. (1996) demonstrated that when average road densities were between 0.4 to 1.1 km/km² (0.7 and 1.7 mi/mi²) on USFS lands, the proportion of subwatersheds supporting "strong" populations of key salmonids dropped substantially. Higher road densities were associated with further declines.

- Lee et al. (1997) concluded, "Our [Interior Columbia Basin] results clearly show that increasing road densities and their attendant effects are associated with declines in the status of four non-anadromous salmonid species [bull trout, westslope cutthroat trout, Yellowstone cutthroat trout, and redband trout]. They are less likely to use highly roaded areas for spawning and rearing, and if found are less likely to be at strong population levels."
- Within colder subwatersheds, bull trout populations were reported as strong nearly seven times more frequently in those with less than 2.5 miles of road per square mile than those with more (Rieman et al. 1997, Table 5).
- Of five watershed integrity indicator variables used, the proportion of a subbasin composed of wilderness or roadless areas seemed most closely associated with subbasins having high integrity indices within the Interior Columbia basin; 81 percent of the subbasins classified as having the highest integrity had relatively large proportions of wilderness and roadless areas (>50 percent). Conversely, of subbasins with the lowest integrity, 89 percent had low proportions of roadless and wilderness areas, and 83 percent had relatively high proportions of at least moderate

- road density (0.27 miles/square mile) (Gucinski et al. 2001, p. 8, citing Quigley et al. 1997).
- Lee et al. (1997) compared projected road densities against known aquatic conditions across the Interior Columbia basin and found that areas with estimated road densities of <0.06 km per square km (0.1 miles per square mile) were most generally associated with areas of low degradation and areas with estimated road densities of >0.43 km per square km (0.7 miles per square mile) were most generally associated with high degradation.
 - Extensive habitat and population surveys on the Clearwater National Forest, Idaho, found that with few exceptions, native salmonid abundance was higher and exotic brook trout abundance lower or zero in unroaded versus managed landscapes (Huntington 1995). Differences were largest (often several-fold to an order of magnitude) and most consistent in the lower-gradient (“B” and “C”) channel types, which are most sensitive to road and other management impacts, and were evident despite less-than-ideal stream habitat conditions in a large proportion of the stream segments in the unroaded landscapes, due to ongoing recovery from large fires within the past 50-150 years.
 - Density of large wood (a crucial element of high quality aquatic habitat) in pools in tributaries to the Elk River, Oregon was negatively correlated with road density at intermediate (“network”) spatial scales (Burnett et al. 2006). Road density was also negatively correlated with forest cover, which was likewise negatively correlated with large wood density, leading the authors to interpret the significant road density effect as an integrator or surrogate for impacts of the timber harvest associated with the road network.
 - Frequency of large pools and all pools (crucial elements of aquatic habitat quality) declined with increasing road density in lower-gradient (<0.02) streams in the Interior Columbia River Basin (Lee et al. 1997).
 - Thompson and Lee (2000) used existing data sets to model landscape-level attributes and snorkel count categories of spring-summer chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*) parr (juveniles) in Idaho. Resulting models predicted that chinook salmon parr would be in low count categories within subwatersheds with >1 km²·km⁻² (1.6 miles per square mile) geometric mean road densities and/or <700 mm mean annual precipitation.
 - Inventoried roadless areas provide or affect habitat for over 55% of the Threatened, Endangered, or Proposed-for-listing species found on or affected by National Forest lands, representing approximately 25% of all animal species and 13% of all plant species listed under the Endangered Species Act within the United States, and for over 65% of Forest Service-designated sensitive species (Brown & Archuleta 2000).

Besides the perennial problem of resources insufficient to the overall restoration need, this prioritization issue takes on greater importance in the context of recent

or current agency policies and legislative initiatives. Though intended to efficiently and/or collaboratively address multiple restoration objectives simultaneously, most existing policies/proposals risk the perverse outcome of directing restoration efforts or expenditures away from the locations of greatest need and most-certain benefit for aquatic/watershed restoration, especially in the absence of robust scientific sideboards circumscribing the decision space. For example, our reviews of recent projects and forest plans (corroborated by private testimony from Forest Service personnel) suggest that while Forest Service Region One's "Integrated Restoration Strategy" includes a high-profile aquatic/watershed component, in practice purported "forest health" and fire-risk concerns drive the planning process and determine locations of projects, with any aquatic/watershed restoration measures subordinated to and entirely dependent for support on those perceived terrestrial priorities. Urgently needed aquatic/watershed restoration is thus held captive to terrestrial considerations, and these terrestrial considerations are often of high public controversy and sometimes of dubious scientific validity. By contrast, the scientific basis for and ecological and cost-effectiveness of aquatic/watershed restoration measures such as road decommissioning or stormproofing and fish-passage barrier removal are thoroughly documented, straightforward, and uncontroversial. Such watershed restoration work is urgently needed to meet acute policy and legal mandates of the National Forest Management Act, Clean Water Act, and Endangered Species Act. The mandates of these environmental laws, and public demand for clean water and healthy fisheries, will not be met if rational road impact reduction programs are subjugated to controversial fuels reduction and salvage timber sales. This programmatic linkage by management agencies hinders the ability of the agency to restore watersheds and remediate roads effectively, creates unnecessary spending inefficiencies that jeopardize aquatic resources, and clearly constitutes bad public policy.

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