Benefits and impacts of road removal

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Road removal is being used to mitigate the physical and ecological impacts of roads and to restore both public and private lands. Although many federal and state agencies and private landowners have created protocols for road removal and priorities for restoration, research has not kept pace with the rate of removal. Some research has been conducted on hydrologic and geomorphic restoration following road removal, but no studies have directly addressed restoring wildlife habitat. Road removal creates a short-term disturbance which may temporarily increase sediment loss. However, long-term monitoring and initial research have shown that road removal reduces chronic erosion and the risk of landslides. We review the hydrologic, geomorphic, and ecological benefits and impacts of three methods of road removal, identify knowledge gaps, and propose questions for future research, which is urgently needed to quantify how effectively road removal restores terrestrial, riparian, and aquatic habitat and other ecosystem processes.

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More than 885 000 km of roads have been built on US federal lands to facilitate resource extraction, recreation, and transportation (Havlick 2002) – enough to drive to the moon and back. While these roads provide important services, their construction and presence can also influence the hydrology, geomorphology, and ecosystem processes. They can substantially alter hillslope hydrology by reducing soil infiltration, concentrating water through road drainage structures, and converting subsurface flow to surface flow (Luce 2002). Overland flow can cause geomorphic changes, including chronic erosion (Megahan and Kidd 1972), extended channel systems (Wemple *et al.* 1996), and increased risk of landslides (Swanson and Dyrness 1975), thereby decreasing aquatic habitat quality. Roads also influence the ecology of terrestrial and aquatic ecosystems through direct habitat loss, fragmentation, and associated human impacts as a result of increased access (Wisdom *et al.* 2000).

Recognition of these wide-ranging effects has recently thrust roads into the forefront of research, resulting in the publication of books (eg Forman *et al.* 2003; Havlick 2002), reviews (eg Gucinski *et al.* 2001; Trombulak and Frissell 2000), special journal issues (eg *Conservation Biology* 14[1], *Earth Surface Processes and Landforms* 26[2 and 3], and *Water Resources Impact* 3[3]), and thousands of peer-reviewed studies. Increasingly, roads are being removed to mitigate these problems. However, to date surprisingly little attention has been given to the short- and long-term benefits and impacts of road removal. Here we describe three methods of road removal, summarize research that has been conducted, and identify knowledge gaps and research needs in this emerging field.

In a nutshell:

- Road removal is being used to mitigate the impacts of roads and restore ecosystem processes
- Preliminary research has found that road removal may temporarily increase sediment loss, but reduce chronic erosion and the risk of landslides over the long term
- More research is needed to determine if aquatic and terrestrial habitats recover following removal

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Road removal

Public and private land managers in the US and Canada are removing roads to restore habitat connectivity and ecosystem processes. For the purposes of this article, we define road removal as "the physical treatment of a roadbed to restore the form and integrity of associated hillslopes, channels, and flood plains and their related hydrologic, geomorphic, and ecological processes and properties". Road removal projects have been undertaken for several reasons: to restrict access, increase hillslope stability, minimize erosion, restore natural drainage patterns, protect endangered plants and wildlife, and restore aquatic and wildlife habitat.

Roads are typically built by using heavy equipment to cut into a hillslope, with extra fill cast aside below the road (Figure 1). Road removal essentially reverses this process. The most common forms of road removal include "ripping" the roadbed, restoring stream crossings, and fully recontouring hillslopes, although a variety of techniques have been applied on the ground (Table 1). Road ripping involves decompacting the road surface to a depth of 30–90 cm, typically done with a bulldozer dragging a specially fitted plow over the roadbed (Figure 2). This is often followed by the addition of soil amendments and by

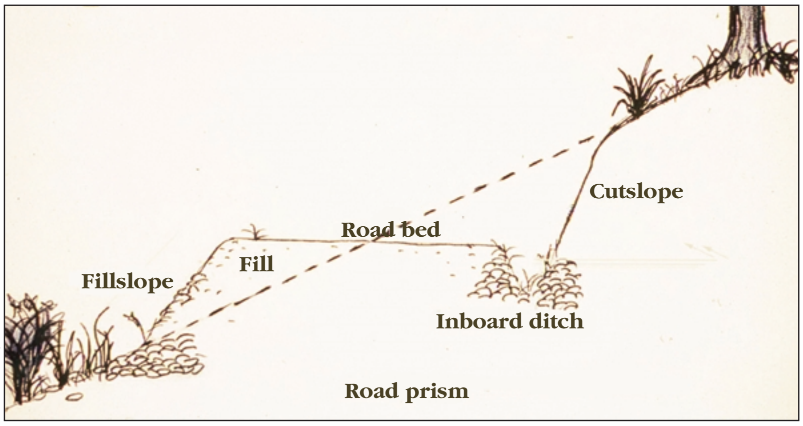

Figure 1. *Components of a road.*

revegetation. Treatment of stream crossings involves removing culverts, excavating the fill down to the original land surface, recontouring streambanks, installing channel stabilization structures, and revegetating (Figure 3). A full recontour involves treating stream crossings, reshaping the roadbed to its original slope, and revegetating the area (Figures 4 and 5).

Revegetation of the treated road surface is an essential component of habitat restoration, and can include natural regeneration or seeding with native or non-native grasses, nursery-grown trees or shrubs, and transplants from adjacent hillsides. Soil amendments, including sidecast topsoil (soil cast aside during road construction), mulches, biosolids (residual materials from wastewater treatment), and fertilizers are often added to increase nutrient cycling. Sediment control structures such as silt fences, check dams, erosion mats, weirs, rock buttresses, and timber cribs are often employed to reduce surface and channel erosion and the risk of landslides immediately following treatment.

Research review

Road removal is an interdisciplinary endeavor requiring broad expertise, particularly in soils, geology, geomorphology, engineering, hydrology, and ecology. For example, the composition of a soil can greatly influence the degree of water retention and subsurface drainage of a road, and thus the risk of erosion and landslides and the degree of revegetation. In addition, natural environmental factors such as landform features, bedrock type and composition, vegetation, hydrological characteristics, and climate can all have considerable effects on erosion and runoff rates. Although many land management agencies have created protocols outlining methods for road removal, a thorough evaluation of the ability of this procedure to restore hydrologic, geomorphic, and ecological processes has not yet been made.

We have gleaned much of our knowledge on road removal from observational studies and monitoring conducted by land managers in the western US. However, few experimental studies have addressed this topic and few published papers exist. Most studies have occurred in areas characterized by high precipitation, highly erodable soils, and/or steep topography. Additionally, many of the studies have been short in duration and often do not account for long-term variability.

Ripping the roadbed

Roads are compacted initially during construction and later by vehicle traffic. This compaction limits water movement and soil aeration, restricts root growth and elongation, and disrupts nutrient dynamics. In severely compacted soils, infiltration is essentially zero, and establishing vegetation can be difficult (Luce and Cundy 1994). Ripping has been used extensively to increase infiltration and promote revegetation on degraded rangelands (Wight and Siddoway 1972), mined lands (Ashby 1997), and forest skid trails and landings (Davis 1990). On flat and gently sloping landscapes, ripping is the primary method of road removal.

Table 1. Different types of road closure and removal and their relative costs and impacts (modified from Bagley 1998)

Road impact and cost consideration	Gating	Permanent traffic barriers (boulders, berms)	Ripping	Stream crossing restoration	Full recontour
Fill stability problems fixed?	No	No	No	Yes (no if not complemented with recontour)	Yes
Long-term surface erosion controlled?	No	No	Yes	Yes	Yes
Wildlife security improved?	No (yes if gate is able to deter access)	No (yes if barriers deter access)	Yes	Yes	Yes
Cost	\$1000–2800	\$800–1000	\$400–1200/km	\$500–150 000 per crossing*	\$3000–200 000/km*

*The complexity and variability of stream crossing restoration and full recontour make it easier to compare costs on a per-m^3 basis. The cost of excavating in Redwood National Park ranges from \$1–3.50 per m^3.

Figure 2. *Ripping the roadbed, Pueblo Mountain Wilderness Study Area, OR.*

Figure 3. *Stream crossing restoration, Clearwater National Forest, ID.*

Studies on road ripping have been carried out in diverse landscapes across North America, in a variety of ecotypes; this procedure has been found to reduce erosion, improve infiltration, increase the rate of revegetation, and discourage weed establishment (defined as non-native invasive species).

Infiltration and erosion

Road ripping increases infiltration and reduces erosion in the short term, but has produced mixed results in the long term. In the boreal forests of west-central Alberta, Canada, ripping substantially reduced bulk density (the mass of dry soil relative to volume) immediately following treatment (McNabb 1994). In western Montana, Bradley (1997) found that ripping successfully improved infiltration rates 3 months after treatment. Following a 12-year return interval storm, Bloom (1998) concluded that ripping greatly reduced landslide erosion on low-risk terrain in northern California.

Other studies, however, report that ripping alone has marginal long-term success. Luce (1997) reported that hydraulic conductivity (a measure for comparing infiltration capacity) increased immediately following the ripping of Idaho logging roads, but a number of the roads returned to their original bulk densities after three simulated rainfall events. Soil texture determined the success of the treatment: soils high in fine silts and clays underwent surface sealing, while soil settlement occurred in sandier, granitic soils. Although straw mulch could be used to treat surface sealing, it had no effect on soil settlement (Luce 1997). In western Montana, however, Bradley (1997) found mulch prepared from slash (forest harvest residues) mitigated surface sealing successfully.

Revegetation and weed invasion

Quickly establishing vegetation is a priority for any road removal project. Vegetation is one of the first visual signs of ecosystem recovery, and creates habitat for a variety of animals. Ripping the road surface loosens soil and increases infiltration capacity, improving the germination and growth of seeded plants (Wright and Blaser 1981). The resulting vegetative cover further protects against erosion and maintains infiltration capacity. Revegetation studies tested the effectiveness of different seeding techniques and measured revegetation trends over time. While results varied, incorporating soil amendments generally increased rates of revegetation.

Road sites are typically nutrient poor, and the addition of organic matter to a ripped roadbed can greatly accelerate the establishment of vegetation. Applying straw mulch decreased erosion and increased the rate of revegetation in northern California (Hektner and Reed 1991) and north-central Idaho (Stonesifer and McGowan 1999). Incorporating biosolids, an amendment rich in

Figure 4. *Results of full recontour, Lolo National Forest, MT.*

Figure 5. *Full recontour, Clearwater National Forest, ID.*

nutrients and organic matter, significantly increased total vegetative cover and native plant biomass on treated roadbeds in western Washington after 3 years of monitoring (Bergeron 2003). Incorporating topsoil to a ripped roadbed increased natural revegetation in northwestern Wyoming (Cotts *et al.* 1991) and northern California (Hektner and Reed 1991). However, in northern Arizona neither topsoil nor mulch increased total plant density or cover after 14 months (Elseroad *et al.* 2003). Bradley (1997) found that lopped slash combined with fertilizer yielded healthy grass communities in northwestern Montana after 12 weeks, but the effects of fertilizer may be short-lived. For example, on restored roadbeds in Connecticut, fertilizer only improved vegetation growth in the first year after application (Maynard and Hill 1992).

While road ripping has been shown to increase the rate of revegetation, it may create conditions conducive to weed invasion. Furthermore, soil amendments may supply higher than normal levels of nitrogen, accelerating revegetation but favoring weeds (Zabinski *et al.* 2002). Monitoring and preliminary research, however, suggest that ripping may actually reduce the risk of invasions, because native vegetation is able to out-compete weeds and because ripping eliminates a primary vector (human access) for further invasions. Moreover, locations with higher precipitation recover faster and are less susceptible to weed invasion. In northern California, some weeds emerged following treatment and natural revegetation on hot dry terrain, but very few weeds appeared in moister areas (Madej *et al.* 2001). Monitoring in the lush forests of north-central Idaho revealed few weeds following treatments (USFS 2003). Bradley (1997) also found that weed invasion was generally reduced following ripping in wet sites in western Montana.

Restoring stream crossings

Where roads intersect streams, there is the potential for large amounts of sediment to be released into the stream system. If a culvert is plugged with debris, the result is often a washout where the streamflow overtops the road and erodes to the original stream grade. These washouts can then cause other downstream culverts to fail in a domino effect. When a blocked culvert does not result in a local washout, streamflow may be diverted down the roadbed itself or along the slope-side ditch, causing large amounts of gully erosion along the roadbed and hill slopes below the road. For example, in northern California, Best *et al.* (1995) recorded that only 15 stream diversions produced 64 000 mt of sediment (about 4000 dump trucks' worth) over a 25-year period.

Stream crossing restoration has been used in many areas in an effort to reduce the risk of catastrophic washouts and associated impacts on aquatic ecosystems. Most stream erosion occurs during times of high streamflow, and the effectiveness of stream crossing restoration was typically measured after a major flood event. There is potential for local erosion immediately after the excavation of a stream crossing, but this can be partially mitigated by using sediment traps – often straw bales placed in streams to catch sediment (Brown 2002). The impacts of short-term sediment loss on aquatic biota have not been evaluated yet. Channel incision and bank erosion were the most common forms of stream erosion reported, and were correlated with stream power (velocity of water flow), the amount of large wood in channels, the percentage of coarse material in stream bank soils, the amount of road fill excavated, and local geology.

Klein (1987) monitored channel adjustments on 24 stream crossings in Redwood National Park, CA following a 5-year return interval flood. Erosion was correlated with stream power and inversely correlated with the percentage of large wood in the channel and coarse material in streambanks. Following a 12-year return interval storm in 1997, two researchers revisited the impacts of stream crossing restoration in Redwood National Park. Madej (2001) examined 207 stream crossings treated between 1980 and 1997, and found that most treated crossings produced very little sediment and none resulted in diversions or debris torrents (rapid movement of large quantities of materials downstream) (Table 2). The amount of sediment eroded was positively correlated with stream power, but was also correlated with the size of the stream crossing (Madej 2001). After surveying 86 treated stream crossings, Bloom (1998) found that only four crossings contributed substantial erosion (>37 m^3). Five to 20 years after culvert removals, pool habitat in excavated streams had only partially recovered (Madej 2001b), but a riparian zone of young red alder (*Alnus rubra*) was providing a closed canopy and shade over the streams (Madej *et al.* 2001).

Full road recontour

Landslides

If a roadbed on a steep slope becomes saturated, there is an increased risk of road-triggered landslides. Full road recontour, the most intensive form of road removal, includes treatment of the road segments between stream crossings, and is often employed to reduce the risk of landslides. Most landslides occur during periods of high rainfall and, like stream crossing restoration, the success of the treatments are gauged following a flood event. Full road recontour has been used effectively to reduce landslides in northern California (Bloom 1998; Madej 2001), western Washington (Harr and Nichols 1993), coastal Oregon (Cloyd and Musser 1997), and north-central Idaho (McClelland *et al.* 1997; USFS 2003). Important factors determining the risk of failure following treatment include hillslope position and history of landslides.

In Redwood National Park, where full recontour was first introduced, a 12-year return interval storm in 1997 provided the opportunity to measure the effectiveness of two decades of road removal. Most treated roads produced very little sediment. Eighty percent of the road reaches had no detectable (> 2 m^3) landslide erosion following treatment (Madej 2001). Untreated roads produced four times as much erosion as treated roads, mostly in the form of landslides (Bloom 1998; Madej 2001; Figure 6). Both Bloom (1998) and Madej (2001) reported that hillslope position (as a surrogate for hillslope steepness and the amount of surface and subsurface water present) was an important factor in determining treatment success. Although treatments dramatically reduced sediment loss from upper- and middle-slope roads (< 40% gradient), steep lower-slope roads continued to have high failure rates, no matter what treatments were used.

The Clearwater National Forest in north-central Idaho experienced a 50-year return interval flood in the winter of 1995/1996. A rain-on-snow event triggered more than 900 landslides on highly erodible granitic soils, half of which were attributed to roads (McClelland *et al.* 1997). Ten kilometers of roads were recontoured prior to the storm. Although ten landslides would have been predicted in McClelland's model prior to recontouring, no landslides occurred on the treated roads (McClelland *et al.* 1997). To date, over 700 km of roads have been removed from this forest with only seven landslides observed, four of which were in areas of historic or pre-existing landslides (USFS 2003). However, the Clearwater has not experienced a serious flood event since then, and a further test of the effectiveness of the road treatments has not occurred.

Chronic erosion

Although most full road recontour studies have only examined landslide events following floods, the reduction of chronic erosion is also a goal of many road removal projects. Chronic erosion from roads can greatly reduce an aquatic system's integrity, and in some cases can be the sole source of sediment input. A short-term problem with road removal is that following a road

Table 2. Sediment loss on treated and untreated stream crossings in northern California

Treated or untreated	Hillslope position	Mean (median) erosion rate (m^3)*	Mean percentage (median) of excavated fill	Storm recurrence interval (yrs)	Source
Treated	All	27 (11)	–	5	Klein (1987)
Treated	Lower	97 (69)	11 (5)	12	Bloom (1998)
Treated	Middle/upper	79 (11)	10 (1)	12	Bloom (1998)
Treated	All	50 (17)	8 (3)	12	Madej (2001)
Treated	All	15	2	2–5	Pacific Watershed Associates (unpublished)
Treated	All	42 (4)	3 (1)	2–5	Six Rivers National Forest (unpublished)
Untreated	Lower	115	–	12	Bloom (1998)
Untreated	Middle/upper	180	_	12	Bloom (1998)
Untreated	All	235	_	50	Best *et al.* (1995)

*Many studies only report mean values for erosion, but because crossing erosion volumes are not normally distributed (commonly there are a few extreme values), median values of erosion may be a more useful indicator of expected erosion in a crossing.

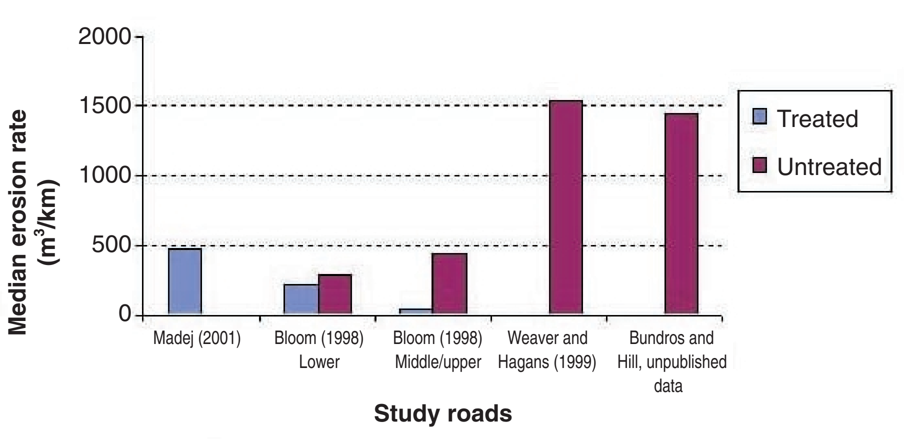

Figure 6. *Sediment loss on treated and untreated roads in northern California. Values from Bloom do not include sediment loss from stream crossings on these roads (reported in Table 2), whereas the other studies include stream crossing erosion as part of the sediment loss.*

recontour, the bare slopes are very susceptible to erosion. As the slope becomes revegetated over time, however, erosion levels eventually mimic natural slope conditions.

Hickenbottom (2000) showed that recently recontoured road segments produced significantly ($P < 0.05$) more sediment than road segments recontoured 12 months prior to analysis. Average sediment yield was 746 g/m^2 for recently recontoured roads (versus 402, 62, and 26 g/m^2 for the untreated roads, 12-month-old recontour, and control plots, respectively). These values are derived across five replicate plots for each treatment type applied across two geologic strata and three slope classes; however, the analyses were all performed within one watershed. Although these numbers demonstrate a great reduction of sediment yield just one year after recontouring, recontoured roads are susceptible to erosion immediately following treatment. Similarly, in north-central Idaho after 5 years of monitoring, the Clearwater National Forest reported that road treatment has eliminated surface erosion outside of treated stream crossings (USFS 2003). Additionally, in fully recontoured roads in eastern Kentucky, there was considerably less sediment produced than in untreated control plots after one growing season (Kolka and Smidt 2001).

Influence on wildlife

One of the many goals of road removal is the restoration of the ecological integrity of terrestrial, riparian, and aquatic habitats. In addition to preservation of habitat, restoration may be essential to maintaining and increasing biodiversity (Sinclair *et al.* 1995). Virtually no research has addressed the impact of road removal on wildlife. Since terrestrial wildlife is greatly influenced by road density (Wisdom *et al.* 2000), it is likely that road removal may also affect wildlife.

Roads influence wildlife in a variety of ways, including reduced numbers of snags and downed logs; altered movement patterns; increased negative edge effects; and increased poaching, hunting, trapping, and additional negative interactions with humans facilitated by easier access, including direct mortality from car collisions (Wisdom *et al.* 2000). Removed and revegetated roads would presumably reverse many of these impacts and create habitat for a variety of animals. Bradley (1997) found Western toads (*Bufo boreas*) on ripped roads in western Montana, where slash created structural diversity and microhabitats. Some wildlife biologists argue that road removal will reduce grizzly bear (*Ursus arctos*) mortality risk (USFWS 1993) and increase elk (*Cervus elaphus*) habitat security.

Roads can greatly impact aquatic systems in complex ways, including blocking fish passages, introducing fine sediment and non-native species, changing amounts of shading and cover, direct channel infringement, and increasing access and predation by anglers (Luce *et al.* 2001). A reduction in sediment delivered to streams should increase the quality of aquatic habitat. For example, suspended sediments can negatively impact salmonid fisheries through direct mortality, hindering the development of eggs and larvae, disrupting natural movements and migration, reducing food organisms (Newcombe and MacDonald 1991), and hindering fish feeding behavior through reduced visibility. (In contrast, inboard ditches can serve as habitat for amphibians and benthic macroinvertebrates, and road removal decreases the amount of this habitat). There is an urgent need for research that specifically addresses the ecological impact of road removal on aquatic, riparian, and terrestrial habitats.

Prioritization

With limited budgets and hundreds of thousands of kilometers of roads, it is essential that land managers prioritize road removal efforts. The process of prioritizing road removal is complex and must take into account ecological, economic, and social costs (Luce *et al.* 2001). Most projects prioritize "problem" roads that contribute large amounts of sediment to streams, reducing the quality of fish habitat. Many road removal projects in the Rocky Mountains have prioritized roads that allow for habitat security for grizzly bears and elk.

An ecologically relevant prioritization approach might attempt to increase the amount of highest quality habitat within watersheds. Selecting roads that affect large reaches of streams or watersheds with already low road densities may be most appropriate. Although handbooks, peer-reviewed articles, and workshops have addressed the issue of prioritization, no comprehensive protocol exists, and field units still commonly apply an ad hoc process for selecting roads to be removed. Better prioritization practices are at least as important as improvements to rehabilitation techniques.

Future research questions

While some research has been conducted on the effectiveness of road removal, there are still large gaps in our knowledge. It is imperative that we support any restoration efforts with sound science. Baseline data are important, as is meta-analysis (an overview analysis of many studies) of similar projects to predict expected outcomes. Monitoring after intervention is essential to understanding the long-term dynamics, as is replication in different soil types and climates. The effectiveness of a particular approach depends on the context (eg soils, climate, and topography) of the treatment. Addressing the impacts of road removal at different spatial scales would also be very helpful.

If the restoration of ecosystem processes is the goal of road removal, then it is also essential that we document ecosystem recovery and modify our mitigation as appropriate. The reduction of erosion and increased infiltration following road removal has been documented (eg Luce 1997; Madej 2001) and continued research on hydrologic and geomorphic restoration will soon allow meta-analysis. However, the effectiveness of restoring natural stream and flood plain function still needs to be addressed. Finally, one of the most important research tasks ahead is quantifying the benefits of road removal on aquatic, riparian, and terrestrial ecosystems. No studies have yet examined the influence of road removal on the recovery of these ecosystems. Although road removal is now ocurring across the US and parts of Canada, a rigorous evaluation of 20 years of restoration in northern California by an interdisciplinary team of experts could be an eminently fundable and important project.

Conclusions

Even after thousands of kilometers of roads have been removed, there is an alarming lack of published analysis of the effectiveness of these efforts. Road removal creates short-term disturbances that can temporarily increase sediment loss, but in the long-term, road removal may reduce chronic erosion and the risk of landslides. Continued research is greatly needed, especially quantifying how effective various road removal techniques are in restoring terrestrial, riparian, and aquatic habitat. As is often the case, however, the best solution is prevention. In northern California, on steep lower slope roads, no form of road removal was able to prevent chronic erosion completely. Increased research on this emerging field will help us more effectively remove roads, set restoration priorities, and ultimately help restore the integrity of entire ecosystems.

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