A conceptual framework for understanding, assessing, and mitigating ecological effects of forest roads

C. Robinson, P.N. Duinker, and K.F. Beazley

Abstract: A review of road-ecology literature suggests that impacts of forest roads on species and ecosystems begin during the road construction phase, but persist and accumulate well after a road is no longer in use. Over this time, impacts stemming originally from construction, but then also from the continued physical presence and human use of the road, follow complex multiple pathways ending in diminished species persistence. Yet in practice, road-impact considerations rarely extend beyond short-term issues related to road construction or beyond the spatial extent of the road corridor. Even when the range of potential impacts is recognized, managers rarely have a framework for assessing those impacts. This can be problematic, as informed decisions regarding the long-term, wide-ranging ecological consequences of road placement, design, and use can lessen the degree to which a road modifies the composition, structure, and function of forest ecosystems. This paper presents a conceptual framework for organizing, synthesizing, and applying our growing understanding of how roads affect forest ecosystems. The framework includes two parts: (1) a series of impact-hypothesis diagrams wherein ecological impacts are organized relevant to three phases of road existence: construction, presence and use; and (2) a five-step approach whereby ecological impact and road importance can be evaluated and a decision matrix used to determine appropriate mitigation strategies. Highlights of a case study conducted in southwestern Nova Scotia are presented to illustrate the applicability of the framework.

Key words: conceptual framework, forest road, road ecology, terrestrial impact, aquatic impact, mitigation.

Résumé : Une revue sur l'écologie des routes suggère que les impacts des chemins forestiers sur les espèces et les écosystèmes commencent au cours de leur construction, mais persistent et s'accumulent bien longtemps après que la route cesse d'être utilisée. Avec le temps, les impacts issus originalement de sa construction et par après de sa présence physique accompagnée de l'activité humaine suivent des cheminements complexes et multiples conduisant à une diminution de la persistance des espèces. Tout de même, en pratique, les considérations sur les impacts des routes s'étendent rarement au-delà des problématiques à court terme reliées à la construction de la route et à l'espace environnant le corridor routier. Même lorsque l'on reconnaît les impacts potentiels, les aménagistes disposent rarement d'un cadre de référence pour évaluer ces impacts. Ceci peut causer des problèmes, puisque des décisions bien informées portant sur le long terme, les conséquences sur de grandes étendues de la localisation des routes, de leur conception et de leur utilisation, peuvent amoindrir le degré selon lequel une route modifie la composition, la structure et le fonctionnement des écosystèmes forestiers. Le cadre de travail comporte deux parties: (1) une série de diagrammes d'hypothèses d'impacts selon lesquels on organise les impacts écologiques selon les trois phases d'existence de la route: construction, présence et utilisation; et (2) une approche en cinq étapes selon laquelle l'impact écologique et l'importance de la route peuvent être évalués avec une matrice de décision permettant d'assurer des stratégies de mitigation appropriées. Les auteurs présentent une étude de cas conduite dans le sud-ouest de la Nouvelle-Écosse pour illustrer le réalisme de ce cadre de référence.

Mots-clés : cadre de travail conceptuel, route forestière, écologie routière, impacts terrestres, impacts aquatiques, mitigation.

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Introduction: The need for a framework addressing forest road impact

Throughout North America, ecosystem functions critical to the persistence of many forest species are heavily impaired by vast networks of roads penetrating and isolating otherwise remote areas (Noss and Cooperrider 1994; Soulé and Noss 1998; DeVelice and Martin 2001; Trombulak and Frissell 2001; Havlick 2002; Switalski et al. 2004). While direct habitat loss has been identified as the most significant threat to species around the world, habitat fragmentation due to roads and related development is considered the principal threat to most species in the temperate zone (Wilcove et al. 1986). Limiting impacts of planned and existing forest roads is gaining increasing importance as people seek to minimize human influence across the landscape that is disruptive to ecosystem function and resilience (Brocke et al. 1990; Moll

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C. Robinson, P.N. Duinker,[1] and K.F. Beazley. School for Resource and Environmental Studies, Dalhousie University, 6100 University Avenue, Halifax, NS B3H 3J5, Canada.

[1]Corresponding author (e-mail: peter.duinker@dal.ca).

1996; Bagley 1998; USDT 2000, 2004; Gucinski et al. 2001; Havlick 2002).

Although ecological impacts of roads and linear features are well researched and described in the literature (see reviews by Noss and Cooperrider 1994; Forman and Alexander 1998; Gucinski et al. 2001; Trombulak and Frissell 2001; Havlick 2002; Forman et al. 2003), long-term and landscape-scale impacts on forest ecosystems are rarely considered in current land-use planning and management (Trombulak and Frissell 2001; Angermeier et al. 2004; Roedenbeck et al. 2007). In many jurisdictions, guidelines and regulations dictate best practices to minimize only site-specific, short-term influences of road building on stream-channel geometry and soil erosion during construction. Other consequences of roads for habitat quality, ecological processes, and biota are largely ignored. In particular, the importance and duration of post-construction maintenance, and the extensive and serious impacts related to subsequent use and development along forest roads are not often accounted for in the planning phase. Incomplete information results in landscape management decisions biased toward more road-building and accelerated deterioration of valuable and increasingly rare remote forest habitat (Angermeier et al. 2004).

Other authors (e.g., Noss 1995; Trombulak and Frissell 2001; Havlick 2002; Forman et al. 2003; CPAWS 2006; Coffin 2007) have spent considerable effort compiling research linking roads to biodiversity loss. This information has served as the basis for management reform in some jurisdictions in North America where guidelines and regulations outline best practices to minimize ecological degradation during road construction (Moll 1996; USDA 1999; USDT 2000, 2004; reviews in CCFM 2000 and Forman et al. 2003). Angermeier et al. (2004) have further applied the information compiled by others to build a framework that organizes impacts of roads on aquatic biota and assists scientists and managers in developing assessment tools that more accurately inform stakeholders and policy-makers about the consequences of road building in aquatic ecosystems. Likewise, a key assumption in this paper is that a greater understanding of spatial and temporal cause-and-effect relationships and familiarity with common measures of impact will help expand the emphasis in road planning and management from individual, direct, localized, and acute impacts to include cumulative, indirect, dispersed, and chronic impacts.

The two-part conceptual framework presented herein provides a basis for this understanding with goals of more accurately anticipating potential ecological impacts associated with planned forest road networks, promoting a logical assessment of those impacts, and better priority-setting of mitigation options on existing roads. The framework is unique in that it guides the user from a thorough assessment and understanding of the impacts through to a logical decision on options that should efficiently and effectively mitigate them. It encourages more-thoughtful decision-making and more carefully considered analysis of road costs and benefits. The framework focuses on roads constructed for resource extraction in forests because most often their intended utility is relatively temporary and consequently they offer more opportunities for mitigation and restoration. For a broader discussion of road ecology, the reader is referred to Forman et al. (2003) and Havlick (2002) and the extensive references therein.

The paper begins with a review of the known physical and biological links between roads and biodiversity loss in forest ecosystems. We then introduce part one of the framework where impact-hypothesis diagrams describe these links as they relate to three main phases of road existence: construction, presence, and use. Further background discussion explores common measures of road influence and conventional mitigation techniques. Principal challenges hindering the thorough consideration of road impacts and mitigation strategies in land-use planning and management are discussed. Next, we present part two of the framework that consists of a five-step approach whereby ecological impact and road importance are evaluated and weighed against each other. A series of decision matrices are used in the comparison to determine appropriate mitigation strategies for each phase of road existence. To illustrate the applicability of the approach, highlights of a case study dealing with the assessment of an existing forest road in southwestern Nova Scotia are presented.

Linking forest roads and biodiversity loss in forest ecosystems

Roads penetrating remote and otherwise intact forested landscapes have been correlated with subtle and extensive changes in species population density and diversity (see reviews by Noss 1995; Trombulak and Frissell 2001; Havlick 2002; Forman et al. 2003; CPAWS 2006). These changes stem from physical, chemical, and biological changes to terrestrial and aquatic habitat (e.g., loss, fragmentation, degradation), direct species mortality (e.g., roadkill, fish and wildlife harvest), and stress (e.g., population subdivision, wildlife harassment). Survival, reproduction, and resistance to disease are negatively influenced by stress in a variety of species (Munck et al. 1984; Moberg 1985; Wingfield and Farner 1993; Wasser et al. 2003).

Even though a relatively small percentage of the land surface in a managed forest is directly occupied by roads, few areas remain untouched by ecological effects originating from them (Trombulak and Frissell 2001; Havlick 2002; Forman et al. 2003). The distance to which effects permeate from the road edge into the surrounding landscape is known as the “road effect zone” (Forman et al. 2003). Alternating sequences of traffic volumes, adjacent lands and the species inhabiting them result in an uneven pattern of effects. Slope and relief of the landscape, permeability of soil and underlying bedrock, depth and movement of groundwater, direction and rate of water movement at stream crossings, amount of annual precipitation, prevailing wind directions, and density of vegetative cover are all relevant biophysical factors that influence the extent that a road will influence a forest (Forman et al. 2003). Ultimately, it is the response of plant and animal species to road-related changes that determines if the impact is detrimental to the ecosystem.

Some species are more vulnerable to road impacts than are others. The level of biotic influence roads exert on species persistence is attributed to the ability of the population to adapt to the selection pressure that a particular road represents. This selection pressure is highly dependent on the characteristics of the species (i.e., degree of road avoidance behaviour and sensitivity to road impacts), as well as characteristics of the road or road network in question (i.e., size of road, road density, traffic volume and speed) (Forman et al. 2003; Jaeger et al. 2005*a*). Characteristics of some forest species make them differentially more susceptible to various types of road-related effects (Table 1). The types of species most at risk from forest road impacts tend to be specialists requiring interior forest conditions, especially those that are K-selected species (i.e., typically having a large body size, long life span, and few offspring). Specific examples are highlighted below.

The diminished amount of available forage and shelter caused by road-induced habitat fragmentation has resulted in many interior-dependent species becoming extirpated, endangered or threatened in North America (Havlick 2002). Forest songbirds, salamanders (*Abystoma spp.*), flying squirrels (*Glaucomys spp.*), pileated woodpecker (*Dryocopus pileatus*), northern goshawk (*Accipiter gentiles*), spotted owl (*Strix occidentalis*), American marten (*Martes americana*), and woodland caribou (*Rangifer tarandus caribou*) are examples of specialist organisms adapted to the forest's shaded interior. Many are sensitive to the influence of humans and their machines on remote habitat and will experience more adverse effects than tolerant, generalist species (e.g., coyote [*Canis latrans*], raccoon [*Procyon lotor*], skunk [*Mephitis mephitis*], deer [*Odocoileus spp.*], fox [*Vulpes spp.*], and crow [*Corvus spp.*]). Habitat specialists often have lower population sizes, lower reproductive rates, and fewer suitable habitats than generalist species (Forman et al. 2003).

Species that occur in low densities, either naturally because they have low reproductive rates and long generation times (e.g., some species or populations of forest songbirds, carnivores, caribou [*Rangifer tarandus*], salmonids [*Oncorhynchus spp.*]) or because they are endangered, are typically more susceptible to direct mortality and stress (With and King 2008). Populations that can compensate for increasing road-related mortality and effects of stress with increasing reproduction will be less affected (e.g., white-tailed deer [*Odocoileus virginianus*], Cheatum and Severinghaus 1950) (Forman et al. 2003; Jaeger et al. 2005*a*).

Species with large area requirements need different habitat types with multiple resources to complete their life cycle (i.e., mating, breeding, seasonal nutrition) and are especially at risk from habitat loss and fragmentation (e.g., American moose [*Alces alces americana*], see review by Snaith and Beazley 2004; northern leopard frog [*Rana pipiens*], Pope et al. 2000; carnivores, raptors, amphibians, and waterfowl, see reviews by Forman et al. 2003 and Atkinson et al. 2004). Populations of wide-ranging carnivores are particularly vulnerable to traffic accidents (e.g., gray wolf [*Canis lupis*], Mech et al. 1988; lynx [*Lynx lynx*], Ray et al. 2002 and Kramer-Schadt et al. 2004; Florida panther [*Puma concolor coryi*], Meegan and Maehr 2002; cougar [*Puma concolor*] and ocelot [*Felis pardalis*], Murdock et al. 2001).

The habitat relationships of species with large home ranges — e.g., grizzly bear (*Ursus arctos*) — can be complex (Nielsen et al. 2006). In such cases, roads may constitute several cumulative stresses on species populations. Of all the human influences in landscapes occupied by large-range carnivores, roads may represent the largest single agent of stress. According to Nielsen et al. (2006, 2008), habitat improvements for grizzly bears in Alberta would be best achieved through road decommissioning, and not through other means such as application of contemporary paradigms of sustainable forest management based on emulation of natural disturbance regimes.

For certain species, a behavioural attraction to roads increases their risk of mortality (see reviews by Noss and Cooperrider 1994; Noss 1995; Jalkotzy et al. 1997; Havlick 2002; and Forman et al. 2003). Roads provide forage for herbivores, improved mobility for larger forest species (Barnes 1997), and thermoregulation opportunities for ectotherms (e.g., reptiles, amphibians) that could be viewed as beneficial. However, if the road exposes them to higher mortality from heavy-metal poisoning or collision with vehicles, increased population density near roads may threaten the persistence of the population. In this sense, roads are known to create "ecological traps" and "population sinks", or areas of low-quality habitat in which animal populations are not sustainable on their own without constant input from source areas (Gates and Gysel 1978; Noss and Cooperrider 1994; Noss 1995; Havlick 2002; and Forman et al. 2003).

Species that benefit from roads are primarily those that tolerate or even thrive on human disturbance of natural landscapes (e.g., bison in Yellowstone National Park [Barnes 1997]), and therefore are not at risk of population decline or extinction. Many of these species are exotic (e.g., earthworms in northern Alberta [Cameron et al. 2007; Cameron and Bayne 2009]) and compete with or prey upon vulnerable native species (Noss and Cooperrider 1994; Noss 1995; Havlick 2002; Forman et al. 2003). For example, roads represent extensive areas of narrow field-forest edge that are attractive to bird species that rely on structural cues to find good nesting sites (e.g., singing and observation perches, cover, food availability). At roadside, unfavourable edge effects including increased predation and brood parasitism are coupled with increased traffic mortality and pollution (Gates and Gysel 1978; Remes 2000). Packed snowmobile trails provide coyote and bobcat (*Lynx rufus*) with easy access to lynx territory, which may be linked to declines in lynx populations (Buskirk et al. 2000). Bison use packed snowmobile trails in Yellowstone National Park (Barnes 1997), resulting in substantial population increase that stresses sensitive winter habitats and leads to greater culling as animals cross the boundaries of the park. Declining moose populations in parts of eastern Canada and the United States have been attributed partially to the northward expansion of white-tailed deer, a highly adaptable species that uses roads to penetrate and thrive in areas traditionally occupied by moose (Anderson 1965, 1972; Karns 1967; Telfer 1968; Gilbert 1973; Saunders 1973; Pulsifer 1995; Parker 2003; Snaith and Beazley 2004). In addition to habitat alterations that accompany road development and interspecific food competition, white-tailed deer carry a parasitic nematode, *Paralephostrongylus tenuis*, which causes a sickness in moose, believed to contribute to their decline (Pulsifer 1995; Parker 2003; Snaith and Beazley 2004).

Animals exhibiting behavioural avoidance of roads may be spared from direct mortality, but their reduced mobility

Table 1. Roads have direct and cumulative impacts on terrestrial and aquatic forest species by contributing to habitat loss and degradation, fragmentation of suitable habitat, direct mortality, and stress. The influence roads exert on species persistence is attenuated by species' ability to adapt (adapted from Forman et al. 2003 and Jaeger et al. 2005*b*).

	Terrestrial and aquatic effects pathways			
Types of forest species threatened by roads	Habitat loss and (or) degradation	Fragmentation	Direct mortality	Stress
Species with interior forest requirements	✔	✔	✔	✔
Species with low population densities		✔	✔	✔
Species with low reproductive rates			✔	✔
Species with large area requirements		✔	✔	
Species with a behavioural attraction to roads and edge			✔	
Species vulnerable to competition, predation, disease			✔	✔
Species with a behavioural avoidance of roads and humans	✔	✔		✔
Species vulnerable to over-harvesting			✔	✔
Species vulnerable to changes in water quality: temperature, chemistry, sediment load	✔		✔	✔
Species vulnerable to changes in hydrologic function: drainage rates, flow pathways	✔	✔	✔	✔

makes them more susceptible to effects of habitat loss, degradation, fragmentation, and stress. In this way, road avoidance can have a much greater impact on the persistence of animal populations compared to other influences (Forman and Alexander 1998). Road-avoidance behaviour is attributed to several factors related to reduced habitat quality including individual species sensitivity to human-related disturbance, the type of habitat influenced by the road (e.g., degree of forest cover), the type of linear feature (e.g., winding trail, straight highway), and the average noise and volume associated with the traffic disturbance (Forman et al. 2003; Jaeger et al. 2005*a*). "Road-avoidance zones" result from these cumulative effects and have been estimated to extend outward from the road edge up to 5 km for some species (e.g., caribou; Nellemann et al. 2001) (Forman 2000) (Table 2). Road avoidance manifests as lower population densities, reduced species richness and genetic diversity, and absence of breeding pairs (Forman et al. 2003). In some cases, animals will perceive the actual road surface itself as inhospitable and avoid it. This is known as the "barrier effect" and it may be attributed to the lack of shelter, different microclimatic conditions (e.g., increased temperature, wind), or changes in soil conditions and vegetation at the edge. Animals with high surface avoidance may approach the road but will hesitate to venture further, effectively limiting their access to resources and mates. Small mammals, reptiles, and amphibians are examples of species that avoid road surfaces (Forman et al. 2003; Jaeger et al. 2005*a*).

Mortality and stress of some species can be dramatically increased when roads open interior forests, lakes and rivers to hunting, fishing and trapping. Incidental takes and poaching can be enough to push rare and threatened populations to the brink of extirpation and extinction. Roadless areas where fish and wildlife harvest is negligible act as nurseries that are critical to ensuring viable populations of some native species (Trombulak and Frissell 2001). In some cases, road access has promoted poaching of commercially valuable tree species that has led to their increased rarity, and that of species dependent on them for survival. Examples include Lawson's cypress (*Chamaecyparis lawsoniana*) (McHugh 1998), western bigleaf maple (*Acer macrophyllum*) (CBC 2007; Cornwall 2007), and Brazilian rosewood (*Dalbergia nigra*) (CBC 2007).

Aquatic species vulnerable to fluctuations in water temperature and sediment loading face local threats where roads and water bodies intersect (Trombulak and Frissell 2001). Chemically-treated timbers used in bridges can be local point-sources for contamination. In particular, polycyclic aromatic hydrocarbons (PAHs) have been found to leach creosote in concentrations causing toxic impacts to freshwater aquatic life (Hutton and Samis 2000). This is especially problematic in old bridges where the timbers were treated prior to best management practices established in 1997 that specify the application of a minimum amount of pesticide required to preserve the wood. Current guidelines call for creosote-treated wood not to be submerged or used in above-water structures where solar heating can result in the expulsion of creosote into the aquatic environment. Every effort should be made to shield the creosote-treated wood from exposure to solar heating and to prevent entry of the pesticide into the aquatic environment. The use of alternative preservatives is recommended for all new bridges over freshwater (Hutton and Samis 2000).

Finally, as demonstrated in the last row of Table 1, roads provide access to interior lakes and rivers creating opportunities for hydro-electric and other forms of development that may indirectly cause dramatic changes in regional hydrologic function and habitat for plant and animal species in riparian and aquatic ecosystems.

Table 2. A summary of some documented road-avoidance zones for various species. Species sensitivity (genetic, learned, seasonal), habitat (woodland, grassland), type of linear feature (road, trail, straight, curved), and degree of traffic disturbance (noise, volume) are key factors in determining effect distances. Effects are measured as decreases in species population density, diversity, and presence of breeding pairs. For a thorough review, see Forman et al. (2003).

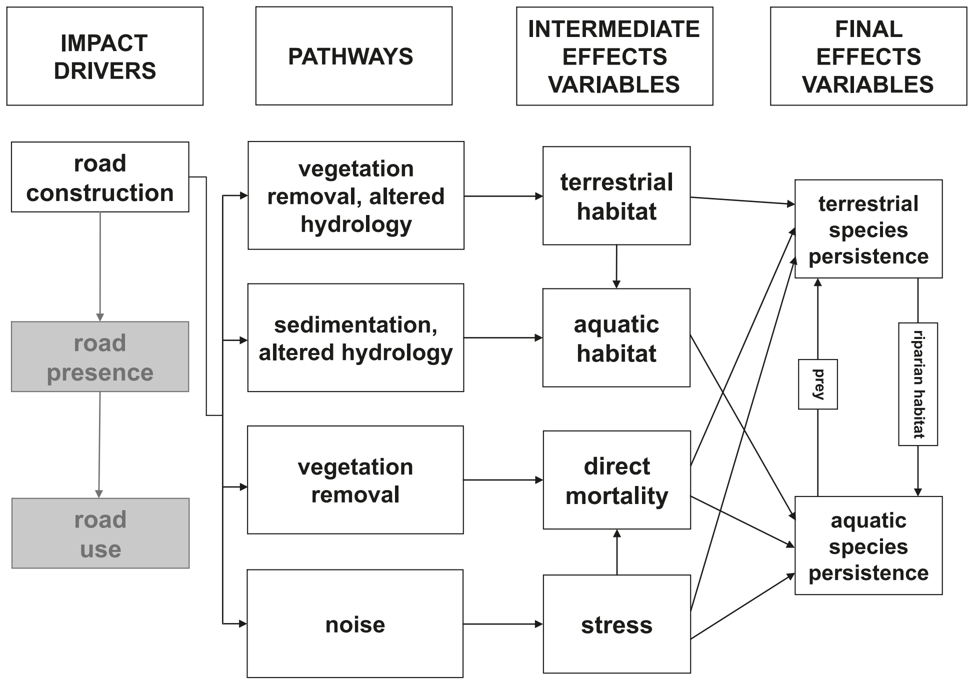
Species	Avoidance zone (m)	Type of disturbance	Reference
Snakes	650	Forestry roads	Bowles (1997)
Salamander	35	Narrow forestry road, light traffic	Semlitsch (2003)
Grassland birds	1200	Multilane highway, heavy traffic	Forman and Deblinger (2000)
	700	Two-lane highway, heavy traffic	
	400	Through street, moderate traffic	
	0	Collector street, light traffic	
	930	Heavy traffic	Reijnen et al. (1996)
	365	Moderate traffic	
Woodland birds	800	Highway, heavy traffic	Forman and Deblinger (2000)
	300	Through street, moderate traffic	
	810	Heavy traffic	Reijnen et al. (1995)
	305	Moderate traffic	
	150	Unpaved roads	Ortega and Capen (2002)
Goshawk	400–500	Human disturbance	Jones (1979)
Spotted owl	400	Forestry roads, light traffic	Wasser et al. (2003)
Marten	<100	Any forest opening	Hargis et al. (1999)
Deer	100–300	Mountain roads depending on traffic volume	Rost and Bailey (1979)
		Snowmobile trails	Dorrance et al. (1975)
Moose	500	Cross-country ski trail (especially in unpredictable locations)	Ferguson and Keith (1982); Jalkotzy et al. (1997)
	150–300	Snowmobile trails	Colescott and Gillingham (1998)
Elk	500–1000	Logging roads, light traffic	Edge and Marcum (1985)
	100–300	Mountain roads depending on traffic volume	Rost and Bailey (1979)
Caribou	250–5000	Roads, pipeline corridors in northern boreal and arctic environments	Nellemann and Cameron (1996, 1998); James and Stuart-Smith (2000); Dyer et al. (2001); Nellemann et al. (2001)
Grizzly bear	800–3200	Open habitat	Weaver et al. (1986)
	200–1600	Areas of cover	
	3000	Fall	Mattson et al. (2002)
	500	Spring and summer	
	883	Heavily traveled trail	Kasworm and Manley (1990)
	274	Lightly traveled trail	
	1122	Open road	Kasworm and Manley (1990)
	665	Closed road	
Black bear	274	Spring, unpaved roads	Kasworm and Manley (1990)
	914	Fall, unpaved roads	

Framework part 1: Impact drivers related to three phases of road existence

A review of the literature and a field examination of indicators of road influence suggest that when planning and managing a forest road network, it is helpful to consider effects as they relate to impact drivers that correspond with three phases of road existence: (1) construction, (2) presence, and (3) use (Havlick 2002; Angermeier et al. 2004). Effects on terrestrial and aquatic species persistence related to these phases vary with the amount and quality of terrestrial and aquatic habitat (habitat loss or degradation, fragmentation), direct mortality, and stress (see Table 1). Pathways and related effects specific to each phase are discussed in more detail below and summarized in a series of subsequent impact-hypothesis diagrams.

Road construction is the first phase of road existence and is characterized by relatively small temporal and spatial frames (Havlick 2002; Angermeier et al. 2004). However, associated impacts can be dramatic and long-lasting for species occupying what was previously an interior forest ecosystem (Fig. 1). Terrestrial habitat is directly altered when vegetation is removed to convert the forested area to a road. Vegetation loss and soil compaction on the road surface influence water retention and natural drainage patterns and may increase the magnitude and frequency of floods and debris flows. The rerouting of drainage during ditch construction and culvert placement can also result in the direct and

Fig. 1. Impact-hypothesis diagram summarizing ecological impacts related to road construction.



indirect destruction of surrounding aquatic habitat through siltation of streams and interrupted water flow (e.g., blocked fish passage, drainage of wetlands). Direct mortality of trees and other vegetation is caused during removal and can directly affect survival of slow-moving terrestrial inhabitants. Vegetation removal in riparian areas can result in increased water temperature and decreased availability of coarse particulate organic matter in streams, making them less hospitable for certain microorganism, invertebrate and fish populations (Angermeier et al. 2004). Noise associated with road construction can be stressful for interior forest species not accustomed to humans and their machines, causing them to abandon otherwise suitable habitat (e.g., woodland caribou; Dyer et al. 2001). Physiological evidence of stress associated with road noise has been measured in some species. For example, northern spotted owls (*Strix occidentalis caurina*) living close to forest roads were found to have higher levels of stress hormones than owls nesting in areas without roads (Wasser et al. 2003).

Road presence effects are sparked simply by the existence of roads on the landscape (Fig. 2). They reflect how a road network interferes with physical and biotic processes that regulate an ecosystem's composition, structure, and function and sustain its evolution (Noss and Cooperrider 1994; Trombulak and Frissell 2001; Havlick 2002; Angermeier et al. 2004; Noss 2005). Terrestrial and aquatic presence impacts occur regardless of human activities and can be subtle and long-lasting. For example, road presence may disrupt the frequency of natural geomorphic events (e.g., accelerate erosion and mass-wasting), alter microclimates (e.g., exacerbate wind-throw [Franklin and Forman 1987]), and truncate successional patterns naturally occurring between forest patches (e.g., creating edge effects in forest interior habitat [Alverson et al. 1994, 2005; Ortega and Capen 2002]) (see reviews in Noss 1995; Trombulak and Frissell 2001; Havlick 2002; Forman et al. 2003). Roads create openings for exotic or generalist species to establish and compete with interior forest plants and wildlife. These impacts degrade and fragment interior forest which is becoming increasingly rare in much of North America (Noss and Cooperrider 1994; Soulé and Noss 1998; DeVelice and Martin 2001; Trombulak and Frissell 2001; Havlick 2002; Switalski et al. 2004).

Alteration of natural drainage associated with road presence (e.g., soil compaction, surface water flow, groundwater recharge) can change and degrade habitat for terrestrial species. Degradation and fragmentation of aquatic habitat occurs if stream crossings are not properly maintained to prevent chronic sedimentation and promote adequate fish passage. Rerouted stream networks (e.g., ditches, culverts) and increased sedimentation at crossings affect local water quality and broader watershed function (Wemple et al. 1996; Jones et al. 2001). Road presence contributes to stress and mortality of forest species by providing an opening for predators, competitors, and disease. In addition, the presence of a road is stressful for species that avoid roads because they are not able to disperse naturally to fulfill their mating and nutrition requirements (Havlick 2002; Angermeier et al. 2004; Jaeger et al. 2005*a*).

Road use effects are caused by human activities on roads and the places people access (Havlick 2002) (Fig. 3). Typically, the first roads built in remote forested landscapes access logging, mining, and hydro-electric operations (Forman et al. 2003). Once roads are established and resources extracted, companies looking to recover operational costs may subdivide and sell lots to eager cottage and housing developers, permanently transforming extensive regions of wild lands (Austin 2005). New roads also provide easy access for recreational activities such as hunting, trapping, fishing, and camping — and invite a host of problems tied to off-highway vehicle (OHV) use (see reviews in Noss 1995; Trombulak and Frissell 2001; Havlick 2002; Forman et al. 2003; Angermeier et al. 2004; Jaeger et al. 2005*a*).

Fig. 2. Impact-hypothesis diagram summarizing ecological impacts related to road presence.

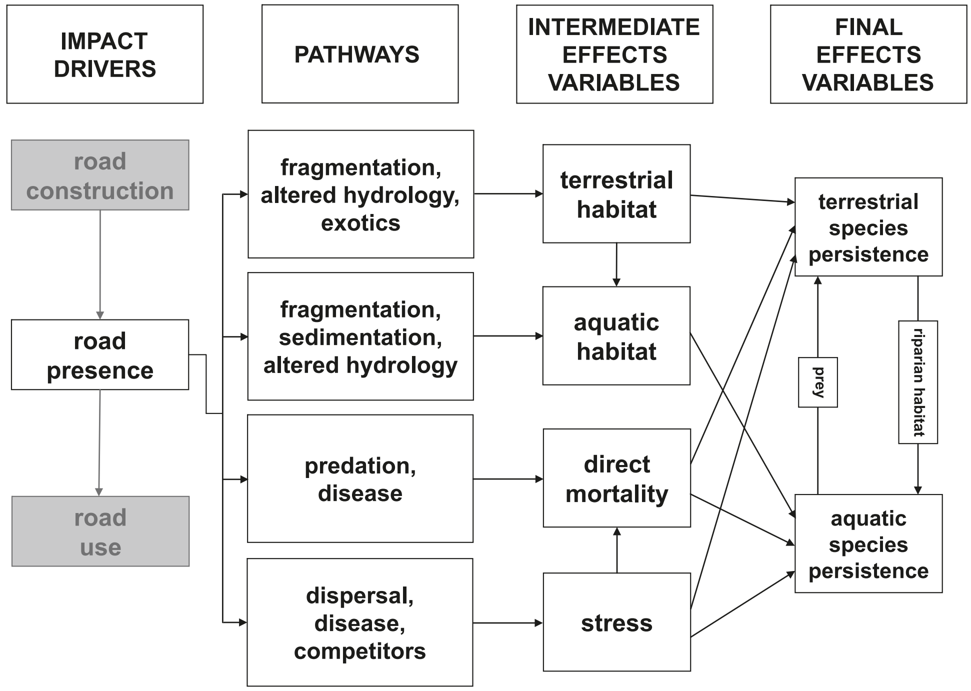
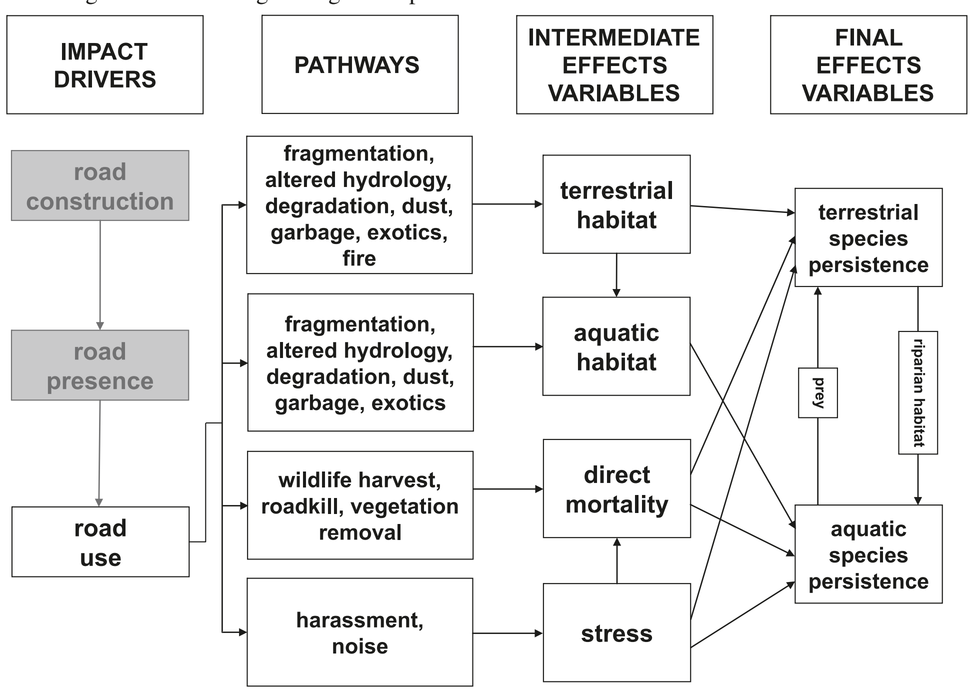


Fig. 3. Impact-hypothesis diagram summarizing ecological impacts related to road use.



Whether for resource development or recreation, road use exacerbates fragmentation and degradation of terrestrial and aquatic habitat caused by road presence. Dispersal of exotic species and forest pathogens along roadsides may further degrade previously remote habitat (Lonsdale and Lane 1994; Parendes and Jones 2000), as does illegal dumping (Sanderson et al. 2000), dust and atmospheric pollution (Forman et al. 2003). Introduced non-native aquatic species could cause shifts in the distribution, abundance, and size of native species (Angermeier et al. 2004). Several studies link the proliferation of road use in the backcountry to increased fire hazard (see reviews in Wein and Moore 1979; Noss 1995; Baxter 2004).

Frequent road use, especially heavy logging-truck traffic and recurring OHV use, enhances soil compaction and perpetuates problems associated with altered hydrologic function (e.g., less terrestrial water retention, increased surface water flow, and stream sedimentation) (Trombulak and Frissell 2001; Angermeier et al. 2004). More access promotes greater incidence of inadvertent and intentional wildlife harassment by people and their machines. Road-kill rates associated with forest roads are much lower than for more frequently travelled highways (Forman et al. 2003). However, heavily-used logging roads fragmenting important remote habitat can lead to increased mortality rates for struggling populations of migrating amphibians, foraging ungulates and wide-ranging carnivores, and may have serious implications for persistence of some populations (see reviews in Forman et al. 2003; Jaeger et al. 2005*a*). Some species (e.g., black bear [*Ursus americanus*]) can become habituated and learn to avoid busy, predictable highway traffic more easily than intermittent traffic patterns on remote forest roads (Jaeger et al. 2005*a*).

Measuring and mitigating effects of forest roads

Measures of road influence

In road ecology literature, researchers often refer to *indicators* and *metrics* interchangeably. In this discussion, *indicators* are attributes that serve as surrogates to assess ecological or biological condition. The term *metric* describes an indicator that is providing a standard measure or system of related measures that facilitates the quantification of a particular ecological condition (Thomson et al. 2003; TWS 2006), or metric may refer to the measurable quality of an indicator (Kurtz et al. 2001). Generally, the most useful indicators have measurable qualities that can be used to monitor and report the success or failure of management practices (Lindenmayer et al. 2000).

As a consequence of increased documentation of road influence on species and landscapes, several researchers have developed measures that provide quantitative and qualitative indication of road-related ecological damage (Table 3). Probably the most accepted and widely applied are those accounting for short-term, fine-scale impacts (e.g., road kill numbers and locations), especially impacts on water resources and fish habitat (e.g., sediment and pollutant concentrations, aquatic species presence and diversity) (Angermeier et al. 2004). Measures of indicators accounting for long-term, broad-scale road-related impacts are increasingly applied in regional conservation planning using geographic information systems (GIS), habitat-suitability models, and other decision-support tools (Girvetz and Shilling 2003; van der Grift et al. 2004; Jaeger et al. 2005*b*).

The most common indicator used to measure landscape-level road influence appears to be ‘‘road density’’. It is defined as the average total road length per unit area of landscape (km/km^2) and is used to infer ecological response to fragmentation, including individual species persistence (e.g., road density thresholds in Table 4), overall biodiversity, and hydrologic function of a landscape. The area enclosed by roads, sometimes referred to as ‘‘interior patch’’ or ‘‘mesh’’ size, is also a useful measure of fragmentation. It can be related to known minimal critical areas (MCA) necessary to maintain viability of certain species. Road type (permanent main road or temporary logging road), width, and average traffic volume strongly influence ecological response and are also useful indicators of road impact, as indicated in Table 2. Combined, road density, characteristics of the road, and the overall size, shape, and arrangement of patches provide a coarse overview of road impacts on habitat quality (Forman et al. 2003).

In a comprehensive analysis of road influence, natural geographic features, vegetation patterns, and species distributions are mapped in relation to existing or planned road networks and locations of any known or predicted individual, acute indicators of impact. Mapped results can be compared to species-specific threshold values for road avoidance, road density, and MCA to indicate important core areas for species and environments sensitive to road presence and human access. This helps to identify key linkages where road closures and crossing structures for specific species could be applied (e.g., Crist and Wilmer 2002; Noss et al. 2002; Girvetz and Shilling 2003; Beazley et al. 2005). In some jurisdictions, road-density caps and wildlife crossings have been proposed to restore critical habitat and improve functional habitat in natural ranges (e.g., Alberta Grizzly Bear Recovery Team 2005).

Thorough ecological impact assessments may be based on a broad spectrum of indicators differing in the spatial scale of the criterion they represent and the degree of scientific rigour on which they are established (Duinker 2001; Geneletti 2003). Some will reflect quantitative measurement and others will be more heavily rooted in qualitative observation (see Table 3 for examples). For some indicators, interpretation of the degree of impact is derived from well established risk-based guidelines and biodiversity conservation targets. For others, determination of high or low impact relies on expert judgement. Indicators of impact based on measurable scales are generally more widely accepted because they offer an objective and replicable basis for the assessment (Duinker 2001; Geneletti 2003). Subjective judgements, if used, must be expressed in a transparent way so the relationship between the facts (e.g., direct measurements of impact) and the values (e.g., the level of importance attached to qualitative observations) is explicitly provided (Geneletti 2003). Results of an ecological impact assessment need to be obtained through appreciation of thoughtful and transparent approach with clearly stated evaluation criteria, and making full use all available information (Antunes et al. 2001; Duinker 2001; Geneletti 2003).

The assessment approach described later in this paper provides guidance on choosing appropriate indicators of road impact based on the management objectives in question. For general guidance on evaluating the quality of indicators and related data concerning ecological assessments in forests, the reader is referred to Duinker (2001).

Forest road mitigation options

Moll (1996), Bagley (1998), and Havlick (2002) sort road mitigation techniques into four general categories: road obliteration, road ripping, road closure, and road abandonment. Methods differ in level of effort and expense. To ensure a successful program, land managers must consider what is most cost-effective, and the nature of the impacts they are targeting for mitigation. These efforts are part of a growing sector some experts have dubbed the ‘‘restoration economy’’ (Cunningham 2002; Criley and Kustudia 2006; Doolittle and Platt 2006; Montana’s Restoration Initiative 2007).

In road obliteration, heavy equipment is used to dig up the entire roadbed and recontour the ground. It is the most

Table 3. A sample of indicators that provide qualitative and quantitative measure of ecological impact of a road or network of roads on terrestrial and aquatic ecosystems (from Weller et al. 2002, Girvetz and Shilling 2003, TWS 2006, Meng et al. 2006, and Kehler et al. 2007).

	Ecological effect	Common indicator (measure)
Terrestrial species habitat, mortality, and stress	Fragmentation	Road density, cherry-stem density (km/km^2)
		Distance of an area from a road (m, km)
		Number, size and shape of remnant patches (ha), perimeter:area (km:km^2)
		Degree of canopy closure in road opening (%, High-Medium-Low)
		Road width (m), road type (e.g., trail, highway), traffic volume (H-M-L)
	Edge	Edge density (km/km^2)
		Exotics, predators, disease (presence or absence, number/km)
	Habitat degradation related to human disturbance	Access possible (car, 4×4, OHV, walk only)
		Resource development operation (presence or absence)
		Camp structure, camping sites (presence or absence)
		Vehicle tracks on and off existing roads (presence or absence), noise (H-M-L)
		Garbage or illegal dumping (presence or absence)
		Official and unofficial road maintenance (presence or absence)
		Proximity to urban area (km), private ownership complexity (H-M-L)
	Direct population loss	Road kill (presence or absence, number/km),
		Traps, deer blinds (presence or absence)
		Road bed, vehicle tracks (presence or absence)
Aquatic species habitat, mortality, and stress	Fragmentation	Density of bridges, culverts (per km water-course, watershed)
		Dams, ineffective bridges and culverts (presence or absence)
	Disrupted drainage	Drainage density (channel length per unit area: km/km^2)
		Roadbed compaction (presence or absence)
		Water-course diversion (presence or absence)
	Erosion	Rills and gullies proximal to roadbed, armouring (presence or absence)
		Slope (%), soil erodability (H-M-L), average annual precipitation (mL/year)
	Sedimentation	Total solids: size (μm), dissolved and suspended (μm/mL), turbidity (NTU)
		Visual evidence of sediment in streams (presence or absence)
	General water quality	Temperature (°C), pH
		Pollutants: metals, organic compounds (mg/L, μg/L)
		Chemically treated timbers (presence or absence)
		Fish or macroinvertebrate (presence or absence, richness, diversity)
		Watershed riparian road mileage (km/km^2), road distance to stream (m)
	Habitat degradation related to human disturbance	Access possible (car, 4×4, OHV, walk only)
		Resource development operation (presence or absence)
		Camps proximal to water (presence or absence), associated pollutants: coliform bacteria (presence or absence) and nutrients (mg/L, μg/L)
		OHV tracks in wet areas (presence or absence)
		Road maintenance proximal to water-course (presence or absence)
	Direct population loss	Boats, traps (presence or absence)
		Road bed, vehicle tracks (presence or absence) in wet areas

costly method, but also the most effective at treating use and presence effects. Obliteration is common practice for land managers working in mountainous regions where old roadbeds risk triggering slope failures by interrupting or redirecting the natural movement of soil and water, particularly during storm events (Moll 1996; Bagley 1998; Havlick 2002). This type of active restoration can result in short-term site disturbance, sedimentation, and other unintended impacts (Benson 2003).

Although road obliteration projects are occurring in west-

Table 4. A summary of some road-density thresholds and correlations for terrestrial and aquatic species and ecosystems (adapted from compilations in Beazley et al. 2004 and Switalski 2006).

Species (Location)	Road density (mean, guideline, threshold, correlation)	Reference
Wolf (Minnesota)	0.36 km/km^2 (mean road density in primary range); 0.54 km/km^2 (mean road density in peripheral range)	Mech et al. (1988)
Wolf	>0.6 km/km^2 (absent at this density)	Jalkotzy et al. (1997)
Wolf (Wisconsin)	0.45 km/km^2 (limited to areas of pack-area mean road density at or below this level)	Lyon (1983)
Wolf (Northern Great Lakes region)	>0.45 km/km^2 (few packs exist above this threshold); >1.0 km/km^2 (no pack exist above this threshold)	Mladenoff et al. (1995)
Wolf (Wisconsin)	0.63 km/km^2 (increasing due to greater human tolerance)	Wydeven et al. (2001)
Wolf, mountain lion (Minnesota, Wisconsin, Michigan)	0.6 km/km^2 (apparent threshold value for a naturally functioning landscape containing sustained populations)	Thiel (1985); van Dyke et al. (1986); Jensen et al. (1986); Mech et al. (1988); Mech (1989)
Elk (Idaho)	1.9 km/km^2 (density standard for habitat effectiveness)	Woodley 2000 cited in Beazley et al. 2004
Elk (Northern US)	1.24 km/km^2 (habitat effectiveness decline by at least 50%)	Lyon (1983)
Elk, bear, wolverine, lynx, and others	0.63 km/km^2 (reduced habitat security and increased mortality)	Wisdom et al. (2000)
Grizzly bear (Montana)	>0.6 km/km^2	Mace et al. (1996); Mattson et al. (2002)
Black bear (North Carolina)	>1.25 km/km^2 (open roads); >0.5 km/km^2 (logging roads); (interference with use of habitat)	Brody and Pelton (1989)
Black bear	0.25 km/km^2 (road density should not exceed)	Jalkotzy et al. (1997)
Bobcat (Wisconsin)	1.5 km/km^2 (density of all road types in home range)	Jalkotzy et al. (1997)
Large mammals	>0.6 km/km^2 (apparent threshold value for a naturally functioning landscape containing sustained populations)	Forman and Hersperger (1996)
Bull trout (Montana)	Inverse relationship of population and road density	Rieman et al. (1997); Baxter et al. (1999)
Fish populations (Medicine Bow National Forest)	(1) Positive correlation of numbers of culverts and stream crossings and amount of fine sediment in stream channels (2) Negative correlation of fish density and numbers of culverts	Eaglin and Hubert (1993) cited in Gucinski et al. (2001)
Macroinvertebrates	Species richness negatively correlated with an index of road density	McGurk and Fong (1995) cited in Gucinski et al. (2001)
Non-anadromous salmonids (Upper Columbia River basin)	(1) Negative correlation likelihood of spawning and rearing and road density (2) Negative correlation of fish density and road density	Lee et al. (1997)

ern Canada, one of the better documented is in Clearwater National Forest in Idaho, where officials estimate that, in some of the most heavily roaded areas, more than one-fourth of the land surface was at one time roaded (including roadbed, cutslopes and fill) (Havlick 2002). In an effort to maintain water quality and threatened or endangered fisheries (e.g., Chinook salmon [*Oncorhynchus tshawytscha*], steelhead [*Oncorhynchus mykiss*], and bull trout [*Salvelinus confluentus*]), forest managers have set a road-removal goal of 130–160 km per year. Actual road lengths obliterated have ranged from a low of 2.25 km in 1994 to a high of 215 km in 1998 (Havlick 2002). During the period 1992–2008, almost 900 km of roads in the Clearwater National Forest have been obliterated (Connor 2009[2]). Havlick (2002) reported that road obliteration costs in the Clearwater National Forest in the 1990s varied depending upon the treatment, but ranged from US$1200 per km to recontour a road entrance to discourage vehicle access, to more than US$6200 per km for recontouring the majority of the road (Havlick 2002). Contemporary estimates put these figures at US$3200 per km for recontouring a road entrance, and near US$100 000 per km for a full recontouring of a major haul road (Connor 2009[2]).

Obliteration projects in Redwood National Park, California (considered to be the ‘‘premier living laboratory for large-scale road obliteration and habitat restoration’’ [Havlick 2002, p. 185]), on average run between US$6 200 and US$156 000 per km (Glasgow 1993), with one documented notable exception. In 1999, obliteration of a 2.4 km section of the road adjacent to Redwood Creek cost the Park

[2] Connor, A. 2009. Restoration Program Leader, Clearwater National Forest, Idaho. 31 Dec 2009. Personal communication.

US$469 000, due to the massive volume of soil moved and gentle recontouring that was required in the sensitive riparian environment (Havlick 2002). Highly effective at terminating both presence and use effects, high costs relegate road obliteration to circumstances where important fish habitat is at risk from chronic sedimentation and acute mass-wasting events, and in steeply sloped landscapes where hydrologic function, erosion and slope instability may persist as lingering hazards over the long term.

Road-ripping is a simple, less-expensive version of obliteration where mechanical soil decompaction restores some ecological functions and discourages access. As a surface treatment, ripping has limited utility on roads that cut across slopes because the roadbed remains largely intact and can continue to disrupt surface hydrology and be susceptible to slope failure even after it revegetates (Bagley 1998; Havlick 2002). A bulldozer fitted with concrete rippers or modified lifters loosens the roadbed to promote water infiltration and reestablish vegetation. The same machines used to build the road are modified to remove it, and in some cases local operators involved in the construction have been re-employed for the restoration. For a project in the Gallatin National Forest in Montana, on relatively flat terrain, a skilled operator covered 1.6 km/h, and equipment costs ranged from US$60 to US$300 per km (Havlick 2002).

Between 1999 and 2001, 4 km of the Laverty Road at Fundy National Park, New Brunswick, were restored through road-ripping. The first of its kind for Parks Canada, managers initiated the project as a means of creating bigger, less-fragmented, more-functional wilderness, which fits their mandate to protect and restore ecological integrity. A backhoe with a rake attachment scarified the road surface to a depth of 15–30 cm allowing the restoration team to transplant small native trees and plants from the adjacent area. Staff laid coarse woody debris across the old roadbed for extra protection and support and to discourage use. Biodegradable erosion-control blankets stabilized steep grades, allowing new plants to find anchor. Erosion control also prompted trenching across the roadbed in some places to facilitate the natural flow of water. In 2007, nearly 95% of the transplants had survived and other natural vegetation was successfully regenerating, actively reducing the forest edge (Watts 2006[3]). Considerably more affordable than obliteration, road-ripping provides managers with an effective and economic method for retiring unwanted roads over long distances, discouraging use, and treating chronic presence effects. As a surface treatment, road-ripping is suitable mainly for roads in flat terrain.

Targeting use effects, road closures involve the strategic placement of gates and barricades to keep out unauthorized users, beyond which the road may or may not be maintained. Closing or removing lightly travelled roads can be an inexpensive way to reap maximum benefits with minimal disruption to legitimate activities (Moll 1996; Bagley 1998; Havlick 2002). Studies suggest that temporary barriers are often not effective at preventing motorized access (see review in Havlick 2002; Henschel 2003). Successful implementation appears to hinge heavily on the location of closure points and the promotion of alternative travel options. Positioning barricades or gates to take advantage of natural barriers (e.g., cliff, wide river) can maximize their effectiveness, preventing users from skirting around them. Landres et al. (1998) recommended posting a closure notice well in advance of a barrier to spare users the annoyance of backtracking. Ultimate success depends on the cooperation of motorized travellers.

Road abandonment describes a complete halt to all road maintenance, where the road is allowed to deteriorate gradually beyond usability (Moll 1996). While considerably slower than more active approaches, with no associated cost or effort with it, abandonment is an attractive option for managers, and in many cases is the default. This may be an acceptable solution in remote areas not burdened by unauthorized use, where roads pose no threat of slope failure or chronic sedimentation problems. However, potential damage from re-routed streams and resulting siltation arising from plugged culverts are an important consideration (Bagley 1998). Coupled with more-active mitigation techniques strategically applied at stream crossings (bridge and culvert removal, drainage restoration) and at the entrance of closed roads (barriers, recontouring to discourage or hide use), passive abandonment can be highly effective and economical in appropriate settings (Havlick 2002).

Challenges to mitigating forest road impacts

Road development is a long-term process and roads affect forest ecosystems at complex spatial and temporal scales (Angermeier et al. 2004). Although many mitigation measures exist, specific and cumulative effects are difficult to evaluate because they extend into the surrounding landscape unevenly and species and ecosystems are not equally affected. Inability to identify precisely how biota are affected is often cited as a main reason that planners and land managers do not pursue road mitigation opportunities (Trombulak and Frissell 2001; Weller et al. 2002; Forman et al. 2003; Angermeier et al. 2004).

In North America, road rehabilitation projects and management reform undertaken by US federal land management agencies within the last decade are a testament to the growing understanding of road ecology and benefits of road mitigation techniques. In 2000, the US Forest Service (USFS) updated the transportation management sections in its regulations (36 CFR 212) and Forest Service Manual (FSM 1920 7700) to include a road analysis process (RAP) (USDA 1999) that incorporates consideration of ecological effects of roads, the economics of road management and maintenance, the social and economic costs and benefits of roads, and the contribution of roads to management objectives (USDA 2001*a*). The intent is to integrate RAP results into watershed analysis and landscape assessments to reduce the impact of roads on habitat connectivity, slope stability and water quality (Moll 1996; USDA 1999; USDT 2000, 2004; reviews in Forman et al. 2003). In 2001, the USFS went so far as to create the *Roadless Area Conservation Rule* (USDA 2001*b*); it contains popular and progressive regulations that restrict road construction in most remaining roadless areas in national forests. Repealed by the Bush Administration in May 2005, it was reinstated in September

[3] Watts, J. 2006. Warden, Parks Canada, Fundy National Park, New Brunswick. 9 May 2006. Personal communication.

2006 following a court decision that the repeal violated the *National Environmental Protection Act* and the *Endangered Species Act* (HFC 2007). The USFS has a publicly stated goal of expanding unroaded areas by 5%–10% through decommissioning up to 160 000 km of roads over the next 20 to 40 years (USDA 2001*a*). Between 1998 and 2003, the USFS claims to have retired over 17 000 km of roads (Switalski et al. 2003).

Measuring and addressing ecological effects of road networks is consistent with legal responsibilities of American public land management agencies. The *Federal Land Policy and Management Act*, the *Endangered Species Act*, and the *National Environmental Policy Act* legislate the prioritization of particular activities such as protection of endangered species over other potential uses — including the construction of roads (Brown 2006). Despite legislative incentive, some maintain that the process for roads analysis and decision-making is still applied "project by project" and does not include the full suite of experts needed to assess landscape-level environmental impacts adequately (Girvetz and Shilling 2003; Angermeier et al. 2004). Ultimately, even the most progressive legislation is only as strong as its application and enforcement.

In Canada, implementation of forest road mitigation techniques is mostly voluntary and policies vary by province. Due to its mountainous terrain and risk of road-induced slope failure, British Columbia has the most comprehensive regulations and policies pertaining to construction, maintenance, and removal of forest roads. The *Forest Practices Code of British Columbia Act* contains extensive regulations for the layout, design, construction, maintenance, and deactivation of roads and stream crossings. It also requires terrain-stability field assessments. Most other provinces and territories offer only guidelines for road construction, stream crossings, and road decommissioning on public forest lands. Direction is provided on how to determine the location of individual roads, but there is no requirement for a comprehensive plan for the development of road networks across the landscape. If existing guidelines were upgraded to regulations and enforced, they could improve environmental conditions and reduce some of the environmental degradation associated with road construction and use (CCFM 2000). More-significant improvements would come from regulatory oversight of road network planning.

Consensus among some experts is that the new science of road ecology is not widely enough applied (Trombulak and Frissell 2001; Angermeier et al. 2004; Forman 2004; Switalski and Noss 2004; CPAWS 2006). Landscape-scale ecological models are data-intensive and critics argue that relevant results require detailed region-specific field research to validate the parameters used. The use of models in multi-species analyses is often considered impractical and expensive (van der Grift et al. 2004), especially when costs associated with long-term road maintenance and mitigation are not considered. Land-use decisions that attempt to incorporate more-ecologically-sensitive transportation planning and mitigation can be politically unpopular, particularly if they are viewed as competing with resource development interests and impinging on freedoms of the travelling public (Noss 1995; Angermeier et al. 2004; Perz et al. 2007). Agencies limited in budget and expertise are often intimidated by the multi-disciplinary nature of road-related issues (Trombulak and Frissell 2001; Weller et al. 2002; Forman et al. 2003; Angermeier et al. 2004). Widespread and long-term ecological impacts of forest roads and the economic burden of maintaining them need to be more accurately considered by planners and managers before we are likely to witness a meaningful shift toward creating and adopting land-use policies that support more-affordable, less-ecologically damaging forest road networks (Havlick 2002). Fundamental to this shift in management priorities is effective communication and application of road ecology (Angermeier et al. 2004).

Framework part 2: A five-step assessment approach

A systematic assessment approach is proposed here to help managers conceptualize ecological effects of forest roads and improve their decisions around road development and management. It is modeled after a framework developed by Angermeier et al. (2004) to assess road impacts on aquatic biota and draws on ecological classifications of road impact described by Trombulak and Frissell (2001), Havlick (2002), Forman et al. (2003), and Jaeger et al. (2005*a*). Steps in the approach (Fig. 4) are described in the following paragraphs. A case study illustrating its application is summarized briefly later in this paper.

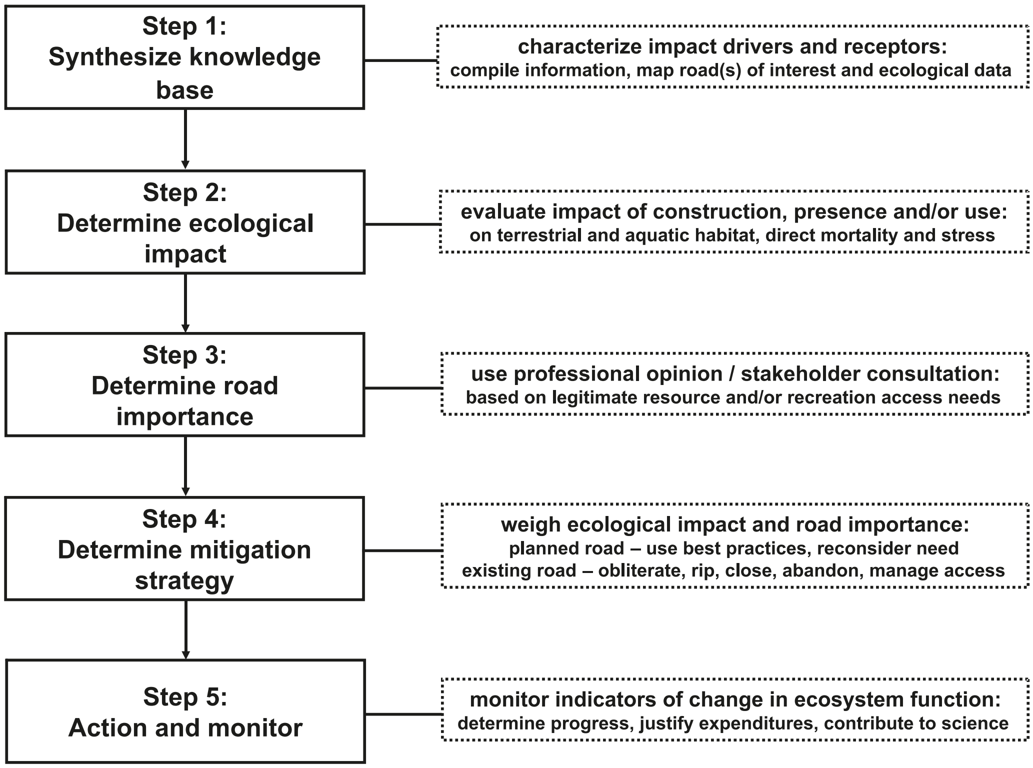
Step 1: Synthesize knowledge base

The initial step synthesizes available data on the forest road and its potential impacts. First, the manager will need to consider what impact drivers may be at play. Are the potential effects related to road construction, road presence or road use? What other characteristics of the road might influence its impact (e.g., road width, traffic volume, vehicle types)? What is the scale of the management unit being considered — a road segment or network of roads, within a forest stand or a watershed? Next, potential receptors should be characterized. What are the physical (e.g., geomorphological), biological (e.g., focal species), and chemical (e.g., water quality) components of the natural landscape potentially influenced by the road or road network? Managers tasked to answer these questions should consult information that summarizes known ecological effects of roads, such as that presented here.

Forest road information and ecological data may already exist such as regional species datasets, maps, and aerial and satellite imagery, but may need to be updated or supplemented with a field investigation. For example, the physical condition of roads and stream crossings, human and animal use patterns, and forest cover may change over time and should be verified. All of this information is best compiled and mapped using GIS to facilitate interpretation and communication of effects, but paper copies of regional or site maps can also be hand-labeled and highlighted to convey areas where impact is expected or known to occur.

With existing data spatially displayed, indicators of local and landscape-level effects can be targeted for further investigation to discern accurately the pathways and effect variables linking forest roads to terrestrial and aquatic species persistence (described in Figs. 1, 2, and 3). Local impacts

Fig. 4. A five-step approach designed to assess ecological effects and importance of forest roads, and inform road development and management that minimizes impact.



generally occur where drivers (e.g., roads) and receptors (e.g., wet areas) overlap, while landscape concerns may be more difficult to pinpoint (e.g., fragmented focal-species habitat and key linkages). Managers should choose a set of indicators from those listed in Table 3 that are relevant to the area of interest (e.g., slope measurements are not necessary in areas with relatively flat terrain) and provide the best measures of road influence given the data available. To ensure that indicators of the highest quality are used, data gaps should be noted and efforts made to collect new data if necessary.

When satisfied with the amount and quality of information compiled, managers can use a form similar to the one in Fig. 5 to help organize the data collected in this first step. The information catalogued in the form is a useful reference in subsequent steps of the interpretation, highlighting strengths and gaps in the dataset. It is important that managers select the most appropriate and relevant indicators, as they will inform the development of the mitigation strategy in step 4.

Step 2: Determine ecological impact

Determining the degree of ecological impact caused by the construction of a new forest road or the presence and use of an existing road is done through an informed review of the indicators examined in step 1. An assessment form (e.g., Figure 5) can help ensure that impacts are reviewed and documented in an organized and consistent fashion. A matrix that relates the three impact drivers or phases of road existence (i.e., construction, presence, use) and four effect variables influencing ecological response (i.e., terrestrial and aquatic habitat, direct mortality, and stress) can be used to organize and evaluate overall ecological impact of a proposed or existing road on the forest ecosystem in question (Fig. 6). Modeled after a framework proposed by Angermeier et al. (2004) for assessing impacts of roads on aquatic biota, this matrix consists of 12 cells, where each cell's relative status reflects the magnitude of expected effects derived from field observations and spatial analysis of local and landscape indicators of road influence, chosen from the list of relevant indicators in Table 3.

For simplicity, impact is described as low or high. Best available scientific information and professional judgement inform each rating and, wherever possible, additional investigation to verify assumptions is made. Ideally, site-specific, scientific investigation would support each cell rating. In reality, for many site evaluations, managers will need to form a professional opinion based on available evidence and similar studies elsewhere. Managers should accompany their matrix results with a written interpretation providing justification for their choice of effect indicators used to inform each cell rating (e.g., use of road-density thresholds for fragmentation, presence or absence of erosion evidence, type of vehicle used to access recreation sites). Higher confidence is placed in results that are grounded in the assessment of several reliable indicators of effect. Cell ratings provide a basis for prioritizing monitoring, mitigation, and restoration efforts, described in step 4. It is important to acknowledge uncertainty in some of the cell ratings to maintain credibility in the assessment and ensure the highest degree of confidence in final recommendations for a remediation strategy (Antunes et al. 2001; Duinker 2001; Geneletti 2003).

The framework and assessment approach guide managers and stakeholders through a wide range of possible ecological consequences of roads in forests and promote informed deci-

Fig. 5. An assessment sheet summarizing the relevant information gathered during step 1 of the road analysis process. Examples of possible qualitative and quantitative measures of ecological impact for each indicator listed are provided in Table 3.

Forest Road Assessment Summary Sheet	
Performed by:	Date:
Location:	
Road:	
Species and/or sensitive ecosystems potentially influenced:	
Impact drivers: ☐ construction ☐ presence ☐ use Effect variables: ☐ terrestrial habitat ☐ aquatic habitat ☐ direct mortality ☐ stress	
Ecological Effect	**Indicator (observation, measurement)**
Terrestrial, presence	
fragmentation	
edge	
Terrestrial, use	
resource development	
recreation pressure	
Aquatic, presence	
fragmentation	
disrupted drainage	
erosion	
sedimentation	
general water quality	
Aquatic, use	
resource development	
recreation pressure	
Overall comments	
Terrestrial habitat:	
Aquatic habitat:	
Direct mortality:	
Stress:	

sions. It provides them with the opportunity to consider and explain interpretations of the data. The matrix may be applied when scoping environmental consequences of proposed roads, assessing impacts of existing roads, or even in gauging the thoroughness of an environmental impact assessment of a proposed or existing road (as in Angermeier et al. 2004). As an added benefit, the approach helps to highlight gaps in regional and site-specific scientific knowledge, providing focus for future research efforts.

Step 3: Determine road importance

Most often, roads are built in forests because someone has determined that access to a particular resource is important. In some cases, however, construction has outpaced a thorough assessment of legitimate need. Historically, this is especially true where the rush to secure access for timber extraction and forest-fire suppression accompanied advances in road-building technology — such as the invention of the bulldozer in the 1920s (Havlick 2002). Access defined importance, without any consideration given to the ecological values of roadless areas. Today in many places in North America, the pace of road construction has slowed somewhat as vast road networks already provide substantial access to much of the continent. Furthermore, budgets for

Fig. 6. A matrix for evaluating the ecological impact of forest roads. Indicators of impact on terrestrial and aquatic habitat, direct mortality, and stress on a species are evaluated for each of the three phases of road existence. Cells are ranked as low or high likelihood of significant impacts occurring. Assigned ranks are based on a professional interpretation of the best available region-specific scientific data and results from similar studies elsewhere (after Angermeier et al. 2004).

	construction	presence	use
terrestrial habitat	low – high	low – high	low – high
aquatic habitat	low – high	low – high	low – high
direct mortality	low – high	low – high	low – high
stress	low – high	low – high	low – high

road-building and maintenance are increasingly being squeezed (Havlick 2002), and public demand for environmental protection has grown. Substantial new road-building is most likely to occur when the economic value of a resource justifies the expense, and is made easier when ecological values are neglected or marginalized during planning and construction (e.g., rainforests in the Brazilian Amazon [Perz et al. 2007], oil and gas reserves in the Canadian north [Plotkin and McEachern 2006; The Pembina Institute 2006]). Ultimately, a judgement of road importance relies on opinions that are rooted in personal or societal values.

Whether planning new roads or assessing priorities for existing ones, decisions on importance should be based on practical and legitimate resource and (or) recreation access needs. It is prudent that consideration of road importance include adequate forecasting of expenses to cover maintenance that will ensure the road's long-term safety and environmental compliance. The degree of potential or existing ecological impact determined from step 2 above should provide a useful basis for accurate maintenance forecasting.

For recreation managers and foresters, a rating of high or low importance will be subjective and may fluctuate throughout the year or lifespan of the project, with active times off-set by dormant times. Typically, important routes for forest managers will be those that facilitate the most cost-efficient access to and extraction of timber. Short- and long-term plans for timber harvest and silviculture will also influence the importance rating. For example, a main haul road accessing a number of stands scheduled for selection harvest and siliviculture treatments over a number of years may have greater importance than a spur road used to access a stand that is clearcut and left to regenerate naturally.

Managers determining importance of roads for recreation activities in forests on public land must decide if benefits of easy access compromise ecological values, and in some cases the backcountry experience sought by users. Consultation with legitimate stakeholders is a key step in determining importance for recreation as their opinions and cooperation will factor heavily in the success of any plan to mitigate ecological impact or restore wilderness (Landres et al. 1998; Benson 2003; USDA 2007). Because the importance of a particular forest road will vary depending on the stakeholder group consulted, discussions can provide managers and users with an opportunity to explore creative mitigation strategies (e.g., seasonal access, closure of redundant roads) and educate one another on actual ecological and economic costs and benefits associated with various road mitigation scenarios.

Step 4: Determine mitigation strategy

It is widely recognized that to preserve and restore threatened native biodiversity, forest managers must avoid building new roads in roadless and sparsely roaded areas, and mitigate impacts of existing road networks (Noss and Cooperrider 1994; Soulé and Noss 1998; DeVelice and Martin 2001; Trombulak and Frissell 2001; Havlick 2002; Forman et al. 2003; Switalski et al. 2004). Steps 2 and 3 provide relative indications of a road's ecological impact and importance. In step 4, these two factors are compared for each phase of road existence (construction, presence, and use) to help managers determine appropriate strategies that will make forest road influence acceptably small (see Figs. 7, 8, and 9).

As indicated in Fig. 1, road construction causes immediate impact on a forest in a number of ways. Some of these impacts such as noise and sedimentation can be lessened, but many others such as vegetation removal and altered hydrology are difficult to avoid. Weighing potential ecological impact against road importance can guide strategies to mitigate effects of construction activities (see Fig. 7). For example, if the placement of a potential road is predicted to have relatively low ecological impact and it is considered essential to the forestry operation (high importance), best practices in road construction should be followed to ensure impacts are acceptably small. Carefully installed bridges and culverts (e.g., use of silt fences) will lessen immediate disturbance to natural drainage and water quality. A narrow road that maintains a closed canopy minimizes many effects associated with forest edge. In situations where the proposed road has high importance but is predicted to have high ecological impact, forest managers should consider the use of temporary roads (with removable bridge decks, controlled access). Construction should be timed to minimize stress for relevant species (e.g., avoiding periods of bird nesting, amphibian migration, and flowering of rare and sensitive flora). Timelines for decommissioning should be included in the land-use plan to reduce the likelihood of long-term presence and use effects.

Once initiated, use of public roads can be difficult to discourage, so roads built to access resources should be limited to that purpose (e.g., gates and signs to discourage use). In

Fig. 7. A decision matrix for weighing potential ecological impact and road importance to determine appropriate strategies for mitigating impacts associated with the construction of forest roads.

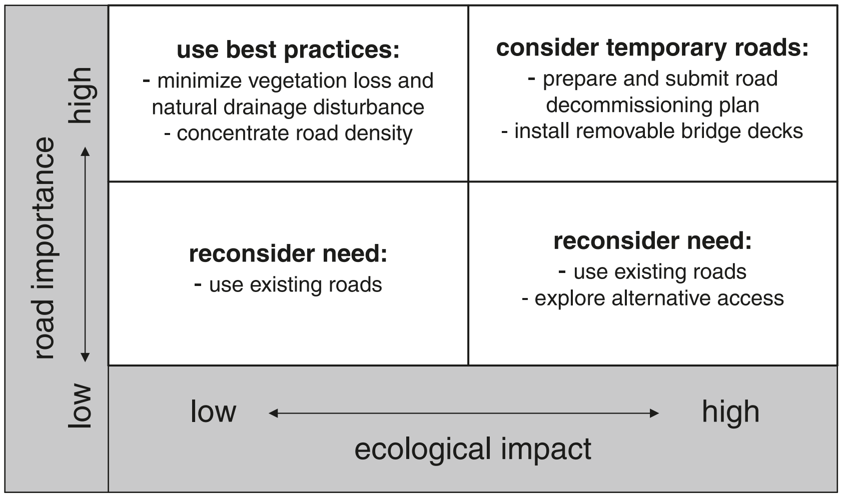


Fig. 8. A decision matrix for weighing ecological impact and road importance to determine appropriate strategies for mitigating impacts associated with the physical presence of forest roads.

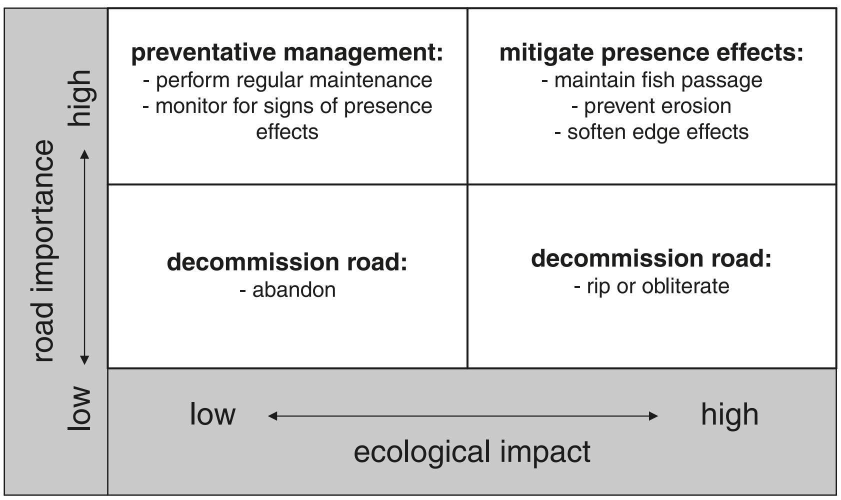
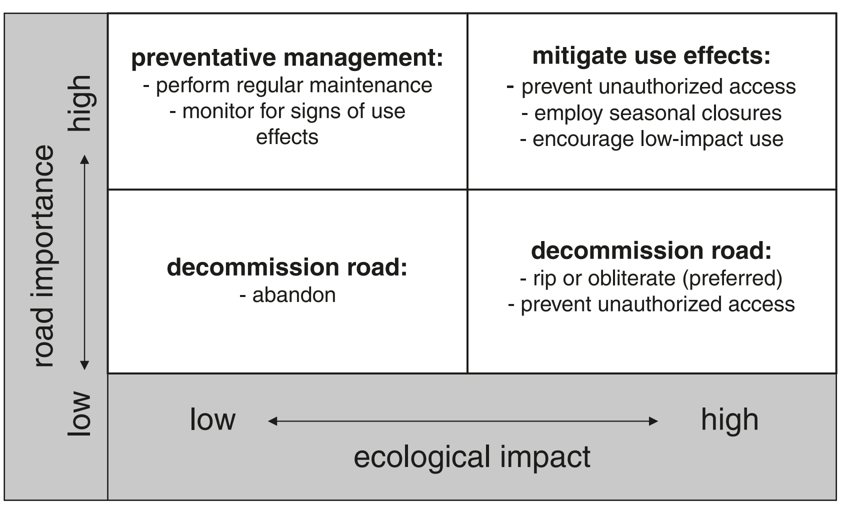


Fig. 9. A decision matrix for weighing ecological impact and road importance to determine appropriate strategies for mitigating impacts associated with human use of forest roads.



general, if access to a particular area is determined to be highly important, alternative options to use existing roads should be thoroughly explored wherever possible. In cases where the need for expanding road access cannot be avoided, road influence should be concentrated spatially to preserve remaining roadless areas. Every precaution should be taken to limit stream crossings and avoid sensitive ecosystems (e.g., wetlands) and important habitat for threatened species. Short-term impacts associated with road construction are best managed through adherence to ecologically sound road-building practices and development and implementation of regionally appropriate, well-enforced guidelines (if they exist). When the importance of a new road to overall forest management is rated as relatively low, in the interest of reducing overall road density managers should reconsider the proposal, even if the potential impact is considered relatively benign.

A matrix-style approach can also be used for considering mitigation options associated with road presence and use (see Figs. 8 and 9). Here the magnitude of measured and inferred ecological impacts is compared to importance ratings associated with present and predicted resource and (or) recreation access needs. Preventive maintenance and monitoring are recommended for important roads that are not exhibiting substantial impacts associated with presence and use. In cases where a road is providing essential access but has a high impact rating, regular monitoring and maintenance are required to reduce safety hazards and ecological damage, especially aquatic presence effects (e.g., blocked fish passage, erosion and siltation at stream crossings). However, managers should be aware that certain maintenance activities can exacerbate some effects by maintaining physical edge, promoting greater use, and preventing restoration of natural drainage. Efforts to make these kinds of effects acceptably small should occur wherever possible.

Roads with low importance are considered no longer to have a legitimate purpose and should be considered for decommissioning. The degree of ecological impact will initially dictate the appropriate mitigation strategy in these cases. Road abandonment is a viable option where presence and use effects are rated as low. More-active decommissioning (e.g., obliterating, ripping or preventing access) is preferable to prevent further ecological damage where impact is found to be high. As discussed previously, significant cost differentials exist among these options. Therefore the strategy chosen will likely depend on the finances available.

In situations where land managers are contemplating new roads, they are encouraged to consider mitigating the potential effects through mechanisms of compensatory habitat creation (Morris et al. 2006) and biodiversity offsets (Kiesecker et al. 2009) and credits (Bruggeman et al. 2005). Such approaches are increasingly being supported with powerful analytical methods (e.g., Bruggeman et al. 2005). For a variety of reasons, though, particularly the challenge of monitoring and enforcement, these approaches need to be considered with caution (Morris et al. 2006; Quigley and Harper 2006; Burgin 2008).

Step 5: Action and monitor

The final step in considering and managing ecological effects of proposed and existing forest roads is to implement the mitigation strategy and establish a program to track the changes in ecosystem function that result. This step applies whether the decision is to build a new road, maintain an existing one, or remove one that is no longer needed. Many forest managers already monitor their roads on a regular basis to determine maintenance requirements. Monitoring for broader ecological impact should be incorporated once managers identify the relevant indicators of road influence for their particular location. For example, areas to target for monitoring can be determined from the locations identified in steps 1 and 2 of the process where impact is expected or has already been measured (e.g., stream crossings, key habitat linkages). Prominent indicators of ecological effect identified during step 2 can be used to make a checklist for monitoring purposes (e.g., presence of sediment, presence of road kill). This can be expanded to include surveys that will measure revegetation, channel adjustment, and mass failure following road decommissioning. Protocols for monitoring species composition and abundance in the areas affected, animal movement patterns, and the rate and frequency of colonization of patches of suitable habitat by species previously present have also been proposed. The reader is referred to Townsend and Switalski (2004) and the references therein for guidance. Monitoring should be timed to capture seasonal variations associated with certain potential effects (e.g., presence of migratory species, rainfall amounts). Managers should be prepared to modify the objectives of the monitoring program over time in response to results (e.g., frequency, parameters investigated) and modify mitigation strategies if they are not proving effective.

A key component of any road-restoration project, monitoring results are used to justify expenditures and provide much-needed data on how effective these types of initiatives are in improving ecological function (Benson 2003; Switalski et al. 2003; Forman 2004; Switalski et al. 2004). To date, peer-reviewed scientific research about the effects of road decommissioning on wildlife, vegetation, and stream integrity is scarce (Townsend and Switalski 2004; Holden 2007).

Case study: Indian Fields Road, Southwestern Nova Scotia

The proposed framework was tested on a publicly owned Provincial Crown forest road in southwestern Nova Scotia suspected of significant ecological impact. The Indian Fields Road is a 17.2 km gravel road with at least a 40-year history of vehicle use for forest management including timber harvest, silviculture, and forest-fire suppression (Smith 2004; Swaine 2006[4]). No longer used for forest management, today it is almost completely surrounded by the Tobeatic Wilderness Area, a provincial protected area. The route receives intermittent truck and OHV traffic, primarily to access legal and trespass camps and popular fishing, hunting, and trapping sites within the Tobeatic. The road is excluded from

[4] Swaine, A. 2006. Assistant Supervisor, Nova Scotia Department of Natural Resources, Shelburne, NS. 27 Nov. 2006. Personal communication.

the protected area and public vehicle use is permitted. The role of the protected area in preserving connected, functional ecosystems may be jeopardized by roads that fragment neighbouring lands and penetrate its core, for example the Indian Fields Road. The Tobeatic Wilderness Area Management Plan (NSDEL 2006) lists addressing environmental, enforcement and public safety issues related to vehicle use along this route as a "priority action", making it an appropriate candidate for testing the framework. Results of the framework analysis are highlighted below, organized according to each of the five steps in the framework. For more detail on this case, see Robinson (2008).

Step 1: Knowledge base

The potential pathways through which the presence and use of the Indian Fields Road may influence the surrounding forest ecosystem were captured in impact-hypothesis diagrams (see Figs. 2 and 3), particularly the main effect variables (e.g., amount and quality of terrestrial and aquatic habitat, direct mortality, and stress of species). Indicators of individual, direct, localized, and acute impacts were targeted through a field program, while cumulative, indirect, dispersed, and chronic impacts were examined on a regional scale using GIS. Spatial information about the road and the local and regional ecological receptors potentially affected by it were compiled and mapped using a GIS, from digital geographic data provided by the Province of Nova Scotia (NSDNR 2006; NSGC 2006). These data include forest cover, ecological land classification (based on soil texture, drainage, and topography), hydrological features (e.g., lakes, rivers, steams, and wetlands), contours, land ownership and Wilderness Area boundaries. Crown land managers from Nova Scotia Department of Natural Resources (NSDNR) and Nova Scotia Department of Environment and Labour (NSDEL, now Department of Environment), and representatives from the Queens County Fish and Game Association and the Tobeatic Wilderness Committee were contacted for insight into management challenges (e.g., maintenance, costs) and public use patterns of the road.

Step 2: Ecological impact

The overall ecological impact of the Indian Fields Road was assessed by considering cumulative effects organized according to the assessment sheet in Fig. 5 (see Fig. 10) and studies summarizing species sensitivities to roads (Tables 2 and 4). Impact was determined to be high, since road presence and use are having a significant negative influence on both terrestrial and aquatic habitat for sensitive and threatened species. For example, important interior forest habitats for endangered moose (Parker 2003), marten (Hargis et al. 1999), and sensitive woodland bird species (Ortega and Capen 2002) are fragmented and degraded by 34.4 km of road-edge. Deer that may carry *P. tenuis*, the parasite harmful to moose (Pulsifer 1995; Parker 2003), are provided easy access to moose habitat along the road. Scotch broom (*Cytisus scoparius*), an invasive species, is present in at least one location along the roadside (Cameron 2006[5]; Helmer 2007[6]). Erosion and sedimentation at three major stream crossings suggest that aquatic habitat is compromised. Timbers in two of three bridges are creosote-treated and could provide a source for PAH contamination (Hutton and Samis 2000). In several road locations, ponded water and rutted sections due to poorly functioning culverts imply disturbed natural hydrologic processes. Disturbances caused by motorized vehicle access include illegal use of OHVs on spur trails within the Wilderness Area. The road provides easy access to camps and popular fishing, hunting, and trapping sites within the Tobeatic — places that have become epicentres for noise, garbage, and fire (NSDEL 2003). Consequently, ecological impacts related to road use are considered to be high, primarily due to habitat degradation and disturbance caused by motorized vehicle access.

Step 3: Road importance

Forestry resource interests along this route were found to be negligible (Eldridge 2006[7]). Recreational use is decreasing and likely to decrease further due to recent government initiatives to retire campsite leases within the Tobeatic (NSDEL 2006) and to develop a designated province-wide OHV trails network, where OHV use on Crown lands will be limited to routes that avoid vulnerable areas (Province of Nova Scotia 2007). The current sporadic OHV use is causing considerable management headaches and conflicts with overall management goals for the surrounding Wilderness Area (NSDEL 2006). Enforcement and maintenance costs to reduce liability and environmental damage associated with continued motorized recreation access are significant (Swaine 2006[4]) — a valid consideration when determining overall importance. Given these factors, legitimate road importance is considered to be low.

Step 4: Mitigation strategy

Preferred mitigation options for a road found to have high ecological presence and use impacts and low importance include active decommissioning (rip or obliterate) and preventing unauthorized access (see Figs. 8 and 9). An efficient and effective strategy could combine relatively low-cost active mitigation techniques in specific localized areas with passive restoration methods along the remainder of the road. In this case, removal of the longest of the three bridges would effectively eliminate many of the use effects associated with this route. The river at this location is too deep and treacherous for OHV users to cross without a bridge. Without vehicle use, the remaining three-quarters of road beyond this bridge would gradually disappear. Active measures could be used to help restore natural drainage (e.g., culvert and ditch removal) and soften the road edge (e.g., felling trees over the right-of-way) where road presence effects are most obvious. Scotch broom could readily be eradicated. Active, cost-effective methods could include removal of key culverts and bridges and

[5] Cameron, R. 2006. Ecologist, Nova Scotia Department of Environment and Labour, Halifax, NS. 26 Sep 2006. Personal communication.
[6] Helmer, L. 2007. Protected Areas Coordinator, Western Region, Nova Scotia Department of Environment and Labour, Bridgewater, NS. 7 Feb. 2007. Personal communication.
[7] Eldridge, B. 2006. Forester, Nova Scotia Department of Natural Resources, Tusket, NS. 27 Nov. 2006. Personal communication.

Fig. 10. A summary of information gathered for the assessment of the Indian Fields Road, southwestern Nova Scotia. The field investigation took place between 20–23 August 2006.

Forest Road Assessment Summary Sheet	
Performed by: *Clare Robinson*	Date: *August – September 2006*
Location: *southwestern NS, Yarmouth-Shelburne county boundary*	
Road: *"Indian Fields Rd." – Crown road from Indian Fields to Silvery and Demoliter Lakes*	
Species and/or sensitive ecosystems potentially influenced: *Tobeatic Wilderness Area (large interior forest, lakes, rivers, barrens, wetlands), endangered mainland moose and marten, rare coastal plain flora, top-level predators (e.g. fisher, black bear, otter, bobcat), furbearers, flying squirrels, woodland and wetland birds, brook trout (NSDEL 2006)*	
Impact drivers: ☐ construction ☑ presence ☑ use Effect variables: ☑ terrestrial habitat ☑ aquatic habitat ☑ direct mortality ☑ stress	
Ecological Effect	**Indicator (observation, measurement)**
Terrestrial, presence	
fragmentation	*road width: min = 2.5 m, max = 6.0 m (for 1.5 km between two S-most bridges), avg = 3.0 m, L-M canopy closure, bisects SE corner of TWA*
edge	*34.4 km of edge in otherwise interior forest, deer penetrating moose habitat, exotics: Scotch broom (Cytisus scoparius) (Cameron 2006, Helmer 2007)*
Terrestrial, use	
resource development	*30 y.o. old white pine (P. strobus) and red pine (P. resinosa) plantations, no market value at present, road not maintained (Eldridge 2006)*
recreation pressure	*OHV and 4x4 tracks/spurs, camps (private inholdings/leases), tent sites (e.g. Silvery Lk.), portages, deer blinds, traps, roadkill, garbage, forest fire (e.g. Wallace Lk. 2003). Moose poaching concerns (Dagley 2006, Rice 2006). Bridge replaced due to pressure from motorized users (Swaine 2006).*
Aquatic, presence	
fragmentation	*at least 12 ineffective culverts (e.g. clogged, collapsed)*
disrupted drainage	*roadbed compaction, potholes, water-course diversion (e.g. ditching, ponded water)*
erosion	*rills, gullies, lack of armouring at some stream crossings (e.g. at new bridge and Beaver Creek)*
sedimentation	*visual evidence of sediment in stream (e.g. at new bridge and Beaver Creek)*
general water quality	*creosote treated timbers in two old bridges (Upset Falls and Beaver Creek)*
Aquatic, use	
resource development	*n/a – no active development, road maintenance (e.g. forestry-related)*
recreation pressure	*OHV and 4x4 tracks/spurs in wet areas, boats, traps, over-fishing concerns (e.g. Silvery Lk., Stoney Bk.)(Swaine 2006, Dagley 2006)*
Overall comments	
Terrestrial habitat: *indicators of fragmented/degraded interior forest habitat, altered hydrology, exotics, major forest fire*	
Aquatic habitat: *indicators of fragmented/degraded habitat, altered hydrology, sedimentation*	
Direct mortality: *indicators of poaching, disease (moose)(Parker 2003), over-fishing (brook trout)*	
Stress: *indicators of stressed moose population (deer: competition, disease)(Parker 2003), OHV noise*	

road-ripping and obliteration targeted at the start of the road to deter access.

Step 5: Action and monitor

Key indicators should be tracked in a post-restoration monitoring phase. At the Indian Fields Road, these should include: (1) seasonal monitoring for erosion and sedimentation at the three main stream crossings (in response to ground disturbance during and after bridge-removal activities); (2) frequent checks for evidence of persistent motorized vehicle use along the decommissioned routes (providing indication of a reduction of all use impacts); (3) vegetation surveys of the roadbed (monitoring revegetation and the presence of exotics, such as Scotch broom); (4) wildlife detection surveys (e.g., monitoring baited track plates and using remotely triggered cameras to capture movement of large fauna along the old road corridor [Townsend and Switalski 2004]); and (5) fish and aquatic macroinvertebrate population studies (providing indication of reduced fishing pressure and improved aquatic habitat).

Conclusion

Roads inflict myriad impacts, with complex spatial and temporal patterns, on forest ecosystems. Their influence on the persistence of terrestrial and aquatic forest species depends on a number of factors including individual species' sensitivity to road effects and characteristics of the road or road network (Forman et al. 2003; Jaeger et al. 2005*a*). Roads compromise not only the quality of remote habitat and functional connectivity of forested landscapes. They also alter the hydrology of watersheds, interfering with natural rates and pathways of surface flow and diminishing the potential for shallow soils and deep aquifers to retain water. Immediate and long-term impacts are significant. Forests fragmented by roads will likely demonstrate less resistance and resilience to stressors, like those associated with climate change (Noss 2001).

Preserving interior forest species and environments sensitive to human presence and development requires that road planners and builders understand the impacts of their work and are willing to create and enforce effective strategies and regulations that limit road influence. A comprehensive framework, like the one presented here, broadens the approach currently used in assessing ecological effects from considering individual, direct, localized, and acute impacts to also addressing cumulative, indirect, dispersed, and chronic impacts. (We caution, though, that a full cumulative impact analysis for a landscape-scale forest-road system would require the use of quantitative spatial simulation [Duinker and Baskerville 1986; Duinker and Greig 2006]). Informed managers can make better choices regarding the necessity and placement of new roads, management of presence and use effects, and appropriate mitigation options for existing roads. The case of the Indian Fields road demonstrated the utility of the framework in (1) identifying and interpreting relevant indicators of impact related to the presence and use of an existing road, and (2) highlighting important linkages between impact drivers and effect variables that can be targeted for the most appropriate mitigation strategy.

There are some limitations in this kind of assessment approach. Gaps in existing regional datasets on species and landscape features may influence the accuracy of the assessment of ecological impact. Field verification and further data collection can strengthen the reliability of extant digital information, but this is not always feasible due to fiscal and time constraints. Qualitative observations and subjective judgements are key components in the overall assessment of road importance and in determining some aspects of ecological impact. Quantitative indicators and methods are generally considered more objective and results therefore more replicable (Duinker 2001; Geneletti 2003). However, an approach such as the one outlined here that makes full use of all available information is potentially more thorough. Managers are required to justify decisions made in the assessment, which is meant to inspire thoughtful analysis and promote accountability in the results.

The framework described above admittedly deals only with the technical domains of roads in forest ecosystems. Land-management decision-makers such as forest managers must, of course, also deal with the political dimensions of roads. Using Lee's (1993) conception of trying to integrate science and politics for environmental sustainability, what we have offered in the framework is a way to organize the scientific information. As land managers mobilize processes of engaging stakeholders to determine appropriate future directions for road access into forest landscapes, the framework should be helpful for participants to order their thoughts and ensure a modicum of rationality in the debates about costs and benefits of alternative decisions. The framework is a decision-assisting tool particularly well suited to application in large heterogeneous forest landscapes; it is not a decision-making formula.

Securing greater fiscal and philosophical commitment is probably the greatest challenge for those aiming to reduce road impacts on forest ecosystems. It would appear that economic and legislative incentives need to be as compelling as the large body of evidence highlighting the ecological degradation caused by forest roads. As land managers actively employ road mitigation strategies that set important precedents, researchers must keep pace by documenting and publicizing the ecological and economic benefits that will inspire broader application.

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