Discussion Paper

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A summary of the environmental impacts of roads, management responses, and research gaps: A literature review

Patrick Daigle[1]

Abstract

There are an estimated 400 000–550 000 km of unpaved resource roads in British Columbia. These roads are used for forest, mineral, and energy development, commercial and public recreation, and in some cases for access to private land holdings. This literature summary lists road effects on terrestrial and aquatic wildlife, plant communities, and physical elements found across landscapes in British Columbia. These effects may be local or may apply to large areas. Road effects can occur during construction or with subsequent road presence, upkeep, and use. Also summarized are recommendations meant to reduce negative road effects. These include taking a strategic approach to road and access management, using structured road planning methods and tools, implementing mitigation techniques, and following up with effectiveness monitoring and reporting. The summary also provides recommendations for further studies of road effects.

KEYWORDS: *access management, mitigation techniques, planning, research needs, road analysis, road assessment, road effects, roads.*

Contact Information

1 Restoration Ecologist, BC Ministry of Environment, PO Box 9338, Stn Prov Govt, Victoria, BC V8W 9M1.
Email: Patrick.Daigle@gov.bc.ca

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Introduction

This article provides an overview of the potential environmental impacts of resource roads[1] in British Columbia. It pulls together research findings and techniques for mitigating negative road effects on wildlife, fish, plant communities, and physical elements found across landscapes in British Columbia. In addition, I review access management approaches. The information summarized includes scientific studies and syntheses as well as management publications (e.g., best management practices at site and landscape scales).

The intent of this article is to draw together and summarize the work of the many people who study or manage a broad range of environmental attributes potentially affected by roads. This information will be of interest to provincial land use planners, legislation and policy makers, foresters, biologists, road engineers, and researchers, as well as the many other specialists managing forest and range resources and amenities in British Columbia. Some readers will want a deeper understanding and information about detailed techniques for mitigating road effects on environmental values. The cited references provide details; further, many of these references are electronically linked for reader convenience.

There are, of course, numerous benefits in having roads and access, although most of these benefits are social or economic rather than environmental. Burnett (2001) summarized some benefits of forest roads, including access for fire management, recreation, and commodity extraction. In addition, resource roads facilitate public transportation, land and resource administration (e.g., research, monitoring), and traditional uses (e.g., plant or berry gathering). The Roads Analysis process (e.g., see Appendix 1 in US Forest Service 1999) poses an extensive list of social and economic questions for consideration during assessment. In some instances, there are environmental benefits; for instance, road corridors create edge habitat suitable for some flora and fauna species (e.g., crows, jays), and roads also provide travel routes for other species (e.g., wolves). In addition, transportation infrastructure can actually provide habitat (e.g., bridges may become bird nesting sites and bat roosts).

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British Columbia context

Paved and unpaved road length in British Columbia increased by 82% between 1988 and 2005 (BC Ministry of Environment 2007). On the approximately 82 million ha of land that the BC Forest Service manages, there are 400 000–550 000 km of unpaved roads (Ferguson et al. 2002; Forest Practices Board 2005a). The following two subsections provide some information about the spatial and temporal scale of road expansion and increases in road-stream crossings. Over recent decades, the environmental effects of roads and road access have received substantial and increasing interest; the final subsection briefly lists the road-related topics studied.

Road expansion in British Columbia

To portray the expansion of roads over time in southeastern British Columbia, McLellan (1990) published a figure illustrating two-wheel drive road expansion between 1952 and 1986 (see Figure 1). Although the author's paper did not include road data, this figure provides a simple graphic display of road expansion over time.

Two recent British Columbia studies document the expansion of road density around Quesnel (Caslys Consulting Ltd. 2008) and in an area west of Kamloops (Caslys Consulting Ltd. 2007). For both areas, Table 1 shows the road-density trends over a two-decade period.

The Quesnel study analyzed an area of about 2.7 million ha. This project took into account total road length and road-stream crossing trends. Overall, road length increased from 14 928 km (1986), to 30 331 km (1995), to 40 355 km (2007), with each year during this period averaging an 8% increase.

[1] Highways and municipal roads also affect the environment; however, this summary focuses on resource roads.

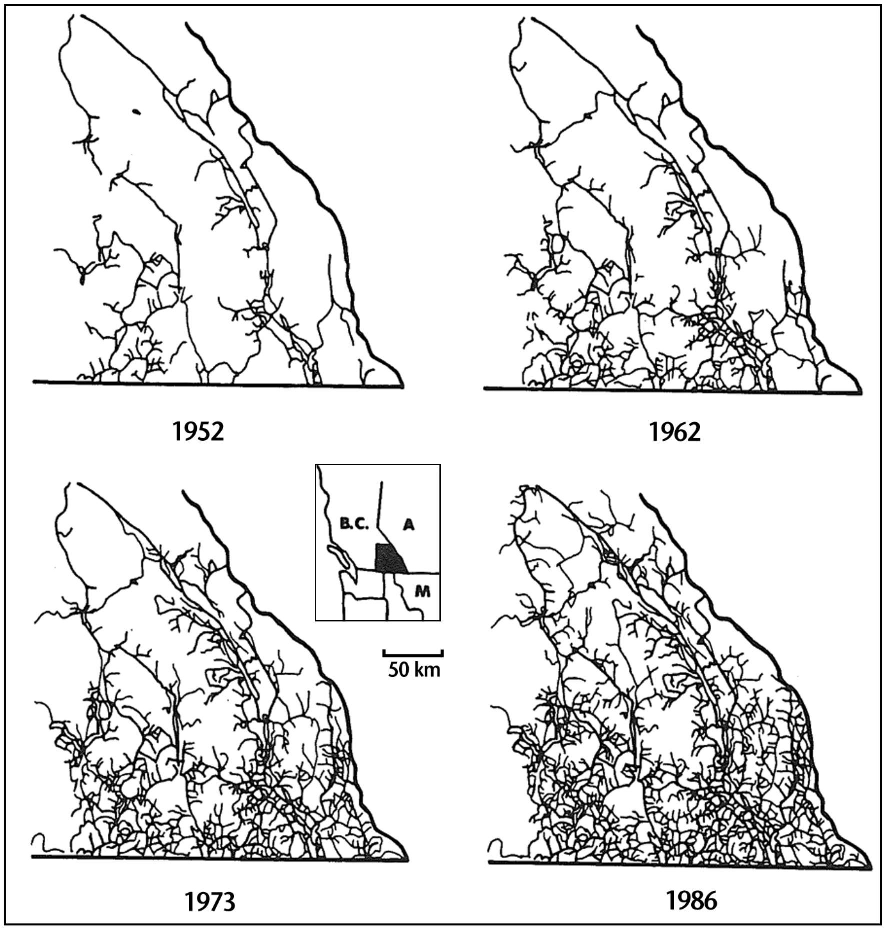

FIGURE 1. Maps of two-wheel drive roads in southeastern British Columbia: 1952, 1962, 1973, and 1986. Residence driveways and cutblock dead-end roads are not included (adapted from McLellan 1990).

TABLE 1. Road density trends in Quesnel and Lower Thompson watersheds (adapted from Caslys Consulting Ltd. 2007, 2008).

Quesnel road density (% of watersheds)			Lower Thompson road density (% of watersheds)		
Road density class (km/km^2)	**1986**	**2007**	**Road density class (km/km^2)[a]**	**1986**	**2005**
< 0.1	25.6	12.4			
0.1–0.5	28.6	11.7	< 0.5	28.0	11.0
0.5–2.0	45.5	44.6	0.5–2.0	67.0	64.4
> 2.0	0.2	31.4	> 2.0	4.9	24.6

[a] The Lower Thompson study did not provide figures for a road density class of less than 0.1 km/km^2.

Road density (expressed as kilometres of road per square kilometre) and road-stream crossing density (e.g., culverts, bridges) also increased substantially (Caslys Consulting Ltd. 2008).

The Lower Thompson study examined approximately 2 million ha west of Kamloops where road densities increased to a large extent between 1986 and 2005 (Caslys Consulting Ltd. 2007).[2]

Road-stream crossings

The BC Ministry of Environment (2007) pointed out that stream crossings (usually culverts) in British Columbia can negatively affect fish and aquatic ecosystems and reached the following conclusion:

> *Analysis shows an estimated total of 421 830 stream crossings in . . . 2000 and 488 674 stream crossings in 2005, an increase of 66 843 crossings or an average increase of 13 369 [~16%] per year (BC Ministry of Environment 2007).*

Other environmental concerns about roads and access

Diverse concerns have been expressed about the environmental effects of roads in British Columbia and thus numerous studies and projects have been undertaken. Many of these studies examined soil and water concerns and road effects on aquatic and terrestrial species and habitats. Table 2 provides an overview of road-related projects addressed in the province.

In addition, the broader theme of provincial road access management has been addressed by numerous studies and projects (McLellan and Shackleton 1988, 1989; BC Ministry of Forests 1989; McLellan 1989, 1990, 1992, 1998; McLellan and Martin 1991; Carmanah Research Ltd. 1995; McLellan et al. 1999; Terry et al. 2000; Forest Practices Board 2001, 2005a; Hamilton and Wilson 2001; Hudson 2001; Ferguson et al. 2002; Apps et al. 2004; Cichowski et al. 2004; Gayton 2007; Long 2007; Daigle 2008; Ross Porcheron, Integrated Land Management Bureau, pers. comm., 2009).

Several Forest and Range Evaluation Program monitoring projects currently focus on the effects of roads on ecosystems and ecosystem components, habitats, and species, including water quality, stream sediments, and riparian processes (Sandy Currie, BC Ministry of Forests and Range, pers. comm., 2009; David Maloney, BC Ministry of Forests and Range, pers. comm., 2009; Peter Tschaplinski, BC Ministry of Forests and Range, pers. comm., 2009), and snakes (Richard Thompson, BC Ministry of Environment, pers. comm., 2009).

To add a little history, in 1989 the BC Ministry of Forests developed *A Guide to Coordinated Access Management Planning* (CAMP), a tool to assist forest managers involved with local road access issues in areas usually ranging from 100 000 to 200 000 ha (BC Ministry of Forests 1989). A follow-up report assessed the CAMP process to learn what worked and what could be improved (Carmanah Research 1995). Although British Columbia has seen access management successes, road construction and expanded human access are still occurring as portrayed by the Caslys Consulting Ltd. projects (2007, 2008).

Environmental impacts of roads

Environmental effects of roads include spatial and temporal dimensions and biotic and abiotic components. Effects can be local (along a road segment) or extensive (related to a large road network).

In addition to direct loss of habitat and ecosystems caused by the footprint of resource roads, another spatial aspect is the "road-effect zone"[3] that can radiate out from the sides of the road and/or extend downstream where effects on aquatic conditions may be located a distance from the source. The road-effect zone also changes light conditions and disturbs soils and thus creates conditions suitable for invasive plants.

Spatial effects of roads vary because species habitat requirements and ecosystem characteristics are diverse. For example, less mobile wildlife species tend to have smaller habitats whereas wide-ranging mammal and bird requirements tend to be spread across macro-environments.

With respect to temporal dimensions, road-related negative effects may occur during road construction or from the subsequent presence, use, and maintenance of

[2] Both highways and resource roads were assessed during the projects completed by Caslys Consulting Ltd. (2007, 2008); however, the vast majority are unpaved resource roads.

[3] The effects of roads can extend over some distance from their centres such that the "effective widths" can be many times their actual widths (Gucinski et al. [editors] 2001).

TABLE 2. British Columbia studies and projects addressing diverse concerns about road environmental effects.

Road-related projects	**Study authors**
Slope failures	Toews and Brownlee 1981; Krag et al. 1986; Rood 1990; Rollerson 1992; Gaboury and Wong 1999; Jakob 2000; Carver 2001; Jordan 2001b; BC Ministry of Forests 2002b; Grainger 2002; Guthrie 2002; Kliparchuk and Collins 2003; Allison et al. 2004; Dunkley et al. 2004; Forest Practices Board 2005b; Fannin et al. 2007; Guthrie and Brown 2008; BC Ministry of Forests and Range 2009
Sediment production and transport	Toews and Brownlee 1981; Christie and Fletcher 1999; Carver 2001; Hudson 2001, 2006; Jordan 2001a, 2006; BC Ministry of Forests 2002a, 2002b; Carson and Younie 2003; Macdonald et al. 2003; Gillies 2007; BC Ministry of Forests and Range 2009; Snetsinger 2009; Hogan and Luzi (in press)
Stream and pond contamination	Christie and Fletcher 1999; Mayer et al. 1999
Groundwater	Smerdon 2009a, 2009b
Stream water temperature	Moore et al. 2003; Story et al. 2003
Peak flows and flooding	Carver 2001; Guthrie 2003
Drinking water quality	Westland Resource Group 2000; Jordan 2001a; Snetsinger 2009
Fish and stream habitat	Toews and Brownlee 1981; Tschaplinski 1994; Tripp 1995; BC Ministry of Forest 2002a, 2002b; Moore et al. 2003; BC Ministry of Environment 2007; Forest Practices Board 2007, 2009; Long 2007; BC Ministry of Forests and Range 2009; Snetsinger 2009
Stream, riparian, and watershed restoration	Polster et al. (in press)
Grizzly bears and their habitat	Archibald et al. 1987; McLellan and Shackleton 1988, 1989; McLellan 1989, 1990, 1992, 1998; McLellan and Martin 1991; Mattson et al. 1996; Wakkinen and Kasworm 1997; McLellan et al. 1999; Kunkel and Pletscher 2000; Wielgus et al. 2002; Apps et al. 2004; Ciarniello et al. 2004, 2005, 2007, 2009; Herrero et al. 2005
Carnivores and their habitat, predator–prey relationships	Boyd and Pletscher 1999; Kunkel and Pletscher 2000; Carroll et al. 2001
Mountain caribou and their habitat	Armleder et al. 2000; Stevenson et al. 2001; Cichowski et al. 2004; Apps and McLellan 2006; Serrouya et al. 2008; Apps et al. (in preparation)
Marbled Murrelets and their habitat	Burger 2002; Burger et al. 2004; Piatt et al. 2006
Wolverines and their habitat	Krebs et al. 2007
Terrestrial ecosystems	Ferguson et al. 2002
Biodiversity	Gayton 2007; Long 2007; Austin et al. 2008
Land use planning, recreation, tourism, and botanical forest products	Forest Practices Board 2001
Retaining relatively undeveloped watersheds as bio-monitoring reference areas	Fenger and Wheatley 2007
Preparing for climate change	Spittlehouse and Stewart 2003; Ogden and Innes 2007, 2009
Road expansion	McLellan 1990; Caslys Consulting Ltd. 2007, 2008

the road and its verges. Some species (e.g., amphibian species such as the salamander) have seasonal life-cycle necessities and require both aquatic and terrestrial habitats to meet their needs.

Roads may negatively affect species, habitats, and physical and chemical characteristics at the site and landscape levels. In some cases, authors group road effects into direct and indirect impacts (e.g., Gucinski et al. [editors] 2001). In another instance, Spellerberg (1998) summarized road effects as those common during construction, those along a newly completed road, and those with long-term impacts. In most reports highlighted in this article, researchers have focused directly on road effects; in other instances, researchers are testing for the effects of an array of variables including roads.

Below, road-related impacts are grouped to identify effects on: (1) soils, water, and aquatic wildlife and habitat; and (2) terrestrial wildlife and habitat. The final subsection highlights other road effects.

Soils, water, and aquatic wildlife and habitat[4]

- Increased fish mortality caused by expanded angling pressures, poaching, and management actions
- Disrupted turtle and amphibian migration patterns and population connections and increased road kills where roads bisect wetlands
- Displaced and compacted soils resulting in loss of biomass productivity
- Altered conditions that change soil pH, plant growth, and the vegetative community structure (i.e., light levels and water retention; soil displacement, temperature, and compaction; and dust)
- Reconfigured landforms can result in changed hydrologic regimes (e.g., altered water table position; interrupted groundwater flow diverted to surface systems; increased water temperatures; changes in the timing of runoff; drained natural wetland habitats; unintentional artificial wetlands; and restricted or altered channels which can result in altered streambed materials)
- Altered streamflow, particularly the timing and intensity of high and low flows
- Increased number and extent of landslides and debris flows, which can affect terrestrial and aquatic systems
- Restricted fish passage (as a result of road infrastructure such as culverts and bridges) that can block up-stream migration, eliminate or reduce access to spawning sites, and thus fragment fish habitat patches
- Reduced number, size, and depth of stream pools, which thus diminish habitat for fish and other aquatic organisms
- Disrupted large organic debris input to streams, which can affect channel morphology and alter habitat
- Reduced stream bank vegetation where roads are located in riparian areas
- Increased erosion leading to sediment and nutrient delivery to streams and wetlands, which results in adverse impacts to aquatic habitats and species (e.g., fish, their prey, and other species)
- Increased non-native fish (e.g., some people use road access to intentionally stock streams and lakes with non-native fish and thus disrupt native aquatic systems)

Terrestrial wildlife and habitat

- Increased wildlife road kills and injuries (e.g., roads warm up quickly and hence are attractive to reptiles and amphibians for basking; this can increase the incidence of road kill)
- Increased road-kill carrion that may become attractants to carrion-feeding wildlife and result in more collisions
- Increased mortality (and injuries) because of expanded hunting and trapping pressures, poaching, and management actions
- Loss of species, habitat, and vegetation (particularly when roads are in riparian areas)
- Fragmented wildlife habitat
- Altered and disrupted habitat caused by logging, human-induced fire ignition, fire suppression and exclusion, fencing, fuel-wood collection, and recreation
- Diminished habitat suitability adjacent to roads caused by edge effects

[4] The references section contains the papers used to develop the list of road effects. In several instances, numerous papers were sources for the bullets listed. To make it easier for readers, citations are not ascribed to each bullet.

- Increased human disturbance of sensitive wildlife (e.g., from noise, traffic movement, lights) resulting in habitat effectiveness being degraded
- Increased wildlife harassment and human–wildlife conflicts
- Modified wildlife behaviour (such as changes to animal movement, dispersal, or migration; home range shifts; reduced body mass, reproduction, or survivorship; habituation to human presence; road avoidance or escape responses)
- Altered predator–prey relations along artificial "hard-edge" habitat created by roads (e.g., nest predation by jays and ravens)
- Contaminant emissions (e.g., road salt, oil, gasoline, metals, or other chemicals), noise and other disturbances may extend into roadside vegetation for varying distances, resulting in changes in species composition and contaminated soil, plants, animals, and water. Road salt may attract animals which then may be killed in vehicle collisions

Other negative effects of roads

- Expanded unmanaged recreation (such as unauthorized snowmobiling and motorized off-road vehicle use) resulting in negative effects on wildlife, and degradation of soils and riparian and wetland areas
- Increased invasive alien plants and animals that establish along the colonization corridors provided by roads; in addition, non-native plant species are often sown to stabilize slopes along roads
- Increased spread of insects and disease
- Increased fuel emissions (e.g., carbon dioxide) into the airshed

Management implications and recommendations

Management recommendations presented in the reviewed literature fall into the following themes.

- Taking a strategic approach
- Using structured assessment and planning
- Planning and implementing access management
- Planning and undertaking on-the-ground mitigation techniques
- Closing and decommissioning roads
- Following up with effectiveness monitoring

These themes, which are summarized below, emerge from publications that describe the environmental impacts of roads and the management of those impacts.

Strategic and comprehensive "big-picture" approaches

Hamilton and Wilson (2001) recommended a provincial strategy for access management that addresses agency and industry responsibilities, legislation and policies, a co-ordinated planning approach, funding, and effectiveness monitoring. Long (2007), the Forest Practices Board (2005a), and Ferguson et al. (2002) also recommended development of legislation and policies to co-ordinate resource road construction and use. Forest sector professionals in British Columbia have a series of guidelines to assist in road-related planning, construction, and rehabilitation (Moore 1994; BC Ministry of Forests 1989, 2002a, 2002b, 2003; Atkins et al. 2001; Association of Professional Engineers and Geoscientists of British Columbia and Association of British Columbia Forest Professionals 2008).

The US Forest Service (2001) completed an environmental assessment of its roads, the purpose of which was to address road system development, maintenance, and funding to meet current and future land and resource objectives and uses. As part of each environmental assessment required by extractive industries, Reed et al. (1996) recommended analysis of the cumulative effects of existing and anticipated roads. Forman et al. (1995) advocated a landscape-scale planning process that assesses road route alternatives before route selection.

Structured assessment and planning

Several papers advise use of a structured approach (e.g., step-by-step) for assessing and planning roads, access management, and maintaining and rehabilitating roads (BC Ministry of Forests 1989; Furniss et al. 1991; McLellan and Martin 1991; Harr and Nichols 1993; Moore 1994; Wisdom 1996; Forman and Alexander 1998; Spellerberg 1998; US Forest Service 1999; Furniss 2000; Lewis 2000a; Lugo and Gucinski 2000; Rieman et al. 2000; Atkins et al. 2001; Gucinski et al. [editors] 2001; Luce et al. 2001; Ferguson et al. 2002; Allison et al. 2004; Wait 2004; Crist and Gehrke 2005; Forest Practices Board 2005a, 2005b; Dodson Coulter et al. 2006; Eschenbach et al. 2007; Grace and Clinton 2007; Steinfeld et al. 2007a, 2007b; Daigle 2008).

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Whether for whole transportation networks or just road segments, structured assessment can help resource and land managers clarify road-related benefits, problems, environmental risks, opportunities, and trade-offs among possible management actions. Structured planning also enables managers to more easily make informed decisions regarding the direction of limited funds to road maintenance and upgrading, decommissioning, storm patrol, seasonal closure, and the identification of roads that can be abandoned (e.g., in cases where vegetation has grown over old roads).

Comprehensive analyses can identify areas without roads or lightly roaded areas. Some project authors recommended the retention of areas without roads to exclude (or minimize) the negative road effects and to retain large wildlife refugia (Rhodes et al. 1994; Espinosa et al. 1997; Dunham and Rieman 1999; Trombulak and Frissell 1999; Borovansky et al. [editors] 2002; Crist and Wilmer 2002; Ferguson et al. 2002; Fenger and Wheatley 2007; Nielsen et al. 2009).

The US Forest Service (1999) approach to road analysis is particularly comprehensive in addressing environmental concerns about roads and access. Reports by Mitchell et al. (2003) and Weber et al. (2003) provided clear examples of road analyses conducted on US Forest Service lands. These analyses give decision makers vital information to develop safe road systems that are responsive to public needs, consider road benefits and liabilities and ways of mitigating risks, protect the environment, and are in accord with available funding for road management.

Some authors recommended using available tools to help during road planning efforts. As a first step, the US Forest Service (1999) recommended a thorough road inventory. These authors, along with Reed et al. (1996), Prasad (2005), and Black et al. (2009) pointed out that global positioning system and geographical information systems will be basic inventory tools to help during road planning, assessment, and maintenance efforts. Computer models have been developed that guide road planning and management investments to minimize stream sedimentation (Elliot et al. 1999; Elliot and Tysdal 1999; Hudson 2001; Aruga et al. 2007) and other negative environmental effects (Dodson Coulter et al. 2006; Stream-Simulation Group 2008).

Planning and implementing access management

Grizzly bear studies over a span of decades in British Columbia have recommended access management (McLellan and Shackleton 1988, 1989; McLellan 1989, 1990, 1992, 1998; McLellan and Martin 1991; Mattson et al. 1996; Wakkinen and Kasworm 1997; McLellan et al. 1999; Apps et al. 2004; Cierniello et al. 2005, 2007, 2009; Herrero et al. 2005). Likewise, mountain caribou studies over the last decade have recommended access management in British Columbia (Armleder et al. 2000; Stevenson et al. 2001; Cichowski et al. 2004).

In a comprehensive study focused on roads and access management in the province, Ferguson et al. (2002) summarized techniques, approaches, and legal mechanisms for managing access; these authors also provided detailed recommendations to prevent or manage access-related concerns.

Krebs et al. (2007) recommended that provincial land managers increase their consideration of spatial human-use data (including road density) during habitat analysis and in forecasts and land use planning. In coastal forests with maintained Marbled Murrelet habitat, Burger et al. (2004) recommended managers avoid constructing roads; the road–forest interface is "hard-edge" habitat that encourages nest predation by corvids. Piatt et al. (2006) proposed consideration of road edge effects when planning protected areas for Marbled Murrelet. To get the public to understand the environmental impacts of roads, McLellan and Martin (1991) emphasized the need to involve and educate the public when developing and implementing access management.

In Alberta, there have also been calls for road access management (Nielsen et al. 2004, 2006, 2009; Alberta Woodland Caribou Recovery Team 2005; Alberta Grizzly Bear Recovery Team 2008). In an examination of wolf–ungulate interactions and roads

(James and Stuart-Smith 2000; Hebblewhite et al. 2009), the scientists involved recommended that forest managers use existing roads, minimize new roads, and remove and restore roads (and other linear developments) after industrial use is concluded. When dealing with topographic and aquatic features (e.g., lakes) that may limit animal movement, Whittington et al. (2004) recommended restricting or reducing road density in situations where roads may further constrain animal passage.

In neighbouring Montana, Mace et al. (1996) emphasized the need to take grizzly bear seasonal habitat use into account when developing access management programs. Regarding potential alien plant invasions in nature reserves, Tyser and Worley (1992) recommended the avoidance of road construction when possible; if it is not possible to avoid road construction, they recommended that resource managers and biologists oversee the work, not just leave it to the road engineers. Regarding grizzly bears, Mace (2004) provided insights to integrate science and road access management, emphasizing ways to enhance committee teamwork that can result in useful guidance for land managers. Wisdom (1996) advised land and resource managers to minimize new road construction through improved planning and pointed out that road obliteration and closures do not mitigate all negative effects to wildlife because habitat recovery can take decades.

The decision-making process concerning access management is complex because road access management must take into account social, economic, and environmental objectives. Nonetheless, once access decisions are made, many existing site mitigation tools and actions can be used to manage road networks.

Techniques for mitigating road-related impacts

This section briefly describes some mitigation techniques as well as road closure and decommissioning methods. Because it is important to understand the effectiveness of management actions, monitoring is necessary while implementing the mitigation techniques (e.g., during construction) and after implementation to determine the outcomes.

Site-level field techniques: Planning and implementation

In some cases, the reviewed publications provided detailed site-level field techniques designed to

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mitigate the negative effects of roads on soils, water, species, habitats, and ecosystems. Table 3 identifies some environmental values and potential mitigation techniques. Many mitigation techniques focus on soil and water issues; few address terrestrial wildlife and ecosystems. These techniques may mitigate conditions along a particular road segment or site; however, in some instances it will be appropriate to close a road (storing it for future use) or decommission (obliterate or dismantle) road segments or extensive road networks.

Road closure and decommissioning techniques: Planning and implementation

Road closure may involve rather simple techniques such as gates and berms. Decommissioning may range from relatively simple site-level techniques (e.g., removing culverts) to full obliteration (e.g., extensive re-contouring of road prisms to natural slopes). To achieve specific objectives, a combination of techniques is often used during road closure or obliteration.

Many of the papers reviewed for this summary suggest the restriction of road density and traffic, or decommissioning roads to achieve specific objectives; Table 4 provides some examples. These approaches address numerous environmental concerns including soil, water, and terrestrial and aquatic animals (particularly red- and blue-listed species) and their habitats.

Other publications recommend road decommissioning for situations in which multiple environmental concerns are evident (Moll 1996; Trombulak and Frissell 1999; US Forest Service 1999; Furniss 2000; Ferguson et al. 2002; Mitchell et al. 2003; Weber et al. 2003; Crist and Gehrke 2005; Forest Practices Board 2005a; Court et al. 2006; Daigle 2008).

TABLE 3. Recommended site-level mitigation techniques to reduce the environmental impacts of roads.

Environmental values	Mitigation technique and sources
Flora, fauna, ecosystems, soils, water	Narrow the road right-of-way and roadside ditches (Roever et al. 2008a)
	Stay away from vulnerable sites by using flexible road standards, which can expand options for locating the roadbed within the right-of-way (Furniss et al. 1991)
Water, soils, aquatic resources, wetlands, riparian areas	Prepare for climate change (e.g., wetter and warmer winters) by maintaining or rehabilitating roads to minimize sedimentation (Spittlehouse and Stewart 2003)
	Identify the most serious problems by assessing road systems at watershed scale, followed by field reconnaissance (Furniss et al. 1991; Moore 1995; Luce and Black 1999; Lewis 2000a; Atkins et al. 2001; Carver 2001; Grainger 2002; Carson and Younie 2003; Fannin et al. 2007; Mills et al. 2007)
	Give extensive thought to road routes, road design, drainage, and road-stream crossings such as culverts and bridges (Krag et al. 1986; Furniss et al. 1991; Harr and Nichols 1993; Skaugset and Allen 1998; Elliot and Tysdal 1999; Elliot 2000; Lewis 2000a; Carver 2001; Megahan et al. 2001; BC Ministry of Forests 2002a, 2002b; Grainger 2002; Carson and Younie 2003; Macdonald et al. 2003; Gillies 2007; Groenier and Gubernick 2007; Robichaud et al. 2010)
	Relocate or realign roads to improve degraded wetland and riparian areas (Elliot and Tysdal 1999; US Forest Service, Riparian Roads Team 2005; Aruga et al. 2007)
	Use appropriate construction, upgrading, and maintenance methods to manage drainage and minimize erosion and sedimentation (Toews and Brownlee 1981; Skaugset and Allen 1998; US Forest Service 1999; Carson and Younie 2003; Macdonald et al. 2003; Spittlehouse and Stewart 2003; Beechie et al. 2005; US Forest Service, Riparian Roads Team 2005; Gillies 2007; Sugden and Woods 2007; BC Ministry of Forests and Range 2009; Jordan et al., in press)
	In wet meadows, install permeable fill under the road surface along with a culvert array (multiple culverts) to maintain subsurface water flow (US Forest Service, Riparian Roads Team 2005)
	Construct lead-out ditches and rock aprons to disperse water-flow energy and reduce erosion (Elliot and Tysdal 1999; Carson and Younie 2003; Beechie et al. 2005; US Forest Service, Riparian Roads Team 2005; Gillies 2007)
	Improve the engineering, construction, and maintenance of roads to reduce landslides (Krag et al. 1986; Atkins et al. 2001; BC Ministry of Forests 2002b; Beechie et al. 2005; US Forest Service, Riparian Roads Team 2005; Fannin et al. 2007)
	Restrict traffic (perhaps during the wet season) or close roads to manage sediment runoff (Rhodes et al. 1994; Tschaplinski 1994; Carson and Younie 2003; Macdonald et al. 2003)
	In burned areas, systematically assess values at risk, post-fire runoff potential, and other considerations (e.g., potential damaging storms, probability of success), then upgrade culverts, create water bars, and clean and armour ditches (Foltz et al. 2009b)
	Bioengineer slopes beside roads to reduce landslides (Lewis 2000b)
	After road construction, seed, mulch, terrace, or combine treatments to control erosion (Elliot and Tysdal 1999; Megahan et al. 2001; BC Ministry of Forests 2002a; Gillies 2007; Polster et al., in press)
Water quality, microclimates, habitat, soils	Provide vegetated buffer zones (e.g., along stream sides) adjacent to roads to reduce stream sedimentation and pollution, increase infiltration, slow surface water flow, and maintain microclimates and wildlife habitat (US Forest Service, Riparian Roads Team 2005)
Karst terrain	Design and construct appropriate roads in suitable locations (BC Ministry Forests 2003)
Native plants	Plant native plants to help control invasive alien plants (Tyser and Worley 1992; Steinfeld 2007a, 2007b; Roever et al. 2008a)
Fish, habitat connectivity	Install appropriate fish-stream crossings to improve fish passage and access to up-stream habitat (Furniss et al. 1991; BC Ministry of Forests 2002a, 2002b; Bates et al. 2003)
Wildlife	Construct fences or gates to limit human access to reduce wildlife mortality (McLellan and Shackleton 1989; Cole et al. 1997; Jalkotzy et al. 1997; US Forest Service 1999; Eubanks 2006; Roever et al. 2008a, 2008b; Fahrig and Rytwinski 2009)
	During appropriate seasons, install road-closure signs to reduce road-related pressures on animals (when road decommissioning is not suitable) (Hunt and Hosegood 2008)
Blue-listed bull trout and their habitat	Remove culverts, decommission road segments, reconstruct stream channels, and revegetate exposed soils to restore bull trout habitat (Wegner 1999)

TABLE 4. Rationale for restricting road density or traffic and decommissioning roads.

Rationale	Sources
Prepare for climate change and maximize productive forest area	Spittlehouse and Stewart 2003; Ogden and Innes 2007, 2009;
Decrease forest fragmentation	Reed et al. 1996
Reduce landslides, erosion, and sedimentation	Krag et al. 1986; Harr and Nichols 1993; Moore 1994; Connor et al. 2000; Elliot 2000; Atkins et al. 2001; Luce and Black 2001; Madej 2001; BC Ministry of Forests 2002a, 2002b; Carson and Younie 2003; Spittlehouse and Stewart 2003; Allison et al. 2004; Beechie et al. 2005; Grace and Clinton 2007; Ogden and Innes 2007, 2009; Polster et al., in press
Increase soil infiltration capacity	Luce 1997
Reduce habitat loss, animal mortality, and traffic disturbance and thus retain or increase animal abundance	Fahrig and Rytwinski 2009
Minimize invasive alien species	Parendes and Jones 2000; Cameron and Bayne 2009
Reduce mortality and retain or restore habitat for red- and blue-listed species in British Columbia, including:	
• Roosvelt elk	Cole et al. 1997
• bull trout	Wegner 1999
• boreal and mountain caribou	Armleder et al. 2000; James and Stuart-Smith 2000; Stevenson et al. 2001; Cichowski et al. 2004
• grizzly bear	McLellan and Shackleton 1989; Kasworm and Manley 1990; McLellan and Martin 1991; McLellan 1992; Mace et al. 1996; Wakkinen and Kasworm 1997; Ciarniello et al. 2004, 2007, 2009; Crist and Gehrke 2005; Nielsen et al. 2006, 2009; Roever et al. 2008a, 2008b
Reduce wolf mortality	Whittington et al. 2004; Hebblewhite et al. 2009
Reduce amphibian mortality	Andrews et al. 2006
Reduce fish mortality	Furniss et al. 1991; Harr and Nichols 1993; Moore 1994; Rhodes et al. 1994; Rieman et al. 2000; Atkins et al. 2001; Forest Practices Board 2001; Eschenbach et al. 2007; McCaffery et al. 2007

Effectiveness monitoring

Napper (2007) prepared a useful framework to develop a road decommissioning effectiveness monitoring plan. Others have developed thorough effectiveness monitoring approaches to address road-related water and riparian issues and management planning and actions (Gaboury and Wong 1999; Stonsifer et al. 2000; Kahklen 2001; Hartsog et al. 2003; US Forest Service, Riparian Roads Team 2005). Beechie et al. (2005) developed stepwise protocols and techniques for effectiveness monitoring (relatively short-term evaluation of sediments and hydrology) and longer-term validation monitoring (of biological, habitat, and stream channel effects).

Kliparchuk and Collins (2003) indicated that satellite imagery could be used to monitor implementation and effectiveness of road deactivation and rehabilitation actions. Court et al. (2006) described a citizen monitoring program to gather information on ecological recovery after roads are decommissioned; this paper explains monitoring protocols and steps to recruit and train citizen volunteers and concludes by making general observations about the benefits of the program.

Some reports focus on monitoring the effectiveness of specific management actions (e.g., removing culverts) and others assess results of full road decommissioning (see Table 5).

TABLE 5. Monitoring the effectiveness of road decommissioning techniques.

Environmental values	Mitigation technique(s) monitored	Findings, sources
Soil, water	Removed culverts; recontoured roads; stabilized stream areas; revegetated	In treated areas, soil infiltration and vegetation improved and erosion was reduced; researchers concluded 4 years was not enough time for obliterated roads to return to "forest floor" conditions, particularly with respect to soil infiltration (Foltz et al. 2007)
	Removed culverts; restored natural drainage; recontoured or ripped roadbeds; relocated unstable soils	Though sediment yields were considerably reduced, treatments did not fully eliminate road-related erosion (Madej 2001)
	Examined road flood damage database; increased bridge spans; improved drainage at chronic failure locations	Reduced flooding problems during big storm years (Doyle and Ketcheson 2007)
	Gravelled or removed roads; restricted road use to vehicles with reduced tire pressure	Low-volume roads made of native material are often rutted, especially during wet weather; to reduce road erosion, add gravel or obliterate roads (Elliot et al. 1999)
	Required road users to reduce tire pressure	Lower tire pressure creates shallower ruts (Foltz and Elliot 1997; Elliot et al. 1999)
	Ripped roads; spread mulch on ripped surfaces	Ripping and mulching improve soil permeability and reduce erosion; treatments on different soil types result in different hydrologic conductivities; road ripping is a reasonable step to reduce erosion; however, the researcher recommends adding organic matter to improve restoration efforts (Luce 1997)
	Retrieved sidecast soils onto road benches; improved water management (trenchs, blankets, French drains)	Improving water management and retrieving sidecast material decompacts the roadbed and appears to reduce road-related landslides (Dunkley et al. 2004)
Water, fish, aquatic habitat	Decommissioned roads	Rain-on-snow events triggered little damage on treated roads (Harr and Nichols 1993)
	Removed culverts; installed waterbars; outsloped roads; pulled unstable material back, ripped, and revegetated roadbeds	Substantial reduction of hydrologic connectivity between roads and streams, thereby reducing erosion and slope stability risk by 70% (Black et al. 2009)
	Repaired, replaced, or removed culverts	Improved fish passage provides potential for substantial expansion of aquatic habitat; relatively small construction footprint (Wait 2004)
	Decommissioned roads; reduced stream crossings	Reduced road and stream crossing density decreases stream sediments and improves fish survival (McCaffery et al. 2007)
Blue-listed bull trout and habitat	Decommissioned roads; removed culverts	Bull trout redds increased; fine sediments decreased (Wegner 1999)
Blue-listed grizzly bears and their habitat	Access managed; roads decommissioned	In some Bear Management Units, open-road density decreased between 1975 and 2001; results include increased grizzly bear security core habitat (Summerfield et al. 2004)
	Closed roads; restricted road use to timber industry	In areas occupied by grizzly bears, restrict road use to timber industry use only wherever possible (Wielgus et al. 2002)
Blue-listed Roosevelt elk	Gated roads to limit access	Poaching declined; researcher concluded that reduced human access may increase Roosevelt elk survival and reproduction (Cole et al. 1997)
Rocky mountain elk	Decreased road density	Researchers found that increased road density altered bull age structure (resulting in fewer mature males) and the bull:cow ratio (fewer bulls) (Leptich and Zager 1991)
Moose	Installed signs to limit traffic during portions of hunting season	Signs limit some (but not all) traffic in these areas (Hunt and Hosegood 2008)

Assessing reopened roads that had been abandoned for 30 years, Foltz et al. (2009a) found that these roads developed higher sedimentation than brushed-in roads and that duff and moss coverage on brushed-in roads likely absorbed raindrop energy and thus reduced erosion; these scientists also found that even though the abandoned roads had been out of use for three decades, water infiltration still did not match an undisturbed forest floor.

Inventory, research, and monitoring recommendations

A number of authors recommended road-related inventory, research, and monitoring topics to address the needs of policy-makers, land and resource planners and managers, road engineers, equipment operators, and maintenance specialists.

Inventory needs

To take a systems approach to road planning, it is necessary to understand "what's out there" (i.e., to have a road inventory). In British Columbia, the Forest Practices Board (2005a) recommended a comprehensive inventory of resource roads. Borovansky et al. (editors, 2002) recommended the development of road inventories and assessments at multiple scales and cited several conservation opportunities that could be identified during the inventory process. As well, Reed et al. (1996), Gucinski et al. (editors, 2001), and Mills (2007) emphasized the need for current, accurate road inventories that include information useful during environmental effects analyses. For example, inventory specialists can gather information about drainage, erosion, wetland and stream-crossing problems, water diversion potential, and road maintenance and repair needs. Along the inventory theme, the Forest Practices Board (2005b) recommended that the provincial Ministry of Forests and Range establish a quantitative landslide hazard classification and a landslide inventory.

Research needs

Numerous authors indicated that further research is needed about the road-related impacts on flora, fauna, habitats, and ecosystems; several examples are provided in Table 6. A few authors cited the need for more information related to road effects on landscapes and regions (e.g., Spellerberg 1998; Whittington et al. 2004), which could help with road planning and access management. A larger number of researchers recommended evaluation of impact mitigation techniques used at particular sites and the need to know how the techniques work over time. Some researchers recommended the development of decision-making tools to help managers.

Within British Columbia, roads will provide many important social and economic opportunities if planned to meet all user needs and desires; however, the information contained in the research and management literature indicates that the environmental consequences of roads are becoming increasingly important in management decisions.

Acknowledging the road-density research applied to grizzly bears in British Columbia, Gayton (2007) recommended similar research for other species. Hunt and Hosegood (2008) and Gucinski et al. (editors, 2001) recommended studies that focus on social and cultural aspects of road use and presence.

Monitoring

Some authors encouraged ongoing learning, and thus recommended studies to monitor, evaluate, and document wildlife responses to road projects and programs (Spellerberg 1998; Ferguson et al. 2002; Nielsen et al. 2009). Similarly, Switalski et al. (2003, 2004) urged effectiveness monitoring of road removal actions on aquatic, riparian, and terrestrial ecosystems. Effectiveness monitoring is also required to clarify whether measures to mitigate road impacts, such as passages for wildlife and fish, are actually achieving the expected or planned benefits to wildlife (Moore 1994; Hartman et al. 1996; Atkins et al. 2001; Andrews et al. 2006; McCaffery et al. 2007).

Conclusion

Within British Columbia, roads will provide many important social and economic opportunities if planned to meet all user needs and desires; however, the information contained in the research and management literature indicates that the environmental

TABLE 6. Research needs identified by study authors.

Environmental values	Research needs, sources
Water; soils; riparian and stream ecology; watershed hydrology	Develop decision-making tools and models and low-impact road construction and removal techniques (Elliot et al. 1999; Elliot 2000; Luce 2002)
	Examine road effects (and their interactions) over time and space (Wemple et al. 1996; Luce and Black 1999; Elliot 2000; Gucinski et al. 2001; Hudson 2001; Grace and Clinton 2007)
	Conduct post-storm validation monitoring to assess mitigation and decommissioning actions (Black et al. 2009)
	Study the effects of roads, groundwater hydrology, climate change (Smerdon et al. 2009a, 2009b) and cutslope hydrology (Luce 2002)
	Systematically evaluate the effectiveness of post-wildfire road treatments (Foltz et al. 2009b; Robichaud et al. 2010)
	Improve prediction of erosion, sedimentation, channel morphology, and risk of slope failure by studying overland and in-stream transport and storage of sediment (Elliot 2000; Jordan 2006)
Flora, fauna, ecosystems, soils, water	Examine how the impacts of road projects are addressed and documented during environmental impact assessments (Spellerberg 1998)
	Study the accumulation and effects of roadside pollutants (e.g., heavy metals) in biota (Spellerberg 1998)
Wolves and their habitat	Study the cumulative effects of roads and trails and how these affect animal movement (Whittington et al. 2004, 2005)
Wildlife, aquatic habitat	At multiple scales, study the effects of road types, transport networks, traffic, seasonal use, stream crossings, and distance between road and stream (Crist and Gerke 2005)
Animal abundance	Study road effects on animal abundance; conduct "before–after" studies at both control sites and road construction sites and examine the effectiveness of road mitigation techniques (Fahrig and Rytwinski 2009)
Habitat fragmentation	Study the effects of roads on habitat fragmentation (Spellerberg 1998; Crist and Gehrke 2005)
	To mitigate the barrier effect in areas of high road density, study the outcomes of increasing vegetative cover along roadsides (Spellerberg 1998; Whittington et al. 2004)
Native plants	Study the spread of exotic plant species along roads (Spellerberg 1998; Parendes and Jones 2000)
Amphibians, reptiles, turtles	Quantify road impacts on amphibians, reptiles, and turtles and identify mitigation methods to reduce these impacts (Andrews et al. 2006)
Blue-listed Marbled Murrelet	Examine the effects of edges (natural and human-caused, such as those along roads) on Marbled Murrelet nesting success (Burger 2002)
Red-listed boreal caribou; blue-listed mountain caribou	Study road avoidance by woodland caribou and wolf predation pressure that may be caused by the presence of linear features such as roads (James and Stuart-Smith 2000)
	Investigate ecological traps (including linear features such as roads) that may lead to mountain caribou mortality (Serrouya et al. 2008)

consequences of roads are becoming increasingly important in management decisions. Indeed, substantial research information and ample recommendations are available from specialists. At the site (or road segment) level, research and management findings have undoubtedly evolved and numerous methods to mitigate road effects exist including the planning, modelling, and implementing of management actions. For example, many studies documented interactions among roads, water, soil erosion and debris flow, fish, and aquatic habitat in British Columbia. As a result of this work, researchers have developed road management approaches and mitigation techniques to improve land and resource management. To protect fish and water resources, a recent study encouraged consistent use of established road-related procedures, guidelines, training, on-the-ground practices, and monitoring (Forest Practices Board 2007). Considerably less work has been focused on mitigating road-related concerns about terrestrial species and their behaviour and habitat.

Another question is much more challenging: How can responsible agencies, stakeholders, and First Nations collaborate to address the scientific findings, complexities, pressures, and choices related to road access management? Over a 20-year period, management recommendations presented in the reviewed literature fell into discernible themes; for instance, I found that more than 20 grizzly bear scientists in British Columbia have recommended road access management. Also recommending road access management were 15 grizzly bear specialists working on the Alberta Grizzly Bear Recovery Plan and another 15 specialists conducting grizzly bear studies in neighbouring Montana, Idaho, and Washington.

Although the challenges of road access management are daunting, numerous studies and projects exist that can help land and resource managers. The comprehensive and thorough guidance contained in these includes:

- setting up a clear planning process;
- using existing information and analysis tools;
- applying a systematic assessment to clarify socio-economic and environmental benefits, problems, risks, and trade-offs; and
- developing recommendations for creating road systems that achieve land and resource objectives.

When potential risks to the environment are identified and assessed and management options thoroughly considered, land and resource managers can develop more-informed policies, decisions, plans, and on-the-ground actions.

The products of the analysis are then used by decision makers (US Forest Service 1999; Mitchell et al. 2003; Weber et al. 2003).

Limited resources (e.g., budgets and staff) will continue to challenge mitigation efforts; however, cited tools and approaches can help managers assess risks, identify priorities, and focus management actions.

In large part, historical decisions may not have adequately considered the environmental effects of roads. When potential risks to the environment are identified and assessed and management options thoroughly considered, land and resource managers can develop more-informed policies, decisions, plans, and on-the-ground actions.

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Test Your Knowledge . . .

A summary of the environmental impacts of roads, management responses, and research gaps: A literature review

How well can you recall some of the main messages in the preceding Discussion Paper?
Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. Between 2000 and 2005, the Ministry of Environment concluded that the number of road-stream crossings in the province had increased by approximately:
   A) 6% per year
   B) 3% per year
   C) 16% per year

2. Land and resource managers in British Columbia have tools available that can assist them to make choices among road access management alternatives.
   A) True
   B) False

3. Going back a few decades in British Columbia, site-level concerns about appropriate road design, construction, and maintenance were usually driven by issues such as:
   A) Soil stability (erosion, landslides)
   B) Water quality (sediments)
   C) Fish and fish survival
   D) Grizzly bears and associated habitat
   E) A, B, and C above

4. In the last decade, a growing number of studies has focused on the increased number, length, and density of roads and the human access provided by these, particularly regarding:
   A) Ungulates such as moose and elk
   B) Grizzly bears and associated habitat
   C) Provincially red- and blue-listed species and their habitats

ANSWERS

1. C 2. A 3. E 4. C