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Forest Roads: A Synthesis of Scientific Information

Editors

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Abstract

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Effects of roads in forested ecosystems span direct physical and ecological ones (such as geomorphic and hydrologic effects), indirect and landscape level ones (such as effects on aquatic habitat, terrestrial vertebrates, and biodiversity conservation), and socioeconomic ones (such as passive-use value, economic effects on development and range management). Road effects take place in the contexts of environmental settings, their history, and the state of engineering practices, and must be evaluated in those contexts for best management approaches.

Keywords: Roads, roadless areas, forest ecosystems, geomorphology, hydrology, habitat fragmentation, biodiversity, nonmarket values, heritage values, economic development, grazing, mineral resources, fire.

Summary

Roads are a vital component of civilization. They provide access for people to study, enjoy, and commune with forested wildlands and to extract an array of resources from natural and modified ecosystems. Roads have well-documented, short- and long-term effects on the environment that have become highly controversial, because of the value society now places on unroaded wildlands and because of wilderness conflicts with resource extraction.

The approach taken in this report is to identify known and hypothesized road-related issues and to summarize the scientific information available about them. The report identifies links among processes and effects that suggest both potential compatible uses and potential problems and risks. Generalizations are made where appropriate, but roads issues and road science usually cannot be effectively separated from the specific ecologic, economic, social, and public lands management contexts in which roads exist or are proposed.

General Consideration of Road Networks at Intermediate and Large Scales

Across a forest or river basin, the access needs, economic dependencies, landscape sensitivities, downstream beneficial uses of water, and so on can be reasonably well defined, but these relations tend to differ greatly from place to place. An effective synthesis of road issues draws local experts together to thoroughly evaluate road and access benefits, problems and risks, and to inform managers about what roads may be needed, for how long, for what purposes, and at what benefits and costs to the agency and society.

Road effects and uses may be somewhat arbitrarily divided into beneficial and detrimental. The largest group of beneficial variables relates to access. We identified access-related benefits as harvest of timber and special forest products, grazing, mining, recreation, fire control, land management, research and monitoring, access to private inholdings, restoration, local community critical needs, subsistence, and the cultural value of the roads themselves. Nonaccess-related benefits include edge habitat, fire breaks, absence of economic alternatives for land management, and jobs associated with building and maintaining the roads.

Undesirable consequences include adverse effects on hydrology and geomorphic features (such as debris slides and sedimentation), habitat fragmentation, predation, road kill, invasion by exotic species, dispersal of pathogens, degraded water quality and chemical contamination, degraded aquatic habitat, use conflicts, destructive human actions (for example, trash dumping, illegal hunting, fires), lost solitude, depressed local economies, loss of soil productivity, and decline in biodiversity.

For each variable, we sought expert assistance from scientists actively engaged in research related to roads and asked them for information, with emphases on results and conciseness rather than exhaustive descriptions, in the following categories: issues relevant to their topic; science findings; an assessment of reliability, confidence, and limitations inherent in the data; the degree to which the information could be generalized to larger geographic scales than in the original research; secondary links for each topic to other topics; and the ability of the existing knowledge to address the issues raised.

Road development histories crucial to understanding their effects—All roads were not created equal and do not behave the same. Road networks differ greatly in how they developed through time and how they were laid out over terrain; they carry this history into their present performance. The geographic patterns of roads in forest landscapes differ substantially from place to place, with commensurate differences in environmental effects. For example, ridgetop, midslope, and valley floor roads all behave differently, based on the topography they cross, the degree and type of interaction with stream networks, their stability in and response to storms, and their effects on wildfire, wildlife, and vegetation. Distinguishing among the effects of building, maintaining, using, decommissioning, or abandoning roads is crucial because each of these actions affects the environment in many ways.

Knowledge of the state of road systems in national forests is inadequate—We currently lack sufficient information to develop a comprehensive history of the building and maintaining of national forest roads or their current condition. The inventories of the roads differ widely, in both content and status, and frequently lack sufficient information to define benefits, problems, and risks.

Roads create interfaces and ecotones—Roads are long, which creates large amounts of interface within the landscapes traversed. The strength of the interactions at these interfaces differs with time and space; it is controlled by the contrast between adjacent resource patches or ecological units. These interfaces may regulate the flow of energy and materials between adjacent systems. Such sites are sensitive. They have relatively high biodiversity, affect critical habitat for rare and endangered species, and serve as refuges and source areas for pests and predators.

Road management involves important tradeoffs—Almost all roads present benefits, problems, and risks, though these effects differ greatly in degree. Roads provide motorized access, which creates a broad spectrum of options for management but forecloses other options, such as nonmotorized recreation or wildlife refugia. Even a well-designed road system inevitably creates a set of changes to the local landscape, and some values are lost as others are gained; for example, road density and fish populations correlate negatively over a large area in the interior Columbia basin. The basin's environmental assessment shows that subbasins with the highest forest-integrity index were largely unroaded, and subbasins with the lowest integrity had relatively high proportions of moderate or greater road density. In general, greater short- and long-term watershed and ecological risks are associated with building roads into unroaded areas than with upgrading, maintaining, closing, or obliterating existing roads.

Confounding variables are difficult to separate from road-related ones—Changes in the habitat of terrestrial vertebrates, frequency of road kill, and transmission of forest diseases result from road use, not from the presence of the road itself. Separating effects of roads from other landscape and ecological modifications that result from changes in land use that roads enable is often impossible.

Direct Physical and Ecological Effects

Geomorphic effects of roads range from chronic and long-term contributions of fine sediment into streams to catastrophic mass failures of road cuts and fills during large storms. Roads may alter channel morphology directly or may modify channel flow and extend the drainage network into previously unchanneled portions of the hillslope. The magnitude of road-related geomorphic effects differs with climate, geology, road age, construction practices, and storm history. Improvements in designing, constructing, and maintaining roads can reduce road-related erosion at the scale of individual road segments, but few studies have evaluated long-term and watershed-scale changes to sediment yields when roads are abandoned or obliterated.

Roads have three primary effects on **hydrologic processes**: (1) they intercept rainfall directly on the road surface and road cutbanks and affect subsurface water moving down the hillslope; (2) they concentrate flow, either on the surface or in an adjacent ditch or channel; and (3) they divert or reroute water from paths it otherwise would take were the road not present. Problems of road drainage and transport of water and debris—especially during floods—are primary reasons roads fail, often with major structural, ecologic, economic, or other social consequences. The effect of roads on peak streamflow depends strongly on the size of the watershed; for example, capture and rerouting of water can remove water from one small stream while causing major channel adjustments in another stream receiving the additional water. In large watersheds, roads constitute a small proportion of the land surface and have relatively insignificant effects on peak flow. Roads do not seem to change annual water yields, and no studies have evaluated their effect on low flows.

Forest roads can significantly affect **site productivity** by removing and displacing topsoil, altering soil properties, changing microclimate, and accelerating erosion. The direct effect of roads on soil productivity is estimated to range from 1 to 30 percent of the landscape area in managed forest lands. Losses of productivity associated with road-caused accelerated erosion are site specific and highly variable in extent.

Natural populations of animal species are affected by **habitat fragmentation** caused by the presence of roads and by avoidance of areas near roads by some species and attractiveness to those areas by other species. Fragmented populations can produce increased demographic fluctuation, inbreeding, loss of genetic variability, and local extinctions. Roads fragment habitat by changing landscape structure, dissecting vegetation patches, increasing the amount of edge, decreasing interior area, and increasing the uniformity of patch characteristics. Road-avoidance behavior is characteristic of large mammals such as elk, bighorn sheep, grizzly bear, caribou, and wolf. Some studies have shown that the existence of a few large areas of low road density, even in a landscape of high average road density, may be the best indicator of suitable habitat for large vertebrates.

On the other hand, roads and their adjacent environment qualify as a distinct **habitat** and result in changes at the species, population, and landscape scales. Some species are associated with edges, including those that use roads as corridors to find food. Roads facilitate **biological invasion** in that disturbed roadside habitats are invaded by exotic (non-native) plant and animal species dispersed by wind, water, vehicles, and other human activities. Roads may be the first points of entry for exotic species into a new landscape, and the road can serve as a corridor for plants and animals moving farther into the landscape. Invasion by exotic species may have significant biological and ecological effects if those species are able to displace natives or disrupt the structure and function of an ecosystem.

Indirect and Landscape-Scale Effects

The effects of roads on **aquatic habitat** are believed to be widespread, although direct, quantitative cause-effect links are difficult to document. At the landscape scale, correlative evidence suggests that roads are likely to influence the frequency, timing, and magnitude of disturbance to aquatic habitat. Increased fine-sediment composition in stream gravel—a common consequence of road-derived sediments entering streams—has been linked to decreased fry emergence, decreased juvenile densities, loss of winter carrying capacity, and increased predation of fishes and can reduce benthic organism populations and algal production. Roads can act as barriers to migration, lead to water temperature changes, and alter streamflow regimes. Improper culvert placement where roads and streams cross can limit or eliminate fish passage. Roads greatly increase the frequency of landslides, debris flow, and other mass movement. At the landscape scale, increasing road densities and their attendant effects are correlated with declines in the status of some non-anadromous salmonid species.

Roads can cause a wide variety of effects to **terrestrial wildlife**. Some species, such as gray wolf and grizzly bear, are adversely affected by repeated encounters with people. Roads can increase harassment, poaching, collisions with vehicles, and displacement of terrestrial vertebrates, which affect many large mammals such as caribou, bighorn sheep, mountain goat, pronghorn antelope, grizzly bear, and gray wolf. It is estimated that 1 million vertebrates are killed annually on roads in the United States. Direct mortality of large mammals on forest roads is usually low, except for those with a home range straddling a road. Forest roads pose a greater hazard to slow-moving migratory amphibians than to mammals. Nearly all species of reptiles seek roads for cooling and heating. Vehicles kill many of them, making well-used roads a population sink.

Chemicals applied to and adjacent to roads can enter streams by various pathways. The effect on **water quality** depends on how much chemical is applied, the proximity of the road to a stream, and the weather and runoff events that move chemicals and ediments. Dust produced by vehicles moving on unpaved roads reduces **visibility** and generates airborne particulates that can pose health hazards, such as in areas with soils containing asbestiform minerals.

Direct Socioeconomic Effects

A variety of products harvested from forests are being transformed into medicinals, botanicals, decoratives, natural foods, and other products, called **nontimber** or **special forest products.** The harvest of these products usually depends on road access. The Forest Service is required by law to permit access to **private inholdings** but can require the owners to comply with standards that apply to building roads on or through national forest land.

Economic pressures affect roads and road use, and roads have multiple economic consequences. Both **benefits and costs** are associated with building, maintaining, and using forest roads. The **economic** effects relate to forest access and user-communities, including loggers, silviculturists, fuels managers, and recreationists. The network of roads on national forest lands has both positive and negative effects on most Forest Service land management programs. Reducing road densities could result in increased timber-harvesting costs, for example. Roads have replaced stock drives for transporting sheep and cattle to and from mountain grazing allotments. Road-related issues associated with **energy and mineral resources** are access rights, property rights, and benefits and detrimental effects. **Public recreational users** of national forests depend on roads for access. Altering the road networks will affect such uses differently across the landscape.

Indirect Socioeconomic Effects

The increasing density of roads in and adjacent to many forest, shrub, and rangeland areas is an important factor in the changing patterns of disturbance by **fire** on the landscape. Roads provide access that increases the scale and efficiency of **fire suppression**, and roads create linear firebreaks that affect fire spread. The benefits roads provide for fire prevention and fire management carries an associated cost: increased access has increased the role of human-caused ignitions. And road networks have resulted in changes in fuel patterns and fire regimes at the broad scale.

Roads also affect many less measurable attributes of the national forests, including **passive-use values:** those values that people hold for things they may not expect to use themselves but that they believe should exist for future generations. For example, building roads in roadless areas may reduce passive-use value significantly; decommissioning of roads may increase such value. But decommissioning of roads also is likely to reduce active-use values. Roads themselves sometimes have **heritage value** because of historical or cultural significance.

The aim of this synthesis is to focus on the scientific information about the benefits, uses, and physical and biological effects of forest roads. Because all aspects of roads in forests have become of great interest to the American public, research is underway in many domains. This document represents the information available as of the date of publication.

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Contents

Introduction and Objectives

Roads have become vital components of the human use of forested systems. Without roads, development of the economic activity critical to the quality of modern life would have been difficult, and roads remain central to many forest uses today. Roads provide access for people to study, enjoy, contemplate, or extract resources from natural and modified ecosystems. Building and maintaining roads is controversial, however, because of the kinds of uses they enable, concerns about their short- and long-term effects on the environment, and the value that society now places on unroaded wilderness (Cole and Landres 1996, Williams 1998).

Decisions about roads—locating, building, maintaining, and decommissioning them—are complex because of the many tradeoffs required. The statement by Chomitz and Gray (1996) that "rural roads promote economic development, but they also facilitate deforestation" exemplifies recent experiences. And a tradeoff exists between access by roads for recreation and resource extraction with the potential effects of that access on biodiversity. Roads have been evaluated from physical, biological, and socioeconomic points of view, often under only one perspective in isolation from the others. Such an approach is useful for identifying issues, but it can lead to conflict and poorly informed policy choices because it may unnecessarily play one set of values against another. For example, a road justified only by economic criteria at the expense of ecological ones—or vice versa—is likely to be questioned by advocates of the missing criteria. A unified approach to analyze building, maintaining, or decommissioning roads is needed to allocate resources wisely. This report represents our attempt to summarize the known desirable properties of roads and their known effects on the landscape, based on the scientific information currently available.

The approach taken was to enumerate the known or hypothesized issues and then provide a summary of the scientific information available about those issues. We provide a synthesis that attempts to reveal where links between processes and effects suggest both potential compatible uses and potential problems and risks.

We find that roads cannot be separated from the ecologic, economic, social, or public land management context in which they exist or are proposed. A virtually limitless variety of context factors renders any single, generalized synthesis to be of limited applicability and value. An effective synthesis of all the interactions of roads, the environment, and people can best be attempted by looking at road systems in actual places where the myriad effects of roads are not hypothesized or generalized. For example, across a national forest or river basin, the array of access needs, economic dependencies, landscape sensitivities, downstream beneficial uses of waters, and so on can be reasonably well defined and will tend to differ greatly from any other place. A synthesis of the effects of roads in a specific context can be attempted by drawing local experts together to thoroughly evaluate road and access benefits, problems, and risks, to inform managers about what roads may be needed, for how long, for what purposes, and at what costs to the agency and society.

The Forest Service recently published a document *Roads Analysis: Informing Decisions About Managing the National Forest Transportation System* (USDA FS 1999), which can be considered a specific application of watershed analysis or a cumulative effects analysis, wherein the principal objective is to focus on road effects. For example, roads analysis and watershed analysis have common steps that include:

- Setting up the analysis
- Describing the situation

- Identifying issues
- Assessing benefits, problems, and risks
- Describing opportunities and setting priorities
- Reporting results and conclusions

Similar approaches to watershed analysis or cumulative effects analysis are being adopted widely by federal (for example, Regional Ecosystem Office [REO] 1995), state (for example, Washington Forest Practices Board 1995), and private (for example, NCASI 1992) agencies and organizations. The exact steps and organization of the analysis are somewhat modified by each application, but the conceptual framework is similar. The focus of each analysis can change, depending on the principal reason for doing it (such as timber production, wildlife, or ecosystem integrity); for example, an analysis focused on timber production in a watershed or region would look at effects on and of road development, water quality, wildlife, recreation, and economics. Exactly the same set of issues would emerge if the focus were on water quality, wildlife, or recreation. The perspective and conclusions might be different, but the issues and approach would be the same.

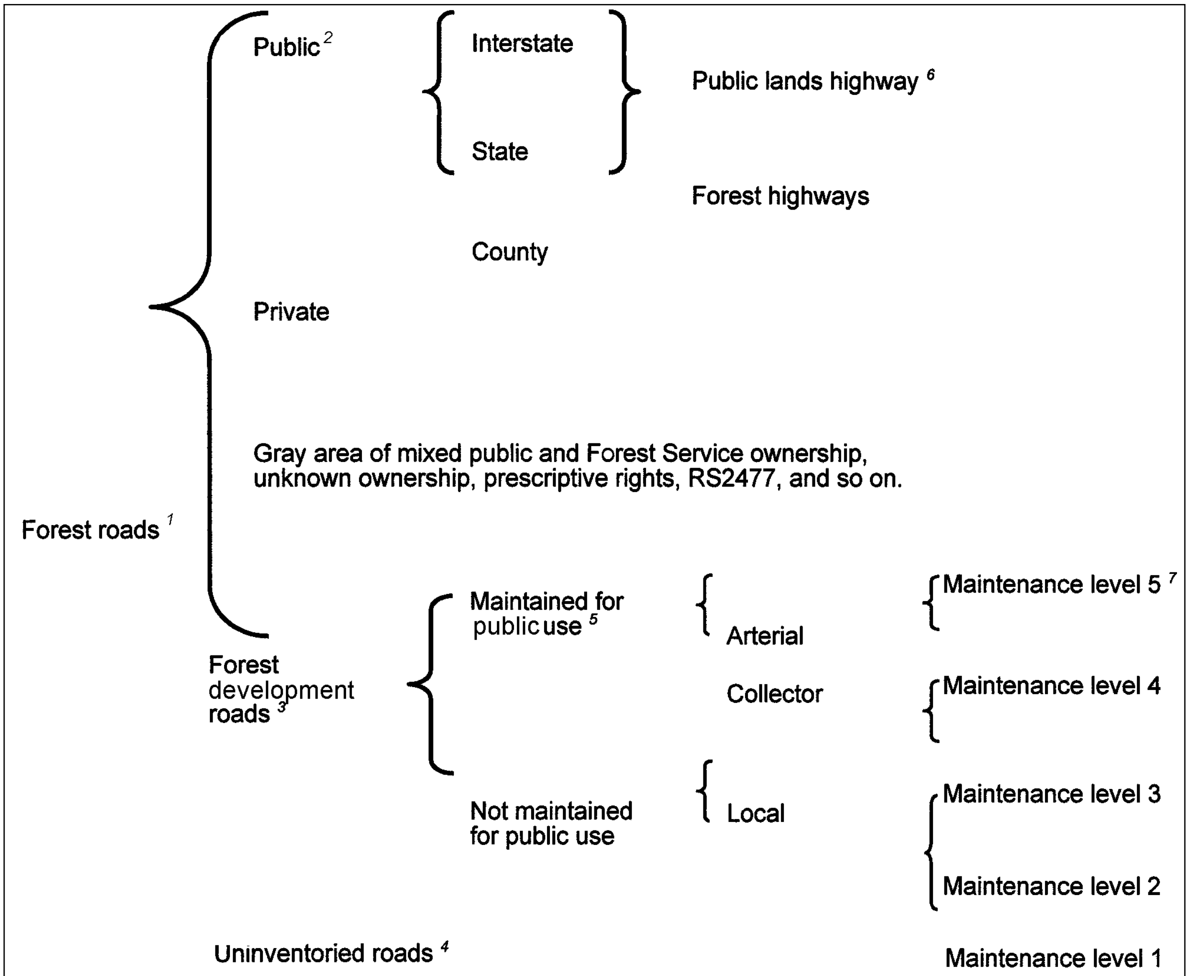
The roads analysis (USDA FS 1999) is intended to be an integrated, ecological, social, and economic approach to transportation planning. It uses a multiscale approach to ensure that the identified issues are examined in context, and it is based on science. Analysts are expected to locate, correctly interpret, and use relevant existing scientific literature in the analysis, disclose any assumptions made during the analysis, and reveal the limitations of the information on which the analysis is based. The analysis methods and the report are to be subjected to critical technical review.

This science synthesis complements the roads analysis by summarizing some of the available scientific information on how roads affect an array of ecological, social, and economic resources. The approach used in this document is mostly reductionist; it is not intended to be a comprehensive encyclopedia of all available knowledge about road effects; but this information, together with the extensive list of questions posed in the roads analysis, should assist interdisciplinary teams in understanding and applying the best available science appropriately to existing and potential road systems in specific geographic contexts, across the national forest system. Commonly used definitions for Forest Service roads are listed in figure 1.

General Considerations of Roads Networks

In this section, we consider what the body of scientific work on roads allows us to understand about how roads function in the landscape. This paper details specific positive and negative consequences of roads; here, we attempt to distill this information into key observations relevant to road policy considerations. The work is a synthesis of a large body of information from many sources. Inevitably, the synthesis creates potential for interpretations beyond the more generally accepted facts about roads contained in the rest of the document. Nevertheless, we believe they represent a reasonable set of principles consistent with the best scientific knowledge.

Road effects and uses may—somewhat artificially—be divided into beneficial and deleterious effects. In the former category, most variables relate to access, with a second group of beneficial uses not related to access. We identified the following access-related benefits or needs: timber acquisition, grazing, mining, recreation, fire control, land management, research and monitoring, access to private inholdings, restoration, community critical needs, subsistence, and the cultural value of the roads themselves. Non-access-related benefits or needs included edge habitat, fire breaks,



[1] **Forest roads:** Roads wholly or partially within, or next to, and serving a national forest and needed to protect, administer, and use the national forest and to use and develop its resources.
[2] **Public roads:** Roads under the jurisdiction of, and maintained by, a public authority that are open to public travel
[3] **Forest development roads:** Forest roads under the jurisdiction of the Forest Service.
[4] **Uninventoried roads:** Short-term roads associated with fire suppression; oil, gas, or mineral exploration or development; or timber harvest not intended for forest-development transportation and not necessary for resource management. Regulations require revegetation within 10 years.
[5] **Maintained for public use:** Forest development roads open to unrestricted use by the general public in standard passenger cars, including those roads closed seasonally or for emergencies.
[6] **Public lands highways, forest highways:** A coordinated Federal Lands Highway Program includes forest highways, public lands highways, park roads, parkways, and Native American reservation roads under the jurisdiction of and maintenance by a public road authority other than the Forest Service and open to public travel.
[7] **Maintenance level 5:** Roads that provide a high degree of user comfort and convenience. Normally double lane, paved facilities, or aggregate surface with dust abatement; the highest standard of maintenance.
Maintenance level 4: Roads that provide moderate user comfort and convenience at moderate speeds. Most are double lane, and aggregate surfaced. Some may be single lane. Some may be dust abated.
Maintenance level 3: Roads open and maintained for travel by a prudent driver in a standard passenger car. User comfort and convenience are not considered priorities. Typically low speed, single lane with turnouts and native or aggregate surfacing.
Maintenance level 2: Roads open for use by high-clearance vehicles. Passenger car traffic is discouraged. Traffic is minor administrative, permitted, or dispersed recreation. Nontraffic-generated maintenance is minimal.
Maintenance level 1: These roads are closed. Some intermittent use may be authorized. When closed, they must have barricades, berms, gates, or other closure devices. Closures must exceed 1 year. When open, a road may be maintained at any other level. When closed to vehicular traffic, they may be suitable and used for nonmotorized uses, with custodial maintenance.

Figure 1—Legal basis and definitions for roads in the national forests.

the absence of economic alternatives for land management, some positive effects on water quality, and the jobs associated with building and maintaining these systems. This analysis uncovered factors that could lessen negative effects of roads by better integrating engineering approaches with knowledge of road effects.

Negative consequences include effects on hydrology, geomorphic features such as debris slides, sedimentation, habitat fragmentation, predation, road kill, invasion by exotic species, dispersal of pathogens, water quality such as chemical contamination, aquatic habitat, use conflicts, human actions (for example, trash dumping, illegal hunting, fires), the cost of lost solitude, local economies, soil productivity, communities, and biodiversity.

For each variable, we sought expert assistance from scientists actively engaged in research related to roads and asked for information in the following categories, with emphases on results and conciseness rather than exhaustive descriptions: issues relevant to the topic variable; science findings; an assessment of the reliability, confidence, and limitations inherent in the data; the degree to which the information could be generalized to larger geographic scales than those of the original research; the secondary links from this topic to other topics; and the ability of the existing knowledge to address the issues raised.

We note that the limitations of science set the bounds for subsequent interpretations, we offer a synthesis of the available scientific information, and we consider how these science-based observations might be used in developing future road policy.

Despite the shortcomings described, we believe that the available science on road effects can provide considerable guidance in evaluating benefits and costs associated with roads. Our interpretation of the scientific literature leads to the following observations.

Roads differ greatly—All roads are not created equal and do not behave the same. Road networks differ greatly in development through time and layout over terrain, and they carry this history into present performance. In many parts of the National Forest System, the major roads were built in the 1950s and 1960s, with secondary and tertiary feeder roads following as the road networks expanded into watersheds. In other areas, logging roads developed from previous road systems used for mining in the Rocky Mountain and Southwestern states or agriculture in the southern Appalachians, Ozarks, and New England. Thus, changes in road standards through time (for example, width, construction methods, position in the landscape) have affected different parts of road networks. Consequently, each road network commonly contains a collection of old and new types and standards of roads designed for various purposes that cross terrain of differing sensitivities. This mosaic of road segments has implications for how roads will be managed in the future (Gullison and Hardner 1993).

The geographic patterns of roads in forest landscapes differ substantially from place to place, with commensurate differences in environmental effects. In the glaciated terrain of southeastern Alaska, for example, main roads were built on the broad, major valley floors, and the high-value timber that grew on lower hillslopes was brought downhill to them. In forests along the west side of the Sierra Nevada in California, on the other hand, major roads were built along broad ridges, with secondary roads leading down into headwater areas. The main roads into western Oregon forests entered watersheds along narrow stream bottoms and then climbed the adjacent steep, unstable hillslopes to access timber extending from ridge to valley floor. These configurations, combined with local geology and climate, resulted in very different effects of roads on watershed, wildlife, vegetation, recreation, and disturbance processes.

Even in the same region, road effects differ by landscape position. Ridgetop, midslope, and valley floor roads all produce different effects, based on the topography they cross, the degree and type of interaction with stream networks, the stability and response to storms, and the effects on fire, wildlife, and vegetation.

Different phases of road development have different effects on the landscape. Distinguishing among the effects of building, maintaining, usage, decommissioning, or abandoning of roads is crucial because they usually affect the environment in several ways.

Road development history crucial to understanding effects—The effects of roads differ over time. Some effects are immediately apparent (such as loss of solitude or creation of edge), but others may require an external event, such as a large storm, to become visible (such as road-related erosion or mass movement). Still other effects may be subtle, such as increased susceptibility to invasion by exotics, pathogens noticed only when they become widespread in the landscape, or increased road use as recreation styles and motor vehicles change.

With time, roads often adjust to the ecosystems they are embedded in. Some segments blend with the landscape and reach a new ecological and hydrological balance, or better, a metastable state. Such a state will be different for a road transecting old-growth forest than for a road in an otherwise highly disturbed landscape. A critical issue in the decommissioning of a road is whether disrupting the new environmental balance created by the presence and aging of the road is desirable. As other segments of the road age, however, some features (such as culverts and disrupted subsurface drainage paths) become increasingly unstable; the probability of failure increases with road age. Sometimes, decommissioning a road can have significant environmental effects because the road has become part of the evolving landscape.

Decommissioning also can avert significant future environmental effects of the road. One last precaution in generalizing about the environmental effects of roads is to determine the age and condition of the road and evaluate the degree of landscape adjustment to the road and vice versa. Roads produce long-term legacies on the landscape. Many roads built by the Roman Empire centuries ago have disappeared from the landscape, but their legacies remain in the sediment layers of Italian lakes (Hutchinson 1973) and in strips of unique vegetation growing on limestone soils (derived from the limestone slabs used to build the road) in landscapes of acid podzolic soils (Detwyler 1971). In Lago di Montesori, Italy, the building and use of Via Cassia resulted in a pulse of eutrophication that lasted 2,000 years before it abated when the road was abandoned (Hutchinson 1973). Strips of fern populations in the Caribbean National and Luquillo Experimental Forests in Puerto Rico, serve as indicators of the skid trails abandoned more than six decades ago in these wet forests (Garcia-Montiel and Scatena 1994). These legacies are useful in historical reconstruction of landscapes because they help to explain the relevance of yesterday's activities to today's landscapes (Burel and Baudry 1990). In the process, more is learned about ecosystem resilience and how ecosystems continuously adjust to change.

We do not currently have sufficient information to develop a comprehensive picture of the construction or maintenance history or the current condition of the roads comprising our national forest road networks. Although much information on roads exists at a variety of scales (district, forest, region), and some national forests have invested in inventorying and developing road databases, no common framework or database exists for accessing road development information. For environmental consequences, little information exists on old, abandoned roads that still pose risks of failure. Other data important to defining effects, such as the location and configurations of road-stream crossings, are not available for most places. Without such a database, developing a comprehensive picture of where the road system currently stands, what parts of it need work, and where restoration activities should be focused will be difficult and analyses may be limited at best.

Knowledge of the State of Road Systems in National Forests Is Inadequate

Road inventories for the national forests are highly variable, frequently incomplete or inaccurate, and lack information needed to define benefits, problems, and risks. For most national forests, the inventory contains very limited, transportation-related data, such as road maintenance level and surface type. These data, though useful for some purposes, may be wholly inadequate to address such considerations as sedimentation hazards, migration barriers, landslide potential, road-stream connectivity, or other important aspects of the environmental effects of roads. Other useful data may exist in various forms, but because they are not systematically collected or maintained, they are nearly impossible to access for analysis. Without suitable data, some important aspects of the analysis of roads cannot proceed.

Roads create interfaces and ecotones—Because roads have great length, the interface surface between roads and the ecosystems of the landscape traversed is maximized. Naiman and Décamps (1997) recognized that the strength of the interactions at these interfaces differs with time and space, and it is controlled by the contrast between adjacent resource patches or ecological units. They compare these interfaces to semipermeable membranes regulating the flow of energy and materials between adjacent systems. They note that interfaces “have resources, control energy and material flux, are potentially sensitive sites for interactions between biological populations and their controlling variables, have relatively high biodiversity, maintain critical habitat for rare and endangered species, and are refuge and source area for pests and predators.” The road interface may be split into two zones (roadside and ecotone) to highlight the difference between vegetation along the roadside and vegetation in the zone at the interface of the road. That interface can be sharp or gradual and form an ecotone that differs from both the roadside and the adjacent natural ecosystem.

The width of the surface of a road differs from the width of its ecological influence (Auerbach and others 1997; Forman, in press; Forman and others 1997; Larsen and Parks 1997; Reck and Kaule 1993). For example, a road may be 30 feet wide, but it may influence an additional 80 feet of adjacent land because of disturbance during construction and the buffer zone for the pavement, making the road effectively 110 feet wide. That same road has an ecological influence that can extend an additional unknown distance from storm water runoff—influence over the home range of wildlife, geomorphic alterations upstream and downstream, distance its noise and dust carry, and views it provides.

Road management usually involves important tradeoffs—Almost all roads present benefits, problems, and risks, though these effects differ greatly in degree. Roads permit motorized access, which creates a broad spectrum of options for management but forecloses other options, such as wilderness, nonmotorized recreation, or some types of wildlife refugia. Even a well-designed and well-built road system inevitably creates a set of changes to the local landscape, and some values are lost as others are gained.

Tradeoffs accompany specific decisions about roads, such as construction method. Full-bench road construction, for example, may decrease the risk of fill slope failure, but it also may increase the potential for groundwater interception with attendant water quality risks.

In public wildlands management, road systems are the largest human investment and the feature most damaging to the environment. Thus the choices about what roads are needed, for what purposes, for how long, and at what cost—to public ecological resources as well as financial—are critical decisions in managing public lands.

Recent Efforts at Describing Roads in the Landscape May Be Helpful

Roads can be thought of as ecosystems—Synthesis of the effects of roads on terrestrial ecosystems may be facilitated by viewing roads as “techno-ecosystems,” as recently described by Lugo and Gucinski (2000). Roads occupy ecological space (Hall and others 1992), have structure, support a specialized biota, exchange matter and energy with other ecosystems, and experience temporal change. Road “ecosystems” are built and maintained by people (techno-ecosystems; Haber 1990) and are characterized by open fluxes of energy and matter and a predominance of respiration over photosynthesis; that is, they are heterotrophic and highly subsidized systems. To appreciate that features associated with roads function as an ecosystem and interact with the surrounding forests requires thinking about the flow of materials, energy, and organisms along road corridors, vegetation zonation, the interaction with the human economy and human activity, and the external forces that converge on the road corridor (Donovan and others 1997; Forman 1995a, 1995b). (See fig. 2).

Roads connect and disconnect—Roads are corridors that can connect contrasting ecosystem types. Because roads provide a somewhat homogeneous condition through the length of the corridor, they provide opportunity for organisms and materials to move along the corridor, thereby increasing the connectivity (Merriam 1984) among those ecosystems interfacing with the road.

The degree of connectivity between roads and streams (that is, the number of stream crossings and areas where roads and streams are near enough to strongly interact) is recognized as a good general indicator of the interactions between the two and of potential effects roads can exert (Wemple 1994). Where both stream and road densities are high, the incidence of connections between roads and streams can be expected to also be high, resulting in more common and pronounced effects of roads on streams than in areas where road-stream connections are less common and dense. (fig. 3).

The economic benefits of roads could be seen as a function of connecting commodities, such as timber, minerals, recreational opportunities, and so on, with potential users.

Roads also can function to disconnect important features of ecosystems. Many roads built next to streams isolate or disconnect streams from their flood plains, with adverse effects to stream dynamics and associated aquatic biota. Roads can block the movement of some animals, such as wolves crossing wide roads or fish being blocked from their upstream movement by perched culverts.

Road density and fish populations correlate across a large area in the interior Columbia basin—One of the few examples of landscape-scale analysis of road influences has been the interior Columbia River basin environmental assessment (Quigley and others 1997). The evaluation of road density and forest and range integrity in that study may serve to illustrate landscape-scale interaction of roads with their surroundings. Forest and range indices of integrity were developed that showed sub-basins having the highest forest-integrity index were largely unroaded and comprised cold forest “potential vegetation groups,” or a mixture of moist and cold forest groups. Of the five indicator variables used, the proportion of a subbasin composed of wilderness or roadless areas seemed most closely associated with subbasins having high integrity indices; 81 percent of the subbasins classified as having the highest integrity had

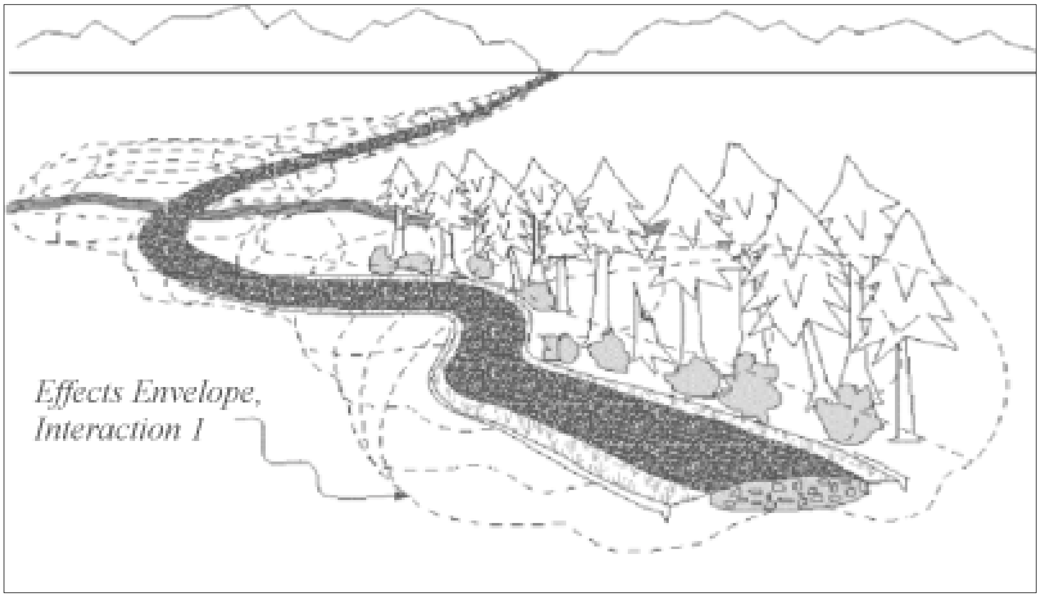


Figure 2—The volume of geographical space occupied by a road, whereby the distance of the road effect is used to define its width and height. The volume changes given the ecological conditions in the area the road traverses (from Lugo and Gucinski 2000).

relatively large proportions of wilderness and roadless areas (>50 percent). Conversely, of subbasins with the lowest integrity, 89 percent had low proportions of roadless and wilderness areas, 83 percent had relatively high proportions of at least moderate road density (0.27 miles/square mile). None of the seven subbasins having high rangeland integrity had areas of moderate or high road densities. The correlation of basin or subbasin integrity is not total, thereby suggesting that other variables and mechanisms are complex and nonuniform (but see text below for additional caveats).

Recreation surveys suggested the three most highly ranked uses of land administered by the Forest Service and Bureau of Land Management in the interior Columbia basin today are timber, fishing, and hunting. Projected major uses by 2045 will be a shift to motor viewing and day and trail use, even though this area has 70 percent of the unroaded areas of >200,000 acres remaining in the conterminous 48 states.

Strong fish populations were more frequently found in areas with low rather than high road densities. Supplemental analyses “clearly shows that increasing road densities and their attendant effects are associated with declines in the status of four non-anadromous salmonid species.... They are less likely to use highly roaded areas for spawning and rearing, and, where found, are less likely to be at strong populations levels” (Lee and others 1997).

These findings are a “consistent and unmistakable pattern based on empirical analysis of 3,327 combinations of known species status and sub-watershed conditions, limited primarily to forested lands administered by BLM/FS” (Lee and others 1997). Although unroaded areas are significantly more likely than roaded areas to support strong populations, strong populations are not excluded from roaded watersheds. Possible reasons for this coexistence are that the inherent productivity of some areas allows fish populations to persist despite disturbances linked to roads; real or detectable effects on fish populations may lag behind the initial physical effects in watersheds where roads have been added in the last several years; and the scale of the subwatershed (18,000 acres

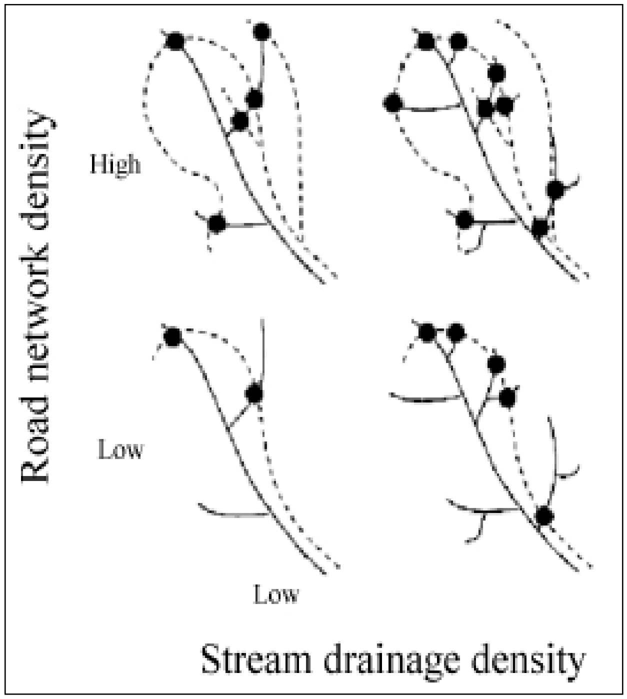


Figure 3—The incidence of road-stream connections, such as stream crossings (the black dots) is related to the density of both roads and streams in the landscape (Swanson and others 2000).

on average) at which strong populations are identified may mask a potential disconnect between the real locations of fish strongholds and roads (identified at resolution of 0.38 square mile). In general, greater short- or long-term watershed and ecological risks are associated with entering an unroaded area than with proceeding continuously with management activities in roaded areas to upgrade, maintain drainage, or close or obliterate existing roads.

Limitations of science—The existing science about roads goes far in establishing what and where problems are likely to arise. More than half a century of research and experience supports designing, building, and maintaining forest roads. Most of the major engineering problems associated with roads have been solved, and a wealth of information exists on many of the physical effects of roads, particularly on hydrologic and geomorphic watershed processes. Information on the biologic effects of roads is improving. Getting this knowledge into practice is more an economic, social, and political issue than a technical one. Less well understood but increasingly studied are the ways that the social and cultural settings of roads influence the benefits, problems, and risks that roads present.

Despite this extensive base of literature and understanding, a striking conclusion from our assessment of the current state of scientific understanding of roads is that virtually no attempt has been made to integrate this information into a comprehensive picture of how roads function in the landscape—physically, biologically, and socially. Despite the ubiquity of roads, no “science of roads” exists. Instead, many disciplines offer their perspectives: engineers study road design and performance, hydrologists evaluate effects of roads on water and sediment, ecologists consider effects on vegetation and wildlife, and transportation planners focus on road layout in relation to other forest resources and uses. Few efforts have been directed toward viewing the gamut of road benefits and effects systematically and simultaneously, or to developing general methods for evaluating risks posed by roads in individual watersheds. Further, the inventory and evaluation of roads is usually limited by ownership: The Forest Service focuses on roads in national forests and generally ignores roads within adjacent ownerships; states evaluate state highways; and the U.S. Department of Transportation evaluates federal highways.

We expect that implementing systematic analyses of road systems in national forests (as part of forest planning and other project planning; USDA 1999) will soon produce abundant examples of intermediate- and large-scale analyses. We hope that those analyses will look beyond ownership to produce a comprehensive evaluation of roads as a system. We have noted that the science information on the benefits of roads is not well developed. The form of scientific approaches for measuring benefits is largely based on economic analyses, which tend to focus on monetary cost differentials produced by the presence or absence of roads. Even in that arena, the data are not rigorously developed. Approaches from the social sciences are based on measurements of public perceptions and public desires, but the total data set does not comprise a highly developed scientific base.

Past studies (with the single, large exception of the interior Columbia River basin environmental assessment) have shed little light on the effects of roads across the whole landscape. Deciphering road effects at large spatial scales is difficult because past studies either focused on the performance of individual road segments, or else road effects were confounded by other simultaneous treatments. Most engineering studies, for example, look at the performance of specific road types (such as arterial, collector), features (road surfaces, cutslopes), or engineered structures (culverts) without examining how the road network functions in relation to adjacent hillslopes and an intersecting stream network. Where roads have been looked at in a watershed context, as in small watershed experiments, effects of roads often have not been distinguished from those of other treatments, such as logging or site preparation, that typically accompany roads. Treatments only of roads are rare and may continue for just a few years before other treatments are applied.

Despite the size of the forest road network, road effects have been examined in only a few places. Much of what we know about forest roads comes from studies in the Appalachians, Pacific Northwest, and Rocky Mountains—areas with known road problems. Given the wide variability in road history, age, construction methods, and use patterns in relation to topography, climate, and social setting, the narrow geographical scope of these studies limits their extrapolation to other regions or their usefulness in addressing more subtle effects.

Research has not typically considered an array of major effects and their interactions. We found only one study (either by way of case study or conceptual framework) addressing the broad range of major road effects. A recent report from the Transportation Research Board that addresses effects of motor vehicles—and by extension, roads—on climate and ecology focuses on the effects of vehicle emissions; only eight pages are devoted to a discussion of the effects of vehicle infrastructure (that is, roads), and the discussion of conserving biodiversity is limited to selected variables. Another recent paper focuses almost exclusively on the ecological damage posed by roads with scant attention to their potential benefits (Forman and others 1997). We know of no studies that provide a systematic way of evaluating risks and benefits from building, using, and removing roads. Such studies are needed to assess tradeoffs among the exceptionally diverse roles of roads in forest landscapes.

Recommendations

This overview of scientific information leads us to conclude that the emerging science of the effects of roads as networks in the landscape requires considerable new research. Because of the high degree of variability of roads from place to place and region to region, a framework for evaluating benefits, problems, risks, and tradeoffs among them would provide a powerful decisionmaking tool. We believe such a framework is now in place (USDA FS 1999). Conducting these analyses is well within the grasp of capable specialists, planners, and managers who can bring their expertise to the problem of reducing risks from past, current, or planned roads and targeting future road-restoration activities. The science pieces are already developed to analyze and integrate road systems and their effects.

Valid and useful analyses of road systems cannot proceed in the face of outdated, incomplete inventories lacking data needed to address important questions. Accurate and current road inventories that include information relevant to environmental effects analyses are needed.

Long-term and ongoing science initiatives would yield valuable information on how the effects of roads develop and change over time. Areas of research should include the effects of progressive road development and how road effects diminish or increase through time, even under constant road configuration. Some observations suggest, for example, that roads systems increasingly connect surface water flow paths to streams over decades, via gullies and landslides in steep terrain. Effects of road restoration practices also need to be evaluated in long-term studies, because both effects and practices are likely to evolve over time. Research on social and cultural perspectives on road use and presence is a key area for future work.

Organization of Sections That Follow

Several possible models might be used to organize a discussion of the ecological and physical effects of roads in forested landscapes. The most logical organization might start from the smallest scale of measurable effects and proceed to the landscape scales. At present, however, our knowledge is too imperfect and too fragmented to fully appreciate and integrate landscape-scale effects. Thus, we have used an approach that goes from the most direct effects to the secondary and indirect effects of forest roads. To a large degree, this model implies we will proceed from understanding effects of road segments to understanding effects of a road network.

We list physical effects first, stressing geomorphic and hydrologic processes, followed by effects on site productivity. Then we move to effects of habitat fragmentation, biological invasion, and other habitat changes that roads introduce. The direct effects—especially the physical ones, such as increased sedimentation and increased risk of slides and debris flows—are much affected by road design and placement on the landscape. Thus, when consequences of roads are aggregated at the landscape scale, the proportion of old roads to new ones that incorporate improved engineering design must be taken into account.

Indirect physical, biological, and landscape-scale effects, sometimes known only from empirical relations, constitute the next set, and include aquatic habitat effects both observed in instream consequences and broad-scale potential effects. Changes in the habitat of terrestrial vertebrates, road kill, and transmission of forest diseases by road traffic are even more complicated, in that they introduce effects not from the road itself, but from road use. Such effects clearly can be stopped by closing a road, but they also can be reduced or altered by changing patterns of road use, allowing for a range of options different from the options roads introduce just by their presence. Lastly, conserving biodiversity is such a broad and unexplained topic that we can sketch only a few of its aspects; we cannot state unequivocally what specific roles roads have in the interplay of populations, modified habitat, the new techno-ecosystem, road kill, and the complex ecological results when alien species modify forest landscapes. We also cannot separate the effects of roads from land-use changes on adjacent lands made accessible by roads; all modify species composition and survival of their populations.

We have addressed socioeconomic effects of roads in forest systems in a manner that follows the pattern introduced in the discussion of physical and biological effects: namely, we examine direct effects first, followed by a discussion of indirect effects or effects at a larger, landscape scale.

Some studies have separated road effects from land-use effects, including timber harvest on adjacent lands; other studies have not. Thus, this synthesis may have allowed these effects to be combined. Although we have made every effort to remove these confounding factors, the reader must carefully evaluate the data presented and consider to what degree we have succeeded.

The following sections are summary discussions of the interaction of roads with adjacent landscape components. They also briefly summarize the available information about the effects of roads on the environment and deliberately have been kept short with references provided for further study.

Direct Physical and Ecological Effects

Geomorphic Effects, Including Sedimentation and Landslides

Issues—More than 50 years of research and many case examples place the effects of forest roads on geomorphic processes squarely at the heart of the debate prompting reexamination of existing and future road networks on public lands. Geomorphic effects of forest roads range from chronic and long-term contributions of fine sediment into streams to catastrophic effects associated with mass failures of road fill material during large storms. The interactions of roads and land surfaces are often complex; for example, on one part of the hillslope, roads may trigger mass failures, and roads downslope from them may trap material derived from these failures. Roads and road building may alter channel morphology directly or may modify channel flow paths and extend the drainage network into previously unchannelized portions of the hillslope. Economic effects of road failures during storms has been discussed; less clearly understood are the cumulative or downstream consequences of road-related changes to geomorphic processes. Major issues motivating concern about road-related erosion include potential degradation of aquatic habitat and water quality and risks to public safety and structures downstream.

Findings—Roads affect geomorphic processes by four primary mechanisms: accelerating erosion from the road surface and prism itself by both mass and surface erosion processes; directly affecting channel structure and geometry; altering surface flow paths, leading to diversion or extension of channels onto previously unchannelized portions of the landscape; and causing interactions among water, sediment, and woody debris at engineered road-stream crossings. These mechanisms involve different physical processes, have various effects on erosion rates, and are not uniformly distributed either within or among landscapes. In steep forest lands prone to landsliding, the greatest effect of roads on erosion rates is from increased rates of mass soil movement after road building. Mass soil movements affected by roads include shallow (three to several feet deep) debris slides, deep-seated (depths of tens of yards) slumps and earth flows, and debris flows (rapid channelized and fluidized movements of water, sediment, and wood). Of these, effects of roads on debris slides and flows have been the most extensively studied, typically by landslide inventories using some combination of sequential aerial photography and ground verification. Accelerated erosion rates from roads because of debris slides range from 30 to 300 times the forest rate, but differ with terrain in the Pacific Northwest, based on a unit area in forest lands ranging from the U.S. Pacific Northwest to New Zealand (Sidle and others 1985). After the 1964 flood in the Pacific Northwest, Swanson and Dyrness (1975) documented increased rates of landslide frequency up to 30 times the rates in unmanaged forested areas. Similar inventories have been conducted elsewhere in the Western United States including Idaho (Megahan and others 1978), Washington (Reid 1981), and northern California, each documenting increased rates of landsliding in road areas relative to unmanaged forested areas. The magnitude of road-related mass erosion differs with climate, geology, road age, construction practices, and storm history. Several studies in the Eastern United States show that landslides are driven more by storm magnitude and geology than by land use. A threshold of 5 inches of rain per day (Eschner and Patric 1982) and metasedimentary geology are associated with large debris slides in the Appalachians. Road drainage can cause small slides in road fills; nevertheless, some major landslides originate in undisturbed forest land (Neary and Swift 1987, Neary and others 1986).

Road-related mass failure results from various causes. Typical causes include improper placement and construction of road fills and stream crossings; inadequate culvert sizes for water, sediment, and wood during floods; poor road siting; modification of surface or subsurface drainage by the road surface or prism; and diversion of water into unstable parts of the landscape (Burroughs and others 1976, Clayton 1983, Furniss and others 1991, Hammond and others 1988, Larsen and Parks 1997, Larsen and Simon 1993). Effects of roads on deep-seated mass movements have been much less extensively studied, although cases are documented of road building apparently accelerating earth-flow movement. This can occur by destabilizing the toe area or diverting water onto the earth-flow complex (Hicks 1982). Little is documented about the potential for increased mass failures from roads resulting from decay of buried organic material that has been incorporated into road fills or landings during road building. Anecdotal evidence is abundant that failures occur predictably after decay of the organic material.

Although mass erosion rates from roads typically are one to several orders of magnitude higher than from other land uses based on unit area, roads usually occupy a relatively small fraction of the landscape, so their combined effect on erosion may be more comparable to other activities, such as logging. Studies by Swanson and others (1981) in the Oregon Coast Range, for example, showed that although unit-area erosion from roads was 30 times greater than the increase from clearcutting alone, road-related landslide erosion accounted for just three times as much accelerated slide erosion in the watershed when the area in roads and clearcuts was taken into account. Road and clearcut erosion were nearly equal in a study in the west side of the Cascade Range in Oregon (Swanson and Dyrness 1975). In the Klamath Mountains of southwest Oregon, erosion rates on roads and landings were 100 times those on undisturbed areas, but erosion on harvested areas was 7 times that of undisturbed areas (Amaranthus and others 1985).

A related point is that only a few sites can be responsible for a large percentage of the total erosion. For example, major erosional features occupied only 0.6 percent of the length of roads studied by Rice and Lewis (1986).

Although road location, design, construction, and engineering practices have improved markedly in the past three decades, few studies have systematically and quantitatively evaluated whether these newer practices result in lower mass erosion rates (McCashion and Rice 1983). Retrospective analysis of road-related landslides in the Oregon Coast Range suggests some reduction in slide frequencies because of improved road siting and building (Sessions and others 1987). No large storms occurred during the study period, however, so these practices remain largely untested. Currently, several studies are ongoing to evaluate road-related mass movements and the influence of road design after several large floods in 1996 in the Pacific Northwest and 1997 in California. These studies are likely to substantially improve understanding of whether “best management practices” are effective in reducing mass erosion from roads, and which specific practices influence mass failure response.

Surface erosion from road surfaces, cut banks, and ditches represents a significant and, in some landscapes, the dominant source of road-related sediment input to streams. Increased sediment delivery to streams after road building has been well documented in the research literature for the Pacific Northwest and Idaho (Bilby and others 1989, Donald and others 1996, Megahan and Kidd 1972, Reid and Dunne 1984, Rothacher 1971, Sullivan and Duncan 1981) and in the Eastern United States (Kochenderfer and others 1997; Swift 1985, 1988). Rates of sediment delivery from unpaved roads are highest in the first years after building (Megahan and Kidd 1972) and are closely correlated to traffic volume on unpaved roads (Reid and Dunne 1984, Sullivan and Duncan 1981). Surface-erosion problems are worst in highly erodible terrain, particularly landscapes underlain by granite or highly fractured rocks (Megahan 1974b, Megahan and Ketcheson 1996). In the Eastern United States, poorly designed and managed forest access and county roads are major sources for higher sediment input rates to streams (Hansen 1971, Patric 1976, Van Lear and others 1995). Roads were identified as the major source of sediment in the Chattooga River basin, where 80 percent of the road sources are unpaved, multipurpose roads (forest and county) paralleling or crossing tributary streams (Van Lear and others 1995). The largest sediment losses were during road building and before exposed soils were protected by revegetation, surfacing, or erosion control materials (Swift 1985, 1988; Thompson and others 1996; Vowell 1985). Soil loss from skid roads in West Virginia ranged from 40 tons/acre during logging, to 4 tons/acre the first year after logging, to 0.1 ton/acre 1 year after logging was completed (Hornbeck and Reinhart 1964). Raw ditch lines and roadbeds are continuing sources of sediment (Miller and others 1985), usually because of lack of maintenance, inadequate maintenance for the amount of road use, excessive ditch line disturbance, or poorly timed maintenance relative to storm patterns (Swift 1984, 1988).

Extensive research has demonstrated that improved design, building, and maintenance of roads can reduce road-related surface erosion at the scale of individual road segments. Key factors are road location, particularly layout relative to stream systems (Swift 1988, USDA FS 1999), road drainage (Haupt 1959), surfacing (Burroughs and King 1989, Kochenderfer and Helvey 1987, Swift 1984), and cut slope and fill slope treatments (Burroughs and King 1989, Swift 1988). Many studies show that surfacing materials and vegetation measures can be used to reduce the yield of fine sediment from road surfaces (Beschta 1978, Burroughs and others 1984, Kochenderfer and Helvey 1987, Swift 1984).

Few studies have evaluated long-term and watershed-scale changes to sediment yields as roads are abandoned, obliterated, or restored. Personnel at Redwood National Park are undisputed experts in road restoration at a watershed scale; they have developed, tested, and applied road-restoration techniques at a scale virtually unprecedented throughout the world (Ziemer 1997). Since Redwood National Park was expanded in 1978, 134 miles of the 300 miles of road within park boundaries have been restored or obliterated. This work has removed about 1,300,000 cubic yards of material from stream crossings, landings, and unstable road benches. The volume of material is about equal to the long-term average annual sediment discharge near the mouth of Redwood Creek (Ringgold, n.d.). To evaluate the success of removing this volume of material, the delivery mechanism, timing, and proportion of the removed material that actually would have found its way to the channel without the restoration activity, the quantity of new material introduced by erosion caused by the restoration work itself, and the relative proportion of the treated areas compared to untreated areas at comparable risk in the basin must be known. Such evaluations are uncommon.

Roads interact directly with stream channels in several ways, depending on orientation to streams (parallel, orthogonal) and landscape position (valley bottom, midslope, ridge). The geomorphic consequences of these interactions, particularly during storms, are potentially significant for erosion rates, direct and off-site effects on channel morphology, and drainage network structure, but they are complex and often poorly understood. Encroachment of forest roads along the mainstem channel or flood plain may be the most direct effect of roads on channel morphology in many watersheds. Poorly designed channel crossings of roads and culverts designed to pass flow also may affect the morphology of small tributary streams, as well as limit or eliminate fish passage. Indirect effects of roads on channel morphology include the contributions of sediment and altered streamflow that can alter channel width, depth, local gradients, and habitat features (pools, riffles) for aquatic organisms (Harr and Nichols 1993).

Roads in midslope and ridgetop positions may affect the drainage network by initiating new channels or extending the existing drainage network. By concentrating runoff along an impervious surface, roads may decrease the critical source area required to initiate headwater streams (Montgomery 1994). In addition, concentrated road runoff channeled to roadside ditches may extend the channel network by eroding gullies or intermittent channels on hillslopes and by linking road segments to small tributary streams (Weaver and others 1995, Wemple and others 1996a). These effects of roads on the channel network have implications for slope stability, sedimentation, and streamflow regimes.

An emerging focus of the postflood studies in the Pacific Northwest is the importance of designing roads to accommodate disturbances (see “Hydrologic Effects” below), particularly in the area of road-stream crossings, which are implicated in most documented road failures (Furniss and others 1997). Another facet of this research is recognizing that roads can serve both as sources (by initiating landslides) and sinks (by trapping debris flows) of sediment during large events (Wemple and others 1996a).

Reliability of findings—These findings represent a broad synthesis of more than 50 years of research on geomorphic effects of roads in a wide range of physiographic and land-use settings. Although they are generally well supported by field, small watershed, and plot studies, specific effects of roads are strongly influenced by local factors, including road building techniques, soil and geology, precipitation and runoff regimes, and topography. As with hydrologic studies, evaluating effects of roads on geomorphic processes is further limited by the short timeframes (one to several years) during which such effects typically are monitored. Few studies have placed road effects in a broad landscape or watershed setting.

Generalizability—Most studies of roads have been conducted in only a few landscapes (the Pacific Northwest, Rocky Mountains, Appalachians, interior highlands, and Piedmont), so the ability to generalize to other terrains is limited. Statements about effects of roads on mass erosion are limited to those landscapes affected by such processes. A large part of the United States, including the Central States, Piedmont, and the coastal plain in the East, do not experience mass erosion processes in the forest. For the most part, only historical road-building practices (pre-1990) have been rigorously evaluated, either by scientists or by the landscape itself through large floods. Little is known, however, about geomorphic effects of old mining and arterial roads (older than 50 years).

Secondary links—The geomorphic and hydrologic effects of roads are closely related. Restoration strategies to reduce either geomorphic or hydrologic effects are likely to be quite different, however, which underscores the need to clearly identify objectives for restoration. For example, practices to reduce road network extension of surface flow paths by draining water back into the subsurface could have the unintended consequence of destabilizing fill slopes. Both the mass erosion and fine-sediment delivery issues are closely linked to concerns about aquatic habitat.

Conclusions—As with the hydrologic issues, evaluating geomorphic effects of roads needs to be addressed at several scales: individual road segments, intermediate-sized watersheds, and the entire road network in the river basin (which may include private lands and roads and roads built for a broad range of purposes, not just forest operations). Key directions for future research work are to systematically evaluate the relation between improved road practices and mass-erosion rates, particularly in light of mid-1990s floods in the Pacific Northwest and California; develop a conceptual and analytical framework for evaluating how roads in different landscape positions (valley bottom, midslope, ridgetop) interact with streams; develop empirical data on the amount of drainage-network extension and drainage-density increases resulting from roads in different geomorphic settings; and place geomorphic effects of roads in broader landscape contexts by using sediment budget and disturbance budget approaches.

Hydrologic Effects

Issues—The interaction between forest roads and water lies at the heart of several key issues surrounding the effects of roads on the environment. At the scale of individual road segments, designing and building roads to drain or channel water away from the road surface is one of the main problems facing road engineers, and it reflects the substantial effects that roads can have on hillslope hydrology. Road drainage problems and water and debris passage problems—especially during floods—are primary reasons for road failure, often with major structural, ecologic, economic, or social consequences. For example, of the $178 million spent on flood recovery on Forest Service lands in the Pacific Northwest Region after the 1996 floods, more than 70 percent was to fix road damage; most of the damage resulted from water drainage problems that, in turn, triggered mass movements (Cronenwelt, n.d.). At a broader scale, roads can influence the size and timing of streamflows from watersheds, with possible consequences for downstream channels and aquatic ecosystems. For these reasons, many road restoration projects are explicitly or implicitly focused on the ways roads influence the routing of water, with consequences for erosional processes.

Findings—Roads have three primary effects on water: they intercept rainfall directly on the road surface and road cutbanks and intercept subsurface water moving down the hillslope; they concentrate flow, either on the surface or in an adjacent ditch or channel; and they divert or reroute water from flow paths that it would take were the road not present. Most hydrologic and geomorphic consequences of roads result from one or more of these processes. By intercepting surface and subsurface flow, for example, and concentrating it through diversion to ditches, gullies, and channels, road systems effectively increase the density of streams in the landscape. This changes the amount of time required for water to enter a stream channel, which alters the timing of peak flows and hydrographic shape (King and Tennyson 1984, Wemple and others 1996a). Similarly, concentration and diversion of flow into headwater areas can cause incision of previously unchanneled portions of the landscape and initiate slides in colluvial hollows (Mongomery 1994). Diversion of streamflow at road-stream crossings is a key factor contributing to road failure and erosional consequences during large floods (Furniss and others 1998, Weaver and others 1995).

Hydrologically, different parts of the road system behave differently. All roads are not created equal and do not perform the same during storms, and the same road segment may behave differently during storms of different magnitudes. Recent, detailed examination of hydrographs at stream crossings with culverts shows that during the same storm, some road segments contribute substantially more flow to channels than others, primarily owing to differences in the amount of subsurface water intercepted at the cut bank (Bowling and Lettenmeier 1997, Wemple and others 1996b). As storms become larger or soil becomes wetter, more of the road system contributes water directly to streams. Slope position has a profound effect on the magnitude of hydrologic change caused by roads. Discharge from hill slopes, height of cut bank, density of stream crossings, soil properties, and response to storms all differ with slope position.

Although hydrologic effects of roads have been studied for more than 50 years, systematic studies with long-term measurement of the full range of potential interactions between water and roads are few. Most studies have emphasized geotechnical issues, including road design, culvert size and placement, and erosion control from road surfaces (see Reid and others 1997, for bibliography; Swift 1988). Of those studies that have attempted to look at the hydrologic behavior of roads, most have been part of small (typically 0.3 to 2 square miles) watershed experiments, where roads were a component of the experimental treatment, which often included other silvicultural practices. Key studies and locales of this type include those by Rothacher (1965, 1970, 1971, 1973), Harr and McCorison (1979), Harr and others (1975), Jones and Grant (1996), and Thomas and Megahan (1998) in western Oregon; Ziemer (1981, 1998) and Wright and others (1990) in northern California; King and Tennyson (1984) in central Idaho; Reinhart and others (1963), Hewlett and Helvey (1970), Swank and others (1982, 1988) in the southern Appalachians, Helvey and Kochenderfer (1988) in the central Appalachians; and Hornbeck (1973) and Hornbeck and others (1997) in the northern Appalachians. Very few studies have focused on the hydrologic behavior of roads alone; in the Pacific Northwest and Rocky Mountains, maximum measurement periods during which roads were the only treatment range from 1 to 4 years (Wemple 1994). Most studies have been conducted as “black box” experiments comparing streamflow hydrographs before and after road building, with little ability to identify key processes. Exceptions include the work of Megahan (1972), Keppeler and others (1994), and Wemple (1994) on subsurface flow interception and Luce and Cundy (1994) and Ziegler and Giambelluca (1997) on road-surface runoff. Few studies have focused on road effects, on hydrology in arid or tropical areas, or on areas dominated by snow hydrology, permafrost, and wetlands.

Even fewer published studies have explicitly considered how road networks affect the routing of water through a basin. We therefore have little basis to evaluate the hydrologic functioning of the road system at the scale of an entire watershed or landscape. Few published studies to date have identified how roads in different landscape positions might influence the movement of water through a basin. Montgomery (1994) looked at the effect of ridgetop roads on channel initiation, and Wemple (1994) documented the magnitude of drainage network enlargement caused by roads in different slope positions.

Based on studies of small watersheds, the effect of roads on peak flows is detectable but relatively modest for most storms; insufficient and contradictory data do not permit evaluation of how roads perform hydrologically during the largest floods. Roads do not appear to affect annual water yields, and no studies have evaluated their effects on low flows. In some studies, roads produced no detectable change in flow timing or magnitude (Rothacher 1965, Wright and others 1990, Ziemer 1981), but in other basins, average time to storm peak advanced and average peak magnitude increased after road building for at least some storm sizes (Harr and others 1975, Jones and Grant 1996, Thomas and Megahan 1998). In a study in Idaho, peak stormflow magnitude increased in one basin and decreased in another after road building, an effect the authors attribute to subsurface flow interception by roads and desynchronization of delivery of water to the basin outlet (King and Tennyson 1984). A whole-tree logging operation in New Hampshire that resulted in 12 percent of the area in roads (Hornbeck and others 1997) showed a maximum average increase of growing-season peak flows of 63 percent in the second year after harvest. This increase disappeared as the forest regenerated, and only 2 of the 24 peak flows in the 6th through the 12th growing seasons showed statistically significant increases. Dormant-season peak flows generally decreased because cutting changed snowmelt regimes. Helvey and Kochenderfer (1988) concluded that typical logging operations in the central Appalachians do not increase flows sufficiently to require larger culverts to accommodate them. Forest harvesting without roads in the southern Appalachians increased stormflow volumes by 11 percent and peak flow rates by 7 percent (Hewlett and Helvey 1970, Swank and others 1988). Harvesting an adjacent watershed with 4 percent of the area in roads increased stormflows by 17 percent and peak flows by 33 percent. Four years later, peak flows dropped to a 10-percent increase after 40 percent of the road system was closed and returned to forest (Douglass and Swank 1975, 1976). Collectively, these studies suggest that the effect of roads on basin streamflow is generally smaller than the effect of forest cutting, primarily because the area occupied by roads is much less than that occupied by harvest operations. Generally, hydrologic recovery after road building takes much longer than after forest harvest because roads modify physical hydrologic pathways, but harvesting principally affects evapotranspiration processes. The hydrologic effect of roads depends on several factors, including the location of roads on hillslopes, characteristics of the soil profile, subsurface water flow and ground-water interception, design of drainage structures (ditches, culverts) that affect the routing of flow through the watershed, and proportion of the watershed occupied by roads.

Most road problems during floods result from improper or inadequate engineering and design, particularly at road-stream crossings but also where roads cross headwater swales or other areas of convergent groundwater. Road redesign that anticipates and accommodates movement of water, sediment, and debris during infrequent, but major storms should substantially reduce road failures and minimize erosional consequences when failures occur. Recent studies after large floods in the Pacific Northwest highlight the importance of water diversion by roads and road-related structures (that is, plugged culverts, ditches) in contributing to road-related failures (Donald and others 1996, Furniss and others 1997). A typical failure resulted from culverts sized only to accommodate the flow of water, but not the additional wood and sediment typically transported during major floods. The culverts became obstructed and diverted water onto the road surface, into neighboring drainages unable to adjust to the increase in peak flow from the contributing basin, or onto unchanneled hillslopes. “Cascading failures” were common, where diversion or concentration of flow led to a series of other events, ultimately resulting in loss of the road or initiation of landslides and debris flows. Analysis of the probability of large floods and how they relate to the design life of roads indicates that most road crossings are likely to have one or more large floods during their lifetimes. Consequently, designing roads with large storms in mind is prudent and well within the reach of current engineering practices (Douglass 1977; Furniss and others 1991, 1997; Helvey and Kochenderfer 1988). The potential for stream diversion on wildland roads indicates that the environmental consequence of road failure during large storms is an option to consider.

Although the ability to measure or predict the hydrologic consequence of building or modifying a specific road network might be limited, general principles and models can be provided that, if followed, may decrease the negative hydrologic effects of roads. These principles will be useful during upgrading or decommissioning of roads to meet various objectives. A partial list of principles includes:

- Locate roads to minimize effects; conduct careful geologic examination of all proposed road locations.
- Design roads to minimize interception, concentration, and diversion potential, including measures to reintroduce intercepted water back into slow (subsurface) pathways by using outsloping and drainage structures rather than attempting to concentrate and move water directly to channels.
- Evaluate and eliminate diversion potential at stream crossings.
- Design road-stream crossings to pass all likely watershed products, including woody debris, sediment, and fish—not just water.
- Consider landscape location, hillslope sensitivity, and orientation of roads when designing, redesigning, or removing roads.
- Design with failure in mind. Anticipate and explicitly acknowledge the risk from existing roads and from building any new roads, including the probability of road failure and the damage to local and downstream resources that would result. Decisions about the acceptable probability and especially consequences of failures should be informed through explicit risk assessments. The many tradeoffs among road building techniques to meet various objectives must be acknowledged. For example, full bench road construction may result in lower risk of fill slope failure, but it also may increase the potential for groundwater interception; outsloping of the road tread may reduce runoff concentration on the road surface but also increase driving hazard during icy or slippery conditions.

Reliability of findings and generalizability—Hydrologic effects of roads are strongly influenced by landscape condition, road design and construction, and storm history. Generalizability of paired-watershed studies is limited by the short timeframes (one to several years) during which road effects alone are typically monitored. In addition, most road studies have been done in only a few landscapes where road problems are common (the Pacific Northwest, Rocky Mountains, and Appalachians), thereby limiting the ability to generalize to other terrain. The general principles represent reasonable interpretations of the available scientific knowledge, however. Some landscapes may be much more sensitive than others to certain key processes, such as interception of subsurface flow and drainage network extension resulting from gullying. For this reason, the specific range of hydrologic effects likely to be encountered needs to be evaluated by both regional and landscape scales.

Secondary links—The hydrologic effects of roads are strongly linked to their sediment and geomorphic effects. Other links can be found with wildlife (for example, road-created wetlands) and invasion by exotics (for example, microclimate related to water availability above and below the road prism), but these links have received little scientific attention.

Conclusions—Future efforts to redesign, restore, or remove road systems because of hydrologic concerns should have clear objectives: What hydrologic processes are considered problems? Where do they occur? What can be done about them? What degree of hydrologic alteration is considered acceptable? This type of evaluation of roads is best accomplished in the context of a watershed analysis (USDA FS 1999). Key areas for future research are to develop analytical models that allow managers to display the predicted hydrologic consequences of alternative road-network designs (these types of models are still in their infancy but should be more widely available in the next 2 to 3 years), expand process-based studies of how roads affect specific hydrologic mechanisms (for example, subsurface flow interception or channel network extension) in different geomorphic settings evaluate at the landscape scale the extent of links between the road and stream networks in different landscapes, and relate type and size of road failures to specific design practices and landscape position.

Site Productivity

Issue—The presence of roads commits a soil resource, and where roads occupy formerly productive land, they affect site productivity.

Findings—Forest roads can have significant effects on site productivity by removing and displacing topsoil, altering soil properties, changing microclimate, and accelerating erosion. The direct effects of taking land out of production by removing trees and displacing soil, or removing soil during building and maintaining roads, has been estimated to range from 1 to 30 percent of the landscape area in managed forest lands (Megahan 1988a). In the Western United States, tractor and ground-cable systems average about 10 percent of the area affected by roads to support harvest operations, and skyline and helicopter operations average 2 percent (Megahan 1988b). Studies in Eastern U.S. forests have consistently found that 4 to 5 percent of the total forested area is taken out of forest production by building roads during logging operations, although more than 50 percent of this area may be reforested within 8 years, but at reduced growth rates and productivity. Total road length required to support logging operations depends on the harvest and silvicultural systems and topographic configuration, but the area disturbed may be surprisingly consistent (Douglass and Swift 1977, Robinson and Fisher 1982, Swank and others 1982, Swift 1988).

Measurable declines in tree growth are common where soil is excavated to build the road prism. Evidence of off-site effects of roads on productivity is conflicting, though road-associated mass erosion may scour soil from steep slopes. Road building changes soil physical properties including depth, density, infiltration capacity, water holding capacity, and gas exchange rate, nutrient concentrations, and microclimate. Fertile topsoils, often containing most of the organic matter and plant nutrient capital of a site, frequently are buried under road fills or sidecast and may be rendered inaccessible to plant roots. Trees can grow on any portion of a closed road, but they can grow only on cut and fill slopes on open roads. Sites are harshest and soils poor or nonexistent on road cuts and the cut portion of road treads. Tree height and diameter growth is reduced on these portions of the road (Smith and Wass 1979, 1980, 1985). Growth is sometimes enhanced on or below fill portions of roads because of reduced competition and greater soil depth. Pfister (1969) documents a 30-percent increase in height growth of western white pine (*Pinus monticola* Dougl. ex D. Don) adjacent to outsloped roads. Megahan (1988a) suggests that this increase is due to enhanced soil moisture below outsloping roads. Smith and Wass (1980) document significant declines of 23 percent in height growth for lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and 20 percent for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) below insloped roads, which they attribute to loss of available water through redirected drainage flow. Improper fill placement and drainage can cause upslope groundwater to rise, and the changed soil moisture kills trees (Boelter and Close 1974, Stoeckeler 1965), although not commonly. Loss of nutrient capital is inevitable with soil disturbance from road building (Swanson and others 1989), but isolating this effect from other site changes has proved difficult. An indirect indication of nutrient loss is the marked growth response of plants on road fills after fertilizer is applied. Fertilizer applied to a granitic road fill in Idaho increased growth of vegetation by 32 to 116 percent (Megahan 1974a), but such increases are not documented after fertilizer is applied on undisturbed soils. Both surface and mass-erosion rates increase after road building, and often roads accelerate erosion on the slope below. Downslope damage generally is associated with mass erosion when a landslide originates from a road and causes scour on lower slopes or gullies related to concentrated road drainage (Megahan 1988a). This problem is widespread on steep slopes of the Pacific States and in the northern Rocky Mountains (Burroughs 1985, Swanson and others 1981), although Megahan (1988b) estimates that productivity is reduced on about 0.3 percent of forested land at a broad scale. These effects may range from decades (Ice 1985) to more than 85 years (Smith and others 1986). Road treads are highly compacted compared to natural soils, but compaction is not a productivity issue so long as roads are open and the running surface is bare. Road decommissioning must take compaction into account in restoring productivity, and various “ripping” treatments are routinely applied to decompact road surfaces.

Reliability, confidence, and generalizability—Direct effects of roads—including lost productivity because of the area occupied by roads themselves, and diminished productivity on cut slopes and road treads on closed roads—are well documented and general in geographic extent. Losses of productivity associated with road-caused, accelerated erosion are site specific and variable in extent, but they are commonly reported for all steep-slope landscapes. Rates of reforestation along road fills are high in the Pacific Northwest and Eastern United States and slower in the inland West and Southwest. Road-caused nutrient imbalances or declines often are confounded by other effects (notably soil moisture losses) in Western States.

Conclusions—A substantial amount of information is available on productivity in road fills and cut slopes and strong anecdotal, but obvious, evidence of lack of productivity on road treads. Information on effects of roads on adjacent site productivity is limited, and variable results confound attempts to generalize and accurately predict effects.

Secondary links—Applying salt to roads is discussed in “Water Quality” and its effects on plant damage are discussed in “Forest Diseases,” both below. Erosional processes and rates are discussed extensively in “Geomorphologic Effects,” above. Loss of site productivity represents a long-term economic loss, and quantifying such losses is confounded by the difficulty in establishing or even estimating the degree of soil productivity changes associated with roads.

Habitat Fragmentation

Issues—Natural populations of animal species are reduced by habitat loss caused by road building and by the animals' avoidance of areas near roads. Populations can be fragmented into smaller subpopulations, thereby causing increased demographic fluctuation, inbreeding, loss of genetic variability, and local population extinctions.

Findings—Habitat loss has broader effects than just the conversion of a small area of land to road surface. Roads fragment by changing landscape structure and by directly and indirectly affecting species. Habitat effects of roads on the landscape include dissecting vegetation patches, increasing the edge-affected area and decreasing interior area, and increasing the uniformity of patch characteristics, such as shape and size (Reed and others 1996). Whenever forest roads are built, changes in habitat and modified animal behavior will lead to changes in wildlife populations (Lyon 1983). Road-avoidance behavior is characteristic of large mammals such as elk (*Cervus canadensis*), bighorn sheep (*Ovis canadensis*), grizzly (*Ursus arctos horribilis*), caribou (*Rangifer tarandus*), and wolf (*Canis lupus*). Avoidance distances of 300 to 600 feet are common for these species (Lyon 1985). Road usage by people and their vehicles has a significant role in determining road avoidance by animals. In a telemetry study of movement by black bear (*Ursus americanus*), bears almost never crossed interstate highways, and they crossed roads with little traffic more frequently than those with high traffic volumes (Brody and Pelton 1989). Bobcats (*Lynx rufus*) crossed paved roads in Wisconsin forests less than expected, possibly to minimize interactions with vehicles and people (Lovallo and Anderson 1996). A few studies have related genetic changes in populations simply to the presence of roads (Forman and others 1997), but the distribution of roads in the environment also must be considered. Road density is a useful index of the effect of roads on wildlife populations (Forman and others 1997). Wolves in Wisconsin are limited to places with pack-area mean road densities of 0.7 mile/square mile or less (Mladenoff and others 1995). Some studies have shown that a few large areas of low road density, even in a landscape of high average road density, may be the best indicator of suitable habitat for large vertebrates (Rudis 1995).

Reliability, confidence, and limitations—The evidence is strong that forest roads displace some large mammals and certain birds such as spotted owls (*Strix occidentalis)* and marbled murrelets (*Brachyramphus marmoratus*) and that displaced animals may suffer habitat loss as a result. Effects of roads on small mammals and songbirds are generally described as less severe, with changes expressed as modifications of habitat that cannot readily be classified as detrimental or beneficial. This interpretation is also probably true for amphibians and reptiles.

Generalizability—For large mammals, general principles have been explained, above, that can be applied to project decisions.

Secondary links—Habitat fragmentation is linked to other habitat-related topics and also links with access-related topics, particularly timber, where the density and distribution of roads is a key technical and economic question.

Conclusions—Specific issues related to wildlife can be addressed directly. Integration with other technical, economic, and social issues (such as timber availability and recreational access) have to be dealt with by management.

Habitat

Issues—Road building introduces new edge habitat in the forest. The continuity of the road system also creates a corridor by which edge-dwelling species of birds and animals can penetrate the previously closed environment of continuous forest cover. Species diversity can increase, and increased habitat for edge-dwelling species can be created.

Findings—Roads and their adjacent environment qualify as a distinct habitat and have various species, population, and landscape-scale effects (Baker and Knight 2000, Dawson 1991, van der Zande and others 1980). Some research has attempted to describe habitat modifications caused specifically by roads, but most of this work is species and site specific (Lyon 1983). Surveys of songbirds in two national forests of northern Minnesota found 24 species of birds more abundant along roads than away from them (Hanowski and Niemi 1995). Close to half these species were associated with edges, including birds like crows (*Corvus brachyrhynchos)* and blue jays (*Cyanocitta cristata)* that use roads as corridors to find food. Turkey hens (*Megapodiidae*) in North Carolina nested near closed and gated logging roads and used them extensively in all stages of brood development (Davis 1992). One study showed that habitat in the roadside right-of-way supports a greater diversity of small mammals than do adjacent habitats (Adams and Geis 1983), but this finding may not apply to forest roads with only narrow cuts and fills on either side. The similarity between forest roads and transmission-line rights-of-way may be important in assessing the contribution of roads to habitat. Studies have shown that wide transmission-line corridors support grassland bird communities of species not found in the forest, and narrow corridors produce the least change from forest bird communities (Anderson and others 1977). The same study notes that increasing edge diversity of birds, for instance, may negatively affect abundance of interior species (see “Biological Invasions,” below).

Reliability, confidence, and limitations—Limited species and site-specific data exist describing the immigration of particular species into habitat created by roads. Detailed information on specific habitat characteristics affected by the building and presence of roads is lacking. The relation of microclimate, vegetation distribution, and water supply to the road network needs to be described.

Generalizability—In general, road building fragments habitat and creates habitat edge, thereby modifying the habitat in favor of species that use edges. Edge-dwelling species generally are not threatened, however, because the human-dominated environment has provided ample habitat for them. Any habitat modifications attributed to the road may be insignificant compared to the effects of the activity, such as timber harvest, for which the road was built.

Secondary links—Links exist to other habitat-related topics and also to biological invasions.

Conclusions—Science information about the underlying principles related to this issue is incomplete. Further study is needed before anything more than site- and species-specific analyses can be undertaken.

Biological Invasions

Issues—A widely cited generalization about biological invasion is that it is promoted by disturbance. Building roads and subsequently maintaining them (including ditch clearing, road grading, and vegetation clearing) in the interior of a forest represents disturbances that create and maintain new edge habitat. These roadside habitats can be invaded by an array of exotic (non-native) plant species, which may be dispersed by “natural” agents such as wind and water as well as by vehicles and other agents related to human activity. Roads may be the first point of entry for exotic species into a new landscape, and the road can serve as a corridor along which plants move farther into the landscape (Greenberg and others 1997, Lonsdale and Lane 1994). Some exotic plants may then be able to move away from the roadside into adjacent patches of suitable habitat. Invasion by exotic plants may have significant biological and ecological effects if the species are able to disrupt the structure or function of an ecosystem. Invasion also may be of concern to land managers, if the exotic species disrupt management goals and present costly eradication problems.

Findings—Although few habitats are immune to at least some invasion by exotic plants, predicting which species will become pests usually is difficult. Assessing the scale of a biological invasion problem is complicated by the lag between when an exotic is introduced and when it begins to expand its distribution and population size in a new area. Cowbirds *(Molothrus ater)*, for example, can be introduced into forested environments by roads and subsequently affect populations of Neotropical migratory birds through nest parasitism. The spread of pathogens where roads act as vectors is described in “Forest Diseases,” below. Few environmentally benign approaches to exotic plant control or eradication have been tested.

Reliability, confidence, and limitations—Field studies of exotic plants tend to focus on a particular geographic region, and observed patterns of road-supported invasion may not apply to other regions. In general, however, observations suggest that biological invasion is often a negative effect of extending roads into forest interiors. Such effects should be considered in the design and execution of road network extensions.

Generalizability—Observations in different settings suggest that the exotic species that successfully invade and the scale of invasion problems differ regionally. Some exotic species can become significant pests, and others remain fairly benign.

Secondary links—Consequences of biological invasions link to habitat quality issues (including changes in plant community structure and function), other edge effects, and effects on sensitive or threatened species.

Conclusions—Information to assess the degree of risk relies on case studies; the risks may be slight or significant. A less than ideal science base exists for identifying which exotic species pose the greatest threat and what preventive or remedial measures are appropriate. Retrospective studies may help identify directions. One study showed that abandoned roads had fewer exotics (both in number of species and frequency of individuals) than did roads that were in use.

Indirect and Landscape-Scale Effects

Aquatic Habitat

Issues—The effects of roads on aquatic habitat are believed to be widespread and profound, and evidence is documented through empirical associations and direct mechanistic effects, although the mechanistic effects become fuzzy when direct, quantitative, cause-effect links are sought. Several studies correlate road density or indices of roads to fish density or measures of fish diversity. Mechanisms include effects of fine sediment, changes in streamflow, changes in water temperature caused by loss of shade cover or conversion of groundwater to surface water, migration barriers, vectors of disease, exotic fishes, changes in channel configuration from encroachment, and increased fishing pressure. A growing body of work indicates that the complexity of habitat and the predictability of disturbance influences species diversity. At the landscape scale, correlative evidence suggests that roads are likely to influence the frequency, timing, and magnitude of disturbance, which are likely to influence community structure.

Findings—Increased fine-sediment composition in stream gravel has been linked to decreased fry emergence, decreased juvenile densities, loss of winter carrying capacity, and increased predation of fishes. Increased fine sediment can reduce benthic organism populations and algal production. Increased sediment production associated with roads is discussed in detail in "Geomorphic Effects," above. Survival of incubating salmonids from embryos to emergent fry has been negatively related to the proportion of fine sediment in spawning gravels (Chapman 1988, Everest and others 1987, Scrivener and Brownlee 1989, Weaver and Fraley 1993, Young and others 1991). Increased fine sediment in stream gravel can reduce intragravel water exchange, thereby reducing oxygen concentrations, increasing metabolic waste concentrations, and restricting movements of alevins (Bjornn and Reiser 1991, Coble 1961, Cordone and Kelley 1960). Survival of embryos relates positively to dissolved oxygen and apparent velocity of intragravel water, and positively to gravel permeability and gravel size (Chapman 1988, Everest and others 1987). Consequently, juvenile salmonid densities decline as fine sediment concentrations increase in rearing areas (Alexander and Hansen 1986, Bjornn and others 1977, Chapman and McLeod 1987, Everest and others 1987, Shepard and others 1984). Increases in fine sediment also can reduce winter carrying capacity of streams by loss of concealment cover (Bjornn and others 1977, Chapman and McLeod 1987, Thurow 1997) and by increasing the likelihood of predation (Chapman and McLeod 1987). Pools function as resting habitats for migrating adults, rearing habitats for juveniles (Bjornn and Reiser 1991), and refugia from natural disturbances (Sedell and others 1990). Pools that lose volume from sediment (Jackson and Beschta 1984, Lisle 1982) support fewer fish (Bjornn and others 1977), and fish that reside in them may suffer higher mortality (Alexander and Hansen 1986). Similarly, populations of tailed frogs can be severely reduced or eliminated by increased sedimentation (Corn and Bury 1989, Welsh 1990), presumably because of their dependence on unembedded interstitial areas in the stream substrate where they hide and overwinter (Brown 1990, Daugherty and Sheldon 1982). Increased sediment reduces populations of benthic organisms by reducing interstitial spaces and flow used by many species and by reducing algal production, the primary food source of many invertebrates (Chutter 1969, Hynes 1970).

The effects of roads are not limited to those associated with increases in fine-sediment delivery to streams; they can include barriers to migration, water temperature changes, and alterations to streamflow regimes. Improper culvert placement at road-stream crossings can reduce or eliminate fish passage (Belford and Gould 1989), and road crossings are a common migration barrier to fish (Clancy and Reichmuth 1990, Evans and Johnston 1980, Furniss and others 1991). In a large river basin in Washington, 13 percent of the historical coho habitat was lost as a result of improper culvert barriers (Beechie and others 1994). Roads built adjacent to stream channels pose additional effects. Changes in temperature and light regime from removing the riparian canopy can have both positive and negative effects on fish populations. Sometimes increased food availability can mitigate negative effects of increased summer water temperatures (Bisson and others 1988). Beschta and others (1987) and Hicks and others (1991) document negative effects, including elevation of stream temperatures beyond the range of preferred rearing, inhibition of upstream migrations, increased disease susceptibility, reduced metabolic efficiency, and shifts in species assemblages. Streamflow stability and predictability (size, timing, duration, and frequency) also strongly influence salmonid densities by influencing reproductive success and overwintering survival (McFadden 1969). For example, high flows after spawning can wash out eggs or displace fry, thereby increasing mortality (Latta 1962, Mortensen 1977, Shetter 1961).

The effect of roads on peak flows is relatively modest (see “Hydrologic Effects,” above), and the issues of changing stability and predictability because of roads may be of little importance to aquatic habitat suitability.

Road-stream crossings have effects on stream invertebrates. Hawkins and others (in press) found that the aquatic invertebrate species assemblages (observed versus expected, based on reference sites) were related to the number of stream crossings above a site. Total taxa richness of aquatic insect larvae (mayflies, Ephmeroptera; stoneflies, Plecoptera; and caddisflies, Trichoptera) were negatively related to the number of stream crossings. Another study (Newbold and others 1980) found significant differences between macroinvertebrate assemblages above and below road-stream crossings.

Several studies at broad scales document aquatic habitat or fish density changes associated with road density or indices of road density. Eaglin and Hubert (1993) show a positive correlation with numbers of culverts and stream crossings and amount of fine sediment in stream channels, and a negative correlation with fish density and numbers of culverts in the Medicine Bow National Forest. Macroinvertebrate diversity negatively correlates with an index of road density (McGurk and Fong 1995). Increasing road densities are associated with decreased likelihood of spawning and rearing of non-anadromous salmonids in the upper Columbia River basin, and populations are negatively correlated with road density (Lee and others 1997).

Reliability, confidence, and limitations—Research evidence of increased erosion and sediment delivery to streams resulting from roads is strong. Subsequent habitat changes from such processes as pool filling and cobble embeddedness are well documented, but these effects depend heavily on channel geometry, flow regimes, and so on. Thus, they range widely in time and space. Measured changes in stream temperature after canopy removal are strong but biological response is highly variable, and existing literature speculates on possible mechanisms. Empirical evidence relating road density to habitat and population response at landscape scales is fairly new. The study by Lee and others (1997) has a large database and is analytically sound, but it demonstrates a statistically valid population response only for non-anadromous salmonids. Because roads are not distributed randomly on the landscape, these studies can be confounded by other landscape variables that may control biological response. This issue is addressed by Lee and others (1997).

Generalizability—Broad-scale patterns in the distribution of roads and fish suggests that the effects of roads are common and widespread across a range of environments and conditions (Bettinger and others 1998, Lee and others 1997). Changes in aquatic habitat resulting from increased erosion and sediment delivery are highly controlled by lithology and slope, however. Road-derived sediment in granitic terrain typically results in an increase in the proportion of fine bedload. In fine-textured parent materials, suspended load may increase but not change pool filling and cobble embeddedness. Changed timing and size of peak and low flows resulting from roads have different implications for storm-generated and snowmelt-dominated hydrologic regimes, and they result in different biological effects for oversummer and overwinter egg survival. The effect of cover removal on elevated stream temperature depends on the rate of vegetation recovery and appears to be brief in the Eastern United States (Swift 1983).

Secondary links—Responses by aquatic habitat depend on geomorphic and sediment changes associated with roads. Road-associated changes in nutrients and hazardous chemical spills are also linked but are issues addressed elsewhere in this report.

Conclusions—Road effects on aquatic habitat and population response are well documented and overwhelmingly negative, but results differ among sites. Measures of the cumulative effects of roads that are closely related to mechanism (for example, the length of roads connected by direct surface-flow paths to streams or the miles of potential habitat blocked by culverts) would be more likely to produce stronger relations between roads and aquatic habitat elements than would road density.

Landscape-Scale Effects on Fish

Issues—The decline of anadromous fish in many parts of the country, especially the salmonids in the West, has led to much research on the diverse causes. Among those, the relation of roads to intensity of land use and adverse effects on aquatic habitats has been discussed in several recent studies and publications (Meehan 1991, Naiman and others 1992, Spence and others 1996). The discussion centers on three themes: the correlation of road density to fish habitat and fish populations is not strong; the legacy of past road building is so vast and budgets for maintaining roads so low that the problems will be with us for a long time; and road building practices have improved in the last decade to the point where we need not worry about the effects of roads on aquatic systems. The scientific assessment for the interior Columbia basin provided an opportunity to examine these issues at a broad, landscape scale in this ecoregion.

Findings—Roads contribute more sediment to streams than does any other land management activity (Gibbons and Salo 1973, Meehan 1991), but most land management activities, such as mining, timber harvest, grazing, recreation, and water diversions, depend on roads. Most of the sediment from timber harvest activities is related to roads and road building (Chamberlain and others 1991, Dunne and Leopold 1978, Furniss and others 1991, MacDonald and Ritland 1989, Megahan and others 1978) and the associated increases in erosion rates (Beschta 1978, Gardner 1979, Meehan 1991, Rhodes and others 1994, Reid 1993, Reid and Dunne 1984, Swanson and Dyrness 1975, Swanston and Swanson 1976). Serious degradation of fish habitat can result from poorly planned, designed, located, built, or maintained roads (Furniss and others 1991, MacDonald and others 1991, Rhodes and others 1994). Roads also can affect water quality through applied road chemicals and toxic spills (Furniss and others 1991, Rhodes and others 1994), and the likelihood of toxic spills reaching streams has increased with the many roads paralleling them.

Roads directly affect natural sediment and hydrologic regimes by altering streamflow, sediment loading, sediment transport and deposition, channel morphology, channel stability, substrate composition, stream temperatures, water quality, and riparian conditions in a watershed. For example, interruption of hillslope drainage patterns alters the timing and magnitude of peak flows and changes base stream discharge (Furniss and others 1991, Harr and others 1975) and subsurface flows (Furniss and others 1991, Megahan 1972). Road-related mass soil movements can continue for decades after roads have been built (Furniss and others 1991). Such habitat alterations can adversely affect all life stages of fish, including migration, spawning, incubation, emergence, and rearing (Furniss and others 1991, Henjum and others 1994, MacDonald and others 1991, Rhodes and others 1994).

Poor road location, concentration of surface and subsurface water by cross-slope roads, inadequate road maintenance, undersized culverts, and sidecast materials all can lead to road-related mass movements (Lyons and Beschta 1983, Swanston 1971, Swanston and Swanson 1976, Wolfe 1982). Sediment production from logging roads in the Idaho batholith was 770 times higher than in undisturbed areas; about 71 percent of the increased sediment production was due to mass erosion (Megahan and Kidd (1972), leaving 29 percent due to surface erosion.

In granitic land types, sedimentation is directly proportional to the road distance (Jensen and Finn 1966). For instance, 91 percent (66,000 cubic yards) of the annual sediment production by land-use activities (72,200 cubic yards) in the South Fork of the Salmon River (Idaho) is attributed to roads and skid trails (Arnold and Lundeen 1968). King (1993) determined that roads in the Idaho batholith increase surface erosion by 220 times the natural rates per unit area. Roaded and logged watersheds in the South Fork of the Salmon River drainage also have significantly higher channel-bed substrate-embeddedness ratings than do undeveloped watersheds (Burns 1984).

Roads greatly increase the frequency of landslides, debris flow, and other mass movements (Dunne and Leopold 1978, Furniss and others 1991, Megahan and others (1992). Mass movement along the west side of the Cascade Range in Oregon was 30 to 300 times greater in roaded than in unroaded watersheds (Sidle and others 1985). Megahan and others (1992) found that 88 percent of landslides in Idaho are associated with roads. Roads were the primary factor in accelerated mass movement activity in the Zena Creek drainage (Idaho batholith) after the 1964-65 winter storms (Gonsior and Gardner 1971). Of 89 landslides examined along the South Fork of the Salmon River, 77 percent originated on road hillslopes (Jensen and Cole 1965). Cederholm and others (1981) found increases (above natural rates) in the percentage of fine sediment in fish spawning habitat when road density exceeded 2.5 percent of the Clearwater River watershed in Washington. Increased stream-channel sedimentation in Oregon and Washington watersheds east of the Cascade Range also is associated with road density (Anderson and others 1992).

Road-stream crossings can be a major source of sediment to streams and result from channel fill around culverts and subsequent road-crossing failures (Furniss and others 1991). Plugged culverts and fill-slope failures are frequent and often lead to catastrophic increases in stream channel sediment, especially on abandoned or unmaintained roads (Weaver and others 1995). Unnatural channel widths, slope, and streambed form are found upstream and downstream from stream crossings (Heede 1980), and these alterations in channel morphology may persist for long periods. Channelized stream sections resulting from riprapping roads adjacent to stream channels are directly affected by sediment from side casting, snow removal, and road grading; such activities can trigger fill-slope erosion and failures. Because improper culverts can reduce or eliminate fish passage (Belford and Gould 1989), road crossings are a common migration barrier for fish (Clancy and Reichmuth 1990, Evans and Johnston 1980, Furniss and others 1991).

Key aspects of aquatic habitat are pools and instream wood (positive attributes) and fine sediment (negative attribute). From an analysis of stream-inventory data for the Columbia River basin (Lee and others 1997), pools declined with increasing road density and were highest in wilderness areas. Relations between wood and surface fines were less clear. In Oregon and Washington, where wood frequency was measured, it was higher for Forest Service lands managed as wilderness or in areas with moderate use; it was significantly related to road density in the northern Cascades, southern Cascades, Columbia Plateau, northern glaciated mountains, and Blue Mountains but not in the Upper Klamath. Only the Lower Clark Fork and central Idaho mountains had sufficient data to model the relation of wood frequency to surface fines. In these latter two areas, the relation with road density was not significant, although the highest mean values of five sediments were associated with the highest road-density class.

Analysis of fish distribution and status data for seven species of anadromous and resident salmonids in the Columbia basin showed that the frequency of strong populations generally declined with increasing road densities. Additional analyses of road effects focused on four non-anadromous species, because effects of roads and other land uses on anadromous species may be masked by migrational and ocean-related factors (for example, dam passage, predation, harvest). Three species showed significant road effects when either occupied spawning and rearing areas were distinguished from unoccupied areas or strong status was differentiated from depressed status. The analysis suggested a decreasing likelihood of occupancy, or a decreasing likelihood of strong status if occupied, with increasing road density. No other variables except ground-slope showed the consistent patterns across all species shown by the road-density measures.

The investigation of the influence of roads on population status clearly showed an increasing absence and a decreasing proportion of strong populations with increasing road density for several subgroups of fish. Additional evidence suggested that the lowest mean road-density values (number of road miles per unit area) are always associated with strong population status.

This trend is apparent for Yellowstone cutthroat trout *(Onchorynchus clarki bouvieri)*, even though it was the only subgroup that did not show a significant road effect in a logistic regression analysis. The lack of statistical significance in the face of apparent trends, however, points to complex interactions among the explanatory variables that are not adequately addressed in the relatively simple logistic model. Consistent, significant effects for other species may be further testament to the presence and pervasiveness of the effects. Strong relations between roads and the distribution and status of these species were detected despite the potential confounding effects of other variables (such as harvest, non-native introductions, and other habitat factors).

These results show that increasing road densities and their attendant effects are associated with declines in the status of four non-anadromous salmonid species. These species are less likely to use highly roaded areas for spawning and rearing and, if found, are less likely to have strong populations. This consistent pattern is based on empirical analysis of 3,327 combinations of known species' status and subwatershed conditions, limited primarily to forested lands administered by the Forest Service and the Bureau of Land Management. The relation would not be expected to be as strong on the conforested, lower gradient lands administered by the bureau. Of the four species examined, the redband trout is the only one supported by the low-gradient lands. Only in forested, high-elevation areas could redband trout status be clearly associated with road-density changes.

Most aquatic conservation strategies acknowledge the need to identify the best habitats and most robust populations to use as focal points from which populations can expand, adjacent habitat can be usefully rehabilitated, or the last refugia of a species can be conserved in unroaded areas where biophysical processes are still operating without effects from many human disturbances. These refugia also provide necessary experimental controls for evaluating the effects of land management activities in other areas. The ecological importance of unroaded areas has been highlighted in the Columbia basin assessment as well as other reports (FEMAT 1993, Henjum and others 1994).

The overlap of unroaded areas—both within and outside designated wilderness areas—with stronghold watersheds for fish and with important conservation watershed efforts in the Columbia basin also was examined. Designated wilderness and unroaded areas are important anchors for strongholds throughout the basin. Unroaded areas occupy 41 percent of the area with known and predicted strongholds in the east-side environmental impact statement area. One-third of this area is outside designated wilderness. Of the known and predicted strongholds in the upper Columbia basin area, 68 percent are unroaded, of which 37 percent are outside wilderness.

Aquatic integrity in the Columbia basin was analyzed in relation to road densities and integrity ratings for other resources (forest, range, hydrology). Forest clusters with the highest integrity ratings were associated with low road densities; low integrity ratings corresponded with moderate or higher road densities. For example, the range cluster with the highest aquatic and composite integrity also had mostly low road densities. But the relations between road densities and integrity ratings for other range clusters were more variable.

The legacy of road building in the Pacific Northwest is enormous. The FEMAT report (1993) notes that federally managed forest lands in the range of the northern spotted owl contain about 180 000 kilometers (111,600 miles) of roads. A major portion of this road system may constitute a potential threat to riparian and aquatic habitats through sedimentation. An estimated 250,000 stream crossings (about 1.3 per kilometer [2.3 per mile]) are associated with these roads, and a significant number of culverts are thought to be unable to withstand storms with a recurrence interval greater than 25 years (FEMAT 1993), a hypothesis tested and affirmed by the February 1996 flood. Analysis suggests more than 205 000 kilometers (127,000 miles) of roads are on Forest Service and Bureau of Land Management lands in the Columbia River basin. Many stream crossings exist, with high densities of crossings in steep, highly dissected terrain and low densities in drier and flatter terrains. Many of the culverts or stream crossings are expected to perform poorly in flood events with recurrence intervals of more than 25 years, similar to their west-side counterparts identified in the FEMAT report. Even with adequate culvert size, lack of maintenance of a road network of this size could lead to significant road-drainage problems and accompanying effects on aquatic habitat.

Budgetary constraints on land management agencies may lead to lack of maintenance, resulting in progressive degradation of road-drainage structures and functions, increased erosion rates, and the likelihood of increased erosion (Furniss and others 1991). Problems are greatest with older roads in sensitive terrain and roads functionally abandoned but not adequately configured for long-term drainage. Applying erosion prevention and control treatments to high-risk roads can drastically reduce risks for future habitat damage and can be both effective and cost-effective. In watersheds that contain high-quality habitat and have only limited road networks, large amounts of habitat can be secured with small expenditures to apply storm proofing and decommissioning activities to roads (Harr and Nichols 1993).

For federal forests with moderate to high road densities, the job of maintaining roads may be expensive because many road networks have not been inventoried to determine their influence on riparian or aquatic resource goals and objectives. Substantial increases in sedimentation are unavoidable even when the most cautious road-building methods are used (McCashion and Rice 1983, Megahan 1980). Improving road-building and logging methods, however, can reduce erosion rates and sediment delivery to streams. The amount of sedimentation or hydrologic alteration from roads that aquatic species can tolerate before a negative response appears is not well known, though general effects of sediments on fishes are known. Sediment exceeding natural background loads can fill pools, silt spawning gravels, decrease channel stability, modify channel morphology, and reduce survival of emerging salmon fry (Burton and others 1993, Everest and others 1987, MacDonald and others 1991, Meehan 1991, Rhodes and others 1994).

Rice (1992) documents an 80-percent reduction in mass erosion from forest roads and about a 40-percent reduction in mass erosion from logged areas in northern California that resulted from improvements in forest practices beginning in the mid-1970s. Megahan and others (1992) used the BOISED sediment-yield production model to evaluate the effects of historical and alternative land management in an Idaho watershed (South Fork Salmon River). They report that current management practices, properly implemented, could reduce sediment yield by about 45 to 90 percent when compared with yields caused by the historical land use in their study watershed. If the improved road design currently practiced by the Boise National Forest is used, however, total accelerated sediment yields are still 51 percent more than natural ones. These improved road designs plus maximum erosion mitigation lead to 24-percent increases over natural yields in unroaded areas. Helicopter logging results in 3-percent increases over natural yields, and wildfire increases sediment yield about 12 percent over natural loads (Megahan and others 1992).

Megahan and others (1995) evaluated the effects of helicopter logging and prescribed burning on south-facing slopes of headwater drainages in the Idaho batholith by using paired watersheds monitored from 1966 to 1986. Average annual sediment yields show a statistically significant increase of 97 percent persisting for the 10 years of posttreatment study after logging and burning. Accelerated surface erosion primarily result from the prescribed burning, not the helicopter logging, because burning results in most of the bare-soil exposure and in connecting the affected area to streams. Surface erosion rates in the logged and burned areas are about 66 times greater than those on undisturbed slopes. The conclusion is that current best management practices can reduce sediment yields compared with historical practices. But the risk of increased sedimentation from forest management continues, particularly with such activities as road building, timber harvest, and prescribed burning.

Temporary roads may have fewer adverse effects than do permanent roads, depending on the extent to which they are decommissioned. As indicated by the analyses for the Columbia basin, distinguishing the direct effects of roads from the cumulative effects of other activities associated with roads is sometimes difficult. Thus, temporary roads may reduce the direct effects of roads, but effects of activities for which the temporary roads were built still will affect the environment.

Reliability, confidence, and limitations—The relations among roads, aquatic species and their habitats, and other variables analyzed for the Columbia basin were developed from predicted road density data developed from actual subsampled road data and a rule-based model. The method used in developing road density classes is not a substitute for actually mapping roads, but the rule-based model approach provides a tool for predicting road densities across a large landscape, when existing road data are incomplete or out of date. Also, the rule-based model assures that the method used in developing road densities is consistent throughout the Columbia basin. The final road density model had inherent uncertainties because of incomplete data layers, limitations of the sampling design, and the limitations of a rule-based model.

A few road types could not be predicted by using this rule-based approach, despite its general utility. For instance, Yellowstone National Park was assigned a road density class of *none* because no unique rule-based model combinations existed for predicting the park's road system. Roads inside the park are based on human recreational interests, which were not accounted for in the model.

Generalizability—Because the Columbia basin assessment was designed specifically as a broad-scale analysis, the relation of roads and aquatic species and their habitats can be applied at the large-landscape scale. Those relations may not be the same for federally managed lands outside the Pacific Northwest, particularly the Columbia basin, although aquatic habitat loss and alterations, which include effects of roads, are associated with the decline of many fish species throughout North America (Miller and others 1989). Those general relations also may differ at finer scales because of specific biophysical characteristics, such as geology and soils, and use of actual rather than predicted road densities.

The declines in population status of non-anadromous salmonids in the Columbia basin should be viewed as indicating the types of responses that may be experienced by other native aquatic species in similar habitats. The species most like the non-anadromous salmonids in distribution or habitat requirements would be expected to show the most similar responses. This group would include the anadromous species—such as steelhead, stream chinook salmon, and Pacific lamprey—that broadly overlap in range with the non-anadromous salmonids and use many of the same habitats for significant portions of their life. No logical reasons exist to expect anadromous fishes to be immune to the effects of habitat change evident in the non-anadromous species. The ranges of other species—including sculpins, dace, and some suckers—also overlap considerably, and these species may follow similar trends in population abundance and distribution.

Although unroaded areas are significantly more likely to support strong populations, strong populations are not excluded from roaded watersheds. Several possible reasons for this coexistence have been suggested: The inherent productivity of some areas allows fish populations to persist despite disturbances linked to roads; real or detectable effects on fish populations may lag behind the initial physical effects in watersheds where roads have been built in the last several years; and the scale of the subwatershed (19,800 acres on average) at which strong populations are identified may mask a potential disconnect between the real locations of strongholds and roads (which are identified at 1-square-kilometer [0.39-square-mile] pixels). This issue of scale can be resolved with a midscale or subwatershed analysis. The fact that strong salmonid populations can coexist in many roaded areas provides opportunities to determine the reasons, which may be instructive for both watershed restoration and future road building. Given current information, the assumption that because roads and strong fish populations coexist in some watersheds, they will in others is not prudent, however. In general, greater short- or long-term watershed and ecological risks are associated with entering an unroaded area than with proceeding cautiously with management activities in roaded areas to close and obliterate existing roads. The data strongly suggest a closer examination of the stronghold subwatersheds and their roaded condition.

Secondary links—The effects associated with roads reach beyond their direct contribution to disruption of hydrologic function and increased sediment delivery to streams. Roads provide access, and the activities that accompany access magnify the negative effects on aquatic systems beyond those caused solely by the roads themselves. Activities associated with roads include fishing, recreation, timber harvest, livestock grazing, and agriculture. Roads also provide avenues for stocking non-native fishes.

Unfortunately, inadequate broad-scale information on many of these attendant effects for the Columbia basin prevents identification of their component contributions. Similarly detailed analyses are needed to address the relations between roads and fish at a landscape scale in other ecoregions.

Conclusions—The range of specific case studies for broad-scale assessment of road relations in the Columbia basin provides a substantial base of information on which to evaluate the direct effects of roads and the cumulative effects of activities associated with roads on aquatic habitats and species in the Northwest.

Terrestrial Vertebrates

Issue—Effects of roads on vertebrate populations act along three lines: direct effects, such as habitat loss and fragmentation; road use effects, such as traffic causing vertebrate avoidance or road kill; and additional facilitation effects, such as overhunting or overtrapping, which can increase with road access.

Findings—In recent research in the interior Columbia River basin, Wisdom and others (2000) identify more than 65 species of terrestrial vertebrates negatively affected by many factors associated with roads. Specific factors include habitat loss and fragmentation, negative edge effects, reduced densities of snags and logs, overhunting, overtrapping, poaching, collection, disturbance, collisions, movement barriers, displacement or avoidance, and chronic, negative interactions with people. These factors and their effects on vertebrates in relation to roads are summarized from Wisdom and others (2000) as follows:

Road construction converts large areas of habitat to nonhabitat (Forman 2000, Hann and others 1997, Reed and others 1996); the resulting motorized traffic facilitates the spread of exotic plants and animals, further reducing quality of habitat for native flora and fauna (Bennett 1991, Hann and others 1997). Roads also create habitat edge (Mader 1984, Reed and others 1996); increased edge changes habitat in favor of species that use edges, and to the detriment of species that avoid edges or experience increased mortality near or along edges (Marcot and others 1994).

Species dependent on large trees, snags, or logs, particularly cavity-using birds and mammals, are vulnerable to increased harvest of these structures along roads (Hann and others 1997). Motorized access facilitates firewood cutting, as well as commercial harvest, of these structures.

Several large mammals are vulnerable to poaching, such as caribou, pronghorn antelope, mountain goat, bighorn sheep, wolf, and grizzly bear (Autenrieth 1978, Bruns, 1977, Chadwick 1973, Dood and others 1986, Greer 1985, Gullison and Hardner 1993, Horejsi 1989, Knight and others 1988, Lloyd and Fleck 1977, Luce and Cundy 1994, Mattson 1990, McLellan 1990, McLellan and Shackleton 1988, Mech 1970, Scott and Servheen 1985, Singer 1978, Thiel 1993, Van Ballenberghe and others 1975, Yoakum 1978). Roads facilitate this poaching (Cole and others 1997).

Gray wolf and grizzly bear experience chronic, negative interactions with humans, and roads are a key facilitator of such interactions (Mace and others 1996, Mattson and others 1992, Thiel 1985). Repeated, negative interactions of these two species with humans increases mortality of both species and often causes high-quality habitats near roads to function as population sinks (Mattson and others 1996a, 1996b; Mech 1973).

Carnivorous mammals such as marten (*Martes americana*), fisher (*M. pennanti*), lynx (*Lynx canadensis*), and wolverine (*Gulo luscus*) are vulnerable to overtrapping (Bailey and others 1986, Banci 1994, Coulter 1966, Fortin and Cantin 1994, Hodgman and others 1994, Hornocker and Hash 1981, Jones 1991, Parker and others 1983, Thompson 1994, Witmer and others 1998), and overtrapping can be facilitated by road access (Bailey and others 1986, Hodgman and others 1994, Terra-Berns and others 1997, Witmer and others 1998). Movement and dispersal of some of these species also is believed to be inhibited by high rates of traffic on highways (Ruediger 1996), but this has not been validated. Carnivorous mammals such as lynx also are vulnerable to increased mortality from highway encounters with motorized vehicles (as summarized by Terra-Berns and others 1997).

Reptiles seek roads for thermal cooling and heating, and in doing so, these species experience significant, chronic mortality from motorized vehicles (Vestjens 1973). Highways and other roads with moderate to high rates of motorized traffic may function as population sinks for many species of reptiles, resulting in reduced population size and increased isolation of populations (Bennett 1991). In Australia, for example, 5 million reptiles and frogs are estimated to be killed annually by motorized vehicles on roads (Ehmann and Cogger 1985, as cited by Bennett 1991). Roads also facilitate human access into habitats for collecting and killing reptiles.

Many species are sensitive to harassment or human presence, which often are facilitated by road access; potential reductions in productivity, increases in energy expenditures, or displace-ments in population distribution or habitat use can occur (Bennett 1991, Mader 1984). Exam-ples of such road-associated effects are human disturbance of leks (sage grouse [*Centrocercus urophasianus*] and sharp-tailed grouse [*Tympanuchus phasianellus*]), nests (ferruginous hawk [*Buteo regalis*]), and dens (kit fox [*Vulpes macrotis*]). Another example is elk avoidance of large areas near roads open to traffic (Lyon 1983, Rowland and others 2000), with elk avoidance increasing with increasing rate of traffic (Wisdom and others 2000, Johnson and others 2000).

Bats are vulnerable to disturbance and displacement caused by human activities in caves, mines, and on rock faces (Hill and Smith 1984, Nagorsen and Brigham 1993). Cave or mine exploration and rock climbing are examples of recreation that could reduce population fitness of bats that roost in these sites (Nagorsen and Brigham 1993, Tuttle 1988). Such activities may be facilitated by human developments and road access (Hill and Smith 1984).

Ground squirrels often are targets of recreational shooting (plinking), which is facilitated by human developments and road access (Ingles 1965). Many species of ground squirrels are local endemics; these small, isolated populations may be especially vulnerable to recreational shooting and potentially severe reductions or local extirpations of populations.

Roads often restrict the movements of small mammals (Mader 1984, Merriam and others 1988, Swihart and Slade 1984), and consequently can function as barriers to population dispersal and movement by some species (Oxley and Fenton 1974).

Many granivorous birds are attracted to grains and seeds along roadsides and as a result have high mortality from collisions with vehicles (Vestjens 1973). And pine siskens (*Carduelis pinus*) and white-winged crossbills (*Loxia leucoptera),* for example, are attracted to road salt, which can result in mortality from vehicle collisions (Ehrlich and others 1988).

Terrestrial vertebrates inhabiting areas near roads accumulate lead and other toxins that originate from motorized vehicles, with potentially lethal but largely undocumented effects (Bennett 1991).

In summary, no terrestrial vertebrate taxa seem immune to the myriad of road-associated factors that can degrade habitat or increase mortality. These multifaceted effects have strong management implications for landscapes characterized by moderate to high densities of roads. In such landscapes, habitats are likely underused by many species that are negatively affected by road-associated factors. Moderate or high densities of roads sometimes index areas that function as population sinks that otherwise would function as source environments were road density low or zero.

Reliability, confidence, and limitations—General effects of roads and road-associated factors on a wide variety of vertebrate taxa are well documented from a broad range of studies conducted in North America, Europe, and other areas (Bennett 1991, Forman and Alexander 1998, Mader 1984, Trombulak and Frissell 2000, Vestjens 1973). Reliability of such effects at large, landscape scales, and for many taxa, is compelling and unequivocal. Reliability of site-specific, small-scale effects, with focus on single species, is less certain. For many species at local scales, the array of factors that could affect habitats or populations have been neither well studied nor documented. Despite such limitations, current knowledge of broad-scale effects on a variety of taxa is highly certain and provides an overarching paradigm from which likely or presumed effects on single species at local scales can be inferred. The many factors associated with roads suggests that mitigating such effects succeeds best at large scales, when focused on multiple species, and when based on a combination of aggressive road obliteration and protection of roadless areas (Trombulak and Frissell 2000).

Generalizability—Although the summary of road-associated effects on vertebrates described here is taken from research conducted in the interior Columbia River basin (Wisdom and others 2000), results likely apply to several species occupying a diversity of forest and rangeland environments in North America. At least four reasons account for this presumed high generalizability: the road and road-associated effects described by Wisdom and others (2000) were synthesized from research conducted across the world; the synthesis focused on multiple species encompassing diverse taxa and environmental requirements; the synthesis addressed an extreme range of environmental conditions on federal lands administered by the Forest Service, the Bureau of Land Management, and state, private, and tribal landowners; and the synthesis focused on large-scale, overarching effects common to many species and conditions.

Secondary links—Many road-associated effects on terrestrial vertebrates are intimately linked to managing human activities related to road access. Accordingly, mitigation of road-use effects requires effective control of human access to roads related to managing livestock, timber, recreation, hunting, trapping, and mineral development.

Conclusions—Comprehensive mitigation of the full array of road-associated effects on terrestrial vertebrates of conservation concern poses one of the most serious of land management challenges. Balancing such mitigation with socioeconomic desires will be controversial and contentious. Comprehensive efforts to mitigate road-associated effects on terrestrial vertebrates is well suited to testing as a large-scale management experiment developed and implemented jointly by managers, researchers, and the public.

Road Kill

Issues—Large numbers of animals are killed annually on roads. In selected situations, such as for some amphibians with highly restricted home ranges, populations of rare animals may be reduced to dangerous sizes by road kills.

Findings—An estimated 1 million vertebrates a day are killed on roads in the United States (Lalo 1987). Studies show that the number of collisions between animals and vehicles is directly related to the position of the nearest resting and feeding sites (Carbaugh and others 1975). Because most forest roads are not designed for high-speed travel, and the speed of the traffic is directly related to the rate of mortality, direct mortality on forest roads is not usually an important consideration for large mammals

(Lyon 1985). An exception is forest carnivores, which are especially vulnerable to road mortality because they have large home ranges that often include road crossings (Baker and Knight 2000). Forest roads pose a greater hazard to small, slowly moving, migratory animals, such as amphibians, making them highly vulnerable as they cross even narrow forest roads (Langton 1989). Nearly all species of reptiles use roads for cooling and heating, so many of them are killed by vehicles. Highways and other roads with moderate- to high-speed traffic function as population sinks for many species of reptiles, resulting in reduced and increasingly isolated populations (Wisdom and others 2000). Predators and scavengers are killed while they feed on road-killed wildlife, as are other species attracted to roads because of salts or vegetation, or because roads facilitate winter travel (Baker and Knight 2000). Although countless animals are killed on roads every year, documented road-kill rates are significant in reducing populations of only a few rare species in North America, and these kills generally are on high-speed highways (Forman and others 1997).

Reliability, confidence, and limitations—A large body of data documents annual road kill, and wildlife science can describe the factors that put wildlife at risk, but little research has focused on how to mitigate the effects on wildlife populations.

Generalizability—Most road-kill questions will be related to individual species and geographic sites, but general principles such as the frequency of travel between known resting and feeding areas for individual species can be used in project decisions.

Secondary links—Road-kill issues link to habitat fragmentation, predation, and access issues.

Conclusions—The issues can be addressed based on site and species. Difficulty will arise in integrating road kill with the social and economic issues related to mitigation.

Forest Diseases

Issues—In general, the existence of roads seems to have little effect on forest tree diseases, but there are some examples where building or using roads caused significant local effects. Nearly always, the negative effects can be ameliorated through simple modifications in how they are built and used. The one benefit of roads, as it pertains to tree diseases, is to provide access for silvicultural activities that protect resources, such as the ability to inoculate decay fungi into trees to create wildlife habitat (Bull and others 1997). One negative effect includes the movement of people on the roads, which allows the pests to be introduced. Road building also may set the stage for an insect attack that further stresses the trees and then a disease outbreak that kills them (Boyce 1961).

Findings—A significant forest disease problem associated with roads is Port-Orford-cedar root disease. This disease of Port-Orford-cedar (*Chamaecyparis lawsoniana* (A. Murr.) Parl.) is a root disease caused by the fungus *Phytophthora lateralis*. Spores of the fungus are carried in water or contaminated soil to uninfected areas. Roads of any sort in the very limited geographic range of the primary host provide a way to move soil—along with the fungus—from infected to uninfected areas. Spread of the fungus can be checked by careful planning to reduce entry to uninfected areas, road closures, partial road closures during wet weather, attention to road surfaces and drainage of possibly contaminated water to streams, wash stations to remove soil from vehicles before entry to uninfected areas, and sanitation strips to remove host plants from near roadsides (Kliejunas 1994, Roth and others 1987, Zobel and others 1985). Building and maintaining roads may exacerbate root diseases. Wounded trees and conifer stumps created and not removed during road building provide infection courts for annosus root disease; the disease may then spread through root contacts to kill a patch of trees

(Otrosina and Scharpf 1989). Trees damaged or stressed by road building—through direct wounding of stems and roots, covering of roots with side castings, or compacting of soil over roots—become susceptible to various tree diseases. Armillaria root disease is benign in deciduous stands where only injured trees are attacked but more serious in conifer stands where pockets of disease are initiated (Shaw and Kile 1991). Oak decline is associated with poor sites, older stands, and road building or other disturbance (Wargo and others 1983). Black stain root disease (*Leptographium wagneri*) attacks stressed conifers associated with disturbance, especially compaction caused by road building; in pinyon pine (*Pinus monophylla*), it is associated with roads and campsites (Hansen 1978, Hansen and others 1988, Hessburg and others 1995). Droopy aspen disease is associated with road building and compaction, but the pathogen identity is unknown (Jacobi and others 1990, Livingston and others 1979). Sap streak disease in sugar maple is associated with compaction from roads and from direct injury to trees (Houston 1993).

Road building can be planned to help reduce the spread of some forest tree diseases: mistletoe is spread by the forcible ejection of the mistletoe seeds. In young plantations or pole-sized stands, roads can subdivide an area to prevent mistletoe seeds from reaching a healthy stand (Hawksworth and Wiens 1996). In Texas, roads could be planned to separate a portion of a stand with oak wilt from healthy trees. The act of building the road (if extensive enough) severs root connections and prevents tree-to-tree movement of the pathogen (Appel and others 1995, Rexrode and Brown 1983). In other areas, new or established roads may have the unintended effect of breaking the continuity of host roots and thus halting the spread of laminated root rot (*Phellinus weirii*) and other root diseases (Hadfield 1986, Thies and Sturrock 1995).

Roads indirectly contribute to disease spread by giving people access to remote forests and ways to transport material long distances. New pockets of both oak wilt and beech bark disease (Houston and O’Brien 1983) may have resulted from moving firewood from the forest to a homesite (Appel and others 1995, Rexrode and Brown 1983). Pitch canker (*Fusarium subglutinans*) was recently reported on Monterey pine (*Pinus radiata*) in California; previously, it had been found on little-leaf and slash pines in the South. A single introduction is thought to be responsible; 117 vegetative compatibility groups are found in Florida but only 5 in California, and 70 percent of the isolations in California are from a single group, likely carried on a tree transported as an ornamental (Correll and others 1992, Storer and others 1995). Campers who use roads to get to remote sites in Colorado and other states have caused significant mortality by carving on aspen and birch, which provides pathways for various fungi that cause cankers and quickly kill the trees. Many trees are unintentionally damaged, for example, when campers hang a gas lantern on a branch too close to the trunk of a tree, thereby causing heat damage.

One abiotic disease has caused significant damage. In the Lake Tahoe basin in California, trees were killed by salt put on the roads to reduce ice. This problem also has appeared in some areas of the Midwest and east coast (Kliejunas and others 1989, Scharpf 1993, Scharpf and Srago 1974). Needle and rust diseases spread long distances by spores and do not appear to be influenced by roads or road building.

Reliability, confidence, and limitations—Field studies tend to focus on a single disease or an insect-disease complex; many of these centers are associated with or influenced by compaction or tree damage associated with roads.

Generalizability—Problems, where they exist, appear to be specific to the pathogen, host, and site.

Conclusions—In general, land managers appear to have the information and technology needed to handle most road, road building, and disease interactions. Additional science-based information is needed to understand and manage the interactions between compaction and black stain root disease and between compaction and droopy aspen disease.

Predation

Issues—The introduction of roads into the closed forest environment creates corridors by which predators can enter and affect native populations.

Findings—Forest roads create corridors by which predators, especially people, can enter the forest environment and affect wildlife populations. Nest depredation of songbirds may increase by predators attracted to edges. Evidence for edge effects, however, is highly variable (Paton 1994). Although evidence has been found for local edge effects in cowbird parasitism and nest depredation, their effects on bird populations is not documented. Geographic location and large-scale patterns in the amount of forest and nonforest habitats may be more important in determining the reproductive success of forest songbirds (Donovan and others 1997, Robinson and others 1995). Forest carnivores apparently travel on roads in winter when snow is deep, and thus the road system alters and enhances their ability to move (Paquet and Callaghan 1996). Wolves and grizzly bears are two key species that have chronic, negative interactions with people, and roads are a key facilitator. Repeated, negative interactions of these two species with people increase mortality of both species and often cause high-quality habitats near roads to be population sinks (Wisdom and others 2000). High road densities are associated with a variety of negative human effects on several wildlife species (Brocke and others 1988). People directly affect snakes by collecting, harassing, and killing them (Wisdom and others 2000). Increases in illegal hunting pressure, facilitated by roads, also negatively affect populations. Moose, wolves, caribou, pronghorn antelop, mountain goat, and bighorn sheep are particularly vulnerable to this kind of predation (Lyon 1985, Wisdom and others 2000).

Reliability, confidence, and limitations—Limited data exist on the effects of introducing natural predators as a result of road building. The evidence is strong that human predation, either legally in game management programs or illegally, is greatly facilitated by roads and can significantly affect populations of animals.

Generalizability—General principles related to human effects on wildlife populations are understood by wildlife managers and can be applied to species and site-specific management.

Secondary links—Predation links to other habitat-related topics, such as fragmentation and road kill, and also to people-related topics such as recreation.

Conclusions—Species-specific issues related to predation facilitated by roads can be addressed for specific sites. Predation related to illegal hunting facilitated by improved access can be addressed by legal measures, or, where legal remedies are ineffective, by closing or decommissioning roads where wildlife values are high.

Biodiversity and Conservation

Issues—Previous issues in this section may be synthesized by the concept of biodiversity. Biodiversity is, in simplest terms, the variety of life and its processes (Keystone Center 1991). Recent syntheses (Heywood and Watson 1995) emphasize the reciprocal relation between biodiversity—conceived as genetic and species diversity—and ecosystem function. The many species comprising the biodiversity of an area play roles essential to ecosystem function and are the source of variation that enables an ecosystem to adapt to change. The healthy, functioning ecosystem, in turn, supports the many species living within it. Appreciating this reciprocity means that biodiversity can be taken as a natural measure of the ecosystem as a whole and thus can integrate the many concerns listed.

Some species may play more important roles than others in the normal functioning of an ecosystem. For example, keystone species may define the major structural elements of an ecosystem, as Douglas-fir does for forests in the Pacific Northwest, or they may—by virtue of their position in a complex trophic structure—act to maintain the diversity as keystone predators do for herbivores. On the other hand, the many species that do not appear to serve an important role in an ecosystem constitute a reservoir of potential adaptation to change. Because an ecosystem cannot predict change, the diversity of species acts as a hedge against it.

Biodiversity is vital to long-term ecosystem function, and human activities that decrease biodiversity can impair it. Our working hypothesis, then, is that measures of biodiversity provide the best integrative assessment of the effects of roads on ecosystems.

Findings—Roads can have major adverse effects on biodiversity, many of which are already described (Forman and Collinge 1996). A recent review by Forman and Hersperger (1996) usefully distinguishes these aspects of the road-biodiversity interaction:

- Road density: As road density increases, thresholds may be passed that cause some species to go locally extinct. The probability of extinction depends, in part, on body size, with larger animals requiring larger residual populations to prevent their extinction.
- Road-effect zone: The effects of roads can extend over some distance from their centers, such that their "effective widths" can be many times their actual widths.

Reliability, confidence, and limitation—The confidence in the general negative relation between roads and biodiversity is high. The current primary limitation, however, is on the utility of measures of biodiversity for assessing road effects. First, both the status of keystone and other important species must be assessed, which seems fairly straightforward. But, second, the status of the pool of all the other species that form the basis for adaptation to change must be assessed, and how to do this assessment is much less clear.

Landscape ecology as well as fragmentation and viability analysis contain relevant scientific uncertainties. Two critical uncertainties must be resolved to understand how roads affect fragmentation and population viability. First, in the mechanistic analysis of the effects of roads and roadlike entities, such as power lines, on landscape fragmentation and species viability, the question of the "effective width" of roads is open. Kiester and Slatkin (1974) predict that, for species using conspecific cuing for movement strategies and habitat selection (likely most vertebrates), a spatially localized source of mortality in an area of otherwise suitable habitat can act as an active sink, drawing individuals in as residents die, making it likely that the new individuals will die as well. Consider a road traversing the habitat of a territorial or conspecific-cuing species. Those individuals whose home range overlaps a road have some probability of being hit each time they venture across it. Eventually they are killed, and their neighbors, in the process of constantly testing the boundaries of their home ranges, move into the vacated area next to the road and themselves run the risk of road mortality. The question is, How far from a road does this probability of mortality spread? Second, at the landscape scale, the relation between patterns of dispersal of individual species and measurements of fragmentation must be clarified. Current information (Schumaker 1996) indicates that most of the commonly used measures of fragmentation do not predict habitat connectivity for individual endangered species; rather, a model of fragmentation must be derived from species-specific dispersal characteristics. This kind of analysis is now available for only a few species.

Generalizability—Exactly how roads affect biodiversity in any particular place is a matter of the devil being in the details. The results given here would generally apply to any area.

Secondary links—Appreciation of biodiversity itself is an important part of the passive-use value of biodiversity. In particular, the aesthetic appreciation of biodiversity through an understanding of how biodiversity is sublime (rather than just beautiful) is now leading to a new link between biodiversity and passive-use value (Kiester 1997).

Conclusions—Forman and Hersperger (1996) conclude " ...that a quantum leap in focus on the ecological effects of roads is warranted, and that the foundations are in place for effective research, planning, public education, and action."

Water Quality

Issues—Roads provide access to and increase the opportunity for applying a variety of chemicals in national forests. Some applications target the roads, such as with road surface treatment; other chemicals are intended for adjacent ecosystems to control pests and fertilize vegetation. Materials also are added to roads by traffic, such as asbestos from brake linings, oil leakage, and accidental spills. Some portion of applied and spilled chemicals eventually reaches streams by drift, runoff, leaching, or adsorption on soil particles. Roads also increase the nutrient delivery to streams by removing vegetation, rerouting water flow paths, and increasing sediment delivery. And roads increase the likelihood of toxic spills associated with accidents along streamside corridors.

Findings—Chemicals applied on and adjacent to roads can enter streams by various pathways. The likelihood of water-quality deterioration from ground applications is a function of how much chemical is applied, the proximity of the road to a stream, and the rainfall, snowmelt, and wind events that drive chemical and sediment movement. The risk is a function of the likelihood of water-quality deterioration and exposure of organisms, including people, and how susceptible the organisms are to the pollutant or pollutants. (A large proportion of Forest Service roads are low standard and few if any chemicals are applied, so the risk of chemical contamination for most Forest Service roads is relatively low.) Chemicals are applied directly to roads and adjacent rights-of-way for various purposes, including dust abatement, stabilizing the road surface, deicing, fertilizing to stimulate plant growth on road cuts and fills, and controlling weeds and the invasion of nonweedy plants onto the roadway (Furniss and others 1991, Norris and others 1991, Rhodes and others 1994). Applied chemicals can enter streams directly when they are applied, but little is known about the effects of these chemicals on stream biota (Furniss and others 1991). Norris and others (1991) provide a comprehensive review of the types and amounts of fertilizers, pesticides, and fire retardants applied to forests in the United States, although little information is given to distinguish road-related from aerial applications. They report that most herbicides are applied by ground-based equipment, presumably using roads for access; that ground-based applications in or near aquatic zones can result in chemicals entering streams by drift or direct application; and that these problems are more serious when the chemicals are applied from the air. Movement of sediment containing adsorbed chemicals is possible, and the risk increases with increasing persistence (Norris and others 1991). The amount of input by this pathway is thought to be small, however; it is a more likely pathway for entry of salts applied for de-icing and of fertilizers applied to road fills.

Increased nutrient supply to streams from roads is proportional to the area disturbed and maintained free of vegetation and the amount of sediment delivered. Increased nutrients rarely have detrimental effects on stream water quality, but they may modify the composition of aquatic biota (Hawkins and others, in press). Few studies examining watershed responses to logging separate the effect of road building from those of the broader disturbance associated with removing timber. In one such study, Swank (1988) monitored stream chemical composition during the pretreatment, road building, logging, and posttreatment phases in a cable-logged watershed in the southern Appalachian Mountains. No stream chemical response was found to result from the road-building phase of the watershed treatment. Nutrient movement to streams often increases significantly after timber harvest operations (Frederiksen and others 1973, Hornbeck and others 1973, Likens and others 1970, Pierce and others 1972, Swank and Waide 1988). The primary intent of these studies was to assess onsite nutrient losses, with changes in water quality a secondary concern. All cited studies report increases in nitrogen cation and phosphorus concentrations in streams after treatment. In general, nutrient loss to streams is roughly proportional to how much vegetation was removed. For example, three studies at Hubbard Brook in New Hampshire compared three treatments: clearcutting with a herbicide treatment to suppress vegetation regrowth (Likens and others 1970), clearcutting without suppressing regrowth (Pierce and others 1972), and strip cutting of one-third of the forest (Hornbeck and others 1973); the three studies found nitrogen concentrations in streams reduced, most by the first treatment, less by the second, and least by the third. These findings suggest that residual or reestablished vegetation immobilizes released nutrients, thus diminishing the disturbance effect. Although roads might not respond in the same way because of drainage rerouting, we expect that nutrient mobility is proportional to the area maintained in a disturbed, non-revegetated state.

Hazardous chemical spills from vehicle accidents can pose a direct, acute threat of contamination to streams. The risk of hazardous chemical spills resulting from vehicle accidents adjacent to waterways is recognized and documented by the National Forest System and by state transportation departments (IDT 1996). Risk-analysis models of accident-related chemical spills are available, but they are designed for paved roads in nonmountainous terrain. Models take into account risk to human health, traffic frequency, vehicle type, and proximity to water. Possible contaminants include any substance being transported, such as fuel, pesticides, chemicals used in mining, fertilizers, and fire retardants.

Reliability, confidence, and limitations—Both anecdotal and scientific bases for linking increased access provided by roads to increased use of a wide variety of introduced chemicals are strong. Potential delivery to streams is mainly anecdotal, and few models are available for predicting delivery. Evidence for increased nutrient delivery to streams from disturbance by roads is strong, but it is confounded by other management activities such as logging.

Generalizability—The use of chemicals that are potential contaminants is well known and often described. The likelihood of routinely or accidentally spilled chemicals is related to type and frequency of traffic, but determining probabilities of spills accurately is difficult or impossible, especially for accidents. The likelihood of contaminants reaching a stream differs widely from site to site; it is most strongly controlled by stream proximity and road drainage features. Soluble and persistent elements and compounds adsorbed on sediment particles have increased probability of contaminating waterways.

Secondary links—Roads have strong links to aquatic health and biological response. A large body of literature exists on bioassays, but little information is available on transport, toxicity, and persistence of potential contaminants in natural systems. Terrestrial effects of chemicals, such as damage to vegetation by road salt, are not addressed here.

Conclusions—Most of the information is anecdotal or requires extrapolation from other studies (nutrient issues). The degree to which aquatic organisms are affected by applied and routinely spilled chemicals is poorly known or not understood in most places. Better information on effects is needed to make decisions about chemical application, road drainage control, and road location. Better models of chemical spill risks on forested roads are needed.

Air Quality

Issues—Dust emitted into the atmosphere by vehicles moving on unpaved roads contributes to reducing visibility and to suspending airborne particulates that can pose health hazards. Issues revolve around the contribution of national forest roads to regional and urban air pollution and what effects maintaining, paving, and shutting down roads on national forests have on this problem. Roads built into or surfaced with serpentinitic rock may contain asbestos-type minerals that could pose a hazard to people exposed to dust from the road surface.

Findings—Scientific literature on this topic is scarce. A study of degraded visibility and its causes in 16 national parks and wilderness areas on the Colorado Plateau, by the Grand Canyon Visibility Transport Commission (available online at http://www.nmia.com/gcvtc/), found that dust from unpaved roads could be a contributing factor. Soils in the Southwest are often very fine textured, and once dust is made airborne by vehicles, it can remain suspended for a long time and be transported long distances by the wind. The commission recommended that the Environmental Protection Agency (EPA) require further study and mitigation of these effects.

The amount of dust emitted into the atmosphere is estimated by a formula that considers the number and speed of vehicles traveling on a road in a given period, the relative humidity, and the composition of the road surface. This model was developed and reviewed by the Department of Transportation and the EPA. Related information about calculations for paved roads can be found at http://www.epa.gov/ttn/chief/ap42/ch13/related/c13s02-1.html.

Dust emissions also raise issues of human health. Where national forests are close to urban areas, dust from national forest roads can contribute to the burden of airborne particulate matter from a wide variety of sources including transportation and industrial activities. The fine fraction of airborne particles with diameters less than 2 microns have been found to contribute to human health problems and increased mortality, especially in young children, old people, and people with lung problems such as asthma and emphysema. Particles of this size and smaller cannot be effectively cleared by human lungs and therefore accumulate. How much road dust from forest roads contributes to the fine particulates in urban atmospheres is not currently known for most cities because the EPA is just beginning wide-spread monitoring of fine particulates, and reliable results will take at least 3 years to gather.

Unpaved roads built into or surfaced with serpentine materials can generate dust containing asbestos or asbestiform minerals. Although few such roads exist, methods have been developed to determine the extent of ambient asbestos coming from them.

During commercial use of unsurfaced roads, watering or other dust-abatement treatment (such as the addition of lignin sulfonate or calcium chloride) is often required by the Forest Service or other road manager to reduce dust emissions and conserve the fine fraction of the road surface. Such treatments do not accompany noncommercial uses, however, and they include most of the traffic for such roads.

The EPA has proposed a regional haze rule calling for more regions to do the kind of analysis done by the Grand Canyon Commission. Such analyses are likely to find similar emissions from unpaved roads and similar visibility problems elsewhere. EPA's recent tightening of the National Ambient Air Quality Standard on the effects of fine particles on human health are likely to require similar analyses of particle emissions, especially as they affect urban air quality. Analyzing the entire transportation system, including national forest roads, would be a logical approach to finding the most efficient means of controlling air pollution. Under emissions-trading scenarios, treatments, like paving or closure to reduce emissions of particles from national forest roads might qualify for highway funds, as cost-effective adjuncts to upgrading major arterials to reduce air pollution.

Reliability, confidence, and limitations—The basic models of dust emission and transport down-wind are generally reliable and widely used by the EPA in regulatory decisions. Much of the basic data to make these calculations for national forest roads have not been collected; thus, most estimates of the emissions are based on very coarse estimates of the conditions that produce dust emissions. Effects of the amount of road maintenance on emissions also are not well understood. The effects of road closures on dust emissions are not easily predicted because they depend on the details of how traffic is rerouted from closed sections and what emissions are created by the rerouted traffic pattern.

Generalizability—Models of emissions are relatively easy to generalize to many parts of the country, if reliable data are collected to use in them.

Secondary links—Reductions in visibility negatively affect recreational values because beauty is one of the major attractions to national forest visitors. Improving national forest roads to reduce dust emissions could be linked to regional transportation plans aimed at reducing air pollution. Such a link might make Forest Service roads eligible for highway funds.

Conclusions—Emissions from national forest roads would need to be included in regional analyses of air emissions. Models to make these analyses are available, but data to represent national forest roads would have to be collected and included in the analysis.

Direct Socioeconomic Effects

Timber Programs

Issues—Road closures are expected to strongly affect Forest Service timber programs. On federal timberlands, the timber program and an extensive road network evolved simultaneously. Many roads were built by purchasers or with purchaser credits from timber sales, but these roads served a variety of users. By the late 1980s, about 25,000 timber sales were recorded per year (of more than $300) supplying 14 percent of the U.S. timber harvest. This harvest supported some 125,000 direct jobs in many communities, mostly in the Western United States. By 1997, the proportion of total U.S. harvest supplied from federal lands had dropped by half because of efforts to protect various habitats for species at risk of extinction.

Along with the evolution of the existing road network went the development of logging systems designed for site conditions, soil-compaction concerns, and costs. Such systems (except for some forwarder systems) are designed to minimize skid distances, both in harvest units and at road-based landings. The most commonly used logging systems (cable yarding or ground-based skidding systems) depend on direct access to a stand. Helicopter and cut-to-length (harvester-forwarder) systems depend on access to nearby stands (usually less than a mile).

Findings—In steep terrain, reducing road densities may require longer cable yarding distances, and because yarding distance is a significant cost factor, especially in thinnings (Hochrein and Kellogg 1988; Kellogg and others 1996a, 1996b) timber harvesting costs likely will increase. In addition, greater reliance could be placed on helicopter logging, which would increase logging costs by as much as 2.5 times. Another result could be more wood left behind in the forest because logs must be bucked to their optimum length to maximize the payload of the helicopter.

In gentler terrain, a reduction in road densities could lead to an increased use of cut-to-length (harvester-forwarder) systems or more reliance on cable yarding. Primary transportation distance (movement of logs from stump to landing) is a variable significantly affecting the productivity of ground-based skidding (Tufts and others 1988) as well as harvester-forwarder systems (Kellogg and Bettinger 1994). Lanford and Stokes (1996) note, however, that at least with similar primary transportation distances in the Southeast, harvester-forwarder systems have comparable costs per unit harvested to traditional ground-based skidder systems, yet with lower environmental effects. If cable yarding replaced some ground-based systems, costs could increase by 1.4 times or more (Kellogg and others 1996b).

Logging cost increases (all else held constant) would reduce the likelihood that proposed sales would sell and lead to reduced harvest. The Forest Service's Washington, DC, office provided an estimate of the extent of these harvest reductions. They estimated that harvests would be reduced by 6 percent in the Northern Region (Montana, northern Idaho, North Dakota, and northwestern South Dakota), 90 percent in the Intermountain Region (southern Idaho, Nevada, Utah, and western Wyoming), and 17 percent in the Pacific Northwest Region (Oregon and Washington). If the issue involves only the use of secondary roads into sale units or just reliance on temporary roads for local sale access, then these effects may be overstated.

More difficult to determine are the long-term effects of focusing future management activities in only the roaded sections of national forests, where one of the primary management tools is stand manipulation through timber-sale contracts. Some management activities, such as prescribed fire, are not road dependent but most of the techniques for stand manipulation require some type of access.

Another issue is how changes in one region relate to changes elsewhere in North America. Reductions in federal timber harvest largely in the West are offset by increases in harvest elsewhere (mostly in Canada and on private timberlands in the South). These offsetting changes are usually sufficient to reduce consumer effects to modest, so that the largest effects are borne by producers (and their employees) in the affected regions.

Reliability, confidence, and limitations—Studies document the effect of skid distances and different logging systems on logging costs (Kellogg and Bettinger 1994, Kellogg and others 1996a, Lanford and Stokes 1996, Tufts and others 1988). Some of these studies were used to support timber appraisal processes. The effect of higher logging costs (because of more expensive logging systems) on stumpage prices has been well documented in the literature (for example, Jackson 1987); stumpage values have to be greater than logging costs for sales to be sold. Increasing logging costs, all else held constant, will result in fewer sales (or more sales being below cost). The effects listed in the findings are uncertain after one to two years because of the ability timber sale planners have to redesign timber sales, including their ability to change harvest unit locations.

Generalizability—The results are generalizable. What does differ are the values for timber throughout the West and the opportunities for less road-dependent logging systems.

Secondary links—The secondary effect of greatest concern is the potential loss of access to stands for forest management activities that remove individual trees. Although much of the current controversy is over final harvest, many other silvicultural practices depend on timber-sale contracts and timber removals to achieve various stand and landscape conditions. Often the forest road network was designed to allow access to multiple stands. Identifying the optimal network in light of potential additions or reductions in roads is difficult (Dean 1997). In addition to considering the loss of access, planners need to consider costs of alternative road building or rebuilding, landslide risks, and expected environmental effects, when they evaluate road management alternatives (Sessions and others 1987). Algorithms to incorporate road management alternatives in forest planning efforts have been described for traditional optimization techniques (Jones and others 1991), as well as heuristic methods (Bettinger and others 1998, Weintraub and others 1995). The effects of road management alternatives on timber programs is a site-specific problem, depending on the road system that exists, the road management alternatives examined, and the condition (age, volume, and so on) of the harvestable timber stands affected by the alternatives. For example, areas of mature forest stands in nonreserved land allocations may be most affected by near-term changes in the road network.

Conclusions—Roads and timber-program issues have been much studied, including attention to the ability to trade off more intensive management on the roaded parts of national forests with the unroaded portions. The ability to address immediate effects (say, for the next fiscal year) is very high, but beyond several years, the ability to predict effects greatly diminishes because no opportunities are available for mitigating the effects of changes in sale location or design. Finally, economic effects tied to changes in timber flows are very real. Roughly 10 direct jobs are generated for each 1 million board feet of harvest from national forests in the West. In addition, payments in lieu of taxes account for significant parts of local government funds in much of the rural West.

From a planning perspective the ability to examine tradeoffs in road system alternatives is moderate. Examinations into the theoretical complexity of road network planning problems have led to the development of planning models designed for integrating road decisions with land management decisions (Bettinger and others 1998; Jones and others 1986, 1991; Nelson and Brodie 1990; Sessions and Sessions 1997; Weintraub and others 1994, 1995; Zuuring and others 1995). These models are particularly useful for measuring tradeoffs among the quantifiable management benefits and costs associated with changes in the road network. Not all issues relevant to a decision can be adequately quantified, however, because the output or response relations are not known or are just being developed. For example, the response variables can be complex and may depend on activities in adjacent stands (see Bettinger and others 1998). In addition to the complex planning model, data development (both geographic information system

[GIS] and associated tabular inventories) is one of the main challenges. The ability to collect and use GIS data as well as the attributes of a road system (and related resources) is evolving and, over time, analyses now based on current data will progressively become more precise and accurate.

Nontimber Forest Products

Issues—A variety of products harvested from the abundant biotic resources of the North Temperate Zone forests are being transformed into medicinals, botanicals, decoratives, natural foods, and a host of other novel and useful products. These renewable, vegetative natural resources harvested for personal or commercial use are called nontimber or special forest products. Consumer forces, changing social climate, and expanding global markets are contributing to the increasing development of these products as viable economic options for sustaining rural communities. Ginseng (*Panax quinquefolius*), goldenseal (*Hydrastis canadensis*), coneflower (*Echinacea angustifolia*), and St. John's wort (*Hypericum perforatum*)—all plants found on national forest lands are major contributors to a multibillion-dollar herbal and botanical industry. Access to these resources has important economic value to those rapidly growing industries. Plants harvested from the wild are "wildcrafted" by harvesters from local communities or contract crews brought in from elsewhere. Particularly for the local harvesters, who operate under the permit system of various public and private land ownerships and who often have low income, access by road to the resource becomes a critical cost factor. In addition, roads create openings important to maintaining diverse species in abundance. How roads will affect the survival and sustainability of nontimber forest products and how access to nontimber forest products will be influenced remain important issues. Both issues are important to the people and communities that already depend on these herbs, shrubs, lichens, fungi, algae, and micro-organisms as part of their economy.

In 1992, the herbal-medicinal market was estimated at just under $1 million and growing at a rate of 13 to15 percent per year (Mater 1997). Traffic USA, a program of the World Wildlife Fund that monitors commercial trade in wild plants and animals, estimates annual retail sales of medicinal plants in the United States in 1997 at $1.6 billion and rising. Of the 25 top-selling herbs in U.S. commerce (Brevoort 1998), more than 50 percent are included in the 1,400 plant species found and traded in the United States. Moss and lichens, harvested extensively from public forest lands and exported to worldwide markets, were valued at more than $14 million in 1995 (Vance and Kirkland 1997). Demand is increasing for huckleberries and mushrooms, important foods harvested for commercial and personal use. In 1995, less than 1 million pounds of the matsutake (*Tricholoma magnivelare*) mushroom were harvested, but in 1997, in one 8-week period, 1.2 million pounds were harvested, which provided the Forest Service with $365,935 in revenue from permit sales (Smith, n.d.). Floral greens are an important mainstay for several markets in the Pacific Northwest. A 1989 study (Schlosser and others 1991) showed that the total value of floral and Christmas greens earned $128.5 million in product sales with about $48 million paid to harvesters, which supported the employment of about 10,000 people and about 675,000 acres in production west of the Cascades. On a single ranger district (Hood Canal Ranger District, Olympic National Forest) from February 1996 through February 1997, 1,500 permits were sold for commercial harvest of greens, bringing in revenue of $63,835. Christmas boughs have continued to increase in demand, and by 1995, harvest in the Pacific Northwest was approaching 20 million pounds per year (Savage 1995).

Findings—Market growth is documented (Mater Engineering 1992, 1993a, 1993b). Collection activities permit information, environmental and other assessments, and maps with roads indicated are part of the written procedures and permitting instructions at forests and districts affected by special forest products. Costs of harvest are recognized as a factor in permit prices, and they influence contract bids in these assessments. Market value is related to cost; increasingly difficult access as plants become scarce may be factored into market value. An assessment in the Southern Region (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, Puerto Rico, South Carolina, Tennessee, Texas, Virgin Islands, and Virginia) identified dozens of plants and products for which free use and commercial permits are issued. Illegal collection is considered a problem in many areas, and some documentation exists in Oregon with the Bureau of Land Management, Forest Service, and state enforcement personnel. Although not explicitly, roads play a role in illegal taking, as well as in monitoring harvest activities. Other reports and inventories have maps indicating roads that offer access to nontimber forest products and often act as a means of pinpointing the desirable harvesting areas. For example, in the special forest products inventory (Karen Theiss and Associates 1996) created for Trinity County, California, roads were used extensively to describe how to find areas where wildcrafters could harvest a particular species.

Reliability, confidence, and limitations—Much of the documentation that relates to special forest products can be found in forest and environmental assessments and in recent reports and papers published in journals and books (Molina and others 1997, Savage 1995, Thomas and Schumann 1993, Vance 1997). In some of these documents, roads are addressed directly about use and compliance with reciprocal agreements where they are in effect. Historically, special products have been administered as a byproduct of timber contracting and road building. The same benefits accrued by recreational collectors of mushrooms, berries, and so on in those areas also could be enjoyed by commercial harvesters. No formal documentation of these benefits going to commercial harvesters is available. Note that some states (e.g., Oregon) require anyone transporting any such product, including firewood, on public roads to have a legal permit or bill of sale.

Generalizability—Generalizing the need for roads or road decommissions for nontimber forest products is impossible. Some populations of harvestable species will benefit from the disturbance caused by building and maintaining roads, and other populations will be harmed. Although enforcement of illegal harvest might be hampered, so would legal harvest. But market forces adjusting for reduced harvest (product scarcity) is unpredictable, and whether any increased value would be transferred to the harvester is not known.

Secondary links—Habitats and plant community structure of some commercially harvested species are linked to roads. From an assessment of 45 commercial species in Oregon, 30 percent can be found in openings and along roadsides. It also is well known that certain species require undisturbed mature forest and would not benefit from the gaps and disturbance caused by roads. Because of the specific habitat requirements of, for example, wild ginger, pitcher plants, and shade-loving mosses, roads would not directly benefit these plants. Some of these species are listed as sensitive, and ready access threatens their survival. Documentation exists for habitat requirements of almost all commercial plants and fungi. Other habitat concerns are related to maintaining roads. A special forest products inventory created for Trinity County, California, suggests that harvesters stay away from roadsides because some Bureau of Land Management and Forest Service districts routinely spray herbicides and pesticides.

Communities and sustainable economies—Many rural areas need more sustainable and diversified economies, for which they may require assistance. The Forest Service recognized this need and developed economic action programs aimed to help communities strengthen their local economies through a range of forest-based resources, including nontimber forest products.

Conclusions—Information on habitat requirements for many of the commercial species is available, and retrospective studies may show how road closures affect species composition; for example, in the prevalence of native versus exotic species (Parendes and Jones 2000). Developing appropriate policies and implementing them for most special forest product species would benefit from information and models that predict regional and general effects from building or closing roads on the species' harvest and sustainability. Information on the economic effects on various components of the industry—from harvester's overhead to product price—is needed. These questions must be answered to determine how building or decommissioning roads would affect the sustainability of particular commercial species and hence the sustainability of the economies reliant on them.

The effects of roads on the economic, social, and biological factors and their effects outlined above need to be documented. Although roads are generally recognized as major components of recreational and commercial-harvest activities that affect hundreds of species in the national forests, systematic studies that integrate these components, much less any individual component, have not been carried out. Only fragmented information on these biological resources, products, uses, values, and habitat considerations is available. Case studies will provide information on local or regional scales, but a comprehensive model of the relation of roads to special forest products nationally requires a comprehensive special forest products database. In addition, an integrated strategy for special forest products that addresses community and resource sustainability together would benefit from targeted and integrated research-based information.

Grazing and Rangeland Management

Issues—According to the 1995 draft RPA program, about 46.2 million acres of national forest lands are considered suitable for livestock grazing. Producing livestock can be an important part of local economies, and livestock grazing is deeply rooted in the culture of the American West and sanctioned by legislation. Grazing was first authorized on national forest lands by the Organic Administration Act of 1897 and confirmed by many later appropriations acts (USDA FS 1989). The Public Rangelands Improvement Act of 1978 reinforced a national policy that public rangelands were to be "managed...so that they become as productive as feasible for all rangeland values." The network of roads on national forest lands has both positive and negative effects on rangelands and the administration of the grazing program. Roads have mostly replaced driveways as a means for transporting sheep and cattle to and from mountain allotments. As a result, these driveways have dramatically improved in rangeland health. Until the 1970s, livestock driveways were considered "sacrifice areas" in the range-management discipline (Stoddart and Smith 1955). Thus, national forest roads can promote ecosystem management objectives along alternative transportation corridors, which they replace. Roads can simultaneously lead to ecosystem changes that reverse rangeland management objectives, however, and increase the administration of the range management program. Administratively, national forest roads allow range conservationists to access allotments quickly by using vehicles rather than horses. But the same roads can produce conflicts between users of the national forests, such as between livestock grazing and recreation interests. And roads can reduce permittee operating costs by providing motorized access to allotments.

Findings—Essentially no scientific information exists that analyzes the ecological, administrative, or economic effects of roads on administering the Forest Service range-management program. Preliminary unpublished analyses from the interior Columbia River basin ecosystem management project addressed the road issue from the perspective of ecological responses to the presence or absence of roads. The analyses found correlations between changes in vegetation composition, riparian functioning, and fire regimes and the presence of forest roads. They could not conclude any cause-and-effect relations from these correlations, however. The program also found higher road densities to be associated with diminished ecological integrity, including those based on range criteria.

To assess the importance of national forest roads for administering the grazing program, as well as their economic value to permittees, an ad hoc interdisciplinary team was formed to provide a nominal assessment. The findings below reflect the input of the team:

- Roads in national forests are essential for administering the grazing program, allowing timely access to allotments. Compliance enforcement was mentioned in particular as an activity greatly benefiting from forest roads. The principal reasons cited were that agency downsizing has resulted in high workloads for remaining range conservationists, which does not allow them sufficient time to carry out their duties; guard stations have been closed; Forest Service personnel no longer have the option of spending nights in the field in some places; and many allotment plans incorporate Forest Service roads into their approved grazing system or as driveways to and from the allotment; for example, in the Black Hills, all driveways are along roads.
- Roads can reduce permittee operating costs by providing motorized access to allotments. The team estimated that, if all national forest roads were closed, permittee costs would increase by three to five times. These costs would accrue from increased riding time, cost of horses and riders, and added equipment costs (such as horse trailers). The grazing program derives benefit from only part of the road system, however, and if arterial and collector roads remained open, the expected cost increases would be less, from none to a twofold increase.
- Roads can heighten conflicts among users of national forests, such as cattlemen and recreationalists, although some evidence shows that concerns about road conditions actually can cause some forest visitors to slightly, but measurably, shift their focus of attention from grazing encounters to roads (Mitchell and others 1996).

Reliability, confidence, and limitations—No peer-reviewed studies have assessed the effects of national forest roads, or roads in general, on livestock grazing or ecosystem management. The results from the Columbia River basin program are tentative and show no causal relations. The results of studies examining the influence of roads on forested landscapes must be carefully extended because the results from studies in Eastern forested landscapes may not apply to Western forested landscapes (Miller and others 1996). The results of the interdisciplinary-team assessment are heavily weighted towards the Rocky Mountain Region (Colorado, Kansas, Nebraska, South Dakota, and eastern Wyoming) and thus may not represent a national perspective.

Generalizations—National forest roads are an important part of range-allotment plans. Roads are also important for administering the grazing program on national forest lands. Ecologically, roads may have a negative effect on rangelands; however, the environmental effects of not having roads are unknown. The team concluded that closing some roads would be acceptable from the perspective of managing the grazing program if the process was systematically evaluated first.

Secondary links—Effects of roads on spread of non-indigenous weeds (biological invasions), wildlife-livestock interactions, and recreation-grazing interactions (particularly with four-wheeling interests) are important.

Conclusions—No science-based information was found on how national forest roads affect livestock grazing. Many questions remain, including the cost of closure to permittees, and the effects of road closure on administering range management programs, including the weeds program, and on compliance.

Energy and Mineral Resources

Issues—The road-related issues associated with energy and mineral resources fall into three overlapping categories: access rights, property rights, and benefits and negative effects. The extractive industries want, and have certain legal rights to, access to public lands to explore for energy and mineral deposits. The access may be on existing forest roads or may require building new roads. The Forest Service road system facilitates providing energy and mineral resources extracted from public lands, which can benefit society. The negative environmental effects of roads used in support of nonrenewable resource extraction are covered in the earlier sections of the synthesis. Mineral developments and oil fields in and of themselves can affect the environment negatively, such as by loss of habitat, increased noise, and added particulate emissions in the air and water, but these effects can be attributed only secondarily to roads; that is, without the road, mineral development might not have taken place.

These issues are a consequence of the inherent nature of the resources and their treatment under existing law. The defining characteristic of energy and mineral resources is nonrenewability; energy and mineral resources are finite, so extraction inevitably leads to resource exhaustion. Depleted deposits must be replaced either through domestic exploration and mine or field development or through importation. In many places, national forest lands are underlain by deposits of nonrenewable resources, some of which are privately held, that make demand for access inevitable.

Federal law and Forest Service policy clearly support exploration for and extraction of resources from public lands. Leasable resources (that is, metallic minerals found on acquired lands and all energy resources) are managed under the Mineral Leasing Act of 1920. Locatable minerals, primarily the metallic ones on public domain lands, are managed under the Mining Law of 1872. Saleable minerals (that is, common varieties such as gravel) are managed under the Mineral Materials Act of 1947. These laws predate the National Forest Management Act of 1976 and the Multiple Use Sustained Yield Act of 1960.

Findings—Under the Mining Law of 1872, U.S. citizens and firms have the right to explore for and stake claims to selected minerals on all public domain lands not specifically withdrawn from mineral entry. Claims are valid in perpetuity or can be converted to private property rights (that is, patented) assuming that appropriate legal requirements are fulfilled. The Forest Service cannot unilaterally deny exploration access to national forest public domain lands, although the agency does have the right to withdraw specific areas from further mineral entry. The agency cannot prevent staking of a claim on these lands, and a claim holder is entitled to use the surface for activities attendant to exploring for, developing, and extracting minerals, within the limits set by federal, state, and local environmental laws. The agency cannot block an otherwise legal patent (that is, deny a claim holder the right to convert the claim to private property). The Congress can, and has, placed a moratorium on new patents, but the moratorium could be lifted in the future. In any event, hundreds of thousands of patented and unpatented claims are already held within the administrative boundaries of the national forests.

The Forest Service has considerably more control over the location of exploration and development activities for leasable minerals than it has for locatable minerals. For national forests and grasslands with completed oil and gas leasing EISs, petroleum exploration activities are restricted to areas designated as appropriate in those documents. The regions also are taking an active role in directing access for leasable minerals. For example, the Northern Region is attempting to restrict oil and gas exploration to areas relatively near existing roads. This approach is not without potential for controversy, however. Decommissioning of roads could be perceived as a de facto withdrawal of the adjacent lands from exploration. The circuit courts are split on the question of whether failure to offer lands for lease is tantamount to withdrawal.

The Forest Service is required by law to provide reasonable access to valid existing mineral rights, regardless of their form, whether unpatented claim, lease, or private property, as a patented claim or subsurface mineral right. An unpatented claim is an implied property right that can be held, sold, or inherited, and access is regulated under the Mining Law of 1872. Patented claims are private property, and access is regulated under the Alaska National Interest Land Conservation Act of 1980 (ANILCA). Coal, oil and gas, and mineral leases also offer a limited form of property right. The rights to individual energy and mineral resources may be held by different legal entities, and the mineral rights may be severed from the surface, which is termed a "split estate." Access to unpatented inholdings, patented claims, leases, and severed mineral rights can be restricted but seldom denied. Access may be by the existing road system or require new roads. The Forest Service is neither required by law nor expected by industry to build or maintain energy and mineral access roads. Roads built for other reasons (for example, in support of recreation development) might be paid for by the Forest Service but also be used by a mining or energy firm. The firm is always required to maintain the road or to pay for road maintenance called for by their activities; they frequently pay through a reimbursement arrangement with the agency.

The Forest Service can affect the location and design of roads built on national forest lands to support energy and mineral activities. In addition, the agency can sometimes place stipulations on access by limiting road use to certain months, permitting aerial access only, or precluding surface occupancy. Constraints that are unduly expensive to fulfill or so restrictive as to make an otherwise economic mineral deposit uneconomic, however, might well be perceived as denying reasonable access. Temporary roads often are built to facilitate energy and mineral exploration activities. Building plans are subject to review and approval by the agency. If no discovery is made, the exploration firm obliterates the road. Otherwise, the road could be upgraded to permanent status, depending on the circumstances and legal authority. Public use of the road might sometimes be limited because road condition acceptable to the mineral industry might be neither acceptable to, nor safe for, the general public. In addition, other means of access, particularly for exploration, do not require roads, including access by helicopter, foot, horseback, and all-terrain vehicles.

The energy and minerals industries use the existing road system in exploration, development, extraction, and reclamation activities. Only a small portion of the entire road system is affected in any given year, but assuming use of most roads over the long term would be reasonable. Designating a subset of the existing road system as having no future benefit to the industry is not feasible because geographic targets for exploration and development change in response to technological advances and market fluctuations. Limiting mineral exploration access to areas where minerals have already been or are being extracted could preclude future discoveries. Road closures or decommissionings are controversial. Firms wanting to rebuild obliterated roads could face long delays because of the lengthy approval process now in place for building new roads. Such delays could disrupt multiyear exploration and development plans and financing.

The energy and mineral resources produced from national forest lands are essential to the manufacturing, farming, building, and power-generating industries, with a value of $4.3 billion in 1995. Forest Service production represents only a small part of the total value of U.S. production, however. For example, the value of copper produced on national forest lands represents only 1 percent of total U.S. copper. Sometimes, production from national forest lands is a significant percentage of domestic production; national forests produced 80 percent of domestic lead in 1995. Significant amounts of coal and molybdenum also are produced from national forest lands. These contributions to the domestic economy are made possible by use of the forest road system.

Reliability, confidence, limitations, and generalizability—Some case law on energy and mineral access and property rights can be applied more broadly than to the specific litigation reported in it. And for certain situations, existing case law, statutes, and regulations clearly demonstrate the right to reasonable access for existing mineral rights. In numerous other situations, however, the right to access for energy and mineral exploration and development is less clear-cut. Unresolved access issues are associated with both ANILCA and Section 8 of the Lode Law of 1866 (R.S. 2477), which granted right of way across unreserved public domain lands. Considerable debate continues on the degree to which this right has been modified by subsequent legislation.

Secondary links—Roads built to provide access for energy and mineral exploration and development often are heavily used for other purposes. Secondary links can be found to recreation, species endangerment, biological invasions, and many other areas. The effects from energy- and minerals-related roads and road usage are comparable to those of other roads in the Forest Service system built to the same specifications and carrying the same types and amount of traffic. Unpaved Forest Service roads frequently are topped with a layer of aggregate or crushed stone, and the material often has been extracted from Forest Service lands. Thus, the extent of the road system also has implications for the volume of aggregates extracted; fewer miles of road built and maintained implies fewer tons of aggregate and crushed stone extracted.

Conclusions—The legal issues surrounding energy and mineral road access and usage will require the input of the Office of General Council: Pamela Piech (202/720/2515) is an expert on the Mining Law of 1872; James Snow (202/720/6055) is an expert on RS2477 and ANILCA. Little or no research has been published on the secondary links associated with energy and mineral road usage. One key area for future nonlegal research is to determine the landscape-scale effects of energy and mineral development; for example, extensive oil-field road networks may lead to habitat fragmentation.

Another need is to determine exactly which roads are currently being used for access to explore, develop, extract, and reclaim. Quantifying the effects on road condition of nonrenewable resource activities by number and size of vehicles is also important, and another management need is to identify the roads leading to or adjacent to valid existing mineral rights.

Resource-Based Outdoor Recreation

Issues—Almost all the different types of public recreational uses of national forests depend in one way or another on roads for access. Whether, when, and where various recreational uses occur depend on the availability of access to, and the extent and location of, the road system. Altering this system is likely to have widespread and differing effects across different types of uses. In considering the future of roads on national forests, the general question is, “What are the direct, indirect, and secondary effects on recreation from possible changes in national forest road systems?” More specifically, “What are the direct effects of changing the class, spatial density, ecological distribution, maintenance, and total mileage of national forest roads on the density, placement (ecologically and socially), mix, economic value, experience quality, and amount of recreation uses?” As well, “What are the indirect effects on access to views of natural scenery and on the quality of scenic resources, and what are the secondary effects on the economic and social viability of communities in the area and the condition of the forest ecosystem?” Answers to these and many other questions are needed as input when national forest road policies are considered and in seeking to optimize net benefits across multiple roads.

Findings and hypotheses—The relations between roads and recreation on national forests is highly complex and includes many direct, indirect, and secondary links that are not well understood. Research findings specifically addressing these links are limited and uneven across the questions we have posed. Indirect evidence and related research provide the following insights and hypotheses:

- Roads provide corridors of access to a variety of national forest sites, settings, and viewing opportunities for widely diverse users. Almost all recreation use in national forests depends to some degree on road access. Sightseeing, driving outdoors for pleasure, and developed camping are examples of activities that directly use roads as a part of the recreation experience. Backpacking, white-water boating, and birdwatching are examples of activities usually away from roads, but the user still must access areas of interest by using them. Altering road systems can disrupt long-established access and use patterns and, at least in the short run, result in not meeting visitors’ expectations. Less road mileage or maintenance, or both, can lead to uneven shifts in recreational opportunities across different user, socioeconomic, and ethnic groups who depend differently on roads for access.
- Roads provide staging access to remote areas and wilderness, but the presence of roads can at the same time reduce opportunities for solitude and perceptions of wildness. The amount, placement, and class of roads are positively correlated with the amount and concentration of recreational uses. But visible roads, greater numbers of users, and sounds from motor vehicles can interrupt solitude and perceptions of wildness for wilderness and other backcountry users.
- As demand for forest recreational opportunities continues to grow locally, regionally, and nationally, even a stable amount and condition of forest roads likely will result in increased congestion, lowered satisfaction, and user conflicts. Outdoor recreation trends show recent strong growth in participation across a wide spectrum of activities and segments of the American public (Cordell and Bergstrom 1991). Projections

show this growth is likely to continue well into the future for all nature-based activities except hunting (Bowker and others 1999). At the same time, access to private lands is continuing to decrease and be limited to lessees and friends of the owners (Cordell and others 1999). Public lands are likely to be the destinations of choice for increasing numbers of people looking for high-quality outdoor recreational experiences in natural settings. Several national parks already have limited motorized access to bus tours or other public transportation as one way to address increased congestion from private cars. Continued growth in demand without increases in road systems or limits to use of private cars likely will lead to lowered satisfaction and more conflicts at the more popular national forests (Tarrant and others 1999). Changes in satisfaction likely will differ significantly by setting (for example, as distinguished in the recreation opportunity spectrum [Tarrant and others 1999]). Direct recreational access, the character of and access to scenic views, and provision of increasingly sophisticated visitor services (including rescue and medical services) will depend on the character of the road system in place.

Reliability, confidence, and limitations—Data on national forest use and the relations of roads to that use are unreliable, but a national project is underway to develop an improved use-monitoring system. Data from the customer project provide insights into user perceptions of experience quality related to national forest attributes, including roads (Tarrant and others 1999). Social group differences between users of roaded, near road, and backcountry settings are available for the U.S. population in general, and to some degree for national forest users. Science-based methods are available for examining in more depth the relations between roads, recreational use, visitor satisfaction, and economic values and effects. Little research exists to guide management for optimizing recreational benefits from roads and globally optimizing multiple benefits across the broad range of national forest road uses.

Secondary links—Even though increased use (on the same or fewer miles of forest roads) or changes in the mix of recreational uses, or both, may increase aggregate visitor spending (and thus general economic effect), the distribution of economic effects among economic sectors and regions is likely to be altered. The biophysical effects of recreational use on forest ecosystem conditions are confined mostly to near-road zones, the site of most use. The biophysical condition of affected sites tends to stabilize after each successive increment of recreation use, although the resulting condition may be unacceptable to managers, users, or both. Specific links between recreational use and conditions of ecological components and links between recreational use and other resource uses are not well known.

Conclusions—Quantitative and qualitative methods, research underpinning the recreation opportunity spectrum, and a wealth of related published and unpublished literature dealing with economic values (Bergstrom and Loomis 1999); secondary economic effects (Archer 1996, Bergstrom and others 1990); visitor perceptions and behavior (Tarrant and others 1999; Williams and Patterson, in press), resource and social capacity (Shelby and Heberlein 1986); conflicts, consumption, and future projections of road-based recreation (Cordell and Bergstrom 1991, Bowker and others 1999, Cordell and others 1999), and social justice assessment are available. For the most part, however, existing databases and literature have only indirectly addressed the hypotheses described above that deal specifically with the relations between roads and recreation (for example, Knight and Gutzwiller 1995). Substantial research is needed to better understand direct and indirect relations between road-system characteristics, recreational use, and ecosystem conditions, including issues such as the introduction of exotics, soil erosion, habitat fragmentation, forest-product harvesting, wildlife disturbance, riparian vegetation, and fire.

Indirect Socioeconomic Effects

Fire

Issues—The increasing density of road networks in and adjacent to many forest, shrub, and rangeland areas has been an important factor in changing patterns of disturbance by fire on the landscape. Roads provide access that has increased the scale and efficiency of fire suppression, and roads have created linear firebreaks that affect fire spread. These factors can be useful in both fire suppression and prescribed fire operations. In addition, road access has undoubtedly contributed to increased frequency of human-caused ignitions in some areas.

Findings—That improved road access leads to increased efficiency and effectiveness of fire-suppression activities is a long-held tenet of fire fighting. Much of the effectiveness of past fire-suppression policies probably can be attributed to increased access for ground crews and equipment, particularly under weather and fuel conditions where fire behavior is not severe. Under the severe conditions associated with intense, rapidly spreading fires, the value of forest roads for access or as fuelbreaks is likely to be minimal. Although little has been published in the science literature to quantify these effects, a study in southern California concluded that the road network had been a key factor in determining what suppression strategies were used, both in firefighter access and because roads were widely used for backfiring and burning-out operations (Salazar and Gonzalez-Caban 1987). Early studies of fuelbreak effectiveness in southern California came to similar conclusions (Green 1977). Daily costs of fire-fighting activities unfortunately are of little value in answering the question of how much road access increases efficiency, because fire-fighting agencies tend to put money and resources into fighting fires with access, which confounds the results. In spite of this, strong anecdotal evidence supports this effect.

An important issue in the Western United States is building new roads to allow harvest and prescribed fire to reduce fuel accumulations in ecosystems where past management (principally fire suppression and harvest) have increased the risk of large, severe wildfires (Lehmkuhl and others 1994). The principal concern here is the tradeoff between reducing the effects of wildfire and increasing the risks of road effects on aquatic habitat. In the Columbia basin, scientists concluded that “it is not fully known which causes greater risk to aquatic systems, roads to reduce fire risk, or realizing the full potential risk of fire,” and that more research is needed (Quigley and others 1997). Some potential considerations in setting priorities for forest health treatments have been suggested in an adaptive management framework for addressing this concern (Rieman and Clayton 1997). We currently have few data on how these processes might be affected by road networks, although a study after the 1987 Stanislaus fires in California suggests that cross-slope road networks reduced sediment delivery to debris basins (Chou and others 1994).

The benefits that roads provide for fire prevention and fire management carry an associated cost. For purposes of simplicity, we will highlight them here in place of a second fire section under the “undesirable or negative effects.” Indirect effects of increased access have increased the role of human-caused ignitions, particularly in areas of expanding urban and rural development into wildland interfaces (Hann and others 1997). The high rate of human-caused fires in the Blue Mountains of eastern Oregon is associated with high recreational use in areas with high road densities (Hann and others 1997). The importance of human-caused ignitions as an issue may depend on what resources are considered of concern. For example, in the Southwest, numbers of ignitions go up with access, but numbers of ignitions are not limiting to maintaining fire regimes, but fuel loadings and climatic conditions are (Swetnam and Baisan 1996). Numbers of ignitions are important determinants of fire risk, however, in areas such as wildland-urban interfaces for which maintaining historical fire-regime patterns is not the overriding issue. In addition, numbers of ignitions are important determinants of fire risk in some wildland-urban interfaces where fire intensities are often higher (such as chaparral), and active suppression of ignitions by people may be critical to maintaining historical fire patterns (Conard and Weise 1998).

Road networks have resulted in changes in fuel patterns and fire regimes at the broad scale. If we accept that road networks have been important in effectively suppressing fire and that they alter fire patterns on the landscape, then road systems are, in some sense, linked to changes in fuel patterns and fire regimes. Before fire-suppression activity in the Western United States, fuels were maintained at relatively low amounts in dry forest types, with high fuel loads restricted to small, isolated patches (Agee 1993). As access increased, areas burned by wildfire declined, at least through the 1960s. As a result of suppression supported by access (in part), fuel accumulations increased and areas with moderate to high fuel loadings became larger and more contiguous. This pattern of change has been documented for the entire upper Columbia River basin, where scientists assert that fire suppression has generally been more effective in roaded areas, which has resulted in roaded areas in the upper basin departing further from unaltered biophysical templates (as measured by dominant species, structures, and patterns) than have the unroaded areas (Hann and others 1997). Roads (along with other human disturbances such as clearcutting) contribute to new disturbance patterns at the landscape scale, both by increasing efficiency of fire fighting and providing barriers to fire-spread that are different from natural barriers (Swanson and others 1990). Increased emphasis on removing roads in certain environmentally sensitive areas will reduce access for fire suppression and prescribed fires, potentially leading to increased fuel accumulation and fire hazard in some areas.

Reliability, confidence, and limitations—Logic and anecdotal evidence for the contention that road access increases effectiveness and efficiency of fire suppression efforts are strong, but quantifying this issue in terms of cost savings or size and severity of fires is not well documented. The scientific support for the contention that roads serve as firebreaks is strong, but how important this effect is in controlling the pattern of fire on the landscape is not clear; the ecological implications of this pattern change also are not clear. The secondary effect of roads providing access for timber harvest that has resulted in changing mosaics of fire is strong; the ecological consequences, while strong, are highly variable. Long-term effects on changing fire regimes in the Western United States are well documented. Increased access probably leads to increased human-caused ignitions, but the implications of this increase differ from area to area. Increased ignitions at urban-wildland interfaces are likely to be a problem, but it may be unimportant in affecting fire regimes in less-developed landscapes in the West. Building roads to provide access to reduce fuel in fire-suppressed forests is likely to enhance this activity, but it may carry added risks to aquatic environments over the risk of fire alone.

Generalizability—Most of the concerns addressed here apply primarily to the Western United States. In much of the East, road networks are well developed and relatively stable because of terrain and vegetation differences. Wildfire interactions are likely to be similar to those described for the West, but the effects are likely to be significantly less. In the Southeast, where use of prescribed fire is widespread, roads are frequently used as firebreaks. Much of this activity is on private lands, however, and a high proportion of the road network is state and county highways rather than Forest Service roads.

Secondary links—Fire issues are linked to issues of forest (ecosystem) health and aquatic habitat.

Conclusions—In general, the importance of roads for providing access and firebreaks is well established, although literature on cost-to-benefit ratios is lacking; most evidence is anecdotal. The issue of road access to lessen fire risk and improve forest health in unroaded areas is heating up, and little published research is available to fall back on for resolving the debate.

Forest Research, Inventory, and Monitoring

Issues—Among the benefits that roads provide is access for research, timber and non-timber forest inventories, and monitoring. Although the economic scale of these tasks may be low compared to some other activities, the knowledge derived may be key for managing other access-related uses, in addition to the more general objectives sought. Hence, understanding the relation of roads to inventory and monitoring activities is not a trivial issue.

Findings—Although finding sufficient data for a complete and wide-ranging analysis is difficult, the role roads play in inventory and monitoring access (that is, the cost per plot) can serve as a surrogate for the larger problem. Plot-survey contracts are based on four categories in which the proximity to roads plays a significant part. For example, costs run about $600 per plot when roads allow access to within 0.25 mile of the plot sites. In the same region, cost rises to $1,300 per plot in roadless areas open only to foot access. In the Pacific Northwest, the nearly 650 wilderness plots, of a total of 11,360 in all terrain, had survey costs only about 23 percent greater ($1,460 per wilderness; $1,174 per nonwilderness plot). The data did not permit comparing the cost difference of road-accessed plots in the Pacific Northwest Region over the montane sites in the Pacific Southwest Region, however. More extreme conditions are encountered in Alaska, where roadless areas are vast, yet helicopter access is permitted. The average cost per plot for roadless areas in the Alaska interior has averaged $4,000 per plot for 170 plots. Obtaining good data for comparing areas covered by these approaches is generally difficult because photo-interpretation based on aerial photo coverage is used to supplement ground-survey efforts.

Reliability, confidence, and limitations—Problems of access to survey plots for research, inventory, and monitoring will clearly raise costs of operations. The exact differences can be quantified by taking terrain differences, size of roadless areas, and means of permitted entry into account. For this study, we used only a few data points from limited regions to understand the extent of this issue. More comprehensive analyses are possible with existing data, given the resources to do them. The data are sufficiently robust to suggest that the cost elements relating to access constitute a factor in research, inventory, and monitoring. Whether the magnitude of the contribution of such uses constitutes a significant economic component when compared to, say, recreation is not clear, however.

Generalizability—The data examined for this order-of-magnitude approach were taken from limited observations originating in the Pacific Southwest, Pacific Northwest, and Alaska, with Alaska representing extreme conditions. Corroboration for the observed higher cost resulting from the absence of road access was attained qualitatively for the Eastern Region of the Forest Service.

Secondary links—Access issues have similar aspects whether extraction (such as timber, mining, and grazing), recreation, inholdings, or related activities are considered. The links do suggest that coordination of overlapping uses be a variable examined when road density and road-network planning are considered.

Private Inholdings

Science-based sources of information have not been found on the relations between roads and private inholdings. The following propositions are therefore offered as hypotheses based on judgment, not scientific findings. These propositions do not necessarily apply to inholdings dedicated to mineral and energy exploration or extraction, which are covered in "Energy and Mineral Resources," above.

- The Forest Service is required by law to permit access to private inholdings.
- The Forest Service can require private inholding owners or lessees to comply with official regulations and standards that apply to building roads on or through national forest land. The regulations and standards are documented in writing as official policy, but they are subject to interpretation and application in specific cases by agency line officers.
- The Chief (of the Forest Service) may consult appropriate national forest policy offices and line officers about the sources of scientific documentation used in practice and official regulations, standards, and procedures applicable to roads on or through national forest lands that provide access to private property.
- In general, the scientific documentation of ecological and human effects of roads on or through national forest land provided elsewhere in this synthesis applies to roads that provide access to private inholdings.
- No scientific basis exists for stating propositions about whether the Forest Service subsidizes access to private inholdings or the effect, if any, of Forest Service roads on the market, use, and passive-use values of private inholdings.
- The Chief needs inventory information about the type, number, acreage, location, use, value, and so on of private inholdings on national forest land and the extent to which private inholdings use national forest roads for access. At present, no systematic inventory procedure or documentation can provide comprehensive and valid information of that type.

Nonmarket and Passive-Use Value

Issues—A comprehensive understanding of the economic effects of roads in the national forests must include both effects that can be measured in dollars (market effects) and those with no direct dollar values (nonmarket effects). The influence and importance of market values to land management decisions is obvious, and measuring and comparing effects of management decisions that affect market values are relatively simple. For example, the cost of building and maintaining a road into a forest can be readily compared to the income generated from harvesting the timber accessed by that road. Also important, but far more difficult to measure and compare, are the things people care about for which no market exists, such as access for hunting, bird watching, and wilderness experience.

Natural resource economists have invested much effort over the last several decades to develop and test methods for estimating nonmarket values. The methods can produce useful information, but they are costly and their validity has not yet been demonstrated sufficiently to satisfy many economists (Arrow and others 1993, Cambridge Economics 1992, Mitchell and Carson 1989, Portney 1994).

Economists generally classify nonmarket values as either active or passive. The term "active-use value" applies to goods and services used in some activity like recreational fishing, skiing, or camping. The term "passive-use value" includes two categories (Peterson and Sorg 1987, Randall 1992): things people appreciate without actually using them or even intending to use them (like a distant wilderness or an endangered plant or animal) are called "existence values"; and things people want to remain available for others (such as their descendants) to use and appreciate are called "bequest values."

Environmental economists often define and measure these nonmarket values in monetary terms, but monetary valuation is often not possible, cost-effective, or appropriate. All nonmarket consequences of national forest roads and of any changes to these roads must be considered in road management and policy decisions. For example, passive-use values are likely to strongly affect decisions about preserving areas without roads or about removing existing roads to create roadless areas. Thus, the nonmarket consequences need to be identified in some way—either in monetary terms or by some other means.

Under regulations of the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA), as amended, 42 U.S.C. 9651 (c), a United States Court of Appeals for the District of Columbia ruled in 1989 that passive-use values "...reflect utility derived by humans from a resource and thus, prima facie, ought to be included in a damage assessment." Thus, if Forest Service roads significantly alter passive-use value, whether positively or negatively, such value needs to be considered in road policy and management decisions. Failure to include these nonmarket values in an economic evaluation, when such values are judged to be important, presents the manager with biased information that could lead to inefficient and unfair allocation of resources.

Significant questions: Under what conditions do people assign passive-use value to national forest landscapes or their attributes? Forest Service officers responsible for road policy and management need to know the forest landscape conditions to which people assign passive-use or other nonmarket values, how such values differ among individuals and groups of people, the strength or significance of the value assigned, how changes in the landscape affect the nonmarket values, and how such values trade off with other forest-related values assigned by affected people.

Do Forest Service roads, road policies, or road management actions strongly affect passive use and other nonmarket values? If so, how and why? A related question is whether the effects of roads on nonmarket values affect people differently and differ by landscape. For example, if the supply of landscape that provides passive-use value is sufficiently large in a given region, small increments of road building or decommissioning may not affect people very much. Many small encroachments could produce severe cumulative effects, however.

Findings—People do assign passive-use value to natural resources, especially roadless areas and natural areas with unique characteristics. And the passive-use value often exceeds the active-use value served (or potentially served) by road access (Bengston and Fan 1997; Brown 1993; Driver and others 1987, 1996; Payne and others 1992; Walsh and others 1984, 1990).

Building roads in roadless areas may reduce passive-use value significantly; decommissioning roads may increase such value. Building roads into roadless areas may serve values that require such access, however, and decommissioning roads may obstruct values and uses that require access. Decisionmakers need to consider all these tradeoffs. Individuals and affected groups often disagree aggressively about the passive-use value of specific roaded and roadless areas and the effects of building or decommissioning those roads (Bengston and Fan 1997). Thus an equity (or distribution) question must be considered: Whose desires should the Forest Service fulfill when stakeholders' values conflict? What criteria should be used to decide among them? What approaches can be taken to resolve the conflict?

The effects of roads on passive-use value differ by location and circumstance. Differences in the quality and uniqueness of landscapes modify passive-use-value effects from building or decommissioning roads. The relation between supply and demand also will affect the extent and strength of a passive-use value. For example, if many substitutes for a given roadless landscape exist, building a road in that area may have little or no effect on its passive-use value, just as the hunter's killing of a single elk does not reduce the passive-use value of elk because the species is still abundant. Likewise, if an abundance of roads are provided to resources that people want for active use, decommissioning or closing one road will have little effect. People with strong attachments to a special place, use, or road may suffer loss, however, unless they can find and adapt to a substitute.

Validly and reliably measuring changes in passive-use and other nonmarket value is costly and can sometimes exceed the cost of being wrong. Managers of national forest roads must understand such values, however, and the circumstances under which they are significant decision factors, to assure that the values can be included where appropriate. A survey-based method called contingent valuation (contingent valuation generally uses surveys or interviews to determine how much people say they would be willing to pay for some nonmarket good) that asks people to state their willingness to pay for nonmarket values can provide a useful indication of relative magnitude, but applying it to passive-use value of public goods is where the method is most vulnerable to flawed results, criticism, and controversy. Studies must be designed and applied carefully and the results interpreted cautiously. Other methods, such as value juries (Brown and others 1995), focus groups, public hearings, and other forms of public participation also can provide useful information. Quantitative measures should be taken only when the scale of the problem justifies sufficient investment for scientifically rigorous results.

If fully and correctly disclosed, the cost of opportunities foregone by preserving a roadless landscape can serve as the price to be paid for the values served by preservation. Preserving a roadless area may sometimes cause an opportunity cost in the form of alternative uses foregone, such as timber harvest, developed recreation, or fire suppression. If the opportunity cost has been fully disclosed to the decisionmaker, a decision to preserve a roadless landscape is a policy acknowledgment that the value created exceeds that opportunity cost. In a decision about whether to designate an area as roadless, opportunity cost can sometimes serve as the price to be paid for whatever values, including intangibles, are served by the designation. Stakeholders and decisionmakers can then decide—by judgment, negotiation, or analysis—whether the gain is worth the price (Bell 1996; Fight and others 1978, 1979; Randall and others 1979).

Reliability and degree of confidence—The scientific literature supports the general propositions that roadless natural landscapes and unique natural features and resources generate passive-use and other nonmarket values; that such values differ among individuals, groups, and landscape conditions; and that disagreement about nonmarket value fuels conflict. Legal precedent also validates policy concern. The effects of roads on passive-use and other nonmarket values have not yet been studied extensively, and the validity and reliability of methods for measuring the necessary values are still questionable.

Generalizability—No science-based procedures, analytical methods, formulas, tables of values, or handbooks are available for applying the general principles we have outlined to specific decisions or to transfer measured values from one place to another. Each project-scale decision requires original human-dimension inventory and assessment techniques, either by technical measurement or through public involvement. Managers making decisions on whether to build or remove roads in specific places always need to consider the principles and questions defined in the findings section. Roadless areas may have significant passive-use and other nonmarket value, depend-ing on the people affected and the availability of substitutes, but obtaining the required information requires original inventory and assessment for each decision. Expensive procedures may not be appropriate where the scale of the problem does not justify the cost.

Research in progress is exploring nonmarket active-use-value transfer (that is, generalizing by formulas and tables) among different site-specific situations. The results thus far are encouraging but not conclusive, although they may offer useful guidance in some situations (Rosenberger and Loomis 2000). We are not aware of any similar work on passive-use-values.

Secondary links—Passive-use value affects public attitudes toward the Forest Service as well as public willingness to accept and support proposed forest policies and plans. Roads and roadless areas sometimes take on symbolic meaning in the broader context of environmental concerns about such things as biodiversity, pollution, and ecosystem health. Passive-use value associated with symbolic issues triggered by changes in road distribution can be an important cause of conflict and litigation.

Conclusions—Extensive scientific evidence exists on passive-use and other nonmarket values in general and on applying them to unique natural environments, environmental accident damage assessment, and sensitive species. Little scientific evidence is available on the relations among roads, roadless landscapes, and passive-use value, however. Published studies demonstrate that people often do assign significant passive-use value to natural areas, including roadless ones, in specific places (Bishop 1978; Brookshire and others 1986; Carson and others 1999; Cicchetti and Wilde 1992; Ciracy-Wantrup 1968; Crowards 1997; Farmer and Randall 1998; Freeman 1993; Krutilla 1967; Krutilla and Fisher 1975; Loomis and White 1996; Mazzotta and Kline 1995; Morton 1999; Walsh and others 1984, 1990). National forest roads can be an important cause of ecological degradation. Under the right conditions and taken together, those studies also imply that national forest roads can cause a significant loss of passive-use values. The actual effect on passive-use value will be specific to the site and situation, however; the only refereed studies we found that document the specific relation between roads and passive-use value are Brown and others (1996) and Champ and others (1997). Rosenberger and Loomis (2000) compiled a comprehensive tabulation of nonmarket recreational values, including a bibliography of 162 studies.

Additional studies are needed to test hypotheses or estimate parameters that apply to specific decisions. General methodological and theoretical research not specifically focused on forest roads is ongoing in several disciplines, including environmental economics, sociology, psychology, political science, and anthropology. Several approaches are being pursued, including social and psychological surveys, ethnographic studies, methods for effective citizen participation, focus groups, citizen and value groups, and monetary valuation. The needed and ongoing research is long term, however, and must not delay making decisions in the short term, based on the best available current knowledge.

Heritage and Cultural Value of Roads

Issues—In addition to satisfying the American penchant for sightseeing by car and other forms of recreation requiring auto travel, roads and their features themselves sometimes have heritage value because of historic significance or architectural features. Roads also may affect areas considered sacred by American Indians or other religious groups. These issues can affect the legal and political framework for Forest Service road policy and management because important historical, social, and cultural values are often part of developing, maintaining, or decommissioning roads. Forest planning for transportation and for individual roads should incorporate information on heritage and cultural values for both roaded and unroaded areas.

Findings—Roads and associated features are part of the history of the nation. Some features are significant for their association with exploration and settlement, others for accomplishments in engineering, and still others for reasons of local history and culture. Roads and other transportation features figured prominently in the early nonindigenous settlement and development of the nation. Roads that were or are significant in this way include early Spanish roads, such as El Camino Real (the Royal Highway) in California and New Mexico; those that follow the routes of American Indian trails (Davis 1961); military roads such as Cook's trail, which crosses the forests of northern Arizona (Scott 1974); and some early routes established for commerce, such as the Santa Fe Trail, which crosses the Cibola National Forest. Given their historical role, such roads (many still in use) often are eligible for the National Register of Historic Places. Of equal importance, historic roads often have special meaning to people who live near them or have used them. Route 66, for example, which crosses the Kaibab National Forest, is considered historically valuable for its role in establishing regular, all-season east-west automobile transportation to California (Cleeland 1988, 1993).

Features forming part of or associated with a road may be historically or culturally valuable for their own merits (Fraser 1987). Bridges and other features built by the Civilian Conservation Corps often are fine examples of engineering and considered eligible for the National Register of Historic Places (Throop 1979). Many such bridges are on Forest Service roads. Roads also may have heritage value as part of a cultural landscape, such as the landscapes associated with homesteading, ranching, or logging. Even roadside advertising can have local cultural significance, such as the hand-painted message along an abandoned highway in the Cibola National Forest that claims "Curandera cures all." The National Park Service and the U.S. Committee of the International Council on Monuments and Sites recognized the heritage value of transportation corridors in a conference held in 1993 (USDI 1993).

Building, maintaining, and decommissioning roads can affect historical and cultural values. Roads often directly affect historical and archaeological sites. Building, maintaining, or decommissioning roads can damage or destroy archaeological sites (Spoerl 1988) with earthmoving equipment used on buried and surface remains, such as structures and other cultural materials. Roads also affect sites indirectly by increasing erosion or by making sites accessible to vandals. Less tangibly, but no less important, roads often affect areas that American Indians consider sacred, may limit their ability to conduct ceremonies that require privacy, and may even diminish the sacred qualities of such places. Building new roads, or adding to existing ones, can affect sacred areas that may qualify for the National Register of Historic Places as Traditional Cultural Properties (Parker and King 1990). The Cibola National Forest has recently been in litigation initiated by Sandia Pueblo over plans to rebuild a road through Las Huertas Canyon in New Mexico. The pueblo claims that the canyon is eligible to be a Traditional Cultural Property. A larger issue in this case is that the road and the traffic it brings affect use of the area for pueblo ceremonies. In northern California, similar issues surrounded the case of the Gasquet-Orleans Road on the Six Rivers National Forest (Theodoratus and others 1979), which concerned road building and resource extraction in an area that local American Indians considered sacred. The dispute over this road lasted many years, and its repercussions continue to be felt.

Generalizability—The findings are partially generalizable to all national forests but not to all decisions. As with sensitive species, some issues arise where heritage and cultural values are especially significant. Because of legal requirements and the intensity of concern among affected stakeholders, however, assessing cultural and heritage values is essential in every Forest Service decision about building or decommissioning roads.

Secondary links—Inadequate participation in road policy decisions by affected stakeholders concerned with heritage or cultural values can lead to litigation and political conflict. It also can stimulate symbolic opposition to the Forest Service on other fronts that even direct amelioration of the heritage or cultural concerns cannot resolve.

Conclusions—Good information is available on cases encountered by the Forest Service; it is generally after the fact, however, and pertains to actions taken to resolve conflicts caused by failure to consider the issues early and effectively in policy and management decisions. Existing information about heritage and cultural values relating to roads and roadless areas often may not be adequate; ongoing inventories tend to be project-specific rather than part of the general program. Obtaining information about sacred places from some American Indian groups is difficult because Forest Service styles of communication and negotiation often are incompatible with these cultures, and revealing sacred values and identifying sacred places to outsiders may be thought to imperil the values in need of protection.

Documentation—Much of the documentation for the heritage and cultural values of roads resides in administrative documents in the 50 state historic-preservation offices and the Advisory Council on Historic Preservation.

Economic Effects and Development

Issues—Both benefits and costs are associated with building, maintaining, and continued use of Forest Service roads. Likewise, benefits and costs are associated with removing existing roads. The issues revolve around whether the good things outweigh the bad things and what the extent of roads should be in national forests.

Findings—Some economic activity is supported by building and maintaining roads: economic activity also is supported by decommissioning roads. Analyses for the 1995 RPA program suggest that about 33 jobs economy wide (nationally) are supported per $1 million expenditure on building and maintaining roads (Alward and others 2000). A reasonable speculation might be that roughly the same rate of employment would be supported by removing existing roads and restoring the land underlying them. Road building and removal represent one-time stimuli to the economy, but maintaining roads is a recurring stimulus. After a road is removed, the jobs supported by road maintenance cease.

The major effects of roads on local economies, however, would be expected to result from the economic activity those roads support by providing access to the national forest and to communities in or near it. On Forest Service roads, that activity includes logging, silvicultural operations, and recreation, among others. Also supported is economic activity that depends on recreation, such as guides, outfitters, and rafting permittees. The roads also provide access for land management and firefighting operations.

Indirect (and approximate) indications of the amounts of economic activity that might be associated with changes in Forest Service roads can be obtained from several sources. Reports indicate that timber harvest from national forests supports about 16.5 jobs economy wide (in the local area) per million board feet harvested (USDA FS 1996). That estimate is conservative because it is based on summed local-area models. Recreational use of national forests supports a range of 1,000 to 2,000 jobs economy wide (nationally) per million trips, depending on the primary activity, based on analyses done for the 1995 RPA program (Alward and others 2000, Archer 1996).

Use of public lands, in general, follows roads. In Alaska, for example, intensity of use by both hunters and nonconsumptive wildlife users follows road corridors (Miller and McCollum 1997). Further, we hypothesize that more casual users—such as scenery gazers, picnickers, car campers, and day hikers that constitute the bulk of national forest recreationists—probably stay closer to the road than do some hunters and backpackers, the minority of national forest recreationists.

Whenever timber is cut and removed from the forest, roads will be needed; even helicopter logging at some point converts to road use by truck hauling. One issue is the quality of the roads and the length of their lives; that is, whether they are permanent and remain after timber harvesting ceases, or temporary and closed after harvest. Permanent roads are available for other activities over time, primarily recreation and management activities. Temporary roads are available for timber activity and some incidental activity during harvest, but when the roads are closed, benefits accruing from those roads cease. That the cost of maintaining a road over time could sometimes outweigh the cost of removing it at the end of one timber harvest cycle and rebuilding it for the next one is at least conceivable. Environmental effects (and cost) of multiple entries and decommissioning of temporary roads must be balanced against those of a single permanent road. Permanent roads cost more to build and maintain than temporary ones, with increased potential for degrading the ecosystem, but they can result in more benefits over longer periods than temporary roads because of the access they allow.

Roads affect spatial patterns of forest use. Changes in roads change those patterns. Recreational users are particularly attracted to or driven away from particular areas by the availability and ease of access. With decreased access to the national forest, some users might drop out and give up outdoor recreation. Others would shift their use to other areas, some on Forest Service land and others off. The result would be reduced economic activity in the locale where forest access was decreased and increased economic activity in areas where displaced users moved. In general, the effects would be reversed if access were increased. Sometimes, however, increased access could lead to decreased use and result in less local economic activity; for example, where new roads and associated commercial activity degrade a viewshed, which could decrease visits to view autumn foliage.

Another result of spatial shifts in recreational use could be to concentrate use in areas to which displaced users move. Concentrated use may increase environmental effects as well as decrease the quality of people's experiences. Crowding imposes costs on existing users in those areas by diminishing the benefits they received from their recreational use because of the inflow of displaced users from areas affected by decreased road access.

Anything that affects the demand for and benefits received from recreation and other uses of Forest Service land has subsequent economic effects, and it may alter development because land uses drive local economic activity. Forests and local economies will be affected differently, depending on the mix of local activities.

Building or removing Forest Service roads and maintaining existing roads can help mitigate ecosystem degradation associated with roads. Note that the tradeoffs are between the expense of minimizing or eliminating environmental degradation associated with Forest Service roads and access to Forest Service lands with associated economic activity.

Many roads are or have been funded by the timber program. Benefits accrue from use of those roads beyond timber, largely for recreation. This contrast presents a classic problem of joint cost allocation, and the accounting problem of attributing cost should not be used as an excuse for looking only at specific programs or components of the Forest Service mission.

The jobs and other economic activity supported by building and maintaining roads must be balanced against the cost of building and maintaining those roads, including costs resulting from choosing not to maintain selected roads. The question is, do the benefits associated with the roads, both direct and indirect from all sources, justify the cost incurred by society, including costs of increased ecosystem degradation from deferred or inadequate maintenance? Reports like this one can provide information on a wide variety of benefits and costs, but answering the question just posed is a policy decision.

Reliability, confidence, and generalizability—Analyses done for the 1995 RPA program provide a broad picture of national effects that can be expressed as averages and rates per unit of activity. They are not site-specific studies, and they do not estimate the effects on local areas. A few recreation-demand studies based on specific sites and regions provide corroborating evidence of the qualitative results (English 1997, McCollum and Miller 1994, Miller and McCollum 1997). The transportation literature contains some studies on roads and development (Berechman 1994, Broder and others 1992, Rephann 1993, Rietveld 1994), but those studies are mainly about highway systems, and though we expect their conclusions to be qualitatively relevant to the types of roads administered by the Forest Service, some attributes of Forest Service roads are so different that creating a complete picture is impossible. A primary gap in knowledge is understanding the links between policy or management actions and their effects on forest-based activity (both in the amount of activity undertaken by users and in the benefits they receive), especially for recreational and noncommodity uses. Changes in road availability and quality affect whether and how much users access the forest in particular areas. Road availability and quality also affect the quality of users' experiences, and thereby affect the benefit they receive. No access or access on a poorly maintained road, for example, could decrease benefit for some activities but have little or no effect on others. We did not find any activity-specific studies documenting the direction and size of such effects. Those factors are relevant because they drive demand for access to Forest Service land and the local economic activity associated with use of these lands.

Further gaps in knowledge exist on the distributive effects of new or improved and degraded or removed roads on forest use in local areas and on local economic activity. To what extent do the existence or lack of Forest Service roads, and their condition, attract or drive away users pursuing particular activities? The general development literature provides some insights and qualitative expectations for Forest Service roads, but empirical findings on the likely size of the effects are absent.

Conclusions—Empirical estimates are not available to document the size of the economic contribution of recreation-dependent commercial activities like guides, outfitters, and rafting permittees. Also missing are empirical estimates of benefits received from and economic activity supported by specific recreation activities in specific areas. Estimates are often obtained from national studies or site-specific studies in other areas and blindly applied to areas being analyzed.

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Appendix

This section draws from the analysis in the main document, with interpretations relevant to roadless and unroaded areas.

Forest Service Roadless Areas: A Synthesis of Science Information

Managing and maintaining existing forest roads has not kept pace with either the shifting balance of forest users or the increased scientific understanding of the ecological effects of roads. In particular, entry into roadless areas merits consideration of both benefits derived and risk of unacceptable impacts. Thus, managing for roadless area protection consists of positive steps such as providing for habitat conservation areas, watershed protection, critical habitat protection, contingency or passive-use values, and related land stewardship objectives. It also consists of restricting actions that may contribute to deteriorating environmental integrity, such as stand-replacing fires or large-scale insect outbreaks.

Questions affecting roadless areas include:

- Are significant and important social values associated with the existence and protection of wilderness and roadless areas?
- Does a road network in itself pose a risk to the integrity (as defined in the interior Columbia River basin study) of roadless forested ecosystems?
- Do roadless areas make substantial contributions to maintaining biodiversity and desirable habitat characteristics?
- Can roadless areas stay intact without management efforts that are facilitated by roads (for example, fire prevention, disease and pest control)?
- Does creating new roads in roadless areas have overriding benefits that outweigh the potential ecological costs?

Existing and perhaps new science information may be needed to assess some or all of the questions posed. In addition, methods from the social sciences are available to conduct surveys and assessments of public perceptions, values, and beliefs to determine the values that roadless areas hold in the mind of the public. This summary of existing information is an attempt to identify the ecological and biophysical characteristics of large nonroaded blocks of the forest and rangeland ecosystems that would permit conclusions about the value of maintaining such landscape features, and to examine the scientific aspects of a possible rationale for road building in currently roadless areas.

Ecological and biophysical aspects of roadless areas—An approach for providing the scientific basis of ecological and biophysical value is to summarize the known information on roadless areas at the landscape or large basin scale and proceed to smaller spatial scales. Questions that may be asked at the larger scale include the following:

- Is retention of existing roadless areas an important as part of a conservation strategy?
- Does the distribution of roadless systems affect the success of conservation strategies?
- Does the size of individual roadless areas affect the success of conservation strategies?

One of the few examples of landscape-scale analysis of road influences is the interior Columbia River basin environmental assessment. Analysis of fish distribution and status data for seven species of anadromous and resident salmonids in the Columbia basin showed that frequency of strong populations generally declined with increasing road densities. Additional analyses of road effects focused on four non-anadromous species, because effects of roads and other land uses on anadromous species may be masked by migrational and ocean-related factors (for example, dam passage, predation, and harvest). Three species showed significant effects from roads, either when occupied spawning and rearing areas were distinguished from unoccupied areas or when strong status was differentiated from depressed. The analysis suggested a decreasing likelihood of occupancy—or a decreasing likelihood of strong status if occupied—with increasing road density. No other variables except ground slope showed the consistent patterns across all species shown by the road density measures.

The investigation of the influence of roads on population status clearly showed an increasing absence and a decreasing proportion of strong populations with increasing road density for several subgroups. Additional evidence suggests that the lowest mean road density values (number of road miles per unit of area) always are associated with strong population status.

Based on the synthesis reported in the main body of this document, this trend is apparent for Yellowstone cutthroat trout, even though it was the only subgroup not showing a significant road effect in a logistic regression analysis. The lack of statistical significance in the face of apparent trends, however, points to complex interactions among the explanatory variables not adequately addressed in the relatively simple logistic model. Consistent, significant effects for other species may be further testament to the presence and pervasiveness of the effects. Strong relations between roads and the distribution and status of these species were detected despite the potential confounding effects of other variables (such as harvest, non-native introductions, and other habitat factors).

These results show that increasing road densities and their attendant effects are associated with declines in the status of four non-anadromous salmonid species. These species are less likely to use highly roaded areas for spawning and rearing and, if found, are less likely to have strong populations. This consistent pattern is based on empirical analysis of 3,327 combinations of known species' status and subwatershed conditions, which were limited primarily to forested lands administered by the Forest Service and the Bureau of Land Management. We would not expect the relation to be as strong on the nonforested, lower gradient lands administered by BLM. Of the four species examined, the redband trout is the only one supported by the low-gradient lands. Only in forested, high-elevation areas could redband trout status be clearly associated with road density changes.

Most aquatic conservation strategies acknowledge the need to identify the best habitats and most robust populations to use as focal points; from these, populations can expand where adjacent habitat can be usefully rehabilitated or the last refugia of a species can be conserved. These strategies also provide necessary experimental controls for evaluating the effects of land management activities in other areas. The ecological importance of unroaded areas has been highlighted in the Columbia basin assessment and in other reports cited in the main body of this paper.

The overlap of unroaded areas within and outside designated wilderness areas with stronghold watersheds for fish and other important conservation watershed efforts in the Columbia basin also was examined. Designated wilderness and unroaded areas are important anchors for strongholds throughout the basin. Unroaded areas occupy

41 percent of area with known and predicted strongholds in the east-side EIS area. One-third of this area is outside wilderness. Sixty-eight percent of known and predicted strongholds in the upper Columbia basin EIS area are unroaded, of which 37 percent are outside of wilderness.

Aquatic integrity in the Columbia basin was analyzed in relation to road densities and integrity ratings for other resources (forest, range, hydrology). Forest clusters with the highest integrity ratings for aquatic organisms were associated with low road densities; low integrity ratings corresponded with moderate or higher road densities. The range cluster having the highest aquatic and composite integrity also had mostly low road densities. The relations between road densities and integrity ratings for other range clusters were more variable, however (FEMAT 1993, Henjum and others 1994, Lee and others 1997). The correlation of basin or subbasin integrity is not total, suggesting the variables and interesting mechanisms are complex and nonuniform. Such data suggest that criteria be developed to examine the role of roadless areas in conservation strategies and permit assessing the risks taken when roadless blocks that are significant features at the landscape level are further intersected by roads.

- Does the distribution of roadless areas contribute to the ecological integrity of forested ecosystems?
- Does a conservation strategy that includes roadless areas need to be spatially explicit?

The distribution and the desirability of having well-distributed roadless area systems pose interesting scientific challenges. Historical trends significantly influenced the extent and distribution of roadless areas. Logging progressed from easily accessible, low-elevation forests to more difficult, high-elevation terrain; thus the remaining road-less areas tended to be at high elevations. We are unaware of a systematic analysis of this issue. Criteria that include assessing how well some roadless areas represent certain native ecosystems should be considered. This is especially the case at lower elevation sites that historically have seen the greatest harvesting effort and attendant road building. If the goal is to have a system of reserves consisting of representative, relatively undisturbed habitats, then roadless areas and the habitat types within them should be distributed over major ecoregions and be derived logically.

- Do corridors connect the high-quality roadless areas?

Biodiversity is, in simplest terms, the variety of life and its processes (Keystone Center 1991). Recent syntheses (Heywood and Watson 1995) emphasize the reciprocal relation between biodiversity—conceived as genetic and species diversity—and ecosystem function. The many species representing the biodiversity of an area play roles necessary for ecosystem function and, importantly, are the source of the variation enabling an ecosystem to adapt to change. The processes of a healthy, functioning ecosystem in turn support the many species. Appreciating the reciprocity means that biodiversity can be taken as a natural measure of the ecosystem as a whole and thus can integrate the many concerns listed.

Some species may play more important roles than others in the normal functioning of an ecosystem. Keystone species, for example, may define the major structural elements of an ecosystem as Douglas-fir does for forests in the Pacific Northwest, or they may—by virtue of their position in a complex trophic structure—act to maintain the diversity as keystone predators do for herbivores. The many species that do not seem to serve an important role in an ecosystem constitute a reservoir of potential adaptation to change.

Because an ecosystem cannot predict change, the very diversity of species acts as a hedge against it. Thus, biodiversity is important to long-term ecosystem function, and human activities that decrease biodiversity can impair it. Our working hypothesis is, then, that measures of biodiversity provide the best integrative assessment of the effects of roads on ecosystems.

Forest roads create corridors that not only permit invasion of alien, weedy species, but also permit entry of predators, including humans, to the forest environment and affect wildlife populations. Limited studies have shown that roads allow exotic species into areas where they historically have been absent or where appropriate habitat was not available (Parendes, 1997). Clearly, these secondary effects are promoted by the existence of roads but are not due to the roads themselves; however, the increase in human access to remote areas allowed by roads has a far more significant effect on native populations. High road densities are associated with a variety of negative human effects on some wildlife species. Black bear populations are inversely related to road density in the Adirondacks (Wisdom and others 2000). Increases in hunting pressure, particularly illegal hunting, have the potential to impact populations. Moose and caribou are particularly vulnerable to this kind of predation (Scott and Servheen 1985). Such connectivity will be important for endangered species where the gene pool is already limited, such as in the case of the Florida panther (*Puma concolor corgi*), and where gene exchange between populations in adjacent habitat may help species viability (Shrader-Frechette 1995). Connectivity also is important for species having large home ranges, and road avoidance or risk from road related mortality constitutes an additional threat to the populations, or may lead to undesirable, even dangerous animal-human interaction, as may be occurring with mountain lion (*Felis concolor*) populations in southern California.

Whenever forest roads are built, modified habitat and changes in animal behavior will lead to changes in risk to viability and distribution and even local extirpation in wildlife populations. Road avoidance behavior is characteristic of large mammals such as elk, bighorn sheep, grizzly bear, caribou, and wolf. Avoidance distances of 100 to 200 yards are common for these species. Road usage by vehicles and humans has a significant role in determining road avoidance behavior. In a telemetry study of black bear movements, interstate highways were almost never crossed, and roads with low traffic volume were crossed more frequently than roads with higher traffic volumes (Wisdom and others 2000.). It appears that in some cases, male bears may actually be using roads as travel corridors (Young and Beecham 1986, Zager 1980). Wolves in Wisconsin are limited to areas with overall mean road densities of 0.07 miles per square mile. Some studies have shown that the existence of a few large areas of low road density, even in a landscape of high average road density, may be the best indicator of suitable habitat for large vertebrates (Wisdom and others 2000.).

- Are roadless areas important to the conservation of high-quality aquatic and terrestrial habitats?

Again drawing on the Columbia River basin assessment, fish with strong populations occurred more frequently in areas with lower road densities. Supplemental analysis further showed that increasing road densities and their attendant effects were associated with declines in the status of four non-anadromous salmonid species. Fish seem to be less likely to use highly roaded areas for spawning and rearing and, where found, are less likely to have strong populations. Patterns based on empirical analysis of 3,327 combinations of known species status and subwatershed conditions are consistent and unmistakable, though limited primarily to forested lands administered by the Bureau of

Land Management and Forest Service. Although unroaded areas are significantly more likely to support strong populations, strong populations are not excluded from roaded watersheds. Possible reasons for this coexistence are that, in general, increased short- or long-term watershed and ecological risks are associated more with entering an unroaded area than with proceeding continuously with management activities in roaded areas to upgrade, maintain drainage, or close or obliterate existing roads (Lee and others 1997). The empirical evidence is correlational and, when the causes for the above observations are fully established, a more complex picture is likely to emerge.

At a more local scale, hydrologic and geomorphic interactions are a potential consequence of road building and presence that can involve altered flow regimes, increased sedimentation, local failures with local and "downstream" consequences for streams, riparian areas, and vegetation cover. For example, the FEMAT (1993) analysis stats, "Management activities in roadless areas will increase the risk of aquatic and riparian habitat damage and potentially impair the capacity of Key Watersheds to function as intended...[while]...most timber-suitable roadless acreage can be harvested either directly from existing roads or from helicopters." Further, "if all timber-suitable roadless remains unroaded in Option 9, then the estimated reduction for the total regional probably sale quantity is less than 0.2 percent." In terms of aquatic effects, the Columbia basin assessment summaries include the following statements: "Roads provide access, and the activities which accompany access magnify the negative effects on aquatic systems beyond those solely due to roads." Among other findings, the assessment "...subwatersheds supporting strong populations were found on Forest Service administered lands (75 percent) and a substantial number (29 percent) are located within designated Wilderness areas and National Parks." Thus, the data "...clearly show increasing absence and decreasing proportion of strong [fish] populations with increasing density for some subgroups" (FEMAT 1993). Other studies found that the length of road segments connected to the stream network at stream crossings or gully-debris slide tracks amounted to a 40-percent extension of the stream network length in a Cascade Range watershed (Jones and others, in prep; Wemple 1999).

High-quality terrestrial habitats may be affected by the potential for invasion of exotic plants and animals that can displace or threaten native populations; that is, affect biodiversity, which can be increased by roads. Migrating populations of rare amphibians may be killed during road use; disease and pathogens are spread more rapidly and widely if roads are present (Kiester and Slatkin 1974). The preponderance of the negative findings in many scientific studies also suggests that the potential for ameliorating or minimizing the unwanted effects exists, even if it has not been made a prime objective historically. Lastly, some positive ecological results may follow (though they are proportionately less significant) that roads create edge environments exploited by small mammals, can sustain some desirable species, and provide useful niches. Maintaining an optimum balance is a function of the long-term magnitude of road networks; for the present system, the need for additional niches and habitats is difficult to demonstrate.

A full scientific view of the data on roadless areas cannot stop at the local scale, but must ultimately view the presence of roaded and roadless areas in a landscape context and be able to draw the distinction between a large road network and small roadless areas or large roadless areas and a small road network. Again drawing on the Columbia basin assessment, we note that "while unroaded areas are significantly more likely to support strong populations, strong populations are not excluded from roaded watersheds.... the scale of the subwatershed (8000 ha on average) at which strong populations are identified may mask potential disconnects between the real locations of strongholds and roads. The significance of the impacts and benefits will be affected and must withstand rigorous scientific approaches over a spectrum of possibilities and of scales" (Lee and others 1997).

Social, aesthetic, and economic values of roadless areas—The interaction between roadless areas and people's aesthetic and spiritual beliefs about the landscape probably affects people's perceptions in many different ways. We know that passive or "nonuse" values include "existence" and "bequest" value. Existence value pertains to things, places, or conditions people value simply because they exist, without any intent or expectation of use. Bequest value pertains to a desire people may have to allow others, such as future generations, to receive benefit from a resource (Peterson and Sorg 1987, Randall and others 1979). The issues are as follows:

- People assign significant passive-use value to national forest landscapes or attributes.
- Forest Service road policies or management actions affect passive-use values.

People do assign passive-use (nonuse) value to natural resources, and passive-use value may exceed the active-use value served by road access to the resource. Invasion of roads will reduce some aspects of passive-use value in natural areas. Likewise, obliteration of roads may increase such value. Building roads into roadless areas may, however, serve values that require access, and obliterating roads may obstruct values and uses that require access, so tradeoffs need to be considered. Though not universally shared, a strong value is doubtless attached to the continued existence of wilderness and roadless areas, including those in national forests.

The relation between roadless areas and recreation on national forests is highly complex. Research findings are limited and uneven on the issues of direct, indirect, and secondary effects on recreation of altering the national forest road system. Indirect evidence and related research provide the following insights:

- Roads provide corridors of access to various national forest sites, settings, and visual and aesthetic experiences; in fact, almost all recreation in national forests depends to some degree on road access.
- Roads provide access to remote areas and wilderness but at the same time can reduce opportunities for solitude elsewhere.
- The amount of roading and the amount of recreation use are positively correlated, sometimes leading to heavy concentrations of use, and roads may be the only means of enjoyment for persons with some forms of disability.
- Demand for forest recreational opportunities continues to grow regionally and nationally.
- Placement, scale, class, and setting of roads can greatly affect the quality of scenic views of national forests and access to outstanding vistas.

The three most highly ranked uses of lands administered by the Forest Service and Bureau of Land Management in the basin today are timber, fishing, and hunting. Projected uses by 2045 will be motor viewing and day and trail use; this for an area where 70 percent of the unroaded areas of >200,000 acres occurs in the lower 48 states (Cordell and Bergstrom 1991, Tarrant and others 1999).

- Does a roadless area preclude needed access for public services and resources as well as conservation management?

Roadless areas not already congressionally withdrawn (for example, as a designated wilderness area) total about 34 million acres in national forests. Of these, 9 million acres have been identified as suitable for timber production. Management practices and natural resource use may suggest strong reasons for entry into the 9 million acres (Coghlan and Sowa 1997). Timber harvesting using roadless approaches in these areas would lead to greater reliance on helicopter logging systems, which increase logging costs. The FEMAT study (1993) suggests that in key watersheds, the reduction in timber volume would be about 0.3 percent, and reduction by prohibiting entry into existing roadless areas not congressionally withdrawn in all areas considered by FEMAT (that is, the range of the northern spotted owl) would be 6 percent.

For the interactions of grazing rights, grazing access, and roads, essentially no scientific information exists analyzing the ecological, administrative, or economic effects of roads on administering the Forest Service range management program, and the synthesis in the main report did not uncover data specific to the relation of roadless areas and grazing practices (Peterson and Sorg 1987).

That improved road access leads to increased efficiency and effectiveness of fire suppression activities is a long-held tenet of fire fighting. Much of the effectiveness of past fire suppression policies probably can be attributed to increased access for ground crews and equipment, particularly under weather and fuel situations where fire behavior is not severe. Under the severe conditions associated with intense, rapidly spreading fires, the value of forest roads for access or as fuel breaks is likely to be minimal. However, quantification of these effects in published research in the United States is minimal. But it should be noted that indirect effects of increased access have increased the role of human-caused ignitions, and this is particularly true in areas of expansion of urban and rural development into wildland interfaces.

Roadless areas: conclusions—The scientific literature provides a framework of general principles regarding the nonuse values of present roadless areas and may even be extended to apply to areas where road decommissioning may recreate roadless areas. Such values include areas (1) having significant amounts of interior habitat for many forest species now being observed under the “survey and manage” concept of the Northwest Forest Plan, (2) maintaining connectivity of habitat for species having large home-ranges, (3) valuing the existence of forest “reserves” that permit the continued functioning of representative habitat types in a state of least human disturbance, and (4) becoming aware that forest-stream interactions seem to confer somewhat stronger fish viability in areas of low to no road densities. At present, no science-based analytical models, formulas, tables, or handbooks are available that the manager can use to apply the general principles to specific decisions, though pilot efforts are now underway by the USDA Forest Service to develop such tools. Such tools will provide methods that permit judgments about offsetting benefits and impacts from road building and usage, which suggests that we will have the means at hand to decide on an agreed on mix of roaded vs. roadless areas in national forests.

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