End of the Road

The Adverse Ecological Impacts of Roads and Logging: A Compilation of Independently Reviewed Research From www.nrdc.org

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INTRODUCTION

Roads, and the logging often associated with them, have a wide range of profound impacts on forest ecosystems. These include direct and indirect effects on individual plant and animal species, as well as broad changes in ecosystem structure and function. Though much remains to be investigated about the full nature and scope of these impacts, a large body of existing scientific literature evaluates their severity, extent, and timescale.

This annotated bibliography provides an overview of primary research, almost all from peer-reviewed journals, documenting the adverse impacts of roads and logging on North American forest ecosystems. The research included focuses on effects that extend beyond the immediate road and its edges. Such impacts compromise the diversity and health of entire landscapes and their species as well as that of the road environs themselves. Literature clarifying the ecological significance of impacts is also reviewed.

Six categories of impact are addressed here, each in its own chapter. These include effects on sensitive wildlife species from displacement, dispersal barriers, road kill, and reduced reproductive success. Also covered is the spread of tree diseases by road construction, tree stumps, and logging wounds. Overlapping with disease problems is the increase in pest infestations at forest edges, in logging debris, and in diseased trees. Fourth, the dispersal of non-native plant and animal species along roads and disturbed habitat is reviewed. A fifth category is damage to soils by logging and road-building equipment. Sixth, the bibliography reviews literature about road- and logging-related degradation of stream ecosystems. A seventh and final chapter summarizes relevant literature reviews, each of which itself discusses numerous studies; it also covers a few studies that attempt to quantify how much of the forest landscape is affected by certain road impacts.

Within these seven chapters, each annotation begins with one or more "Key Findings," identifying the central significance of a published work (these Key Findings are also listed in the Summary following this Introduction). A synopsis of the article follows, providing a brief account of the study's methodology, geographical location, and pertinent results.

The body of work investigating how forest management affects wildlife is particularly extensive. Chapter One in this report (Harm to Wildlife) focuses on a subset of this research – that showing the direct impacts of management on sensitive wildlife. It includes studies documenting changes in behavior, reduced reproduction rates, increased mortality, and changes in community composition and diversity. Generally, however, this report does not attempt to review the voluminous literature about habitat associations for individual species. From much of this latter work, good inferences can be drawn concerning the adverse wildlife impacts of road building and, even more, of logging.

Also not included are studies that show the significant threat roads pose by providing poachers access into pristine areas. Many large mammals, such as grizzly bears, black bears, and elk, suffer from increased hunting pressure near roads and may not be able to maintain their populations near roadsides.

Finally, the impact of roads or logging on forest fire hazard is an important issue that has not been addressed in this bibliography. Increased ignition frequency along roads has been well established. In addition, some published studies indicate that logging can increase fire hazard, perhaps because of slash left behind, drier forest conditions under open canopies, damage to residual trees, compromised soil resources, or disrupted ground water regimes. This is a complex topic that deserves separate consideration in its own right.

SUMMARY OF KEY FINDINGS

1. Harm to Wildlife

Roads displace species sensitive to disturbance or dependent on forest interior habitat. For example, species like grizzly bears, wolves, and elk avoid otherwise suitable habitat near roads. They may modify their home range, and they have been shown to select areas with lower road densities than the average on the landscape. As a result, high-quality habitat becomes effectively unavailable to them.

Roads also create barriers to the movement of many species. In particular, small animals such as salamanders, frogs, and mice will rarely cross roads or are killed by vehicles when crossing. As barriers to dispersal, roads isolate populations on one side of the road from those on the other. Biologists fear a likely consequence of this isolation and the resultant loss of gene flow between populations is, over the long-term, increased vulnerability of some species to inbreeding or environmental catastrophes. Larger species such as moose, white-tailed deer, and mule deer also have high rates of mortality due to roadkill. The impact of high roadkill rates on species' total population number is not thoroughly understood, but roads may act as ecological "sinks" (areas of net loss) for some species, endangering their continuing viability.

Species that live in the forest interior are also adversely affected by logging, which fragments habitat by destroying old-growth and mature forest and by creating poor quality habitat "edges" in otherwise continuous forest. Species that prefer old-growth and closed canopy forest, such as martens, California red-backed voles, northern flying squirrels, and red-backed salmanders, to mention a few, have declined in abundance in logged forests relative to unlogged forests. These species' decline in turn has impacts on other parts of the ecosystem. For instance, a reduction in salamander populations (which are an integral part of the forest food chain) affects bird and mammal species that rely on them as food, as well as forest floor ecology and nutrient cycles.

Research has also shown that forest interior birds are sensitive to disturbance, whether in the form of roads, logging, or the increased access they provide to nest predators or parasitic cowbirds. Breeding success has declined in many of these affected areas. For example, bald eagle nesting success is lower near clearcuts. In eastern forests, cowbirds have invaded the edges (and in some cases, the interior) of many forest fragments. This species parasitizes the nests of other bird species, destroying their eggs or young and laying its own eggs in the nest instead. Research has shown that this behavior may be partly responsible for the population declines of many neotropical migrant bird species.

Displacement of wildlife

- Grizzly bear use of suitable habitat in Montana declined as road density and road traffic increased.
- Grizzly bears used habitat near roads less than expected in the Northern Rockies, resulting in less habitat available in roaded areas.
- Black bears crossed roads with higher traffic volumes less frequently than roads with lower traffic volumes.
- Habitat occupied by wolves in Minnesota had a lower road density than unoccupied habitat.
- Wolves showed a preference for areas with low road density rather than high road density when establishing packs in the northern Great Lakes region.
- Wolves in Alaska avoided roads that were open to regular public use.
- Roadless areas are important reservoirs for maintaining wolf populations in adjacent, high-road-density areas.

- Mountain lions avoided improved dirt roads and hard-surfaced roads and selected home range areas with lower densities of these road types.

- Female Roosevelt elk reduced their daily movements, core area size, and home range size, and therefore, their energy needs, when disturbance due to vehicular access on roads was limited by gate closures.

- Mule deer and elk avoided roads and areas within 200 m of roads.

- Columbian black-tailed deer were displaced from their usual home ranges by increased vehicular traffic during the hunting season.

- Eastern massasauga rattlesnakes avoided roads in all seasons.

- Prairie voles and cotton rats tended to move away from a narrow dirt road rather than toward it.

Barriers to dispersal

- Roads were a barrier to movement by the eastern chipmunk and the white-footed mouse.

- Highways were a barrier to movement for seven of 10 rodent species studied.

- A narrow dirt road was a significant barrier to movement by prairie voles and cotton rats.

- A highway in southern Nevada acted as a barrier to crossing for all eight rodent species studied.

- Roads impeded movement by amphibians and could result in population isolation. Despite some speculation, road ruts and ditches have not been shown to provide successful amphibian breeding habitat rather than acting as ecological traps. Amphibians play a key role in the forest ecosystem, affecting nutrient cycling and also serving as high quality prey for many species.

- Roads impeded dispersal of all six amphibian species studied.

- Road mortality of 7 amphibian species, 10 reptile species, 21 mammal species, and 62 bird species was documented during four years of study, exceeding 32,000 individuals on a 3.6 km stretch of highway.

- Frog and toad density near paved roads decreased with increasing traffic intensity.

- Frog and toad mortality on roads increased with increasing traffic intensity.

- Road mortality of 20 species of snakes was recorded along a 44-km stretch of highway passing through Organ Pipe Cactus National Monument, Arizona.

- Mortality due to roadkill was documented for northern saw-whet owls and eastern screech-owls over a 10-year period in New Jersey.

- Road mortality along a highway in Ohio was surveyed for one year and included 11 species of mammals, 12 species of birds, 11 species of amphibians, and at least 249 species of insects.

- Collision with a vehicle was the highest cause of death for female moose studied in Alaska.

- Mortality of white-tailed deer due to roadkill was documented for 18 months along an interstate highway.

- Road mortality rates of white-tailed deer were documented after the construction of an interstate highway through their wintering area.

- Mortality of mule deer due to roadkill was documented for two years along a highway and two state roads.

Loss of habitat

- Marten capture rates declined as forest fragmentation increased, and the animals were rarely detected in sites with more than 25% non-forested area in a total 9 km2 area.

- Mountain lions avoided logging areas and established home ranges in areas with lower road densities than the average in the area.

- Northern flying squirrels, the primary prey of northern spotted owls, occurred at lower densities in logged, shelterwood stands than in unmanaged, old-growth forest.

- California red-backed voles were more abundant in old-growth forest and naturally regenerated stands than in young, managed stands. Their higher abundance correlated well with the deeper organic soil layers measured in unmanaged stands.

- California red-backed voles were adversely affected by habitat fragmentation: they were absent in clearcuts, had low densities at the edges of forest remnants, increased in density toward the forest interior, and had higher abundances in large forest fragments compared to small fragments. Truffles, the primary food source of red-backed voles, were absent in clearcuts and near the edges of forest remnants, but occurred in forest interiors.

- Red-backed salamanders, sensitive to forest moisture and temperature levels, were more abundant in old-growth forest and 60-year-old second-growth than in clearcuts or selectively logged forest. Salamanders are a critical part of the forest food chain: they are important food sources for birds and mammals, and as predators themselves, they cycle large amounts of energy through the forest ecosystem.

- The abundance of amphibians was significantly lower in clearcuts, plantations, and forest edges than in mature forest interior sites.

- Lungless salamanders, such as the red-backed salamander, are particularly vulnerable to population declines due to clearcut logging.

- Clearcuts had a significantly lower abundance and fewer species of salamanders compared to mature, 50- to 70-year-old forest stands in the southern Appalachians. Plethodon salamanders are unlikely to survive logging because individuals are closely tied to small home ranges and unlikely to relocate to intact forest from logged areas.

- The relatively abundant land salamander Plethodon jordani, an important part of the food chain, disappeared from forest sites in the southern Blue Ridge Mountains after they were clearcut.

- In the first two years after clearcutting, salamander numbers, including Plethodon jordani, declined to almost zero on all three forest sites studied.

- Adult and juvenile wood frog and spotted salamander capture rates declined along a gradient from closed-canopy forest to recently clearcut habitat.

- Juvenile wood frogs, dispersing from breeding pools at the forest edge, preferred to migrate toward closed-canopy forest habitat and away from open habitat.

Reduced nesting success

- The density of bald eagle nests in southeast Alaska decreased with proximity to clearcuts.
- Productivity of nesting bald eagles decreased with proximity to clearcuts.
- Three of four forest interior bird species declined in abundance after logging, whether clearcutting or lower intensity logging.
- The brown-headed cowbird, a species that parasitizes other birds' nests, increased in abundance after logging.
- As forest fragmentation increased, nests of all nine bird species studied suffered higher rates of parasitism and predation.
- The reproductive success of ovenbirds, a forest interior species, was significantly lower in forest fragments than in continuous forest, partly due to cowbird parasitism of their nests.
- The density of breeding male ovenbirds was lower in forest fragments than in continous forest, with birds avoiding habitat within 100 m of the forest edge.
- All three species of tanagers studied were sensitive to forest fragmentation, with a declining probability of breeding tanagers occurring at a given site as fragmentation increased.
- Nesting success of forest birds decreased within 50 m of forest edges.
- In five of six studies, nesting success of forest birds decreased as forest patch size decreased.
- Nest predation rates in southern Appalachian forest fragments increased as fragment size decreased.
- Artificial nests had higher rates of predation on the edges of forest fragments than in the interior of fragments.

2. Spread of Tree Diseases and Bark Beetles

Logging and road construction have increased the incidence of damaging or lethal tree diseases, including annosus root disease, Armillaria, laminated root rot, black-stain root disease, and Indian paint fungus. Tree stumps have a high likelihood of infection, become centers of infection in a stand, and facilitate the spread of a disease to adjacent, living trees. For some diseases, such as black-stain root disease, woody debris left after thinning attracts insects that are vectors for infection. For at least one disease, Port-orford-cedar root rot, road construction and logging equipment have been directly linked to the spread of the disease to new stands. Black-stain root disease has also been found to occur at higher rates along roads and skid trails.

Trees stressed by disease are more susceptible to attack by bark beetles. For example, ponderosa pines infected with black-stain root disease have suffered higher bark beetle attack rates than undiseased trees. Attempts to mitigate some of these problems have not been easy or fully successful. Stump treatments, such as borax, are not one hundred percent effective, while other efforts, such as stump removal, damage essential ecosystem functions through soil compaction.

Increased occurrence of tree diseases

- Multiple studies have shown that annosus root disease, often fatal or damaging for a number of conifer species, has increased in western forests as a result of logging.

- The incidence of annosus root disease in true fir and ponderosa pine stands increased with the number of logging entries.
- The proportion of western hemlock trees infected by annosus root disease increased after thinning, due to infection of stumps and logging equipment wounds.
- The percentage of western hemlock trees infected by annosus root disease greatly increased after thinning, with infected stumps being the primary source of infection.
- Annosus root disease was found on 89% of true fir stumps in stands that had been logged five to 10 years earlier.
- Annosus root disease and Armillaria infected freshly cut stumps of young western hemlock and Sitka spruce in southeastern Alaska.
- Armillaria is a primary, aggressive root pathogen in western interior forests, where it spreads into healthy stands from the stumps and roots of cut trees.
- Armillaria root disease was present in stumps of old-growth ponderosa pine, logged up to 35 years earlier. The oldest stumps of ponderosa pine had the highest rate of infection by Armillaria.
- Mortality of saplings was significantly correlated to the number of Douglas-fir stumps infected with Armillaria and laminated root rot.
- The pathogenic fungus Armillaria had a threefold higher occurrence on disturbed plots compared to pristine plots at high productivity sites in the Northern Rockies.
- Infection and mortality from the root disease Armillaria ostoyae was several times higher in forest stands with logging disturbance than in undisturbed stands.
- Thinning and soil disturbance led to an increased risk of infection and mortality by black-stain root disease in Douglas-fir.
- The majority of black-stain root disease infection centers were close to roads and skid trails.
- Black-stain root disease occurred at a greater frequency in Douglas-fir trees close to roads than in trees located 25 m or more from roads.
- Thinned stands attracted a greater number of black-stain root disease insect vectors.
- Mechanical wounding of grand fir and white fir by logging equipment activated dormant decay fungi, such as the Indian paint fungus.
- Port-orford-cedar root rot, a fatal fungus, is spread by logging equipment, road maintenance equipment, and construction equipment, which transport its spores to new areas.

Attack by bark beetles

- Root disease fungi predispose some conifer species to bark beetle attack and/or help maintain endemic populations of bark beetles.
- More mountain pine beetles and western pine beetles (two species of bark beetle) were captured on ponderosa pine infected with black-stain root disease than on healthy trees.

- Two species of beetle were more frequently attracted to wounds on trees that were also diseased than to uninfected trees.

- Loblolly pines colonized by annosus root disease had a greater probability of being infested with southern pine bark beetle. Trees infected by annosus root disease had significantly less radial growth than trees not infected.

- A significantly higher percentage of plots attacked by the southern pine beetle were infected by blue-stain fungi.

Problems with mitigation

- Borax-treated plots did not have lower rates of annosus root disease infection compared to untreated plots 20 years after thinning.

- Mitigation measures for Armillaria root disease were problematic in several regards.

- Stump removal, a method of Armillaria root disease control, resulted in high levels of soil compaction in ash-cap soils.

- Restricting thinning to summer months, a recommended practice for mitigating the spread of annosus root disease in southern forests, was not a reliable form of disease control.

- Annosus root disease may spread via root systems from stumps to neighboring trees even following treatment of stumps with borax.

3. Promotion of Insect Infestations

Forest edges created by logging or road construction sustain higher populations of tree pest species such as the tent caterpillar, jack pine budworm, and gypsy moth. Possible mechanisms for this include increased larval development due to higher light levels and increased mortality of natural pathogens.

Biologists predict that logging and habitat destruction will increase the severity of a variety of insect outbreaks because the loss of habitat diversity and old-growth forest has meant a decrease in the diversity of natural pest predators. Natural predators of the western spruce budworm for instance include ant and bird species whose habitat needs include large standing and downed logs that are reduced or eliminated by logging.

Insect infestations

- Forest fragmentation due to cleared forest increased the duration of tent caterpillar outbreaks.

- Forest edges were predicted to be source populations for tent caterpillars.

- Mortality of tent caterpillars in the forest understory due to a natural virus (NPV) decreased as forest cover decreased and edge habitat increased.

- Abrupt edges along mature jack pine stands increased the levels of defoliation by jack pine budworm in Michigan.

- Trees at forest edges created by roads had 2.4 times more gypsy moth egg masses than trees in the forest interior.

Loss of ecological complexity

- A diversity of predators is important for preventing pest outbreaks.
- Old-growth and roadless areas, with their greater diversity of composition, structure, and predators, are predicted to be less vulnerable to pest outbreaks than forests simplified through management.
- Species diversity and functional diversity of arthropods were much higher in old-growth stands than regenerating logged stands.
- Old-growth forests, which have a greater diversity of insect predators, are predicted to help control pest populations.
- Ant and bird predation reduced adult western spruce budworm densities by approximately 10- to 15-fold at low budworm densities, and by approximately twofold at high budworm densities.
- Thatching ants play an important role in suppressing insect defoliator populations.
- Ants, important predators of the western spruce budworm, require sufficient down wood in a range of sizes and decomposition stages.

4. Invasion by Harmful Non-native Plant and Animal Species

Roads facilitate the spread of invasive non-native (exotic) plants, animals, and insects. For example, vehicles can transport the seeds of exotic plants to new areas. Reduced canopy cover (with correspondingly higher light levels) and increased soil disturbance along roads have favored numerous exotic plant species, including Oriental bittersweet and spotted knapweed, as well as exotic ant species such as the red imported fire ant and the Argentine ant. Over time, some exotic species spread from roadsides into adjacent, undisturbed areas.

Exotic species disrupt natural ecosystem processes and the species that depend on them. For example, exotic plants have been shown to replace native understory vegetation, inhibit seedling regeneration, and change soil nutrient cycling. Some weedy species can cause higher erosion rates or change fire regimes. The abundance and diversity of native ants has decreased in areas invaded by the red imported fire ant or the Argentine ant. This can change the entire food base for other species. The decline in other species, such as the northern bobwhite, has been directly documented in habitat infested with exotic ants.

Invasion by non-native species

- Non-native plant species occurred on high-use, low-use, and abandoned forest roads, with the greatest frequency on roads with the highest level of disturbance and lowest percentage of canopy cover.
- Exotic annual plants invaded an ecological reserve in California along a pipeline corridor and were still dominant in the corridor 10 years after the disturbance occurred.
- Oriental bittersweet, an exotic vine of the eastern United States, responded vigorously to increased light intensity after disturbances such as road construction, logging, or windthrow.
- Spotted knapweed invaded new areas along roadsides.
- Spotted knapweed preferred open canopies and disturbed areas.
- Spotted knapweed and diffuse knapweed, two exotic species, preferred open, disturbed habitat, including roads, over shaded areas.

- Exotic weeds spread along logging roads in forests at all elevations in western Montana.
- Exotic weeds invaded clearcuts in mid-elevation forests.
- In a regional survey, a greater proportion of anthropogenically disturbed plots in the southeastern and northeastern United States contained at least one exotic species compared to undisturbed plots.
- The red imported fire ant, an exotic pest in the southeastern United States colonized roads, power lines, and forest gaps created by logging.
- The density of red imported fire ant mounds was correlated with the degree of soil disturbance and direct sunlight exposure.

Spread into undisturbed areas

- Exotic annual plant species invaded adjacent undisturbed oak woodland, coastal sage, and grassland communities from a pipeline corridor in an ecological reserve in California.
- Exotic weeds spread outward from roadsides in lowland forest and rangeland in Montana, invading relatively undisturbed areas.
- Originally confined to roadways and abandoned farmland, cheatgrass now invades shrub, ponderosa pine, and pinyon-juniper ecosystems.
- The red imported fire ant, an exotic pest in the southeastern United States, is believed to disperse into forest gaps from adjacent roads and power lines.

Damage to ecosystem processes

- Oriental bittersweet, an exotic vine in the eastern United States, inhibited seedling regeneration and damaged young hardwood stands through stem girdling.
- Tree seedling density decreased with increasing cover of an exotic honeysuckle, Lonicera tatarica.
- The diversity and density of herbaceous species declined as honeysuckle cover increased in three of four northeastern forest stands.
- In shrub-steppe ecosystems, invading weed species, which were usually non-mycorrhizal, disrupted succession by native species, 99% of which were mycorrhizae-dependent.
- An exotic weed, bull thistle, reduced growth rates of ponderosa pine seedlings by up to 33% in a forest plantation.
- Forest litter depth and soil organic layers were lower and pH was higher in sites invaded by two exotic plant species (Japanese barberry and a Japanese grass species), when compared to adjacent uninvaded forest sites.
- Native oaks and shrubs occurred at a lower density in forested sites invaded by Japanese barberry and a Japanese grass species than in uninvaded sites.
- Surface runoff and soil erosion were greater from spotted knapweed-dominated sites than natural bunchgrass-dominated sites.

- Fires have become more common and extensive in pinyon-juniper woodlands and sagebrush ecosystems invaded by cheatgrass, an exotic grass.

- The incidence of fire has increased in ponderosa pine forests and pinyon-juniper woodlands where cheatgrass, an exotic annual, has invaded. This grass has proven difficult to control.

- Invasion in Texas by the red imported fire ant resulted in a 90% decrease in native ant abundance and a 70% decrease in ant species richness.

- Native ants had a lower abundance and diversity in areas invaded by the Argentine ant, an exotic ant.

- The trophic structure of invertebrate communities changed in areas invaded by Argentine ants, with higher numbers of scavengers at the expense of herbivores, predators, and parasites.

- Northern bobwhite populations in Texas decreased after invasion by the non-native red imported fire ant. Densities of northern bobwhites increased after treatment to reduce infestation by the red imported fire ant.

5. Damage to Soil Resources and Tree Growth

Logging and road construction compact soils, disturb or destroy organic layers, and cause high rates of soil erosion. Soil compaction, which can last for several decades, is typically measured by changes in soil bulk density or porosity. Trees' access to nutrients and water is reduced because of restricted root growth in compacted soils, reduced water infiltration rates, and decreased oxygen and water available to root systems. Soil compaction also has a detrimental impact on microorganism communities, which play a critical role in nutrient cycling and tree growth. The loss of organic layers also affects mycorrhizal fungi, which are important to many tree species in accessing nutrients. As a result of this damage to soil resources, trees can suffer from moisture stress, reduced growth rates, inability to establish seedlings, and reduced resilience in the long term.

Compacted soils are also more susceptible to surface erosion. The frequency of mass erosion events, such as debris slides, also increases in landscapes that have been roaded or logged, thus increasing total soil loss. In forests where overland (surface) water flow is unlikely, roads have been documented to intercept water at road cuts, converting subsurface flow to surface flow. This greatly increases runoff-related erosion.

This loss of soil due to erosion not only reduces the productivity of the local site by removing top, nutrient-rich layers of soil, but the sediment that is generated often runs into streams, where it has a range of detrimental impacts on aquatic ecosystems.

Damage to soils

- Logging resulted in soil compaction, displacement of surface mineral soil, loss of organic matter, and loss of nitrogen, an essential nutrient.

- Logging on volcanic ash soils in the Pacific Northwest caused soil compaction, as measured by increased soil bulk density.

- Average soil bulk density was 15% greater on skid trails than on undisturbed soils in a ponderosa pine site 23 years after logging, and 28% greater on a lodgepole site 14 years after logging.

- Compacted volcanic and granitic soils were slow to recover on skid trails in western Idaho, and after 23 years, only the bulk density of the granitic soil's top few centimeters had returned to undisturbed values.

- Stump removal, a method of Armillaria root disease control, resulted in high levels of soil compaction in ash-cap soils.
- Soil bulk density increased, aeration porosity decreased, and water conductivity decreased in the upper layers of soil after logging in the Piedmont region.
- Logging was documented to cause soil compaction in a variety of soil types in the southern United States.
- Logging resulted in soil compaction and disturbance of organic matter in three New England forests.
- Logging activity caused significant soil erosion in the Pacific Northwest.
- Soil compaction leads to surface erosion.
- Clearcutting and post-logging slash burning were associated with high rates of ravel (upslope erosion) on various soil types in the Northwest.
- Roads caused debris slides in areas that would be relatively stable otherwise.
- The likelihood of surface runoff increased on the compacted soils of skid trails.
- Subsurface flow converted to surface flow by road cuts could trigger soil erosion and mass movement.
- Soil erosion rates due to debris slides were many times higher on forests with roads, landings, and logging activity than on undisturbed forests.
- Roads were responsible for 61% of the soil volume displaced by erosion in northwestern California.
- Clearcutting increased the frequency of mass soil movements from hillsides.

Impacts on tree growth and health:

- Soil compaction results in root damage and decreased root growth, which decrease plants' ability to access nutrients and water.
- Soil compaction and organic matter disturbance cause a decline in mycorrhizal fungi.
- Soil compaction results in reduced infiltration rates and increased surface erosion.
- Soil compaction results in a loss in site productivity as measured by tree growth.
- Soil compaction restricted root growth and increased moisture stress in southern U.S. forests.
- Soil compaction after logging resulted in a loss of soil pore space and a 33% reduction in water to plants.
- Soil compaction by logging reduced the movement of water through the soil (saturated hydraulic conductivity), with increases in runoff predicted.
- Soil compaction reduced growth of young ponderosa pine.
- Beneficial soil microorganisms and mycorrhizal fungi occur primarily in soil organic layers. Soil compaction and the disturbance of organic layers of the soil due to logging activities alter soil microbial activity and adversely affect mycorrhizal populations.

- Ectomycorrhizal abundance and diversity on Douglas-fir seedlings were much lower in soils compacted by stump removal than in undisturbed soils.

- A 20% increase in soil bulk density due to soil compaction significantly reduced the numbers of root tips on Douglas-fir and western white pine seedlings.

- Ectomycorrhizal root tip abundance and diversity in Douglas-fir seedlings were decreased by soil compaction and organic layer removal.

- Soil erosion results in the loss of nutrients and water availability, degraded soil structure, and the loss of important soil organisms including mycorrhizal fungi.

- Erosion of the topmost soil layers, which are the most important for nutrients, water, and soil biota, is the most damaging to site productivity.

- Roads in mountainous areas affected site productivity upslope and downslope of the road through changes in the groundwater system and through debris slides.

Role of soil microorganisms and mycorrhizae:

- Healthy ectomycorrhizal populations are important for forest stability and recovery after a disturbance.

- Mycorrhizal fungi increase nutrient uptake in plants.

- A healthy population of soil organisms is critical for nutrient cycling.

- Mycorrhizae increase the uptake of nutrients and water.

6. Impacts on Aquatic Ecosystems

Roads and logging can significantly degrade stream ecoystems by introducing high volumes of sediment into streams, changing natural streamflow patterns, and altering stream channel morphology. The frequency of landslides in steep terrain is higher in roaded areas and in forests that have been clearcut. Much of the resultant eroded soil ends up in streams. Fine sediment from road surfaces runs into streams during storm events. The interception of subsurface flow by road cuts also increases surface flow and therefore surface erosion.

Streamflow patterns can change in watersheds that are roaded and/or have been logged. Roads, ditches, and new gullies form new, large networks of flow paths across the landscape; this changes the rate at which water reaches streams. As a result, peak discharge volumes in some watersheds are higher and after large storms begin earlier than they would in undisturbed watersheds.

These changes in stream habitat affect the health of aquatic organisms. The survival rates of many salmonid species, for instance, decrease as fine sediment levels increase. Deposition of fine sediment on the stream bed degrades spawning areas, reduces pool refuge habitat, decreases winter refuge areas for juveniles, and impedes feeding visibility. For example, survival rates of coho salmon, chum salmon, and steelhead trout fry decrease as stream sediment levels increase. Sensitive amphibian and invertebrate species are also adversely affected by increased sediment loads, decreasing in abundance and/or diversity. Thus, large-sized aquatic invertebrate species may be replaced by smaller-sized species. Changes to aquatic invertebrate communities not only affect the food supply available to other stream organisms such as fish, but also to non-aquatic forest species. As adults, stream invertebrates emerge from streams and occupy riparian forests, where they are an important source of food for birds, bats, and various other mammals.

Changes in stream channel structure lead to decreases in the habitat available to fish and other organisms. In addition, increases in stream peak discharge volumes and/or sediment loads can affect egg survival rates of salmon adapted to natural stream flows or streambed scour rates.

Increases in sediment and altered streamflows

- Roads degraded stream habitat for aquatic species, including salmonids, by accelerating erosional processes and modifying natural drainage networks.
- Logging activities degraded stream habitat by changing the amount, quality, and timing of flowing water, increasing erosion rates, and reducing stream habitat diversity.
- Soil erosion rates due to debris slides were many times higher on forests with roads, landings, and logging activity than on undisturbed forests.
- Roads were responsible for 61% of the soil volume displaced by erosion in northwestern California.
- Clearcutting increased the frequency of mass soil movements from hillsides.
- During storm events in southwestern Washington, average sediment levels in runoff from forest roads ranged from 500 mg/l to 20,000 mg/l.
- Roads were direct sources of sediment delivery to streams, with approximately 34% of road drainage points entering stream channels.
- Very fine sediment washed from a forest road surface directly into a stream during rainfall events.
- Forest road erosion was a source of fine sediment in stormflow runoff, even after mitigation measures.
- Gravel forest roads generated up to 440 ton of sediment/km/year from surface erosion.
- The volume of fine sediment present in streams increased in direct proportion to logging in the watershed and stream crossings by roads.
- Logging and forest road construction led to an increase in landslides and surface erosion, disrupting the riparian vegetation along first- and second-order tributaries of a river in Oregon.
- Roads intercepted subsurface flow on mountainous slopes in the Idaho Batholith, converting it to surface flow. Subsurface flow converted to surface flow by intercepting roads would be likely to trigger soil erosion and soil mass movement.
- The peak rate of subsurface flow increased by an average of 27% after clearcutting, and due to its interception by a road cut and conversion to surface flow, was believed likely to lead to increased levels of erosion from the road and the slopes below the road.
- Roads and clearcut logging increased peak stream discharges and advanced the timing of peak discharges in multiple paired watershed studies, most likely because of subsurface flow being converted to surface flow at road cuts.
- Even after many years, roads and clearcut logging, both together and separately, resulted in significant increases in stream peak discharges.
- Roads formed new surface flow paths to natural channels and incised new gullies, so increasing the routing efficiency of water; thereby probably explaining some higher stream peak flows.

- Almost 30 years after clearcut logging occurred, average and peak stream flows in the watershed studied were still higher than pre-logging flows.

- Natural streamflow rates during periods of high flow were significantly altered in two watersheds after logging road construction.

- Subsurface flow intercepted by logging roads was converted to surface flow and was the most likely cause for increases in streamflows during snowmelt runoff and heavy summer storms.

- Stream peak flows increased significantly in a watershed with 12% of its area in roads, before any logging occurred.

- Stream peak flows increased as the percentage of watershed area clearcut increased.

- Forest roads extended the natural channel network, initiated new channels, and increased the susceptibility of steep slopes to landsliding.

- Road cuts intercepted subsurface flow and diverted it to roadside ditches.

Adverse impacts on aquatic species

- Salmonid survival rates decreased after logging and road construction as fine sediment levels in streams increased and as important habitat characteristics, including the number of pools and winter cover, decreased.

- Coho and chum salmon fry survival declined after logging and associated increases in fine sediment deposited in spawning areas.

- Survival rates of coho salmon and steelhead trout fry decreased as the proportion of fine sediment in spawning gravel increased.

- Brook trout populations declined significantly after stream sedimentation levels increased.

- Populations of stream benthic invertebrates (the major food source of brook trout) declined significantly after stream sediment levels increased.

- Higher fine sediment levels in a stream resulted in a loss of pool habitat, fish cover, changes in stream velocity, and higher summer water temperatures.

- Salmonids avoided water with suspended sediment in Alaskan streams and lakes.

- Delivery of fine sediments to streams and deposition on spawning and rearing substrate decreased after a moratorium on logging, but increased again after logging resumed.

- Fine sediment deposition on cobble substrates decreased the availability of interstitial spaces (used as winter refuges), and winter densities of juvenile chinook salmon decreased correspondingly.

- Chum salmon eggs were susceptible to mortality from increased streambed scour associated with logging and/or roads.

- Salmonid embryo survival rates decreased as the proportion of fine particles in stream spawning substrate increased and dissolved oxygen levels decreased.

- Adult and juvenile salmonids exposed to suspended fine sediment in streams had an increasingly negative response as concentrations and duration of exposure increased.

- Juvenile coho salmon avoided water with high turbidity levels.

- Basins with more than 25% of their area logged had lower stream habitat diversity, as measured by the number of pools and pieces of wood, than basins with less than 25% of their area logged.

- The diversity of juvenile anadromous salmonid populations was lower in basins with more than 25% of the area logged than in basins with less than 25% logged.

- The density of all three stream amphibian species studied was lower in streams affected by sediment due to road construction than in control streams. Two of three species had significantly lower numbers in all five stream microhabitats.

- A higher proportion of fine sediment occurred in streams flowing through forest stands with logging than streams flowing through unlogged forest stands.

- Abundance, density, and biomass of all aquatic amphibian species studied were lower in streams flowing through logged forest than unlogged forest streams.

- Stream insects preferred fully exposed cobble on the streambed to cobble partly or fully embedded in fine sediment.

- Adult aquatic insects were an important part of the insect community in forests adjacent to streams, and were believed to be an important part of the food web for forest animals such as birds and bats.

- The remaining intact watersheds in southeast Alaska are key to maintaining sustainable salmon stocks.

- Trout standing stocks decreased as the density of road culverts (a measure of the extent to which roads crossed watercourses) increased.

- During the summer, adult chinook salmon preferred pool habitat and cool stream reaches over other kinds of stream habitat.

7. General review papers on the ecological effects of roads

A few papers have reviewed and summarized research from both within and outside North America on the effects of roads on aquatic and terrestrial ecosystems. These papers cover not only the six issues highlighted in this bibliography, but also additional concerns such as higher poaching pressure along roads, stream pollution from runoff of heavy metals and deicing salts, impaired plant photosynthesis due to roadside dust, and impacts on wetlands over the long-term.

Some researchers have also attempted to quantify the total area of landscape affected either directly or indirectly by roads. They estimate that overall, up to 15-20% of the United States' land area is affected by roads.

Ecological effects of roads

- Roads were associated with a diversity of negative effects on the biotic integrity of both terrestrial and aquatic ecosystems.

- Based on numerous studies on the ecological impact of roads, 15-20% of the United States land area was estimated to be affected by roads.

- The zone of ecological effects surrounding roads averaged more than 600 m wide, and for some factors extended more than 1 km from the road surface.

- Roads are a major cause of forest fragmentation because they divide large landscape patches into smaller patches and convert forest interior habitat into edge habitat.

- Clearcuts and roads affected 2.5 to 3.5 times more of the landscape than the surface area occupied by the actual clearcuts and roads themselves.

- Road networks affected stream systems, increasing the frequency and/or magnitude of peak flows, debris flows, and landslides.

- Richness of plant, bird, amphibian, and reptile communities in wetlands decreased as road density within the adjacent 2 km increased, with the full impact on biodiversity not evident for several decades.

Chapter 1

HARM TO WILDLIFE

Displacement of wildlife: Sensitive wildlife species are displaced by roads. They move or modify their home range as road density increases and avoid roads during daily movement activities.

Key Finding: **Grizzly bear use of suitable habitat in Montana declined as road density and road traffic increased.**

Source: Mace, R. D., J. S. Waller, T. L. Manley, L. J. Lyon and H. Zuuring. 1996. Relationships among grizzly bears, roads and habitat in the Swan Mountains, Montana. Journal of Applied Ecology 33: 1395-1404.

The authors investigated the relationship between grizzly bears (Ursos arctos horribilis), their habitat, and road density in the Swan Mountains, Montana. Radio-telemetry data from 1990 to 1994 were used to analyze home ranges. Female grizzly bears' ranges had lower road densities than non-range areas. The bears also avoided areas within a 0.5 km buffer surrounding roads that had more than 10 vehicles per day.

Eight of the grizzly bears marked in the study were killed by humans between 1988 and 1994. Improved road access resulted in illegal killings as well as management removal of bears conditioned to human foods. Combined with natural mortality, these death rates were considered too high to allow local population growth.

Key Finding: **Grizzly bears used habitat near roads less than expected in the Northern Rockies, resulting in less habitat available in roaded areas.**

Source: McLellan, B. N. and D. M. Shackleton. 1988. Grizzly bears and resource-extraction industries: Effects of roads on behaviour, habitat use and demography. Journal of Applied Ecology 25: 451-460.

The authors studied 27 grizzly bears (Ursus arctos) over seven years, using radio-telemetry in the Rocky Mountains at the British Columbia/Montana border. Road use or avoidance was analyzed. Bears used habitats within 100 m of roads less than expected in spring and habitats within 250 m of roads less than expected in summer through autumn. Avoidance of roads was independent of the volume of traffic on the roads.

An analysis of habitat characteristics supported the authors' conclusion that bears were displaced by the roads themselves rather than by unfavorable habitat types along roads. The authors note that many of the habitats close to roads had important bear foods, and avoidance of these areas resulted in a habitat loss of 8.7%.

Key Finding: **Black bears crossed roads with higher traffic volumes less frequently than roads with lower traffic volumes.**

Source: Brody, A. J. and M. R. Pelton. 1989. Effects of roads on black bear movements in western North Carolina. Wildlife Society Bulletin 17: 5-10.

The frequency of road crossing by bears was investigated using telemetry data from 17 black bears (Ursus americanus) in Pisgah National Forest, North Carolina. The bears rarely crossed the interstate highway within the study area. Crossing of abandoned, restricted, and unrestricted roads was also analyzed, with

highest crossing rates found on abandoned roads. Roads of low traffic volume were crossed more frequently than roads with higher traffic volume.

Key Finding: **Habitat occupied by wolves in Minnesota had a lower road density than unoccupied habitat.**

Source: Mech, L. D., S. H. Fritts, G. L. Radde and W. J. Paul. 1988. Wolf distribution and road density in Minnesota. Wildlife Society Bulletin 16: 85-87.

Road density and wolf distribution were studied in northeastern Minnesota to evaluate threshold road densities for the occurrence of wolves. Wolf distribution data were obtained from authors who had a long-term knowledge of the area, from Department of Natural Resources personnel, and from surveys of 112 canid trappers.

Road density was found to be inversely correlated with current wolf populations. Road densities within the entire wolf range in Minnesota, as well as within the primary wolf range, peripheral areas, and disjunct areas, all fell below the threshold road density of 0.58 km/km2 previously determined by Thiel (1985) and Jensen et al. (1986).

Key Finding: **Wolves showed a preference for areas with low road density rather than high road density when establishing packs in the northern Great Lakes region.**

Source: Mladenoff, D. J., T. A. Sickley, R. G. Haight and A. P. Wydeven. 1995. A regional landscape analysis and prediction of favorable gray wolf habitat in the northern Great Lakes region. Conservation Biology 9: 279-294.

The authors analyzed recolonization by the eastern timber wolf (Canis lupus lycaon) into northern Wisconsin and upper Michigan from Minnesota. They used data from radiocollared wolves and GIS information to evaluate characteristics within new wolf pack areas. Road density and land cover complexity proved to be the most important variables in their models for predicting occurrence of wolf packs. Wolves strongly selected areas with low road density as opposed to high road density.

The authors believe that wolves moved through a wide area, including unfavorable habitat, but established successfully only in higher quality habitat, low human access being one of the characteristics of the latter. They report that upper Michigan and Minnesota, with their greater area of contiguous forest, are a source population of wolves for the state of Wisconsin, where forests are more fragmented.

Key Finding: **Wolves in Alaska avoided roads that were open to regular public use.**

Source: Thurber, J. M., R. O. Peterson, T. D. Drummer and S. A. Thomasma. 1994. Gray wolf response to refuge boundaries and roads in Alaska. Wildlife Society Bulletin 22: 61-68.

Sixty-four radiocollared gray wolves (Canis lupus) were studied from 1976 to 1980 in Kenai National Wildlife Refuge, Alaska. Their response to different road types and human presence was evaluated by computing levels of wolf activity at varying distances from roads and boundaries. Wolves avoided oilfield access roads, which were open to regular and frequent public use. Roads with limited human use (gated pipeline access roads and secondary gravel roads) were used as travel corridors. The authors concluded that the absence of wolves from settled areas and heavily used roads was due to behavioral avoidance.

Of the total radiocollared wolf mortality in the study area, 87% were killed by humans, with one illegal killing. Hunting by people was concentrated in areas of easy human access. A wolf pack using a den within 1 km of a highway did not obviously avoid the highway. Ten of the 12 pack members were killed by hunting in the last years of the study, between 1978 and 1979.

Key Finding: **Roadless areas are important reservoirs for maintaining wolf populations in adjacent, high-road-density areas.**

Source: Mech, L. D. 1989. Wolf population survival in an area of high road density. American Midland Naturalist 121: 387-389.

Seventy-one wolves were radiocollared from 1969 to 1986 in a study area in Superior National Forest, Minnesota, with an average road density of 0.73 km/km2. The area is adjacent to a roadless area - the Boundary Waters Canoe Area Wilderness. Mortality attributed to human causes (including roadkill and trapping) was high - 69% of radiocollared wolves were killed. Wolf survival in this study area was considered below the threshold necessary to maintain a wolf population.

No human-caused mortality was detected in the roadless area. Of 53 wolves tagged in a roaded area north of the study area, 22 had emigrated from the roadless area. The author concludes that wolf populations in an area of high road density could only be sustained if there are suitable roadless reservoirs nearby.

Key Finding: **Mountain lions avoided improved dirt roads and hard-surfaced roads and selected home range areas with lower densities of these road types.**

Source: Van Dyke, F. G., R. H. Brocke and H. G. Shaw. 1986. Use of road track counts as indices of mountain lion presence. Journal of Wildlife Management 50: 102-109.

Mountain lions were radiocollared in Arizona and Utah on three study sites to assess their interactions with roads and the efficacy of track surveys for determining populations. Improved dirt roads and hard-surfaced roads were crossed less often than unimproved dirt roads, suggesting avoidance. These roads were also less likely to occur within lion home range areas. Of the home range areas evaluated, 58% had improved dirt roads, 23% had hard-surfaced roads, while 85% had unimproved dirt roads.

Key Finding: Female Roosevelt elk reduced their daily movements, core area size, and home range size, and therefore, their energy needs, when disturbance due to vehicular access on roads was limited by gate closures.

Source: Cole, E. K., M. D. Pope and R. G. Anthony. 1997. Effects of road management on movement and survival of Roosevelt elk. Journal of Wildlife Management 61: 1115-1126.

The effect of road closures on female Roosevelt elk (Cervus elaphus nelsoni) in the Southern Oregon Coast range was examined. Movements and survival were studied before and after limits were imposed on vehicle access. Roads were closed using gates; monitoring indicated that access was successfully limited to up to 4 vehicle trips per week (including legal entry for management purposes and illegal entry). Of the 29 radiocollared elk, 20 survived through the entirety of the study and were used for much of the analysis. Elk using the study area were compared with a control group that used less than 30% of the study area. During the period of limited vehicle access, core area size and home range size were significantly reduced for the former group than during open access. There was also a reduction in elk daily movement distances.

The authors conclude that limiting access by vehicles reduced human disturbance of elk. Their reduced movements as a result would suggest that the elk would use less energy, potentially increasing fat reserves, survival rates, and productivity. Poaching mortality was also reduced in the areas with limited vehicle access.

Key Finding: **Mule deer and elk avoided roads and areas within 200 m of roads.**

Source: Rost, G. R. and J. A. Bailey. 1979. Distribution of mule deer and elk in relation to roads. Journal of Wildlife Management 43: 634-641.

Mule deer (Odocoileus hemionus) and elk (Cervus canadensis) responses to roads during winter was assessed by counting fecal-pellet groups at varying distances from roads. The study was conducted in Colorado - east of the continental divide in Roosevelt National Forest, and west of the divide in White River National Forest. Transects perpendicular to roads, 400 m long, with 40 plots each, were established at each study site.

Only study sites having at least 50 fecal-pellet groups were included in the analysis. For deer, pellet group locations were analyzed at a total of 63 sites. Pellet group densities increased with distance from the road. Deer showed greater avoidance of roads east of the continental divide, with statistically significant results at 69% of the sites. West of the divide, this relationship was significant for 35% of the sites.

For elk, pellet groups were analyzed at 20 sites. East of the continental divide, elk avoided roads in 90% of the sites, with statistically significant results from 50% of the sites. West of the divide, elk pellet group density decreased at 60% of the sites, with 20% decreases being significant. The authors note that elk behavior relative to roads on the west slope could not be clearly established from these results. Deer and elk frequently avoided both heavily traveled roads and roads near human habitation.

Key Finding: **Columbian black-tailed deer were displaced from their usual home ranges by increased vehicular traffic during the hunting season.**

Source: Livezey, K. B. 1991. Home range, habitat use, disturbance, and mortality of Columbian black-tailed deer in Mendocino National Forest. California Fish and Game 77: 201-209.

The movements and home ranges of Columbian black-tailed deer (Odocoileus hemionus columbianus) were studied in an area on the west slope of California's Coast Range, including part of the Mendocino National Forest. Sixteen female deer were radiocollared and observed over almost 2½ years. Traffic increased considerably on secondary roads and smaller roads during the hunting season. Four of the radiocollared deer used areas 10-200 m from secondary roads in the summer and fall season. However, during the fall hunting period, these deer were displaced and moved 0.6-2.5 km away from their usual areas. The authors conclude that displacement by increased traffic reduced the amount of habitat available to the deer.

Key Finding: **Eastern massasauga rattlesnakes avoided roads in all seasons.**

Source: Weatherhead, P. J. and K. A. Prior. 1992. Preliminary observations of habitat use and movements of the eastern massasauga rattlesnake (Sistrurus c. catenatus). Journal of Herpetology 26: 447-452.

The authors used radiotelemetry to track 12 eastern massasauga rattlesnakes (Sistrurus c. catenatus) for 419 days. This species persists in small relict populations in the U.S. and Canada and is considered threatened. Tracking data showed that the snakes avoided open areas, including roads and trails, mixed forest, and open water at all times of the year. The snakes were most strongly associated with coniferous forests and wetlands. In contrast, capture rates were higher in open areas, and the authors believe this to be due to easier detection in these areas.

Barriers to dispersal: Roads fragment populations of many small mammals, amphibians, and reptiles by creating barriers to dispersal. Direct mortality through roadkill also affects populations of both large and small animal species.

Key Finding: **Roads were a barrier to movement by the eastern chipmunk and the white-footed mouse.**

Source: Oxley, D. J., M. B. Fenton and G. R. Carmody. 1974. The effects of roads on populations of small mammals. Journal of Applied Ecology 11: 51-59.

Trapping and observation were used to study small mammal population movements along roads in southeastern Ontario and in Quebec. Four types of roads were included - county gravel roads, county paved roads, two-lane highways, and four-lane highways. All sites except one were oak-maple mixed forest; the exception was primarily coniferous forest. A total of 589 individuals were trapped.

Out of a total of 651 recaptures, 98% were white-footed mice (Peromyscus maniculatus) and eastern chipmunks (Tamias striatus); therefore, analysis focused on them. Only eight of 254 trapped white-footed mice and six of 179 trapped eastern chipmunks crossed roads; none crossed highways involving more than 30 m of clearance.

Road clearance was determined to be the most important factor for crossing by forest mammals. Road surface (gravel vs. paved) was not a significant factor. Traffic was not necessarily an inhibiting factor - one of the divided highways had very low traffic volume (four vehicles per hour), but experienced very little crossing. Wider roads were crossed almost exclusively by medium-sized mammals, such as skunks and porcupines, rather than by small mammals.

Road mortality was highest in July, when traffic levels were highest and when the young of several species were emerging and dispersing. More than 380 mammals were found killed over 116 days, as well as 150 amphibians, 228 reptiles, and 217 birds.

The authors conclude that roads may affect the survival of populations by fragmenting gene pools and that this effect should be considered when planning roads.

Key Finding: **Highways were a barrier to movement for seven of 10 rodent species studied.**

Source: Wilkins, K. T. 1982. Highways as barriers to rodent dispersal. Southwestern Naturalist 27: 459-460.

The authors examined road-crossing behavior of rodents by capturing and marking 1,968 rodents of 10 species. The study was conducted adjacent to four highways in southeastern Texas. Individuals from only three of the 10 species crossed the roads - five Baiomys taylori (1.8% of marked individuals); one Reithrodontomys fulvescens (1% of those marked); and 86 Sigmodon hispidus (5.6% of those marked).

Key Finding: **A narrow dirt road was a significant barrier to movement by prairie voles and cotton rats.**

***Key Finding*:Prairie voles and cotton rats tended to move away from a narrow dirt road rather than toward it.**

Source: Swihart, R. K. and N. A. Slade. 1984. Road crossing in Sigmodon hispidus and Microtus ochrogaster. Journal of Mammalogy 65: 357-360.

During a nine-year period, prairie voles (Microtus ochrogaster) and cotton rats (Sigmodon hispidus) were live-trapped in abandoned farmland on both sides of a lightly traveled narrow dirt road in Jefferson County, Kansas. Out of a total of 1,865 captured prairie voles, only 23 were recorded as crossing the road. Out of 823 captured cotton rats, 47 crossed the road. Preference for certain habitat rather than road avoidance was tested as a reason for this behavior, but found not to be a factor.

The effect of roads on vole and mouse behavior was examined in three ways. First, voles and mice near the road were found to move preferentially away from rather than toward the road: 92% of captured voles moved away from rather than across the road; 81.5% of cotton rats moved away from the road. Second, the behavior of individual roadcrossers was compared with non-roadcrossers. The majority of roadcrossers were found to cross the road only once each. The authors interpret this as indicating that the road-crossing individuals did not incorporate the road into their home range. Third, the likelihood of increased road crossing with increasing population density was tested. Road crossing was found to be density dependent for cotton rats but not for voles. That is, in years of lower population size, fewer cotton rats crossed the road, but no effect was found on voles, which always had a very low crossing rate.

The paper also addresses the question of whether the road functions as a barrier to gene flow. The authors observe that it is a difficult question to answer, but that the inhibitory effect of the road on voles may be strong enough to have ramifications on the population's genetic diversity.

Key Finding: **A highway in southern Nevada acted as a barrier to crossing for all eight rodent species studied.**

Source: Garland, T., Jr. and W. G. Bradley. 1984. Effects of a highway on Mojave Desert rodent populations. The American Midland Naturalist 111: 47-56.

A rodent trapping study was conducted from March 1979 through February 1980 near a divided four-lane highway in southern Nevada. The study area, a grid over 9 ha, was in a creosote bush community. A total of 612 rodents of eight species was captured over the course of the study. Of these, almost two thirds, 387 individuals, were recaptured.

The road was found to inhibit crossing by all rodent species. All species traveled distances large enough to permit crossing the highway. However, only one individual, an adult male antelope ground squirrel (Ammospermophilus leucurus), crossed the entire highway. There was no relationship between proximity to the highway and home range size or life span. There was no road mortality in the study area, and the authors believe that crossing inhibition prevented roadkill.

Key Finding: **Roads impeded movement by amphibians and could result in population isolation.**

Key Finding: Despite some speculation, road ruts and ditches have not been shown to provide successful amphibian breeding habitat rather than acting as ecological traps.

Key Finding:Amphibians play a key role in the forest ecosystem, affecting nutrient cycling and also serving as high-quality prey for many species.

Source: deMaynadier, P. G. and M. L. Hunter, Jr. 1995. The relationship between forest management and amphibian ecology: a review of the North American literature. Environmental Reviews 3: 230-261.

This article reviews the impact of a variety of forest management practices, including logging roads, on amphibians. Studies reported significant roadkill on busy roads. A more significant impact of roads, however, may be as barriers to dispersal. Isolated populations could suffer a loss of genetic diversity.

Although the barrier effect on many small mammals has been shown, almost no studies have been performed on the effect of unpaved roads and amphibian movement. The authors report some of their own findings, however, from a drift fence study along a 5-m-wide dirt track and a 12-m-wide gravel logging road in Maine. Although the dirt track had no significant impact on amphibian movement, the wider, gravel track inhibited movement by salamander species.

Road puddles and roadside ditches have been discussed as potential new breeding habitat. Salamanders and frogs have been documented breeding in rut ponds on abandoned logging roads in Kentucky. However, deMaynadier and Hunter note that no study had been done as yet to prove the level of reproductive success in these sites compared to natural breeding pools and to confirm that these road breeding sites are not serving as ecological traps, with high mortality through higher drying rates or higher predation rates.

The authors also review the ecological importance of amphibians. They are an important part of forest food chains as high-quality prey for many predators including birds, small mammals, snakes, and other amphibians. Amphibians are also believed to play an important role in forest nutrient cycling. Salamander species, for example, are top predators within the detritus food web and regulate populations of soil microfauna. The authors therefore believe that any practice that modifies local salamander populations may affect decomposition and nutrient cycling rates.

Key Finding: **Roads impeded dispersal of all six amphibian species studied.**

Source: Gibbs, J. P. 1998. Amphibian movements in response to forest edges, roads, and streambeds in southern New England. Journal of Wildlife Management 62: 584-589.

Amphibian dispersal relative to roads, forest edges, and streambeds was examined on a 100-ha preserve near New Haven, Connecticut. Six species, for which more than 10 individuals were captured, were included in the analysis: spotted salamander (Ambystoma maculatum), marbled salamander (Ambystoma opacum), pickerel frog (Rana palustris), redback salamander (Plethodon cinereus), wood frog (Rana sylvatica), and red-spotted newt (Notophthalmus viridescens). Capture rates of each species varied. For all species, forest-road edges had lower permeability than forest-open land edges and forest-residential edges. Red-spotted newts exhibited the strongest avoidance of forest edges.

Key Finding: **Road mortality of 7 amphibian species, 10 reptile species, 21 mammal species, and 62 bird species was documented during four years of study, exceeding 32,000 individuals on a 3.6 km stretch of highway.**

Source: Ashley, E. P. and J. T. Robinson. 1996. Road mortality of amphibians, reptiles and other wildlife on the Long Point Causeway, Lake Erie, Ontario. Canadian Field-Naturalist 110: 403-412.

The authors censused the mortality of amphibians, reptiles, and other wildlife along 3.6 km of a two-lane paved causeway next to Big Creek National Wildlife Area on Lake Erie. Censusing was carried out from spring 1979 to autumn 1980 and again from 1992 to 1993, for a total of 716 days.

The total recorded mortality was greater than 32,000 individuals, from 100 different species - 7 amphibians, 10 reptiles, 21 mammals, and 62 birds. Road mortality rates averaged 11.65 amphibians/km/day, 0.34 reptiles/km/day, 0.51 birds/km/day, and 0.11 mammals/km/day. Amphibians accounted for 92.1% of the total road mortality, the majority being young leopard frogs (Rana pipiens). Amphibian and reptile mortality had seasonal patterns based on their dispersal behavior.

Key Finding: **Frog and toad density near paved roads decreased with increasing traffic intensity.**

Key Finding: **Frog and toad mortality on roads increased with increasing traffic intensity.**

Source: Fahrig, L., J. H. Pedlar, S. E. Pope, P. D. Taylor and J. F. Wegner. 1995. Effect of road traffic on amphibian density. Biological Conservation 73: 177-182.

Frog and toad populations were studied along two-lane paved roads in two regions of Ottawa, Canada. Traffic intensity was categorized as low, medium, or high. Dead and live frogs and toads were counted along each 1-km segment of the roads. Relative densities of the amphibians were estimated using breeding chorus intensity rankings. Choruses were identified to species and given an intensity rating of 1 (for 1 individual); 2 (distinguishable individuals); or 3 (indistinguishable individuals).

In total, 1,856 dead frogs and 591 live frogs were counted over a total road distance of 506 km. The proportion of dead frogs and toads increased with increasing traffic intensity. After correcting for effects of local habitat, date, time, and region, frog and toad density was found to decrease with increasing traffic intensity.

Key Finding: **Road mortality of 20 species of snakes was recorded along a 44-km stretch of highway passing through Organ Pipe Cactus National Monument, Arizona.**

Source: Rosen, P. C. and C. H. Lowe. 1994. Highway mortality of snakes in the Sonoran Desert of southern Arizona. Biological Conservation 68: 143-148.

The authors studied snake mortality on Arizona State Routes 85 and 86 for four years, on a section of the highway passing primarily through Organ Pipe Cactus National Monument (ORPI). Because of their earlier mark-recapture work, the authors also had information on the abundance and movement ecology of snakes in ORPI.

Snakes were observed by driving slowly and recording all snakes, dead or alive, on the road surface ("quantitative road-cruising"). During their four years of research, the authors recorded the mortality rates for 20 species of snakes due to roadkill. Snake mortality was highest in spring. The authors computed an estimate of 13.5 snakes killed/km/year.

The Organ Pipe shovelnosed snake (Chionactis palarostris), which occurs only at and near ORPI, was found almost exclusively at road-modified habitat. Most individuals found were dead (70%). The authors believe that this species' population status may be strongly affected by highway mortality.

Key Finding: **Mortality due to roadkill was documented for northern saw-whet owls and eastern screech-owls over a 10-year period in New Jersey.**

Source: Loos, G. and P. Kerlinger. 1993. Road mortality of saw-whet and screech-owls on the Cape May peninsula. Journal of Raptor Research 27: 210-213.

Mortality of raptors due to roadkill was documented for 10 years along a 145-km route in New Jersey that included county roads, state roads, and highways. The location, age, and sex of birds were recorded. A total of 250 road-killed raptors representing six owl and six hawk species were found. Northern saw-whet owls (Aegolius acadicus) accounted for 45% of all roadkills, with 79% of these being less than one year old. Eastern screech-owls (Otus asio) accounted for 36% of all roadkills, with 88% of these being less than one year old.

Key Finding: **Road mortality along a highway in Ohio was surveyed for one year and included 11 species of mammals, 12 species of birds, 11 species of amphibians, and at least 249 species of insects.**

Source: Seibert, H. C. and J. H. Conover. 1991. Mortality of vertebrates and invertebrates on an Athens County, Ohio, highway. Ohio Journal of Science 91: 163-166.

The authors walked 1.6 km of a highway in Ohio, with 50 excursions over the course of more than a year to document the species killed along roads. The highway was bordered by a riverine elm-maple-sycamore woodland on one side and a red oak-white oak hillside forest on the other. Both sides of the road were surveyed, generally at weekly intervals.

They found 79 roadkilled mammals, representing 11 species, 21 birds representing 12 species (including non-roadside feeders), and 74 amphibians, representing 11 species. Amphibian road mortality was particularly high after a rainfall. Over 1,000 killed insects were collected from the road, belonging to at least 249 species.

Key Finding: **Collision with a vehicle was the highest cause of death for female moose studied in Alaska.**

Source: Bangs, E. E., T. N. Bailey and M. F. Portner. 1989. Survival rates of adult female moose on the Kenai Peninsula, Alaska. Journal of Wildlife Management 53: 557-563. *

The authors radiocollared 51 adult female moose in two wintering areas on the Kenai National Wildlife Refuge. They tracked the survival of the tagged moose for six years and mapped their home ranges. Of the 13 deaths recorded, six were due to vehicle collisions. The remainder were due to hunting, old age, predation, and natural accidents. Roads were present in a high percentage of moose home ranges: of the tagged moose, 23 had highways within their home range, and 30 had gravel roads within their home range.

Key Finding: **Mortality of white-tailed deer due to roadkill was documented for 18 months along an interstate highway.**

Source: Puglisi, M. J., J. S. Lindzey and E. D. Bellis. 1974. Factors associated with highway mortality of white-tailed deer. Journal of Wildlife Management 38: 799-807.

The number of white-tailed deer (Odocoileus virginianus) killed along a 313-mile-long interstate highway in Pennsylvania was analyzed from monthly reports completed by state game protectors. Over a period of 18 months, 874 deer were killed due to collisions with vehicles. Mortality was highest during November and December. Vegetation, fence type, fence location, and topography were recorded along the highway in order to investigate mitigation possibilities.

Key Finding: **Road mortality rates of white-tailed deer were documented after the construction of an interstate highway through their wintering area.**

Source: Reilly, R. E. and H. E. Green. 1974. Deer mortality on a Michigan interstate highway. Journal of Wildlife Management 38: 16-19.

Information on white-tailed deer (Odocoileus virginianus) mortality along an interstate highway was collected from the Michigan Department of Natural Resources. The authors investigated a 5-mile stretch of a new interstate highway that intersected a deer wintering area (already with one road).

Roadkill data from 1960 through 1972 were available. After construction of the interstate, rates of deer mortality rose, and in the first year were 500% greater than the average of the previous four years. Mortality rates declined over the following years, but remained twice as high as pre-interstate mortality figures. The decline in mortality was attributed to deer moving away from wintering in areas affected by the highway as well as the deer families formally occupying the highway area having already been killed.

Key Finding: **Mortality of mule deer due to roadkill was documented for two years along a highway and two state roads.**

Source: Romin, L. A. and J. A. Bissonette. 1996. Temporal and spatial distribution of highway mortality of mule deer on newly constructed roads at Jordanelle Reservoir, Utah. Great Basin Naturalist 56: 1-11.

Mortality of mule deer (Odocoileus hemionus) due to roadkill was studied on segments of three highways in northeastern Utah. Deer roadkill data were collected over a total of 47.3 km for two years. One highway was a four-lane road, the other two were two-lane state roads. Vegetation characteristics, topography, traffic volume, and road variables were also noted.

The authors recorded 397 deer roadkills during their study period. Of the total, 51.6% were does, 18.9% bucks, 21.7% fawns. Roadkill rates were highest along the four-lane highway.

Loss of habitat: Wildlife species associated with forest interior habitat or old-growth are adversely affected by habitat degradation and by forest fragmentation due to logging or roads.

Key Finding: **Marten capture rates declined as forest fragmentation increased, and the animals were rarely detected in sites with more than 25% non-forested area in a total 9 km2 area.**

Source: Hargis, C. D., J. A. Bissonette and D. L. Turner. 1999. The influence of forest fragmentation and landscape pattern on American martens. Journal of Applied Ecology 36: 157-172.

The authors investigated the extent to which the abundance of American martens (Martes americana) changed with incremental increases in forest fragmentation. Their study was conducted for three years in the Uinta Mountains of northern Utah, during a moratorium on commercial marten trapping. Eighteen study sites were selected, each 9 km2 in area and large enough to potentially overlap several martens' ranges. Sites were composed of mature forest, dominated by Engelmann spruce, lodgepole pine, and subalpine fir. The area of open, non-forested habitat (natural openings and areas clearcut at least five years earlier) ranged from 2% to 42% of a site. The dominant vegetation in these openings was grasses and forbs.

Twenty-five traps were placed on each site over the summer. Martens' reproductive status, weight, body condition, and recapture rates were used as indicators of their health. Habitat fragmentation was quantified using five measures: the percentage of landscape in openings, edge density (m of edge per ha), isolation of each open patch, nearest-neighbor distances of openings, and mass fractal dimension. Clearcuts and natural openings were combined to determine the percentage of landscape in openings.

Marten captures decreased with increasing loss of forest habitat as measured by the percentage of each site in open areas. Their capture rates were lowest in landscapes that had large, closely spaced open areas. Landscapes with an average distance between open areas of less than 100 m had no marten captures. Landscapes with high edge densities also had few marten captures. Prey availability did not correlate with marten captures.

***Key Finding*:** **Mountain lions avoided logging areas and established home ranges in areas with lower road densities than the average in the area.**

Source: Van Dyke, F. G., R. H. Brocke, H. G. Shaw, B. B. Ackerman, T. P. Hemker and F. G. Lindzey. 1986. Reactions of mountain lions to logging and human activity. Journal of Wildlife Management 50: 95-102.

Radiocollared mountain lions (Felis concolor) were studied in northern Arizona (Kaibab Plateau) and south-central Utah (Escalante Study Area) to evaluate the lions' reactions to logging, road densities, and human activity. Mountain lions using the same area for six or more months were considered residents; all

others were considered transients. Lion locations were classified as: lions in an active timber sale, within 1 km of an active sale, in an inactive sale, within 1 km of an inactive sale, or not in or near a sale. The area of timber sales within a mountain lion's home range was also examined. Daily lion activity patterns were recorded.

Lions used timber sale areas less frequently than expected given the proportion of the landscape in which there was sale activity. Resident lions rarely occurred in areas within 1 km of sites logged within the previous six years. Only one of seven lion home ranges in the Kaibab Plateau included timber sales, although six included portions of the overall timber zone. Lions in the Escalante study site had larger home ranges than did lions in the Kaibab Plateau. Their home ranges included all or part of at least one timber sale, perhaps because timber sales were more dispersed through the landscape. Home ranges for established residents and for newly established young lions were in areas with lower road densities than the study area average.

Key Finding: **Northern flying squirrels, the primary prey of northern spotted owls, occurred at lower densities in logged, shelterwood stands than in unmanaged, old-growth forest.**

Source: Waters, J. R. and C. J. Zabel. 1995. Northern flying squirrel densities in fir forests of northeastern California. Journal of Wildlife Management 59: 858-866.

The density of northern flying squirrels (Glaucomys sabrinus) was compared in three different stand types: old-growth forest, shelterwood stands that had been logged and burned, and young, naturally regenerated stands 75 to 95 years old. All study sites were located in Lassen National Forest in the Cascade Range of California. White and red fir were the dominant tree species. Flying squirrels were trapped at locations 40 m apart. Vegetation characteristics, including logs, snags, stumps, and canopy cover were measured. Sporocarps of hypogeous fungi, the preferred food of northern flying squirrels, were also sampled.

The mean density of flying squirrels was greatest in old stands and lowest in shelterwood stands. Mean densities did not differ between old and young stands. Body mass (a measure of habitat quality) of adult males and females did not differ between stand types. Fungal sporocarps were found most frequently in old stands and least frequently in shelterwood stands. Sporocarp density was found to be correlated with mean flying squirrel density.

Key Finding: **California red-backed voles were more abundant in old-growth forest and naturally regenerated stands than in young, managed stands. Their higher abundance correlated well with the deeper organic soil layers measured in unmanaged stands.**

Source: Rosenberg, D. K., K. A. Swindle and R. G. Anthony. 1994. Habitat associations of California red-backed voles in young and old-growth forests in western Oregon. Northwest Science 68: 266-272.

The abundance of California red-backed voles (Clethrionomys californicus) was investigated in the Willamette National Forest in the Oregon Cascades. Ten stands were included in the study: five stands were old-growth, dominated by Douglas-fir and western hemlock, four stands were young, managed stands 30 to 60 years old (clearcut and planted), and one stand was a young forest that had naturally regenerated after a wildfire. Voles were trapped using Sherman live-traps spaced at 20-m intervals on trapping grids of 3.2 ha.

During the four years of the study, 209 individual voles were captured. Significantly more voles (80.4%) were captured in old-growth than in young stands (19.6%). Of the young stands, the majority captured were from the unmanaged, naturally regenerated stand (80%). No voles were captured in one of the managed young stands.

Vegetation and soil characteristics were also recorded. The density of large trees, large snags, and organic soil layer depth were most highly correlated with vole abundance. The authors concluded that of these,

forest floor depth may be most predictive of vole abundance since the animals nest in underground burrows or under debris, forage in the organic layer of soil, and use coarse woody debris for cover, travel, and as a source of fungi to feed on. Average organic soil depths were similar in the naturally regenerated young stand (7.8 cm) and in the old-growth (7.9 cm) stand.

The authors note that other scientists' research on California red-backed voles has shown that these voles are an important prey species for many birds and animals and are key dispersers of mycorrhizal fungi, and, therefore, may be an important part of forest ecological processes.

Key Finding: **California red-backed voles were adversely affected by habitat fragmentation: they were absent in clearcuts, had low densities at the edges of forest remnants, increased in density toward the forest interior, and had higher abundances in large forest fragments compared to small fragments.**

Key Finding: **Truffles, the primary food source of red-backed voles, were absent in clearcuts and near the edges of forest remnants, but occurred in forest interiors.**

Source: Mills, L. S. 1995. Edge effects and isolation: red-backed voles on forest remnants. Conservation Biology 9: 395-403.

The author investigated the influence of forest edges on the distribution of California red-backed voles (Clethrionomys californicus) in the Klamath Mountains of Oregon. Thirteen mature-to-old-growth forest remnants were studied, ranging from 0.6 to 2.5 ha in size. Each was surrounded by 1- to 30-year-old clearcuts. Five control sites, mature-to-old-growth forests more than 250 ha in size, were also included.

Voles were trapped for two years between June and September. Trap locations were assigned to one of four edge classes based on the trap's distance into the forest interior from the edge: 0-15 m, 16-30 m, 31-45 m, and 46-90 m. Log number and volume was sampled in each edge class. The distribution of truffles (a vole food source) was also sampled in forest remnants and clearcuts.

Voles were exceptionally rare in clearcuts, and out of 1,404 trap nights, only three voles were captured in clearcuts. Voles were captured on all five control sites and on 10 of 13 forest remnants, with marginally fewer voles per trap in remnants than in controls. Edges had a significant negative effect on vole numbers, with fewer voles captured closer to the edge compared to the forest interior. Vole density increased as forest remnant area increased, confirming the negative impact of edges.

Truffles (sporocarps of mycorrhizal fungi) were essentially absent on clearcuts and in the first edge class, but occurred further into the forest interior. The authors reported that truffles account for three quarters of the diet of this species of vole, and their presence or absence may be an important mechanism explaining the decrease of voles in clearcuts and edge habitat. Log presence or absence did not explain the negative effect of edges on voles, which they speculated may have been because degree of log decay was not included in the sampling.

Key Finding: **Red-backed salamanders, sensitive to forest moisture and temperature levels, were more abundant in old-growth forest and 60-year-old second-growth than in clearcuts or selectively logged forest.**

Key Finding: **Salamanders are a critical part of the forest food chain: they are important food sources for birds and mammals, and as predators themselves, they cycle large amounts of energy through the forest ecosystem.**

Source: Pough, F. H., E. M. Smith, D. H. Rhodes and A. Collazo. 1987. The abundance of salamanders in forest stands with different histories of disturbance. Forest Ecology and Management 20: 1-9.

Four pairs of study plots were established in New York State - four in old-growth forest and four in adjacent disturbed stands, the latter of which included a seven-year-old clearcut forest, a 25-year-old clearcut planted with conifers, a forest cut selectively for firewood, and a 60-year-old second-growth forest. Two 50 x 2 m transects were established in each plot. Understory vegetation cover, leaf litter depth, and soil properties were sampled. Salamanders were counted at night, with each pair of stands being surveyed a total of five times during the study.

The authors found two species of salamanders along their transects - red-backed salamanders (Plethodon cinereus) and the terrestrial eft stage of red-spotted newts (Notophthalmus viridescens). The largest source of variation in salamander numbers, other than night-to-night differences, was stand stage. Red-backed salamanders were most abundant in second-growth forest and its adjacent old-growth control plot, and least abundant in the recent clearcut. This species is believed to be particularly susceptible to changes in microhabitat as it spends all its life on land rather than partly in water and must have suitable forest habitat through all its life stages. Depth of leaf litter was the best predictor of the frequency of above-ground activity by these salamanders.

The authors report red-spotted newts as having been previously shown to be more tolerant of heat and dry conditions than red-backed salamanders. This species spends its larval and later adult life in the water and is only on land during the eft stage. Efts were most abundant in the old-growth plot next to the conifer plantation and rarest in the plantation, but more abundant in the firewood stand than its adjacent old-growth. The authors suggest that this may be because of the abundant piles of down wood present in the firewood forest stand.

The authors also review research on salamanders in various forests of the United States and report that these amphibians' high biomass makes them an important part of the forest food chain. In places such as the Hubbard Brook Experimental Forest in New Hampshire, the biomass of salamanders is twice that of birds and equal to that of small mammals. They are important food sources for birds and mammals and themselves exploit much of the small prey, thereby contributing greatly to the forest ecosystem energy flow.

Key Finding: **The abundance of amphibians was significantly lower in clearcuts, plantations, and forest edges than in mature forest interior sites.**

Key Finding: **Lungless salamanders, such as the red-backed salamander, are particularly vulnerable to population declines due to clearcut logging.**

Source: deMaynadier, P. G. and M. L. Hunter, Jr. 1998. Effects of silvicultural edges on the distribution and abundance of amphibians in Maine. Conservation Biology 12: 340-352.

Five sites in Maine were chosen to study the effects of logging and edges on amphibian populations. Three clearcut stands (ranging from 2 to 11 years old) and two conifer plantations (5 and 25 years old) were paired with adjacent mature forest stands as controls. Transects 140 m long were established perpendicular to the forest edge and 70 m into each stand type. Drift fences and pitfall traps were used to capture the amphibians. Habitat variables were also recorded, including ground cover, vegetation characteristics, litter depth, and ambient light levels.

A total of 2,394 amphibians of 14 species were captured. This included six salamander species and eight anuran (frog and toad) species. All statistical analyses were based on a catch-per-unit effort (number of animals per 100 trap nights) to standardize sampling efforts.

The overall amphibian capture rate was significantly lower in clearcuts and plantations than in the mature forest control sites. The abundance of all six salamander species and seven out of eight anurans increased significantly on plots closer to the forest interior than to the edge. Four species were identified as being particularly sensitive to forest management: red-backed salamanders (Plethodon cinereus), spotted salamanders (Ambystoma maculatum), blue-spotted salamanders (Ambystoma laterale), and wood frogs

(Rana sylvatica). Red-backed salamanders were the most sensitive to clearcutting and forest edge effects. All four management-sensitive species occurred in higher numbers in forest interior habitat than at edges.

Both the distance that edge effects extended into the forest interior and edge contrast were analyzed. The four management-sensitive amphibian species were found to be negatively affected at distances up to 25 to 35 m from silvicultural edges. For salamanders as a group, high-contrast forest edges had a stronger negative impact on abundance than low-contrast edges.

The microhabitat variables that potentially limited populations were also identified. There was a strong positive association between species abundance and canopy cover levels, percent cover by snags, stumps, and root channels, and litter coverage and depth.

Key Finding: **Clearcuts had a significantly lower abundance and fewer species of salamanders compared to mature, 50- to 70-year-old forest stands in the southern Appalachians.**

***Key Finding*: Plethodon salamanders are unlikely to survive logging because individuals are closely tied to small home ranges and unlikely to relocate to intact forest from logged areas.**

Source: Petranka, J. W., M. E. Eldridge and K. E. Haley. 1993. Effects of timber harvesting on southern Appalachian salamanders. Conservation Biology 7: 363-370.

The authors compared the species richness and abundance of salamanders in recent clearcuts and mature forest stands in Pisgah National Forest in the southern Appalachian Mountains of North Carolina.

Plots 50 m by 50 m in size were established on 47 sites, including six recent clearcuts (2-10 years old) and 34 mature, mixed deciduous forest stands (more than 50 years old). Plots in clearcuts were at least 20 m from adjacent uncut forest. A total of 12 species of salamanders were collected (828 individuals) during day searches, primarily in the genus Plethodon and Desmognathus. Statistical analysis was restricted to the five most abundant species.

Logging adversely affected almost all species. Clearcuts contained on average about half as many species of amphibians as mature forest sites. Catches of salamanders from plots in mature forest stands were about five times higher than catches in clearcuts.

The authors' discussion section reviews literature indicating that southern Appalachian salamander species, sensitive to moisture and temperature stress, are adversely affected by clearcutting, which degrades forest floor habitat by eliminating shading, reducing leaf litter, increasing soil surface temperature, and reducing soil surface moisture. In addition, due to having small home ranges and being closely tied to their home ranges, salamanders do not disperse away from logged areas. The authors believe that these factors make high mortality after clearcutting likely.

Key Finding: **The relatively abundant land salamander Plethodon jordani, an important part of the food chain, disappeared from forest sites in the southern Blue Ridge Mountains after they were clearcut.**

Source: Ash, A. N. 1988. Disappearance of salamanders from clearcut plots. The Journal of the Elisha Mitchell Scientific Society 104: 116-122.

The effects of clearcutting on the salamander species Plethodon jordani were studied for four summers after logging in the Nantahala National Forest in the southern Blue Ridge Mountains. This species was selected for study because, as an abundant predator in southern Appalachian forests, it plays an important role in ecosystem energetics.

Four 225 m2 plots were established: two in clearcuts and two in the adjacent oak-hickory forest. Plots were at least 40 m from the edge of the patch in which they were located. Salamanders were toe-clipped to permit individual identification. Searches were done at night, from June through August.

Throughout the study, between 19 and 49 salamanders were caught on forested plots. During the first summer after logging, salamander abundance in clearcuts was 40% of the numbers on forested sites. During the following summers, no salamanders were found in clearcuts. Due to the limited numbers of plots, statistical analysis was not performed.

Key Finding: **In the first two years after clearcutting, salamander numbers, including Plethodon jordani, declined to almost zero on all three forest sites studied.**

Source: Ash, A. N. 1997. Disappearance and return of plethodontid salamanders to clearcut plots in the southern Blue Ridge Mountains. Conservation Biology 11: 983-989.

The impact of clearcutting on terrestrial salamanders was studied at three sites in the southern Blue Ridge mountains, North Carolina. Clearcuts ranged in size from 10 to 23 ha. Salamander abundance was compared on plots (225 m2 in size) in clearcuts and in adjacent forest. Salamander sampling was conducted before and after clearcutting, with searches done at night.

A total of 1,355 salamanders were captured during the study, mostly of the species Plethodon jordani. Salamander populations decreased dramatically at all three clearcut sites in the first two years after clearcutting. Salamander numbers on clearcuts were 30-50% of populations on adjacent forest sites. By the second year, salamanders were essentially absent from clearcuts. Data on salamander abundance was collected for up to eight years after cutting on one site and 15 years after cutting on a second site.

Key Finding: **Adult and juvenile wood frog and spotted salamander capture rates declined along a gradient from closed-canopy forest to recently clearcut habitat.**

Key Finding: **Juvenile wood frogs, dispersing from breeding pools at the forest edge, preferred to migrate toward closed-canopy forest habitat and away from open habitat.**

Source: deMaynadier, P. G. and M. L. Hunter, Jr. 1999. Forest canopy closure and juvenile emigration by pool-breeding amphibians in Maine. Journal of Wildlife Management 63: 441-450.

The authors examined habitat selection by natural populations of wood frogs (Rana sylvatica) and spotted salamanders (Ambystoma maculatum) in three upland, mixed-forest sites in Maine. Sampling was conducted using drift fences along transects that extended 70 m into relatively mature forest and 70 m into an adjacent clearcut. The abundance of both captured adults and migrating juveniles significantly declined across the transect from closed-canopy forest to recently clearcut areas.

The authors also released an experimental population of wood frogs just before metamorphosis into artificial dispersal pools along the forest edge of a 75-m-wide power line right-of-way. Dispersal of the frogs was evaluated using pitfall traps in the adjacent closed canopy, at the edge itself, and in an adjacent open right-of-way. Juvenile frogs showed a strong immigration preference for closed-canopy habitat rather than edge or power line habitat. Highest capture rates were in habitat with dense understory and canopy.

Reduced nesting success: The reproductive success of interior forest bird species decreases in areas fragmented and/or disturbed due to logging or roads. Some species are sensitive to disturbance; others suffer from increased rates of nest parasitism and nest predation.

Key Finding: **The density of bald eagle nests in southeast Alaska decreased with proximity to clearcuts.**

Source: Gende, S. M., M. F. Willson, B. H. Marston, M. Jacobson and W. P. Smith. 1998. Bald eagle nesting density and success in relation to distance from clearcut logging in southeast Alaska. Biological Conservation 83: 121-126.

The authors studied bald eagle (Haliaeetus leucocephalus) nesting success in the shoreline forests of Chichagof and Catherine Islands in the Tongass National Forest, southeast Alaska. Old-growth Sitka spruce and western hemlock were the dominant tree species. Study areas included forest units clearcut logged between 1970 and 1979 and forest units with little or no clearcutting. The distance from each nest to the nearest clearcut was recorded in 100-m intervals, up to a distance of 500 m. The distance between active nests was also recorded. This information was used as an indirect estimate of the density of active nests along the shoreline. Nesting success was recorded as the number of young per active nest.

Results showed that the distance between active nests increased as their proximity to clearcuts increased, i.e. nest density decreased near clearcuts.

Key Finding: **Productivity of nesting bald eagles decreased with proximity to clearcuts.**

Source: Anthony, R. G. and F. B. Isaacs. 1989. Characteristics of bald eagle nest sites in Oregon. Journal of Wildlife Management 53: 148-159.

The authors surveyed 201 bald eagle nest sites in the Oregon Cascades between 1979 and 1982. Nests were located in three forest types: Douglas-fir, mixed-conifer, and ponderosa pine. Forest stand characteristics were sampled in a 100- m radius around the nest trees - this approximated the buffer zone recommended for nest trees by the U.S. Fish and Wildlife Service. Transects were laid out in the four cardinal directions around the nest tree, with sample points established every 25 m. Human activity within 1.6 km of the nest tree was also recorded.

The productivity of nests was averaged over 1978 though 1982 and accounted for distinctions between unoccupied nests, occupied nests, and nests where young had successfully fledged. In mixed-conifer and ponderosa pine forests, mean productivity of bald eagle nests was negatively correlated with their proximity to clearcuts and main logging roads, decadence of nest trees, and the level of nonrecreational activities. In Douglas-fir forests, nest productivity was negatively correlated to proximity of clearcuts, but the other variables showed no clear relationship. Recently used nests, compared to old nests in the same territory, were located in areas farther from all types of roads and from recreational facilities.

Key Finding: **Three of four forest interior bird species declined in abundance after logging, whether clearcutting or lower intensity logging.**

Key Finding: **The brown-headed cowbird, a species that parasitizes other birds' nests, increased in abundance after logging.**

Source: Baker, M. D. and M. J. Lacki. 1997. Short-term changes in bird communities in response to silvicultural prescriptions. Forest Ecology and Management 96: 27-36.

The impact of logging on bird communities and on individual bird species was investigated in the Daniel Boone National Forest, Kentucky. Sixteen forest stands with four silvicultural treatments were included: no logging, clearcut logging, two-age high-leave logging (with 7m2 basal area left uncut) and two-age low-leave logging (3.5 m2 basal area left). Trees left uncut in the two-age stands were 15.2-40.6 cm dbh. Birds' relative abundance was obtained by using fixed-radius point count surveys. Data were collected before and after logging.

Data for 29 bird species were analyzed. Only bird species with 10 or more detections after logging were included in this analysis. Four species were classified as forest interior species. Of these, two (the ovenbird and the red-eyed vireo) were less abundant in all three treated stands than in unlogged stands. One species (Acadian flycatcher) was less abundant in the low-leave and clearcut stands than in stands with no logging, and showed no significant pattern for high-leave stands. The fourth species, the hooded warbler, was most abundant in low-leave and high-leave stands. The authors attributed this to the hooded warbler's preference for well-developed understory vegetation, which was higher in these stands.

The brown-headed cowbird, a nest parasite, increased in abundance in all logging treatments. The species was not recorded in any of the unlogged stands.

Key Finding: **As forest fragmentation increased, nests of all nine bird species studied suffered higher rates of parasitism and predation.**

Source: Robinson, S. K., F. R. Thompson III, T. M. Donovan, D. R. Whitehead and J. Faaborg. 1995. Regional forest fragmentation and the nesting success of migratory birds. Science 267: 1987-1990.

The impact of forest fragmentation was studied for nine bird species (eight being neotropical migrants) in the Midwest. More than 5,000 nests on nine study areas were monitored for five years. Mean percent forest cover within a 10-km radius of the center of each site was estimated from forest cover maps. As percent forest cover decreased, nest parasitism by brown-headed cowbirds increased for all species, with statistically significant increases for five of the nine species. Nest predation rates increased for all species as percent forest cover decreased, with three of nine species having significant correlations.

Key Finding: **The reproductive success of ovenbirds, a forest interior species, was significantly lower in forest fragments than in continuous forest, partly due to cowbird parasitism of their nests.**

Key Finding: **The density of breeding male ovenbirds was lower in forest fragments than in continuous forest, with birds avoiding habitat within 100 m of the forest edge.**

Source: Porneluzi, P. A. and J. Faaborg. 1999. Season-long fecundity, survival, and viability of ovenbirds in fragmented and unfragmented landscapes. Conservation Biology 13: 1151-1161.

The authors compared the breeding success of ovenbirds (Seiurus aurocapillus) in a fragmented landscape versus an unfragmented landscape. There were seven study sites: three located in large forest patches (greater than 2,000 ha) and four within continuous forest (1.8 million ha). All sites were located in oak-hickory forest in Missouri. Analysis was based on the number of territorial males at each study site. The majority were captured and color-banded. Territories were mapped throughout the breeding season. The locations of all nests were mapped, nests were monitored every three to four days, and nests were inspected for the presence of cowbird eggs or nestlings. A pair of ovenbirds was considered reproductively successful only if it was observed caring for a fledgling out of the nest.

Reproductive success over the entire breeding season was lower in the fragmented forests than in the continuous forest sites. In the fragmented landscape, 72% of nests experienced cowbird parasitism, in

contrast to 4% of nests parasitized in the unfragmented landscape. Annual productivity in the fragmented landscape was 0.70 juvenile female ovenbirds per female, compared to 1.47 juvenile females per female in the unfragmented landscape.

The average density of males (number per 10 ha) was also lower in the fragmented landscape (1.61) than on sites in the unfragmented landscape (2.2). Avoidance of forest edges was observed, with territorial males occupying significantly less habitat within 100 m of an edge than habitat greater than 200 m from an edge.

Key Finding: **All three species of tanagers studied were sensitive to forest fragmentation, with a declining probability of breeding tanagers occurring at a given site as fragmentation increased.**

Source: Rosenberg, K. V., J. D. Lowe and A. A. Dhondt. 1999. Effects of forest fragmentation on breeding tanagers: a continental perspective. Conservation Biology 13: 568-583.

The impact of forest fragmentation on tanagers (Piranga spp.) was evaluated by collecting data from more than 1,000 study sites throughout the United States and Canada. Data were analyzed for three species of tanagers - scarlet, western, and summer tanagers (P. olivacea, P. ludoviciana, and P. rubra). Volunteer participants established census points, which they visited during the season of bird territory establishment as well as during nesting. The presence of nest predators and brown-headed cowbirds was also recorded.

Data were used to construct models to predict the probability of a breeding tanager occurring at a study site. The probability of finding breeding tanagers decreased with increasing fragmentation for all three tanager species. Sensitivity to fragmentation varied geographically and was highest in the Midwest and Atlantic Coast regions.

Key Finding: **Nesting success of forest birds decreased within 50 m of forest edges.**

Key Finding: **In five of six studies, nesting success of forest birds decreased as forest patch size decreased.**

Source: Paton, P. W. C. 1994. The effect of edge on avian nest success: how strong is the evidence? Conservation Biology 8: 17-26.

To investigate the decline in neotropical migrant bird populations, the author reviewed research on nesting success and its relationship to habitat fragmentation and artificial edges. The author reanalyzed data from a number of studies in order to be able to compare results from research conducted under varying experimental designs. Study sites included forest as well as shrub-grassland and prairie habitat in North America and Europe, with one study from Central America.

Data from 14 studies using artificial bird nests in forests were reanalyzed. The majority (71%) demonstrated that nest success was lower near forest edges, with nest predation rates greatest at distances within 50 m of an edge. Results on effects further than 50 m from an edge were less conclusive. In addition, information on the influence of the type of edge (abrupt or feathered, for example) was inconclusive.

Of the seven studies that used natural nests, four (57%) demonstrated significantly higher nest predation rates near forest edges. Two of the other studies were located in grasslands and found no effect of edges. A third study, based on exposure days, could not be reanalyzed. Of the five studies on parasitism of natural nests, three (including forest and grassland study sites) demonstrated that cowbird parasitism increased near edges. A fourth indicated a similar trend, but results were not significant. Of the six studies investigating forest patch size and its relation to nest predation rates, five demonstrated that nest success decreased as patch size decreased.

Key Finding: **Nest predation rates in southern Appalachian forest fragments increased as fragment size decreased.**

Source: Keyser, A. J., G. E. Hill and E. C. Soehren. 1998. Effects of forest fragment size, nest density, and proximity to edge on the risk of predation to ground-nesting passerine birds. Conservation Biology 12: 986-994.

A study of nest predation rates relative to forest fragment size was conducted at Fort McLellan in the southern Appalachians, Alabama. Forest fragments ranged in size from 4 to 849.4 ha and were located in a variety of surrounding habitat types. Artificial ground nests contained two fresh quail eggs and two clay eggs. The former were included to detect large predators and to provide visual and olfactory cues, and the latter were included to obtain a record of claw and tooth marks from small-mouthed predators. Predator species were not identified for this study, and were only categorized as small (including small rodents such as chipmunks) or large (including blue jays, American crows, gray foxes, raccoons, Virginia opossums, and white-tailed deer). Snake predation could not be accounted for by this study design.

The authors laid out 22 linear transects in 10 forest fragments, each with 30 nests 20 m apart. Larger fragments had several transects. To test for clustering effects, nests were also grouped in grid formations rather than in linear transects. Nests were checked seven to eight days after placement.

Total nest predation rates per transect increased as forest fragment size decreased. Large predator activity increased as fragment size decreased, but no difference in small predator activity was detected. Large predator activity also increased among clustered nests, but total predation rates for clustered versus unclustered nests showed no significant difference. There was no difference in predation rate based on distance from edge. The authors concluded that edge types and the adjoining habitat were too variable among the fragments to discern any effects specific to edges.

Key Finding: **Artificial nests had higher rates of predation on the edges of forest fragments than in the interior of fragments.**

Source: Marini, M. A., S. K. Robinson and E. J. Heske. 1995. Edge effects on nest predation in the Shawnee National Forest, southern Illinois. Biological Conservation 74: 203-213.

The authors studied the effect of edges (forest-farm edges) on nest predation rates in the Shawnee National Forest, Illinois. Five transects (1,000 m long) were established 10-15 m in from the forest edge and five transects were established in the forest interior, at least 300 m from the edge. Artificial nests with quail eggs were placed at thirty 25-m intervals along each transect. Nests were placed on the ground, in shrubs, and in saplings. Predation levels were checked after five, 10, and 15 days. Nests were also placed in groups of five to compare predation on low versus high nest densities. Bird abundances were estimated from singing male counts along each transect through the breeding season. Mid-sized mammal abundance was determined from track censuses. Small mammals were trapped using Sherman live-traps.

Sapling nests had higher levels of predation on forest edge sites than in the forest interior. Ground and shrub nests had higher predation levels as well, but these differences were not statistically significant.

The authors were not able to determine the mechanism by which edges may increase predation. Predation rates were independent of singing bird abundances. Nor did nest density seem to be a factor. The authors note that their methodology did not incorporate possible predation by squirrels.

Chapter 2

SPREAD OF TREE DISEASES AND BARK BEETLES

Increased occurrence of tree diseases: Logging, disturbance, and roads promote the spread of damaging and lethal tree diseases.

Key Finding: **Multiple studies have shown that annosus root disease, often fatal or damaging for a number of conifer species, has increased in western forests as a result of logging.**

Source: Smith, R. S., Jr. 1989. History of Heterobasidion annosum in Western United States. pp. 10-16 in Proceedings of the Symposium on Research and Management of Annosus Root Disease (Heterobasidion annosum) in Western North America. W. J. Otrosina and R. F. Scharpf, tech. coord. GTR-PSW-116. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station.

This study reviewed research on Heterobasidion annosum (formerly named Fomes annosus), a fungal root pathogen of pine, fir, and hemlock in western forests. With the 1950s logging boom, forest pathologists observed that the disease characteristically appeared in pine stands several years after logging and was associated with stumps as well as with logging wounds in remnant trees. The disease spread from stumps to adjacent living trees via root contacts. Infection of western hemlock through logging wounds was also reported. In the 1970s, it was noted that true fir understories, released after high-grade logging of pines, were also suffering extensive mortality from annosus root disease. The Forest Service instituted a policy requiring treatment of stump surfaces with borax in recreation areas. However, there is continuing concern that annosus can infect stumps via the roots rather than just through the stump surface, and that borax treatment may not be fully successful in preventing the disease.

Key Finding: **The incidence of annosus root disease in true fir and ponderosa pine stands increased with the number of logging entries.**

Source: Goheen, E. M. and D. J. Goheen. 1989. Losses caused by annosus root disease in Pacific Northwest forests. pp. 66-69 in Proceedings of the Symposium on Research and Management of Annosus Root Disease (Heterobasidion annosum) in Western North America. W. J. Otrosina and R. F. Scharpf, tech. coord. GTR-PSW-116. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station.

The authors reviewed research on the occurrence of annosus root disease (Heterobasidion annosum) in the Pacific Northwest. Studies east of the Cascades indicated that it was a significant disease of true firs. The authors presented results of stand surveys in the Fremont and Ochoco National Forests in Oregon. Logged stands had a higher incidence of annosus root disease than unentered stands, with the highest incidence in stands with a history of multiple entries. Stumps 18 inches or larger served as infection foci for the stand. True firs of all size classes died due to the disease. The Fremont National Forest, where logging began earlier than in Ochoco National Forest, had a higher incidence of the disease.

Pine species, in particular ponderosa pine, were also infected by annosus root disease. The disease reportedly caused more mortality on dry sites. Mortality was centered around old ponderosa pine stumps, which were usually greater than 18 inches in diameter. Trees of all size classes died, although significant mortality was not obvious until 10 to 15 years after logging.

Key Finding: **The proportion of western hemlock trees infected by annosus root disease increased after thinning, due to infection of stumps and logging equipment wounds.**

Source: Edmonds, R. L., D. C. Shaw, T. Hsiang and C. H. Driver. 1989. Impact of precommercial thinning on development of Heterobasidion annosum in western hemlock. pp. 85-94 in Proceedings of the Symposium on Research and Management of Annosus Root Disease (Heterobasidion annosum) in Western North America. W. J. Otrosina and R. F. Scharpf, tech. coord. GTR-PSW-116. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station.

The authors reviewed research on annosus root disease (Heterobasidion annosum) in western hemlock forests, focusing particularly on studies of precommercial thinning. The disease has been reported to cause root and butt-rot of western hemlock in coastal Oregon, Washington, British Columbia, and Alaska. Thinning provided fresh stump sources, which became infection courts for airborne spores of annosus. Summer and winter temperatures were rarely extreme enough to inhibit the fungus, and stumps of all sizes were infected. Wounds to live trees from logging equipment also contributed to higher rates of infection in thinned stands.

The authors noted that there was great variability in virulence among strains of Heterobasidion annosum. A strain at a study site near the Olympic Peninsula, Washington, was less virulent than strains collected from other sites in Washington. In the latter stands, thinning activities could result in more severe problems.

The efficacy of stump treatment, particularly with borax, was reviewed. The authors reported that borax may be ineffective because it washes off stumps and that high stump densities in precommercial thinnings make it difficult to apply. Evaluation 20 years after precommercial thinning revealed that plots with borax-treated stumps did not have significantly lower annosus infection than did untreated stands.

Key Finding: **The percentage of western hemlock trees infected by annosus root disease greatly increased after thinning, with infected stumps being the primary source of infection.**

Source: Chavez, T. D., R. L. Edmonds and C. H. Driver. 1980. Young-growth western hemlock stand infection by Heterobasidion annosum 11 years after precommercial thinning. Canadian Journal of Forest Research 10: 389-394.

The authors examined the extent to which infection rates of western hemlock trees by annosus root disease (Heterobasidion annosum) increased after precommercial thinning. The two study plots were on the Olympic Peninsula, Washington, in young, 26-year-old stands, composed primarily of western hemlock. The stands had been precommercially thinned 11 years earlier. Stumps on each plot were examined for the presence of the fungus. Twenty trees on each plot were also felled and examined for infection.

Of the stumps sampled, 92 and 56% in the two plots, respectively, were colonized by the fungus. Stumps were determined to be the primary source of standing tree infection, accounting for 61% of infections. Excavation of stumps and roots indicated that the fungal pathogen was transferred to standing trees via root grafts from infected stumps. Infection levels in the stand increased from an average of 8% of trees before thinning to an average of 90% of sampled trees 11 years after thinning (17 out of 20, and 19 out of 20 trees were infected in the two plots, respectively).

Key Finding: **Annosus root disease was found on 89% of true fir stumps in stands that had been logged five to 10 years earlier.**

Source: Filip, G. M., C. L. Schmitt and K. P. Hosman. 1992. Effects of harvesting season and stump size on incidence of annosus root disease of true fir. Western Journal of Applied Forestry 7: 54-56.

Three hundred grand fir stumps were investigated for the presence of annosus root disease (Heterobasidion annosum). The study was conducted in Umatilla National Forest, northeastern Oregon, in stands logged five to 10 years earlier. A high frequency of true fir stumps (89%) of all size classes (12 inches and greater)

had annosus root disease. Stump size or the season in which logging had occurred did not affect the percentage of decay.

Mortality rates for regenerating trees surrounding infected stumps did not appear to be higher, but the authors note that more time may be needed for effects of this disease on mortality rates to become apparent.

Key Finding: **Annosus root disease and Armillaria infected freshly cut stumps of young western hemlock and Sitka spruce in southeastern Alaska.**

Source: Shaw III, C. G. 1981. Infection of western hemlock and Sitka spruce thinning stumps by Fomes annosus and Armillaria mellea in southeast Alaska. Plant Disease 65: 967-971.

The susceptibility of western hemlock and Sitka spruce cut stumps to two root diseases (Fomes annosus and Armillaria mellea) was investigated in seven naturally regenerated, 10- to 20-year-old stands. A total of 182 trees of each species were cut, and stumps (7-15 cm in diameter) were examined six to15 months later. Infection through deposition of natural, airborne spores was measured, as well as infection due to artificial inoculation by choosing half the stumps at random and inoculating them with Fomes annosus.

Twelve percent of the western hemlock stumps and 16% of Sitka spruce stumps became naturally infected with Armillaria mellea. Annosus root disease was found on 3% of the western hemlock stumps and 20% of Sitka spruce stumps. Of the stumps inoculated, annosus root disease infected 11% of western hemlock and 15% of Sitka spruce stumps.

Key Finding: **Armillaria is a primary, aggressive root pathogen in western interior forests, where it spreads into healthy stands from the stumps and roots of cut trees.**

Source: Wargo, P. M. and C. G. Shaw, III. 1985. Armillaria root rot: the puzzle is being solved. Plant Disease 69: 826-832.

This review article describes the occurrence of Armillaria root rot throughout the United States. In interior western forests, Armillaria is a primary, aggressive root pathogen of pines, true firs, and Douglas-fir. The fungus colonizes stumps and roots of cut trees, then spreads to adjacent healthy trees. Roots of large trees in particular can support the fungus for many years because they are moist and large enough for the fungus to survive. Disease centers can expand to several hectares in size, with greater than 25% of the trees affected in a stand.

In western coastal forests, Armillaria occurs as a root disease primarily in plantations and in stands less than 25 years old. In eastern deciduous forests, Armillaria is a secondary pathogen that primarily attacks trees weakened by stress factors, such as soil compaction, waterlogging, drought, or insect defoliation.

The authors indicate that it is not yet well understood why some stressed stands become infected, while others do not. They also point out that losses due to Armillaria alone are hard to estimate since in many cases other root pathogens or bark beetles may also be involved.

Key Finding: **Armillaria root disease was present in stumps of old-growth ponderosa pine logged up to 35 years earlier.**

Key Finding: **The oldest stumps of ponderosa pine had the highest rate of infection by Armillaria.**

Source: Roth, L. F., L. Rolph and S. Cooley. 1980. Identifying infected ponderosa pine stumps to reduce costs of controlling Armillaria root rot. Journal of Forestry 78: 145-151.

Root rot of ponderosa pine by Armillaria mellea was studied in southcentral Washington on 100 old-growth stumps, ranging in age since cutting (two to 35 years). Infectious stumps were identified by the condition of surrounding trees and by locating pockets of infected trees in the area. Lab cultures were used to confirm the diagnosis when uncertain.

Eighty-two percent of the ponderosa pine stumps that had dead saplings within the area occupied by roots of the stump were infected. The oldest stumps showed the highest incidence of infection. The authors recommend concentrating disease treatment on the oldest stumps in a stand.

Key Finding: **Mortality of saplings was significantly correlated to the number of Douglas-fir stumps infected with Armillaria and laminated root rot.**

Source: Filip, G. M. 1979. Root disease in Douglas-fir plantations is associated with infected stumps. Plant Disease Reporter 63: 580-583.

Thirty-nine of 43 10- to 27-year-old Douglas-fir plantations examined near Quilcene, Washington, had tree mortality caused by either Armillaria mellea or laminated root rot (Phellinus weirii). Mortality averaged 0.5 trees/ha, was clustered within plantations, and resulted in understocked openings of 0.04 to 0.1 ha. Mortality due to root diseases was significantly correlated with the number of infected stumps.

***Key Finding*:** **The pathogenic fungus Armillaria had a threefold higher occurrence on disturbed plots compared to pristine plots at high productivity sites in the Northern Rockies.**

Source: McDonald, G. I., N. E. Martin and A. E. Harvey. 1987. Armillaria in the Northern Rockies: Pathogenicity and Host Susceptibility on Pristine and Disturbed Sites. USDA Forest Service. Research Note INT-371. 5 p.

Root systems of living and dead trees in disturbed and pristine sites were inspected for evidence of Armillaria. Pristine sites were at least 75 m from a road and had no evidence of logging activity. The authors also investigated the relationship between the relative productivity of a site (site index) and the incidence of Armillaria. In high productivity sites, a threefold greater incidence of pathogenic Armillaria was recorded in disturbed as opposed to undisturbed plots in forests of the grand fir, western red cedar, and western hemlock series. In low productivity sites, the effect of disturbance on Armillaria infection rates was not clear as results were not statistically significant. The authors indicate that incidence of pathogenic Armillaria was higher in low productivity sites compared to high productivity sites, but the data were significant only for undisturbed sites, not for disturbed sites.

The authors also review past studies on Armillaria, noting a clear link between management and the severity of Armillaria-caused disease. They also report that significant Armillaria-related mortality has occurred in conifer plantations.

Key Finding: **Infection and mortality from the root disease Armillaria ostoyae was several times higher in forest stands with logging disturbance than in undisturbed stands.**

Source: Morrison, D. and K. Mallett. 1996. Silvicultural management of armillaria root disease in western Canadian forests. Canadian Journal of Plant Pathology 18: 194-199.

The authors review the occurrence of the root disease Armillaria ostoyae in British Columbian forests and report unpublished results. Surveys showed that the severity of the disease was significantly higher in forest stands with logging disturbance than with no logging disturbance. Stumps created during logging, thinning, or brushing were colonized by Armillaria. Adjacent residual trees as well as new regeneration became infected when their roots came into contact with roots from infected stumps. Infection occurred within one to 20 days of logging, depending on the age of the trees and type of cutting. The authors report that the

number of infected and killed trees was several times higher in disturbed than undisturbed stands and that losses to the disease can be significant.

The authors also review the efficacy and practicality of various strategies for protecting stumps from infection. Treatments were either too expensive or difficult to apply, or did not adequately reduce mortality. Stump removal can reduce mortality due to Armillaria, but it may not be feasible on sites where soils are sensitive or slopes are steep. In addition, not all infected roots can be removed.

***Key Finding*: Thinning and soil disturbance led to an increased risk of infection and mortality by black-stain root disease in Douglas-fir.**

***Key Finding*: The majority of black-stain root disease infection centers were close to roads and skid trails.**

Source: Hansen, E. M., D. J. Goheen, P. F. Hessburg, J. J. Witcosky and T. D. Schowalter. 1988. Biology and management of black-stain root disease in Douglas-fir. pp. 63-80 in Leptographium Root Diseases on Conifers. T.C. Harrington and F.W. Cobb, Jr. eds. APS Press. St. Paul, Minnesota.

The authors summarize 10 years of research on black-stain root disease (Leptographium wageneri) on Douglas-fir in California, Oregon, and Washington. Black-stain root disease was reported to be increasing in incidence and severity in Douglas-fir plantations. Originally reported just from locations west of the Cascades, it was also more recently documented east of the Cascades.

Three insect species were determined to be vectors that spread the black-stain root fungus and created new infection centers. They were attracted to stumps of precommercially thinned trees, where they introduced the fungus into stump roots. The insects also wounded roots of healthy trees, another possible route for fungus introduction.

Several studies documented significantly greater numbers of these insects in thinned versus unthinned stands. Changing the timing of thinning can decrease, although not eliminate, insect activity. Most infection centers were reported to be close to roads and on sites such as skid trails, which had compacted soils and displaced topsoil.

Black-stain disease infection centers were variable in size, some remaining small, others spreading rapidly and causing heavy losses. The authors recommend avoiding management activities that involve tree injury, including road building and maintenance, and conducting thinning treatments during the months of June and early August.

***Key Finding:* Black-stain root disease occurred at a greater frequency in Douglas-fir trees close to roads than in trees located 25 m or more from roads.**

Source: Hansen, E. M. 1978. Incidence of Verticicladiella wagenerii and Phellinus weirii in Douglas-fir adjacent to and away from roads in western Oregon. Plant Disease Reporter 62: 179-181.

A survey was conducted comparing the incidence of root disease in Douglas-fir forests in paired 0.1 ha study strips adjacent to, and 25 m or more distant from, two roads in western Oregon. Black-stain root disease (Verticicladiella wagenerii) was found more frequently in roadside strips than in strips at a distance from roads. Distribution of laminated root rot (Phellinus weirii) was not influenced by proximity to roads. Black-stain was found in 15- to 25-year-old plantations but not in mature stands.

***Key Finding:* Thinned stands attracted a greater number of black-stain root disease insect vectors.**

Source: Witcosky, J. J., T. D. Schowalter and E. M. Hansen. 1986. Hylastes nigrinus (Coleoptera: Scolytidae), Pissodes fasciatus, and Steremnius carinatus (Coleoptera: Curculionidae) as vectors of black-stain root disease of Douglas-fir. Environmental Entomology 15: 1090-1095.

The authors compared precommercially thinned plots to unthinned plots (a total of 32 plots) in two 12-year-old plantations of Douglas-fir in the coast range of Oregon. Pitfall traps and sticky traps were used to capture the three insect vectors of black-stain root disease: Hylastes nigrinus, Pissodes fasciatus, and Steremnius carinatus. Significantly more beetles of each species were captured in thinned plots than in unthinned plots. Also, significantly more trees had beetle wounds in thinned than unthinned plots. The authors also verified transmission of the disease by these insects by collecting insects in established infection foci, killing insects, incubating the fungal isolate, and later using it as an artificial inoculant.

The authors artificially inoculated root systems of both cut and uncut Douglas-fir to determine their susceptibility to black-stain root disease. Root systems of cut trees were determined to be susceptible to infection for at least seven months.

Key Finding: **Mechanical wounding of grand fir and white fir by logging equipment activated dormant decay fungi, such as the Indian paint fungus.**

Source: Aho, P. E., G. M. Filip and F. F. Lombard. 1987. Decay fungi and wounding in advance grand and white fir regeneration. Forest Science 33: 347-355.

Grand and white fir were studied in 24 stands on eight national forests east of the Cascades in Washington and Oregon. A total of 464 trees, ranging in age from 43 to 115 years, were dissected to detect infections by decay fungi and their proximity to wounds. Most wounds were caused by equipment (as opposed to fire, animals, or insects), and more than 45% of the trees with wounds had various decay fungi species present. Infections causing decay were located within 30 cm of an external wound. The authors believe that wounds activate dormant decay fungi, including the Indian paint fungus (Echinodontium tinctorium), if the fungus is present within 30 cm of a wound. These fungi originally enter the host through small branchlet stubs but become dormant after the stubs close.

Key Finding: **Port-orford-cedar root rot, a fatal fungus, is spread by logging equipment, road maintenance equipment, and construction equipment, which transport its spores to new areas.**

Source: Zobel, D. B., L. F. Roth and G. M. Hawk. 1985. Pathology and control of Port-orford-cedar root rot. Chapter 7 in Ecology, pathology, and management of Port-orford-cedar (Chamaecyparis lawsoniana). GTR-PNW-184. USDA Forest Service. Pacific Northwest Research Station. 161 pp.

This report on the ecology of Port-orford-cedar, also reviews the biology and spread of its primary pest, the fatal fungus known as Port-orford-cedar root rot (Phytophthora lateralis). This disease has spread through much of Port-orford-cedar's range since its first appearance, killing trees of all sizes. The disease is believed to have originally been introduced to the region from infested soil of nursery stock. In 1952, the root rot was reported in natural stands. Epidemic conditions are closely correlated to high human activity at a site, with the disease occurring at the lowest intensity in less accessible sites. Machines such as logging equipment or road maintenance equipment are reported to transport the fungal spores in wet mud. Subsequently, the disease can spread to other areas through surface water. Cattle and elk are also important carriers during wet weather. Hauled earth, gravel, and soil-bearing debris are carriers during dry weather.

Attack by bark beetles: Diseased trees are more susceptible to bark beetle attack.

Key Finding: Root disease fungi predispose some conifer species to bark beetle attack and/or help maintain endemic populations of bark beetles.

Source: Goheen, D. J. and E. M. Hansen. 1993. Effects of pathogens and bark beetles on forests. pp. 175-196 in Beetle-Pathogen Interactions in Conifer Forests. T.D. Schowalter and G.M. Filip, eds. Academic Press. San Diego.

The authors review the association between pathogenic fungi and bark beetles in coniferous forests. Five interactions were looked at in detail.

1) Laminated root rot (Phellinus weirii) is a widespread disease of Douglas-fir west of the Cascades. Fungi can survive for up to 50 years in stumps and snags. Live trees infected with this fungus, and therefore stressed, have a greater likelihood of attack by Douglas-fir beetles (Dendroctonus pseudotsugae). By increasing the chance of windthrow of diseased and weakened trees, the likelihood of beetle outbreaks in a stand with many fallen trees also increases. By providing stressed host trees, the disease also helps maintain small populations of bark beetles until the next major outbreak.

2) Black-stain root disease (Leptographium wageneri var. pseudotsugae) is another disease of Douglas-fir. Black-stain root disease is closely associated with disturbance and has been documented to be greatest along roads, in tractor trails and landings where soils have been compacted, and areas where drainage patterns have been changed. Mortality due to black-stain is a particularly severe problem in 10- to 30-year-old plantations and young natural stands on disturbed sites in northwestern California and southwestern Oregon. Although the disease is primarily documented in younger trees, the disease has also been observed in 60- to 80-year-old trees in northwestern California. Disease-weakened trees are attacked and killed by a variety of bark beetle species, including the Douglas-fir bark beetle (D. pseudotsugae) and the Douglas-fir engraver (Scolytus unispinosis).

3) The root disease Leptographium wageneri var. ponderosum predisposes ponderosa pine to several bark beetle species, including the mountain pine beetle (D. ponderosae) and the western pine beetle (D. brevicomis). This disease and beetle association results in rapidly expanding mortality centers, particularly in ponderosa stands 60 to 100 years old, although mortality can occur in stands of any age. The disease is most common in northeastern California and the central Sierra Nevada, in pure, heavily stocked stands. Many of these stands are in areas that have had heavy logging disturbance.

4) A variety of root diseases, including black-stain, Armillaria, and brown cubical butt rot (Phaeolus schweinitzii), predispose lodgepole pine to attack by mountain pine beetles in the interior west. The diseases are also believed to provide stressed host trees that help maintain endemic populations of mountain pine beetle or trigger population increases at the start of an outbreak.

5) Grand and white fir trees in interior mixed-conifer forests have been found to have a high likelihood of attack by the fir engraver (Scolytus ventralis) when they are infected by root diseases, such as laminated root rot, Armillaria, and annosus. Diseased trees also maintain small endemic populations of the fir engraver.

Key Finding: More mountain pine beetles and western pine beetles (two species of bark beetle) were captured on ponderosa pine infected with black-stain root disease than on healthy trees.

Key Finding: Two species of beetle were more frequently attracted to wounds on trees that were also diseased than to uninfected trees.

Source: Goheen, D. J., F. W. Cobb Jr., D. L. Wood and D. L. Rowney. 1985. Visitation frequencies of some insect species on Ceratocystis wageneri infected and apparently healthy ponderosa pines. Canadian Entomologist 117: 1535-1543.

Thirty overstory ponderosa pine trees were selected for study and categorized as healthy, moderately diseased, or severely diseased with black-stain root disease (Ceratocystis wageneri). The study was conducted in El Dorado County, California. Traps were mounted on each tree to monitor insects landing on the tree. Consistently more western pine beetles (Dendroctonus breviformis) and mountain pine beetles (D. ponderosae) were captured on diseased trees than on uninfected trees.

All trees were mechanically wounded as part of the sampling methodology. The red turpentine beetle (Dendroctonus valens) attacked trees at wounds, with attack rates seven-to-eight times higher on trees infected with black-stain root disease than uninfected trees. Spondylis upiformis attacked only wounded trees, not unwounded trees.

Key Finding: Loblolly pines colonized by annosus root disease had a greater probability of being infested with southern pine bark beetle.

Key Finding: Trees infected by annosus root disease had significantly less radial growth than trees not infected.

Source: Alexander, S. A., J. M. Skelly and R. S. Webb. 1981. Effects of Heterobasidion annosum on radial growth in southern pine beetle-infested loblolly pine. Phytopathology 71: 479-481.

The study was conducted in thinned loblolly pine plantations in Virginia, Texas, and Georgia. Trees colonized by annosus root disease had significantly less radial growth (an indicator of stress) over the last 10 years than trees not colonized. Those trees with reduced growth and greater disease incidence also had a significantly higher probability of being infested with southern pine bark beetle (Dendroctonus frontalis). The authors conclude that annosus-stressed trees can play a large role in the proliferation of southern pine bark beetle in plantations.

Key Finding: A significantly higher percentage of plots attacked by the southern pine beetle were infected by blue-stain fungi.

Source: Otrosina, W. J., N. J. Hess, S. J. Zarnoch, T. J. Perry and J. P. Jones. 1997. Blue-stain fungi associated with roots of southern pine trees attacked by the southern pine beetle, Dendroctonus frontalis. Plant Disease 81: 942-945.

Forty paired plots were established in southern pine stands (loblolly pine, slash pine, mixed loblolly and slash, and longleaf pine) from Alabama to Texas. Plots with evidence of attack by the southern pine beetle (Dendroctonus frontalis) were compared to non-attacked control plots. Roots from a total of 240 trees were examined for the presence of several different blue-stain fungal species (Ophiostoma ips, Leptographium terebrantis, and L. procerum).

A significantly higher percentage of beetle-attacked plots (50%) had blue-stain fungi than unattacked plots (25%). When the three fungal species were analyzed separately, L. terebrantis had a significantly higher presence in beetle-infested plots than uninfested plots, while the other two insect species also had higher numbers, though these were not statistically significant. Plots in plantations and natural stands were also analyzed separately. Plantations had a significantly higher proportion of the fungi in attacked plots, while results for natural stands, although also higher, were not statistically significant.

Problems with mitigation: Forest management spreads root diseases despite the use of mitigation techniques, with methods like stump removal causing additional problems such as soil compaction.

Key Finding: Borax-treated plots did not have lower rates of annosus root disease infection compared to untreated plots 20 years after thinning.

Source: Edmonds, R. L., D. C. Shaw, T. Hsiang and C. H. Driver. 1989. Impact of precommercial thinning on development of Heterobasidion annosum in western hemlock. pp. 85-94 in Proceedings of the Symposium on Research and Management of Annosus Root Disease (Heterobasidion annosum) in Western North America. W. J. Otrosina and R. F. Scharpf, tech. coord. GTR-PSW-116. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station.

The authors reviewed research on annosus root disease (Heterobasidion annosum) in western hemlock forests, focusing particularly on studies of precommercial thinning. The disease has been reported to cause root and butt-rot of western hemlock in coastal Oregon, Washington, British Columbia, and Alaska. Thinning provided fresh stump sources, which became infection courts for airborne spores of annosus. Summer and winter temperatures were rarely extreme enough to inhibit the fungus, and stumps of all sizes were infected. Wounds to live trees from logging equipment also contributed to higher rates of infection in thinned stands.

The authors noted that there was great variability in virulence among strains of Heterobasidion annosum. A strain at a study site near the Olympic Peninsula, Washington, was less virulent than strains collected from other sites in Washington. In the latter stands, thinning activities could result in more severe problems.

The efficacy of stump treatment, particularly with borax, was reviewed. The authors reported that borax may be ineffective because it washes off stumps and that high stump densities in precommercial thinnings make it difficult to apply. Evaluation 20 years after precommercial thinning revealed that plots with borax-treated stumps did not have significantly lower annosus infection than did untreated stands.

Key Finding: Mitigation measures for Armillaria root disease were problematic in several regards.

Source: Morrison, D. and K. Mallett. 1996. Silvicultural management of armillaria root disease in western Canadian forests. Canadian Journal of Plant Pathology 18: 194-199.

The authors review the occurrence of the root disease Armillaria ostoyae in British Columbian forests and report unpublished results. Surveys showed that the severity of the disease was significantly higher in forest stands with logging disturbance than with no logging disturbance. Stumps created during logging, thinning, or brushing were colonized by Armillaria. Adjacent residual trees as well as new regeneration became infected when their roots came into contact with roots from infected stumps. Infection occurred within 1 to 20 days of logging, depending on the age of the trees and type of cutting. The authors report that the number of infected and killed trees was several times higher in disturbed than in undisturbed stands, and that losses to the disease can be significant.

The authors also review the efficacy and practicality of various strategies for protecting stumps from infection. Treatments were either too expensive or difficult to apply, or did not adequately reduce mortality. Stump removal can reduce mortality due to Armillaria, but it may not be feasible on sites where soils are sensitive or slopes are steep. In addition, not all infected roots can be removed.

Key Finding: Stump removal, a method of Armillaria root disease control, resulted in high levels of soil compaction in ash-cap soils.

Source: Page-Dumroese, D. S., A. E. Harvey, M. F. Jurgensen and M. P. Amaranthus. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Canadian Journal of Soil Science. 78: 29-34.

The authors examined the impact of stump removal, a method that is sometimes used to control Armillaria root disease in the western United States. Control (no compaction), stump-extraction treatments, and severe compaction treatments were investigated on a site in northern Idaho with an ash-cap soil. Soil bulk density increased by 15-20% to a depth of 30 cm in the compaction treatment. Stump removal increased bulk density at the 20-30 cm depth, though surface soil bulk density decreased. Soil strength increased at the 40-45 cm depth after stump removal and was similar to values in the compacted treatment. This increase in soil strength was believed to be due to equipment vibration because volcanic ash soils are apparently particularly susceptible to vibrational compaction. The authors reported that increased soil strength has been shown to impede root growth.

A year after planting, Douglas-fir seedlings had reduced root volume in the soil compaction treatment. Soil compaction and stump removal also resulted in decreased ectomycorrhizal development and non-ectomycorrhizal short roots on Douglas-fir seedlings. After stump removal, there was a 70% decline in numbers of ectomycorrhizal root tips and a 63% reduction in morphological types on Douglas-fir compared to the no-compaction treatments. After three years, the height of Douglas-fir seedlings in the stump-removal plot was 20% lower and root collar diameter was 30% lower than for seedlings in the other treatments.

Western white pine seedling root volumes were not affected. They had smaller root collar diameters in the stump-removal and compaction treatments, but greater height in the compaction treatment. Western white pines' numbers of non-ectomycorrhizal root tips decreased significantly, although ectomycorrhizal diversity was not affected. Seedlings' ability to capture site resources was considered to be negatively affected.

Key Finding:Restricting thinning to summer months, a recommended practice for mitigating the spread of annosus root disease in southern forests, was not a reliable form of disease control.

Source: Witcher, W. and C. L. Lane. 1980. Annosus root rot in slash pine plantations in the sandhill section of South Carolina. Plant Disease 64: 398-399.

This study addresses whether or not thinning during the summer months can be a successful method of controlling annosus root disease on freshly cut tree stumps. Annosus has been reported to be less viable during hot dry summer months in the southern U.S. The authors investigated slash pine stump infection and mortality based on cutting in each month of the year. Differences among months were not significant, and the authors indicate that disease prevention based on summer thinning may have inconsistent results from year to year because of annual variation in temperature and humidity.

Key Finding: Annosus root disease may spread via root systems from stumps to neighboring trees even following treatment of stumps with borax.

Source: Smith, R. S., Jr. 1989. History of Heterobasidion annosum in Western United States. pp. 10-16 in Proceedings of the Symposium on Research and Management of Annosus Root Disease in Western North America. W. J. Otrosina and R. F. Scharpf, tech. coord. GTR-PSW-116. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station.*

This study reviews research on Heterobasidion annosum (formerly named Fomes annosus), a fungal root pathogen of pine, fir, and hemlock in western forests. With the 1950s logging boom, forest pathologists observed that the disease characteristically appeared in pine stands several years after logging and was associated with stumps as well as with logging wounds in remnant trees. The disease spread from stumps to adjacent living trees via root contacts. Infection of western hemlock through logging wounds was also reported. In the 1970s, it was noted that true fir understories, released after high-grade logging of pines, were also suffering extensive mortality from annosus root disease. The Forest Service instituted a policy requiring treatment of stump surfaces with borax in recreation areas. However, there is continuing concern that annosus can infect stumps via the roots rather than just through the stump surface, and that borax treatment may not be fully successful in preventing the disease.

Chapter 3

PROMOTION OF INSECT INFESTATIONS

Insect infestations: Forest fragmentation from human activity exacerbates insect pest outbreaks.

Key Finding: Forest fragmentation due to cleared forest increased the duration of tent caterpillar outbreaks.

Key Finding: Forest edges were predicted to be source populations for tent caterpillars.

Source: Roland, J. 1993. Large-scale forest fragmentation increases the duration of tent caterpillar outbreak. Oecologia 93: 25-30.

The author examines historical data on the spatial extent of tent caterpillar (Malacosoma disstria) outbreaks from 1950 through 1984 in Ontario, Canada, and compares these to township forest resource inventory maps. The degree of forest fragmentation was based on the percentage of cleared areas, forested areas, and the extent of edges. He found that the duration of tent caterpillar outbreaks was higher with increasing forest fragmentation. Townships with continuous forest had outbreaks lasting one to two years, while townships with 2-2.5 km of edge per km2 had outbreaks lasting four to six years.

The author did not investigate the mechanisms for this pattern but, based on research reported for other lepidopteran species, speculates that edges may have acted as source populations for caterpillar larvae. This could be either because more eggs were laid along edges (sunnier and warmer) than within the forest interior or because of more rapid development of larvae at the forest edge. He also suggests that forest fragmentation may limit the dispersal of parasitoids and pathogens that are natural enemies of tent caterpillars.

Key Finding: Mortality of tent caterpillars in the forest understory due to a natural virus (NPV) decreased as forest cover decreased and edge habitat increased.

Source: Rothman, L. D. and J. Roland. 1998. Forest fragmentation and colony performance of forest tent caterpillar. Ecography 21: 383-391.

The tent caterpillar (Malacosoma disstria) is reported to occur through most of the United States and southern Canada. A nuclear polyhedrosis virus (NPV) is the dominant natural enemy of the caterpillar. The authors introduced colonies of tent caterpillar larvae to two sites of trembling aspen/balsam poplar in Alberta, Canada. They measured larvae survival, net reproductive rates, and the relationship to forest cover. Their models showed forest cover to be the best predictor of tent caterpillar performance. As forest cover decreased, caterpillar colony performance improved, with the greatest effect during larval and prepupal/pupal stages. This relationship was due to increasing NPV-caused mortality with increasing forest cover. The authors report other studies where NPV became inactive after 10 hours of exposure to direct sunlight, confirming their hypothesis that increased area of edge habitat contributed to a greater caterpillar outbreak.

Key Finding: Abrupt edges along mature jack pine stands increased the levels of defoliation by jack pine budworm in Michigan.

Source: Kouki, J., D. G. McCullough and L. D. Marshall. 1997. Effect of forest stand and edge characteristics on the vulnerability of jack pine stands to jack pine budworm (Choristoneura pinus pinus) damage. Canadian Journal of Forest Research 27: 1765-1772.

The authors surveyed 104 managed jack pine stands in Hiawatha National Forest, Michigan, during a jack pine budworm (Choristoneura pinus pinus) outbreak. Defoliation by the budworm, its relationship with local stand factors, and characteristics of adjacent stands were evaluated. Pine stands ranged from 8 to 72 years old. Older stands had higher levels of defoliation than younger stands and, of these, mature stands with younger/shorter stands adjacent to them had the highest levels of defoliation.

The authors hypothesize that these higher rates of defoliation may have been due to higher light levels along edges. They discuss other studies that report pollen cone abundance (the food source for budworm larvae) to be higher than expected along roads and other forest edges where light availability was greater. This increased pollen cone production along edges may result in higher jack pine budworm populations.

Key Finding: Trees at forest edges created by roads had 2.4 times more gypsy moth egg masses than trees in the forest interior.

Source: Bellinger, R. G., F. W. Ravlin and M. L. McManus. 1989. Forest edge effects and their influence on gypsy moth (Lepidoptera: Lymantriidae) egg mass distribution. Environmental Entomology 18: 840-843.

The authors compared numbers of gypsy moth (Lymantria dispar) egg masses on forest edge trees versus interior trees in Virginia. A total of 160 trees (primarily oak species) were sampled in early May, along both sides of rural roads and fire roads. Trees designated as interior trees were 40.2 m from the edge. Edge and interior trees were of similar size and species. Edge trees had 2.4 times more gypsy moth egg masses than interior trees, and the edge side of edge trees had about 3.2 times more egg masses than the edge side of interior trees. Authors note that the edge effect still existed 40 m into the forest.

Loss of ecological complexity: Reduced habitat for insect predators due to roads and other management activities is predicted to increase the severity of pest outbreaks.

Key Finding: A diversity of predators is important for preventing pest outbreaks.

Key Finding: Old-growth and roadless areas, with their greater diversity of composition, structure, and predators, are predicted to be less vulnerable to pest outbreaks than forests simplified through management.

Source: Schowalter, T. D. and J. E. Means. 1989. Pests link site productivity to the landscape. pp. 248-250 in Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. D. A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, R. F. Powers, eds. Timber Press, Portland, Oregon.

The authors discuss landscape patterns and their influence on pests. Three components are important in terms of their impact on pests - intersection by roads or other corridors, patch size, and diversity of stand age classes. They state that pest success increases with forest simplification as the diversity of habitats decreases, resulting in declines of important pest predators, such as spiders and birds. Similarly, reduced stand size and age-class diversity, planting of monocultures, and intersection by roads increases pests' likelihood of finding suitable hosts. They maintain that old-growth forests should be less vulnerable to pest outbreaks than the simplified forests created through management.

Key Finding: Species diversity and functional diversity of arthropods were much higher in old-growth stands than in regenerating logged stands.

Source: Schowalter, T. D. 1989. Canopy arthropod community structure and herbivory in old-growth and regenerating forests in western Oregon. Canadian Journal of Forest Research 19: 318-322.

Arthropod communities were compared in old-growth forest and regenerating forest by establishing study plots in six old-growth stands and six 7- to 11-year-old stands created through logging. All sites were located in the central western Cascades of Oregon, in the H. J. Andrews Experimental Forest. Old-growth stands were dominated by Douglas-fir, western hemlock, and western red cedar, while young stands were dominated by Douglas-fir. Foliage at upper, middle and lower crown levels was sampled in old-growth trees by climbing and clipping sample branches. Canopies of young Douglas-fir were sampled randomly from the ground. The sampling period extended from mid-June to early October.

Arthropod species diversity and functional diversity were much higher in canopies of old-growth trees compared to young trees. Aphid biomass was significantly higher in young stands compared to old-growth stands. The ratio of defoliating insects to sap-sucking herbivores was found to be different between the stands, with higher ratios in old-growth. The ratio of predator species to herbivore species was higher in old-growth than young stands, and predator species richness was much greater in the old-growth.

Key Finding: Old-growth forests, which have a greater diversity of insect predators, are predicted to help control pest populations.

Source: Franklin, J. F., D. A. Perry, T. D. Schowalter, M. E. Harmon, A. McKee and T. A. Spies. 1989. Importance of ecological diversity in maintaining long-term site productivity. pp. 82-97 in Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. D. A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, R. F. Powers, eds. Timber Press, Portland, Oregon.

The authors discuss the importance of ecosystem resilience - the "ability to absorb stress or change without significant loss of function." Forest management has resulted in increased simplification of forests - structurally, genetically, on the landscape scale, and in terms of successional stages.

Stresses on forests such as pollutants, global climate change, and pests and pathogens are reviewed. The authors report studies indicating that disease and pest problems may be worse in managed stands than in natural stands, and that thinning practices contribute to diseases such as root rot. The authors also review findings that suggest that old-growth forests have a greater diversity of insect predators that may help limit pest populations. They state that damage by herbivorous insects could increase as the area of old-growth forests increasingly diminishes.

Key Finding: Ant and bird predation reduced adult western spruce budworm densities by approximately 10- to 15-fold at low budworm densities, and by approximately twofold at high budworm densities.

Source: Campbell, R. W., T. R. Torgersen and N. Srivastava. 1983. A suggested role for predaceous birds and ants in the population dynamics of the western spruce budworm. Forest Science 29: 779-790.

Ants, birds, or both were excluded from individual trees using sticky barriers for ants and whole-tree exclosures for birds in order to examine these predators' impacts on western spruce budworm (Choristoneura occidentalis) density. Study sites were in central Idaho (interior Douglas-fir/grand fir/ponderosa pine) and northcentral Washington (Douglas-fir/ponderosa pine). Budworm densities were sampled from the fourth instar to adult stage. At the lowest budworm density, trees protected from both birds and ants had 10 to 15 times as many adult moths as control trees. At higher densities of budworms (25 insects per m2 of foliage), protected trees had two times as many adult moths. Birds alone or ants alone also greatly dampened survival rates of spruce budworm.

Key Finding: Thatching ants play an important role in suppressing insect defoliator populations.

Source: McIver, J. D., T. R. Torgersen and N. J. Cimon. 1997. A supercolony of the thatch ant Formica obscuripes Forel (Hymenoptera: Formicidae) from the Blue Mountains of Oregon. Northwest Science 71: 18-29.

The authors review studies on thatching ants (Formica-rufa group). Their ability to reduce populations of defoliators during outbreaks was believed to be due to their high metabolic demands and ability to switch to foods that become more abundant. The authors also observe that stands with a large population of thatching ants experienced less defoliation from spruce budworm than stands lacking these ants, although experimental evidence had yet to be collected. Reasons for the decline in thatching ant populations in the Blue Mountains are unknown.

The authors describe a rare supercolony of western thatching ants (Formica obscuripes) from the Blue Mountains. Total nestbound population was estimated to be 56 million individuals. The authors calculated that this population would require at least 470 kg dry weight of food annually, which is about 11 times the total dry weight of western spruce budworm that might occur during an outbreak.

Key Finding: Ants, important predators of the western spruce budworm, require sufficient down wood in a range of sizes and decomposition stages.

Source: Torgersen, T. R. and E. L. Bull. 1995. Down logs as habitat for forest-dwelling ants (the primary prey of pileated woodpeckers in northeastern Oregon. Northwest Science 69: 294-303.

Down logs, important habitat for forest-dwelling ants, were examined for their key characteristics and the species of ants using them. The 12 study sites were in uneven-aged mixed-conifer stands of the Blue Mountains, northeastern Oregon. Ants were of interest because many species are predators of the western spruce budworm (Choristoneura occidentalis), and 12 of the 13 ant species are reported to colonize standing or down dead wood. Ants are also an important food source for pileated woodpeckers.

All logs * 15 cm in diameter at the larger end and * 2 m long were sampled and classified according to five decomposition classes. In total, 1,385 logs were sectioned. Six logs per plot were sectioned to collect ant specimens. Ants were grouped into Camponotus species, Formica species, and other species.

Logs in the largest diameter class (51-120 cm), although only accounting for 8.3% of the logs, represented 37.6% of the down log volume. Nearly half of the total logs were in the smallest class (15-22 cm) and accounted for 11.9% of the volume.

Of the sectioned logs, 61.8% had ant groups in them, comprised of 13 species. Lasius alienus was the most common, followed by Formica neorufibarbis and Camponotus modoc. Camponotus ants occurred significantly more frequently in logs of the largest diameter class. Formica and other ants occurred in logs of all size classes but significantly favored logs * 7m long over 1-3 m long logs. Formica ants occurred significantly less commonly in the most decomposed logs compared to the other decomposition classes; Camponotus species also tended to avoid these logs.

The authors report that three Camponotus and three Formica species identified in this study are known to be predators of western spruce budworm. At least one of these species was found in 31.8% of the sectioned logs. The authors conclude that these ants use a range of logs of different sizes, species, and stages of decomposition. They caution that leaving insufficient amounts and kinds of down wood, because of logging or firewood cutting, could affect pileated woodpecker populations and the control of western spruce budworm.

Chapter 4

INVASION BY HARMFUL EXOTIC (NON-NATIVE) PLANTS AND ANIMALS

Invasion by non-native species: Roads, soil disturbance, and reduced forest cover facilitate invasion by exotic (non-native) species.

Key Finding: Non-native plant species occurred on high-use, low-use, and abandoned forest roads, with the greatest frequency on roads with the highest level of disturbance and lowest percentage of canopy cover.

Source: Parendes, L. A. and J. A. Jones. In press. Light availability, dispersal, and exotic plant invasion along roads and streams in the H. J. Andrews Experimental Forest, Oregon. Conservation Biology.

The authors surveyed exotic (non-native) plant species along road segments and streams in the western Cascades and their association with different levels of light, disturbance, and dispersal mechanisms. Three types of forest roads were studied: high-use roads, low-use roads, and abandoned roads. Five transects were placed in each of the habitat types. The presence or absence of 21 exotic species was recorded, along with light levels (as measured by percentage canopy cover). Nearly three hundred 50 x 2 m sampling units were surveyed.

All of the sample sites on high-use and low-use roads had at least one exotic species present. Roads abandoned for 20 to 40 years varied in terms of exotic species being present or absent, but had up to eight species on some sample units. Exotic species were more frequent along high-use and low-use roads than on abandoned roads. These roads also had higher light levels and a greater frequency of disturbance due to traffic and maintenance. The six most frequently occurring exotic species (occurring in more than 50% of the sample units) were clearly correlated with higher light levels and had a higher frequency on roads that had a greater use. The relationship with plant dispersal ability was relatively complex.

The authors concluded with a discussion of the role roads play in facilitating exotic invasions, by providing suitable habitat of higher light levels due to reduced canopy cover and frequent disturbances, and through transport of seeds on vehicle tires.

Key Finding: Exotic annual plants invaded an ecological reserve in California along a pipeline corridor and were still dominant in the corridor 10 years after the disturbance occurred.

Source: Zink, T. A., M. F. Allen, B. Heindl-Tenhunen and E. B. Allen. 1995. The effect of a disturbance corridor on an ecological reserve. Restoration Ecology 3: 304-310.

Sample plots were established in the Santa Margarita Ecological Reserve in California to investigate plant species composition and soil properties on a pipeline corridor and in four adjacent undisturbed habitats - oak woodland, coastal sage, grassland, and chaparral. Exotic annual plants were found to dominate the entire length of the corridor, with little reestablishment of native plant species, although more than 10 years had passed since the last disturbance. Exotics also were invading adjacent grassland (19% exotic species coverage), coastal sage (16% exotic species coverage) and oak woodland (13% exotic species coverage) communities, but were not present in undisturbed chaparral.

Significantly less organic matter was present in soil layers of the disturbed corridor than in the adjacent undisturbed areas. Available nitrogen and extractable phosphorus were higher in soils of the disturbed corridor. The authors believe that the more rapidly decomposing leaf litter of exotics and higher nutrient mineralization rates in the pipeline corridor will continue to favor dominance by the exotic plant species.

Key Finding: Oriental bittersweet, an exotic vine of the eastern United States, responded vigorously to increased light intensity after disturbances such as road construction, logging, or windthrow.

Source: McNab, W. H. and M. Meeker. 1987. Oriental bittersweet: a growing threat to hardwood silviculture in the Appalachians. Northern Journal of Applied Forestry 4: 174-177.

The authors review the threats posed by the exotic vine oriental bittersweet (Celastrus orbiculatus) and present information collected from foresters' first-hand experiences in the Appalachian mountains. The vine is considered a pest in forested areas of the northeastern and southern United States. It forms impenetrable thickets and maintains dominance through heavy shading of the ground layer. It is a problem for both regeneration and pole-sized timber, rapidly overgrowing seedlings in forest openings and shading out crown foliage in young stands.

Much of the information collected for this article was from the Bent Creek Experimental Forest in North Carolina. Bittersweet seedlings, which can persist in the shade, exhibited rapid growth with increased light from disturbances, such as construction of logging roads, logging, or windthrow. Construction of the Blue Ridge Parkway in the 1960s apparently provided a new, sunny corridor, and oriental bittersweet was observed to expand along the highway and other roads in the Bent Creek Experimental Forest. Oriental bittersweet was present on 79% of road segments sampled. The vine also rapidly overgrew a small clearcut in mature oak forest in the Experimental Forest within seven years.

Once established, oriental bittersweet expands easily into shaded forest. Birds help disperse the seeds, and seedlings of bittersweet can reportedly survive in dense shade. A 15-year-old sapling stand in Bent Creek Experimental Forest was invaded by the vine, which girdled many of the trees and caused stem and crown deformities. These trees were later more susceptible to ice storm damage, as well.

The authors review efforts to control the vine, noting that it is very difficult to control mechanically, although herbicides may be effective.

Key Finding: Spotted knapweed invaded new areas along roadsides.

Key Finding: Spotted knapweed preferred open canopies and disturbed areas.

Source: Marcus, W. A., G. Milner and B. Maxwell. 1998. Spotted knapweed distribution in stock camps and trails of the Selway-Bitterroot Wilderness. Great Basin Naturalist 58: 156-166.

The authors review the history and spread of spotted knapweed (Centaurea maculosa), a non-native plant. The plant was introduced in the early twentieth century and now reportedly covers almost 3 million ha in the northwestern United States. It inhabits areas with a broad range of elevations, soil types, and moisture levels. In forested areas, spotted knapweed poses the greatest threat to low-elevation ponderosa pine and Douglas-fir habitat. The weed is reported to spread rapidly along roads by dispersing from the undercarriage of vehicles. It can also be carried into new forest areas in hay or on camping equipment.

The authors surveyed spotted knapweed in campsites and trails on the Selway-Bitterroot Wilderness (Montana/Idaho). There was no spotted knapweed in camp sites with closed tree canopies. Spotted knapweed was restricted to camps with an open canopy and with high disturbance levels. Along trails, most of the spotted knapweed was within 0.5 km of the trailhead, and abundance decreased with increasing distance (and correspondingly lower disturbance) from the trail.

Key Finding: Spotted knapweed and diffuse knapweed, two exotic species, preferred open, disturbed habitat, including roads, over shaded areas.

Source: Watson, A. K. and A. J. Renney. 1974. The biology of Canadian weeds. Centaurea diffusa and C. maculosa. Canadian Journal of Plant Science 54: 687-701.

The authors summarize information on the distribution and ecology of two exotic plant species in Canada. Spotted knapweed (Centaurea maculosa) is present in British Columbia, Southern Alberta, Ontario, Quebec, and the Maritimes, while diffuse knapweed (Centaurea diffusa) occurs in southern British Columbia and Alberta. Both knapweeds are reported to prefer open habitat and to invade roads, railroad right-of-ways, and overgrazed rangelands. They usually are not found in shaded areas. Both knapweeds colonize a variety of soil types, with density significantly correlated with degree of soil disturbance.

The two weeds outcompete native plant species. Their dense, spiny growth prevents the growth of other species. They are also reported to be allelopathic (chemically inhibiting growth of other species).

Key Finding: Exotic weeds spread along logging roads in forests at all elevations in western Montana.

Key Finding: Exotic weeds invaded clearcuts in mid-elevation forests.

Source: Forcella, F. and S. J. Harvey. 1983. Eurasian weed infestation in western Montana in relation to vegetation and disturbance. Madroño 30: 102-109.

Exotic plant species were surveyed along roadsides and along an elevational gradient in western Montana. Exotic plants occurred along roadsides at all elevations. In grasslands and the low-montane zone (ponderosa pine), exotic weeds had also invaded adjacent communities of native vegetation. In mid-montane forests, exotic plants occupied up to 60% of the plant cover in areas that had been clearcut, but were not present in undisturbed areas. Exotic plants were not present in undisturbed areas of the subalpine zone.

The authors suggest that the amount of light available plays an important role in exotic plant establishment and that loss of canopy cover encourages invasion by weeds. They also note that climate may play a role, with higher weed coverage in lower elevation communities, which have more frost-free months and higher mean July temperatures.

Key Finding: In a regional survey, a greater proportion of anthropogenically disturbed plots in the southeastern and northeastern United States contained at least one exotic species compared to undisturbed plots.

Source: Stapanian, M. A., S. D. Sundberg, G. A. Baumgardner and A. Liston. 1998. Alien plant species composition and associations with anthropogenic disturbance in North American forests. Plant Ecology 139: 49-62.

As part of the Forest Health Monitoring Program (administered by the USDA Forest Service), exotic species were measured on 279 forest plots during the summer of 1994. Plots were distributed in seven regions of the United States - the Northeast, the Mid-Atlantic, the Southeast, California, Minnesota, Colorado, and the Pacific Northwest. However, only four regions * the Southeast, the Northeast, the Mid-Atlantic, and California * had a large enough sample size for statistical analysis. Types of anthropogenic disturbances were recorded for each plot, although more undisturbed plots than disturbed were available, so limiting the information available on effects of disturbance.

A total of 139 alien plant species were recorded. The proportion of plots with at least one exotic species was significantly higher in disturbed areas than undisturbed areas in the Southeast. In the Northeast, a slightly higher proportion of disturbed plots had exotic species, compared to undisturbed plots. Although exotic plant occurrence in the Mid-Atlantic and California did not have a significant relationship with disturbance, exotic species occupied the highest proportion of ground cover in these regions (20% and 25% respectively).

Key Finding: The red imported fire ant, an exotic pest in the southeastern United States, colonized roads, power lines, and forest gaps created by logging.

Key Finding: The density of red imported fire ant mounds was correlated with the degree of soil disturbance and direct sunlight exposure.

Source: Stiles, J. H. and R. H. Jones. 1998. Distribution of the red imported fire ant, Solenopsis invicta, in road and powerline habitats. Landscape Ecology 335: 335-346.

The red imported fire ant (Solenopsis invicta), an exotic pest species, colonizes roads, power lines, and gaps in forests created by logging, displacing native ants, reducing native arthropod diversity and abundance, and increasing predation of young birds, small mammals, and reptiles. The authors report that in South Carolina, roads and power line cuts may provide a source population for dispersal into adjacent forest gaps, where they have observed fire ants.

The authors studied the density and volume of fire ant mounds along four road types with varying canopy cover and disturbance frequency, as well as in power line cuts. Mound density was correlated with light levels and degree of soil disturbance. Mound density was higher along open canopy roads with intermediate to frequent disturbance than roads or power lines with infrequent disturbance. Mean size of mounds was inversely related to frequency of disturbance, with lowest volume in most disturbed habitat. The authors believe that mound density rather than volume is the key factor when evaluating the impact of fire ants.

Spread into undisturbed areas: Exotics can spread into adjacent undisturbed areas from roads and other disturbed sites.

Key Finding: Exotic annual plant species invaded adjacent undisturbed oak woodland, coastal sage, and grassland communities from a pipeline corridor in an ecological reserve in California.

Source: Zink, T. A., M. F. Allen, B. Heindl-Tenhunen and E. B. Allen. 1995. The effect of a disturbance corridor on an ecological reserve. Restoration Ecology 3: 304-310.

Sample plots were established in the Santa Margarita Ecological Reserve in California to investigate plant species composition and soil properties on a pipeline corridor and in four adjacent undisturbed habitats - oak woodland, coastal sage, grassland, and chaparral. Exotic annual plants were found to dominate the entire length of the corridor, with little reestablishment of native plant species, although more than 10 years had passed since the last disturbance. Exotics also were invading adjacent grassland (19% exotic species coverage), coastal sage (16% exotic species coverage), and oak woodland (13% exotic species coverage) communities, but were not present in undisturbed chaparral.

Significantly less organic matter was present in soil layers of the disturbed corridor than in the adjacent undisturbed areas. Available nitrogen and extractable phosphorus were higher in soils of the disturbed corridor. The authors believe that the more rapidly decomposing leaf litter of exotics and higher nutrient mineralization rates in the pipeline corridor will continue to favor dominance by the exotic plant species.

Key Finding: Exotic weeds spread outward from roadsides in lowland forest and rangeland in Montana, invading relatively undisturbed areas.

Source: Forcella, F. and S. J. Harvey. 1983. Eurasian weed infestation in western Montana in relation to vegetation and disturbance. Madroño 30: 102-109.*

Exotic plant species were surveyed along roadsides and along an elevational gradient in western Montana. Exotic plants occurred along roadsides at all elevations. In grasslands and the low-montane zone (ponderosa pine), exotic weeds had also invaded adjacent communities of native vegetation. In mid-montane forests, exotic plants occupied up to 60% of the plant cover in areas that had been clearcut, but were not present in undisturbed areas. Exotic plants were not present in undisturbed areas of the subalpine zone.

The authors suggest that the amount of light available plays an important role in exotic plant establishment and that loss of canopy cover encourages invasion by weeds. They also note that climate may play a role, with higher weed coverage in lower elevation communities, which have more frost-free months and higher mean July temperatures.

* See also key finding above.

Key Finding: Originally confined to roadways and abandoned farmland, cheatgrass now invades shrub, ponderosa pine, and pinyon-juniper ecosystems.

Source: Monsen, S. B. 1994. The competitive influences of cheatgrass (Bromus tectorum) on site restoration. pp. 43-50 in Proceedings (Ecology and Management of Annual Rangelands. S. B. Monsen and S. G. Kitchen, eds. INT-GTR-313. USDA Forest Service. Intermountain Research Station.

The author reviews the spread of cheatgrass (Bromus tectorum) in the Intermountain Basin and the Columbia Basin and describes the resulting cycle of increasing fire frequency and cheatgrass abundance. Initially reported on roadways and abandoned croplands in the early 1900s, cheatgrass has now invaded shrub systems as well as ponderosa pine forests and pinyon-juniper woodlands. Fire frequency has increased on all these sites as a result. An aggressive species, cheatgrass outcompetes many native species and is quick to reestablish after a fire.

The author also reviews restoration attempts in cheatgrass-dominated areas. On treated areas, few native species planted for restoration can compete successfully, and cheatgrass from untreated areas can rapidly reoccupy treated sites. Mechanical tilling and herbicides are necessary for any reseeding attempts to be successful. It is also difficult to prevent cheatgrass from spreading. However, cheatgrass has been documented to naturally disappear from some areas after periods of drought.

Key Finding: The red imported fire ant, an exotic pest in the southeastern United States, is believed to disperse into forest gaps from adjacent roads and power lines.

Source: Stiles, J. H. and R. H. Jones. 1998. Distribution of the red imported fire ant, Solenopsis invicta, in road and powerline habitats. Landscape Ecology 335: 335-346.*

The red imported fire ant (Solenopsis invicta), an exotic pest species, colonizes roads, power lines, and gaps in forests created by logging, displacing native ants, reducing native arthropod diversity and abundance, and increasing predation of young birds, small mammals, and reptiles. The authors report that in South Carolina, roads and power line cuts may provide a source population for dispersal into adjacent forest gaps, where they have observed fire ants.

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The authors believe that mound density rather than volume is the key factor when evaluating the impact of fire ants.

* See also key finding above.

Damage to ecosystem processes: Exotic species disrupt essential ecosystem processes, including natural succession, nutrient cycling, erosion rates, disturbance regimes, and community composition and dynamics.

Key Finding: Oriental bittersweet, an exotic vine in the eastern United States, inhibited seedling regeneration and damaged young hardwood stands through stem girdling.

Source: McNab, W. H. and M. Meeker. 1987. Oriental bittersweet: a growing threat to hardwood silviculture in the Appalachians. Northern Journal of Applied Forestry 4: 174-177.*

The authors review the threats posed by the exotic vine oriental bittersweet (Celastrus orbiculatus) and present information collected from foresters' first-hand experiences in the Appalachian mountains. The vine is considered a pest in forested areas of the northeastern and southern United States. It forms impenetrable thickets and maintains dominance through heavy shading of the ground layer. It is a problem for both regeneration and pole-sized timber, rapidly overgrowing seedlings in forest openings and shading out crown foliage in young stands.

Much of the information collected for this article was from the Bent Creek Experimental Forest in North Carolina. Bittersweet seedlings, which can persist in the shade, exhibited rapid growth with increased light from disturbances, such as construction of logging roads, logging, or windthrow. Construction of the Blue Ridge Parkway in the 1960s apparently provided a new, sunny corridor, and oriental bittersweet was observed to expand along the highway and other roads in the Bent Creek Experimental Forest. Oriental bittersweet was present on 79% of road segments sampled. The vine also rapidly overgrew a small clearcut in mature oak forest in the Experimental Forest within seven years.

Once established, oriental bittersweet expands easily into shaded forest. Birds help disperse the seeds, and seedlings of bittersweet can reportedly survive in dense shade. A 15-year-old sapling stand in Bent Creek Experimental Forest was invaded by the vine, which girdled many of the trees and caused stem and crown deformities. These trees were later more susceptible to ice storm damage, as well.

The authors review efforts to control the vine, noting that it is very difficult to control mechanically, although herbicides may be effective.

* See also key finding above.

Key Finding: Tree seedling density decreased with increasing cover of an exotic honeysuckle, Lonicera tatarica.

Key Finding: The diversity and density of herbaceous species declined as honeysuckle cover increased in three of four northeastern forest stands.

Source: Woods, K. D. 1993. Effects of invasion by Lonicera tatarica L. on herbs and tree seedlings in four New England forests. American Midland Naturalist 130: 62-74.

The impacts of an exotic honeysuckle species, Tatarian honeysuckle (Lonicera tatarica), on herb species richness, density, and tree seedling success was studied in four stands in southwestern Vermont and northwestern Massachusetts. Sample plots were 2 x 2 m, further divided into four 1 m2 quadrats.

Herb richness and cover decreased as honeysuckle cover increased in all three Vermont stands. No effect of competition was apparent in the Massachusetts stand, a site with poor soils. The authors believe that moisture may have been the primary variable driving both herb and honeysuckle cover at this site, where honeysuckle was confined to moist microsites. The effects of honeysuckle on native herbaceous species varied by species, probably due to varying life-history traits.

Density of tree seedlings (less than 1 m tall) declined significantly with increasing honeysuckle cover in all stands. Seedlings established prior to the honeysuckle invasion (1-2 m tall) were not affected by the invading honeysuckle.

The study did not evaluate causal mechanisms, but the authors hypothesize that honeysuckle may outcompete other species by leafing out earlier in the spring than trees and other woody species, thereby shading the forest floor at a time critical for the development of many herbs.

Key Finding: In shrub-steppe ecosystems, invading weed species, which were usually non-mycorrhizal, disrupted succession by native species, 99% of which were mycorrhizae-dependent.

Source: Wicklow-Howard, M. C. 1994. Mycorrhizal ecology of shrub-steppe habitat. pp. 207-210 in Proceedings (Ecology and Management of Annual Rangelands. S. B. Monsen and S. G. Kitchen eds. INT-GTR-313. USDA Forest Service. Intermountain Research Station.

The author reviews the importance of mycorrhizal fungi in shrub-steppe habitat in southwestern Idaho, including their crucial role in acquiring nutrients and water. Studies show that 99% of native plants on undisturbed sites were mycorrhizal, while only 1% of successful exotics were mycorrhizal. The author discussed the long-term impact this may have on succession by native plants in disturbed sites. Sites disturbed and then invaded by exotics reportedly had no vesicular-arbuscular mycorrhizae for up to 10 years. With no host plants to support the mycorrhizae, the fungal propagules may not be able to survive. As a result, establishment of mycorrhizal-dependent plants is expected to be difficult.

Key Finding: An exotic weed, bull thistle, reduced growth rates of ponderosa pine seedlings by up to 33% in a forest plantation.

Source: Randall, J. M. and M. Rejmanek. 1993. Interference of bull thistle (Cirsium vulgare) with growth of ponderosa pine (Pinus ponderosa) seedlings in a forest plantation. Canadian Journal of Forest Research 23: 1507-1513.

In the absence of other vegetation, the exotic bull thistle Cirsium vulgare was found to suppress the growth of ponderosa pine seedlings in a plantation in the western Sierra Nevada. The relative growth rate of ponderosa pine seedlings was negatively correlated with the density of thistles growing within 2 m of seedlings. Growth was reduced by 25-33 % in the treatments having the highest density of thistles. The authors did not determine the causal mechanism. They note that soil moisture, nitrogen, phosphorus, and potassium limitations were not a factor. Competition for nutrients not examined may have been a factor limiting seedling growth or bull thistle may be allelopathic.

Key Finding: Forest litter depth and soil organic layers were lower and pH was higher in sites invaded by two exotic plant species (Japanese barberry and a Japanese grass species), when compared to adjacent uninvaded forest sites.

Key Finding: Native oaks and shrubs occurred at a lower density in forested sites invaded by Japanese barberry and a Japanese grass species than in uninvaded sites.

Source: Kourtev, P. S., J. G. Ehrenfeld and W. Z. Huang. 1998. Effects of exotic plant species on soil properties in hardwood forests of New Jersey. Water, Air and Soil Pollution 105: 493-501.

The effect of invasion by two exotic plant species, Japanese barberry (Berberis thunbergii) and a Japanese grass (Microstegium vimineum) was examined in three deciduous hardwood forests of northern New Jersey. The authors established transects extending through invaded sites and adjacent uninvaded sites and sampled vegetation, woody debris and soils at 50-m intervals.

For all three sites, significant differences in soil and vegetation characteristics existed between invaded and uninvaded plots. The pH of soils in the invaded plots was significantly higher than in the uninvaded plots. Soil organic layers and litter were thinner in invaded plots than in uninvaded plots. Invaded areas had fewer oaks (Quercus spp.) in the canopy and lacked native understory shrubs (Vaccinium spp.).

Key Finding: Surface runoff and soil erosion were greater from spotted knapweed-dominated sites than natural bunchgrass-dominated sites.

Source: Lacey, J. R., C. B. Marlow and J. R. Lane. 1989. Influence of spotted knapweed (Centaurea maculosa) on surface runoff and sediment yield. Weed Technology 3: 627-631.

The authors compared 12 paired plots, dominated either by the exotic, spotted knapweed (Centaurea maculosa), or by natural bunchgrass communities. A 30-minute simulated rainfall was conducted on each plot to measure surface runoff and sediment yield. Spotted knapweed plots had lower average infiltration rates, higher surface runoff, and greater sediment yield than bunchgrass plots. However, there was great variability in volume of runoff and sediment. Slope and percent vegetation cover explained much of the variation in sediment yield, and slope was a significant factor in predicting surface runoff.

Key Finding: Fires have become more common and extensive in pinyon-juniper woodlands and sagebrush ecosystems invaded by cheatgrass, an exotic grass.

Source: Billings, W. D. 1994. Ecological impacts of cheatgrass and resultant fire on ecosystems in the western Great Basin. pp. 22-30 in Proceedings - Ecology and Management of Annual Rangelands. S. B. Monsen and S. G. Kitchen eds. INT-GTR-313. USDA Forest Service. Intermountain Research Station.

The author reviews research on cheatgrass (Bromus tectorum), an exotic grass in the western United States. Cheatgrass is highly competitive and has replaced most of the natural bunchgrasses in the sagebrush ecosystem of the Great Basin. Growing more densely than the naturally scattered bunchgrasses, it utilizes much of the open space between shrubs. During the dry summers of this region, cheatgrass rapidly dries out and becomes an abundant and pervasive source of fuel. Extensive and disastrous fires became common in the sagebrush ecosystem of the western Great Basin in the mid-1930s.

By the 1950s, cheatgrass had also invaded pinyon-juniper woodlands. Fires became more common. Trees were slow to return, with little cover reestablished even after 60 years. Cheatgrass, however, was quick to reestablish, and these woodlands have been replaced by extensive areas of annual grasslands.

The author monitored the effects of cheatgrass on permanent plots established in a Great Basin sagebrush community for 47 years in Nevada. After a large wildfire of 260 ha, little above-ground vegetation remained. More than 40 years after the fire, some shrub species had still not been able to reestablish, while cheatgrass had rapidly returned and increased in abundance.

Key Finding: The incidence of fire has increased in ponderosa pine forests and pinyon-juniper woodlands where cheatgrass, an exotic annual, has invaded. This grass has proven difficult to control.

Source: Monsen, S. B. 1994. The competitive influences of cheatgrass (Bromus tectorum) on site restoration. pp. 43-50 in Proceedings (Ecology and Management of Annual Rangelands. S. B. Monsen and S. G. Kitchen, eds. INT-GTR-313. USDA Forest Service. Intermountain Research Station.*

The author reviews the spread of cheatgrass (Bromus tectorum) in the Intermountain Basin and the Columbia Basin and describes the resulting cycle of increasing fire frequency and cheatgrass abundance. Initially reported on roadways and abandoned croplands in the early 1900s, cheatgrass has now invaded shrub systems as well as ponderosa pine forests and pinyon-juniper woodlands. Fire frequency has increased on all these sites as a result. An aggressive species, cheatgrass outcompetes many native species and is quick to reestablish after a fire.

The author also reviews restoration attempts in cheatgrass-dominated areas. On treated areas, few native species planted for restoration can compete successfully, and cheatgrass from untreated areas can rapidly reoccupy treated sites. Mechanical tilling and herbicides are necessary for any reseeding attempts to be successful. It is also difficult to prevent cheatgrass from spreading. However, cheatgrass has been documented to naturally disappear from some areas after periods of drought.

* See also key finding above.

Key Finding: Invasion in Texas by the red imported fire ant resulted in a 90% decrease in native ant abundance and a 70% decrease in ant species richness.

Source: Porter, S. D. and D. A. Savignano. 1990. Invasion of polygyne fire ants decimates native ants and disrupts arthropod community. Ecology 71: 2095-2106.

The authors studied the ecological impact of invasion by the exotic fire ant Solenopsis invicta in central Texas. Multiple-queen (polygyne) colonies, which have five to 10 times higher nest densities than single-queen colonies, are reported to be increasing in frequency. The authors used pitfall and bait traps to measure ant abundance and diversity in a 32-ha tract of woods and grassy fields. Density of fire ant mounds ranged from 60 mounds/ha in wooded areas to 400 mounds/ha in open areas.

The fire ant populations had a significant adverse effect on the native ant population, which declined in number of individuals by 90%. Species richness of ants decreased by 70%. The abundance and diversity of other arthropods were also affected, declining by 75% and 30% respectively in fire ant infested areas.

Fire ants were 10 to 30 times more numerous than the native ants had been before invasion. Competition for food and nesting sites is the most likely explanation for fire ant success over native ant species.

Key Finding: Native ants had a lower abundance and diversity in areas invaded by the Argentine ant, an exotic ant.

Key Finding: The trophic structure of invertebrate communities changed in areas invaded by Argentine ants, with higher numbers of scavengers at the expense of herbivores, predators, and parasites.

Source: Human, K. G. and D. M. Gordon. 1997. Effects of Argentine ants on invertebrate biodiversity in northern California. Conservation Biology 11: 1242-1248.

A pitfall trapping study was conducted in Jasper Ridge Biological Preserve, northern California, to study the impact of the Argentine ant (Lipepithema humile) on native ant species. Approximately 30% of the preserve had been invaded by Argentine ants, primarily along edges. Sampling was done in grassland, open oak woodland, closed canopy oak forest, and chaparral sites. Captured non-ant invertebrates were classified according to their diet - predators, herbivores, parasites, and scavengers (which included saprophages and mycophages).

Native ant abundance was lower in invaded than uninvaded areas: 19 native ants were trapped in the invaded areas compared to 1,994 in uninvaded areas. Ant communities were also less diverse. Below-ground foraging ants seemed to suffer less displacement by the Argentine ant than above-ground species and composed a much greater percentage of native ants in invaded areas. The total number of ants (including Argentine ants) was higher in invaded areas than in uninvaded areas.

Non-ant invertebrate communities were also less diverse in invaded areas, and the trophic structure had changed. Scavengers were overrepresented in invaded areas, and herbivores, predators, and parasites were underrepresented. Changes in populations were attributed to competition and some predation, although Argentine ants are primarily scavengers.

Key Finding: Northern bobwhite populations in Texas decreased after invasion by the non-native red imported fire ant.

Key Finding: Densities of northern bobwhites increased after treatment to reduce infestation by the red imported fire ant.

Source: Allen, C. R., R. S. Lutz and S. Demarais. 1995. Red imported fire ant impacts on northern bobwhite populations. Ecological Applications 5: 632-638.

The vulnerability of northern bobwhite (Colinus virginianus) populations to red imported fire ants (Solenopsis invicta), a non-native ant species, was studied in 15 Texas counties. Christmas Bird Count data were used for determining bobwhite abundances. No trend in bobwhite abundance was detected during the 12 years prior to fire ant infestation. The species abundance declined, however, after fire ant infestation, while uninvaded counties showed no decline.

Field experiments were also conducted to determine the efficacy of treating ant-infested sites. Densities of northern bobwhites increased on treated areas. The mechanism through which red fire ants affect northern bobwhites was not determined. The birds' eggs may be vulnerable to predation, or declines in the native insect communities may reduce their food source.

Chapter 5

DAMAGE TO SOIL RESOURCES AND TREE GROWTH

Damage to soils: Logging activities, including roadbuilding, result in soil compaction, organic layer disturbance, and soil erosion, which may persist for decades.

Key Finding: Logging resulted in soil compaction, displacement of surface mineral soil, loss of organic matter, and loss of nitrogen, an essential nutrient.

Source: Jurgensen, M. F., A. E. Harvey, R. T. Graham, D. S. Page-Dumroese, J. R. Tonn, M. J. Larsen and T. B. Jain. 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland Northwest forests. Forest Science 43: 234-251.

The authors review scientific literature on the impact logging has on soil properties and site productivity (e.g. tree growth) in the Inland Northwest. Logging and site preparation result in soil compaction, displacement of surface mineral soil, and loss of organic matter (including woody residues and forest floor layers). Loss of soil organic matter also results in the loss of soil nitrogen and decreased ability of a site to fix new nitrogen. Soil organic matter is important for ectomycorrhizal development, which in turn plays a role in nutrient uptake and seedling survival. Studies on tree growth indicated that growth is reduced on soils affected by logging, and losses of soil organic matter and nutrients are estimated to last from 10 to 250 years, depending on site conditions.

Key Finding: Logging on volcanic ash soils in the Pacific Northwest caused soil compaction, as measured by increased soil bulk density.

Source: Geist, J. M., J. W. Hazard and K. W. Seidel. 1989. Assessing physical conditions of some Pacific Northwest volcanic ash soils after forest harvest. Soil Science Society of America Journal 53: 946-950.

The authors studied the impacts of logging on volcanic ash soils in 11 forest harvest units in the Blue Mountains of eastern Oregon and Washington (Umatilla National Forest, Malheur National Forest, and Wallowa Whitman National Forest). Sites logged 14 to 23 years earlier were compared to unlogged sites. The soil surface condition was evaluated along 30-m-long line transects, which included skid trails and landings, but excluded the primary transportation system.

Average bulk densities were higher on logged sites than unlogged sites, and frequency distributions of bulk density measurements in logged areas were skewed toward higher bulk densities. Damage due to soil compaction was evaluated at the 15% and 20% standards, i.e. when soil bulk densities were * 15% higher than the mean from unlogged areas; or soil bulk densities were * 20% higher. Under the 15% standard, 28% of the logged area had detrimental compaction. Under the 20% standard, 19% of the logged area had detrimental compaction.

Key Finding: Average soil bulk density was 15% greater on skid trails than on undisturbed soils in a ponderosa pine site 23 years after logging, and 28% greater on a lodgepole site 14 years after logging.

Source: Froehlich, H. A., D. W. R. Miles and R. W. Robbins. 1986. Growth of young Pinus ponderosa and Pinus contorta on compacted soil in central Washington. Forest Ecology and Management 15: 285-294.

The authors conducted a study to determine the effect of soil compaction on the growth of natural regeneration. The two study areas (ponderosa pine and subalpine fir) were located in southern Washington, on the eastern slope of the Cascade Mountains. Multiple regression equations were developed to determine the relationship between tree growth and the variables of age, site index, overstory basal area, number of trees per plot, bulk density, and surface organic matter.

Ponderosa pine regeneration was nine to 18 years old, growing on a ponderosa pine site selectively logged 23 years earlier. The growth of 61 ponderosa pine trees was measured and soil bulk densities were obtained. Mean soil bulk density on the skid trails was found to be 15.4% higher than on undisturbed soils. Total growth of ponderosa pine as well as growth over the last five years was significantly correlated to tree age, site index, stand basal area, and percent increase in soil bulk density. Total tree height, diameter, and volume growth were reduced by 5%, 8%, and 20% respectively at the mean increase in soil bulk density. Height and diameter growth over the previous five years showed a stronger effect of bulk density, and the authors conclude that height and diameter growth may be more affected by compaction as trees develop.

Lodgepole regeneration in the subalpine fir zone was 10 to 13 years old on a stand that had a group selection cut 14 years earlier. Twenty-five lodgepole pine trees were sampled. Mean soil bulk density was found to be 27.5% higher on disturbed than on undisturbed soils. No relationship was found between bulk density and tree growth. Age and organic matter presence were the most important variables correlated to lodgepole pine growth.

Key Finding: Compacted volcanic and granitic soils were slow to recover on skid trails in western Idaho, and after 23 years, only the bulk density of the granitic soil's top few centimeters had returned to undisturbed values.

Source: Froehlich, H. A., D. W. R. Miles and R. W. Robbins. 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Science Society of America Journal 49: 1015-1017.

Rates of recovery were studied on compacted skid trails on granitic soils and volcanic soils in mixed-conifer sites of west-central Idaho. Soil bulk densities were measured at 5.1-, 15.2-, and 30.5-cm depths and compared with adjacent undisturbed soil. Volcanic soils showed greater initial compaction than granitic soils. Recovery rates for the two soil types were not significantly different, however. After 23 years, only the surface 5.1 cm of granitic soil had returned to bulk density values equivalent to undisturbed values.

Key Finding: Stump removal, a method of Armillaria root disease control, resulted in high levels of soil compaction in ash-cap soils.

Source: Page-Dumroese, D. S., A. E. Harvey, M. F. Jurgensen and M. P. Amaranthus. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Canadian Journal of Soil Science. 78: 29-34.*

The authors examined the impact of stump removal, a method that is sometimes used to control Armillaria root disease in the western United States. Control (no compaction), stump-extraction treatments, and severe compaction treatments were investigated on a site in northern Idaho with an ash-cap soil. Soil bulk density increased by 15-20% to a depth of 30 cm in the compaction treatment. Stump removal increased bulk density at the 20-30 cm depth, though surface soil bulk density decreased. Soil strength increased at the 40-45 cm depth after stump removal and was similar to values in the compacted treatment. This increase in soil strength was believed to be due to equipment vibration because volcanic ash soils are apparently particularly susceptible to vibrational compaction. The authors report that increased soil strength has been shown to impede root growth.

A year after planting, Douglas-fir seedlings had lower root volume in the soil compaction treatment. Soil compaction and stump removal also resulted in decreased ectomycorrhizal development and non-ectomycorrhizal short roots on Douglas-fir seedlings. After stump removal, there was a 70% decline in numbers of ectomycorrhizal root tips and a 63% reduction in morphological types on Douglas-fir compared to the no-compaction treatments. After three years, the height of Douglas-fir seedlings in the stump-removal plot was 20% lower and root collar diameter was 30% lower than for seedlings in the other treatments.

Western white pine seedling root volumes were not affected. They had smaller root collar diameters in the stump removal and compaction treatments but greater height in the compaction treatment. Western white pines' numbers of non-ectomycorrhizal root tips decreased significantly, although ectomycorrhizal diversity was not affected. Seedlings' ability to capture site resources was considered to be negatively affected.

* See also key finding in Chapter 2.

Key Finding: Soil bulk density increased, aeration porosity decreased, and water conductivity decreased in the upper layers of soil after logging in the Piedmont region.

Source: Gent Jr., J. A., R. Ballard, A. E. Hassan and D. K. Cassel. 1984. Impact of harvesting and site preparation on physical properties of Piedmont forest soils. Soil Science Society of America Journal 48: 173-177.

A study was conducted in a 22-year-old loblolly pine (Pinus taeda) plantation in Vance County, North Carolina, before and after logging. Soils were sandy loam grading down to clay loam at a depth of 23-30 cm. Plots were established on primary skid trails and on areas that were whole-tree harvested. Soil core samples were collected at varying depths, down to 30 cm, and soil bulk density, aeration porosity, and saturated hydraulic conductivity were measured. Soil bulk density increased by 36% in the top soil layer (0-8 cm) of skid trails and by 20% in the 8 to 15 cm layer. The new bulk densities were 1.52 mg/m3 and 1.8 mg/m3 respectively, which the authors believe may be high enough to impede root growth. In whole-tree plots, bulk density increased by 17% in the top 8 cm and by 7% in the 8 to 15 cm layer. The authors noted that bulk density increases in the top 8 cm could be high enough to impede root growth.

Aeration porosity significantly decreased at depths from the surface horizon to a depth of 23 cm on both skid trails and in whole-tree harvest areas. Saturated hydraulic conductivity significantly decreased down to depths of 8 cm on skid trails and down to depths of 15 cm in whole-tree plots. This affects the rate at which water can move through the soil system. The authors report that critical values for conductivity have not been established. At depths of 23-30 cm in whole tree plots, saturated hydraulic conductivity increased.

Key Finding: Logging was documented to cause soil compaction in a variety of soil types in the southern United States.

Source: Reisinger, T. W., G. L. Simmons and P. E. Pope. 1988. The impact of timber harvesting on soil properties and seedling growth in the South. Southern Journal of Applied Forestry 12: 58-67.

The authors review research done since 1970 on the effects of logging on soil properties and productivity in a variety of soil types in the southern United States - in the Piedmont, Coastal Plain, and mountainous areas. They report great variability in the severity of soil disturbance and compaction depending on the equipment used, soil type, and soil moisture content. However, measures of compaction such as bulk density, porosity, and hydraulic conductivity were affected in all studies reviewed. For example, bulk density increases of 10%, 13%, and 20% were reported. Aeration porosity was documented to decrease by 49% in silt loam soils and by an average of 68% in loamy sands and silty clay loams. Infiltration rates also decreased in compacted soils, and a study in the Lower Coastal Plain indicated that mean infiltration rates were down to 10-22% of original rates. Skid trails and yarding corridors reportedly suffered the greatest soil compaction.

The authors also report numerous studies that indicate decreased seedling establishment and growth on compacted soils. While some compaction effects may be ameliorated over the years, research shows that compaction may persist in the lower soil horizons.

Key Finding: Logging resulted in soil compaction and disturbance of organic matter in three New England forests.

Source: Martin, C. W. 1988. Soil disturbance by logging in New England - review and management recommendations. Northern Journal of Applied Forestry 5: 30-34.

The extent and severity of soil disturbance and compaction was assessed on three whole-tree harvest sites - a central hardwood site in Connecticut, a northern hardwood site in New Hampshire, and a spruce-fir site in Maine. At all three sites, 48-81% of the soil had some compaction. Compaction was potentially serious on 23-35% of the sites, and even one pass of a crawler-tractor was shown to reduce soil macropore space. Soil disturbance included disruption or removal of organic layers, compression ruts, and mounding of soil.

Key Finding: Logging activity caused significant soil erosion in the Pacific Northwest.

Key Finding: Soil compaction leads to surface erosion.

Key Finding: Clearcutting and post-logging slash burning were associated with high rates of ravel (upslope erosion) on various soil types in the Northwest.

Key Finding: Roads caused debris slides in areas that would be relatively stable otherwise.

Source: Swanson, F. J., J. L. Clayton, W. F. Megahan and G. Bush. 1989. Erosional processes and long-term site productivity. pp. 67-81 in Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. D. A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, R. F. Powers, eds. Timber Press, Portland, Oregon.

The authors review various soil erosion processes and their impact on site productivity in the Pacific Northwest. Clearcutting and road construction have been reported to result in surface erosion and increase the frequency and extent of debris slides. The authors pinpoint surface erosion as the most likely to affect site productivity because of the large areas that can be affected and the fact that it is the most nutrient-rich layers that are lost due to soil erosion. Comparative studies showed that surface erosion was significantly higher in clearcuts than in undisturbed forest. A study in Oregon demonstrated that five years after clearcutting, surface erosion rates on a steep slope were stabilized, but still three times higher than in the forested control. Erosion was even higher in clearcut and burned forest. The authors also report overland water flow and erosion being common where soils were compacted.

Rates of soil ravel are high after slash burning on loamy soils, clay loams, and gravel loam soils in the Oregon coast range, particularly on slopes over 60%. Skeletal soils, widespread in the Klamath Mountains and Idaho Batholith are also very susceptible to ravel erosion, and soil removal could progress upslope by 50 m or more from a road cut, small slide scar or stream. The greatest loss reported was in areas with clearcutting and hot slash burning.

The impacts of forest roads on site productivity through erosion was variable according to studies on the issue. Areas downslope of roads were affected to varying degrees by the changes in drainage, depending on species' moisture requirements. Roads can also affect upslope and downslope areas by causing debris slides and modifying the groundwater system. Debris slides due to roads can apparently occur on areas that otherwise would have little chance of sliding. These slides can experience further erosion from road runoff.

The authors note that little comparative information was available on the impact of wildfires on erosion. They also state that the long-term effects of accelerated erosion are unknown at present and urged further study.

Key Finding: The likelihood of surface runoff increased on the compacted soils of skid trails.

Source: Gardner, B. D. and S. K. Chong. 1990. Hydrologic responses of compacted forest soils. Journal of Hydrology 112: 327-334.

Soil hydrologic properties were measured at a logging site in Shawnee National Forest, Illinois. The average slope of the logging trail was 19%. Soil cores were collected from undisturbed areas adjacent to the trail and from the skid trail. Bulk density, sorptivity, and hydraulic conductivity were obtained from the cores. These values were used to calculate incipient ponding time, which is used as a parameter for measuring runoff potential of an area. The authors' results show that ponding time decreased from 34.3 seconds to 19.1 and 5.8 seconds in log ruts and wheel tracks, respectively, and that runoff potential correspondingly increases.

Key Finding: Subsurface flow converted to surface flow by road cuts could trigger soil erosion and mass movement.

Source: Megahan, W. F. 1972. Subsurface flow interception by a logging road in mountains of Central Idaho. pp. 350-356 in Watersheds in Transition. Proceedings of a symposium on "Watersheds in Transition." S. C. Csallany, T. G. McLaughlin and W. D. Striffler, eds. Fort Collings, Colorado. June 19-22, 1972. AWRA. Urbana, Illinois.

The author's study site was located in the Idaho Batholith, where water in undisturbed forest rarely flows overland after a heavy rainstorm or snowmelt, but instead is primarily subsurface flow. Megahan's study measured the volume of subsurface flow intercepted by a road in two undisturbed micro-watersheds. The forest was composed primarily of ponderosa pine, Douglas-fir, and Engelmann spruce. Slopes ranged from 35% to more than 70%.

Water was collected at road cut banks where bedrock was exposed. Subsurface flow emerged on the face of the bedrock and ran down to a collection trough. Subsurface flow was therefore converted to surface flow. The author calculated that along a given length of road, the amount of subsurface flow intercepted by the road was 7.3 times greater than surface runoff from the road alone after a precipitation event.

The author discusses the impacts of converting subsurface flow to surface flow. Total watershed runoff volume probably increases. Surface flow commonly causes significant surface erosion, and excess soil water can result in mass erosion. In addition, the author mentions the potential broader ecological impacts of rerouting subsurface flow from downslope habitat, such as the alteration of vegetation species composition and growth rates.

Key Finding: Soil erosion rates due to debris slides were many times higher on forests with roads, landings, and logging activity than on undisturbed forests.

Source: Amaranthus, M. P., R. M. Rice, N. R. Barr and R. R. Ziemer. 1985. Logging and forest roads related to increased debris slides in southwestern Oregon. Journal of Forestry 83: 229-233.

The authors inventoried mass erosion events occurring over a 20-year period in the Siskiyou National Forest in the Klamath Mountains of southwestern Oregon. Aerial photos were analyzed from 24 forest sites and erosion attributed to roads, logging, or natural events. The volume of soil mass movements was estimated from the photographs, with partial field checking to confirm accuracy. Debris slides were found to be the primary type of mass erosion, accounting for about 80% of the volume of soil moved and 90% of

mass erosion events inventoried. A total of almost 1.5 million yd3 of debris slide erosion occurred. Roads, occupying 2% of the area studied, were the sites for more than half the slides and 60% of the erosion volume. Clearcut areas, occupying 10% of the area studied, were the sites for 34% of the slide events and 18% of the slide volume. The authors also analyzed slides with respect to position on slopes, aspect, precipitation, and geology of study area.

Key Finding: Roads were responsible for 61% of the soil volume displaced by erosion in northwestern California.

Source: McCashion, J. D. and R. M. Rice. 1983. Erosion on logging roads in northwestern California: How much is avoidable? Journal of Forestry 81: 23-26.

The authors investigated erosion due to forest roads and logging in northwestern California. Their inventory covered 344 miles of roads in the Coast and Klamath Mountains. Roads were thinly rocked, graveled, or heavily rocked and regularly maintained logging roads. Slope, grade, aspect, cut-and-fill height, and soil volume displaced by erosion were recorded on each 1-mile road segment.

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In a separate study, erosion due to roads relative to logging areas was studied in 30,000 acres of commercial timberland in Six Rivers National Forest. The road network occupied less than 4% of the total logging area. Total erosion from the 30,000 acres was 137,800 cubic yards. Of this total, 40% came from the roads and 60% from the logged areas. The average erosion rate in the road rights-of-way (47 cubic yards per acre) was 17 times the average erosion rate in the logging areas (2.82 cubic yards per acre).

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A review of the scientific literature, including research from Alaska, Utah, California, Oregon, and Japan, demonstrates that clearcutting on slopes increased the frequency of mass soil movement events (landslides, earthflows, slips, etc.). The loss of forest cover is believed to affect slope stability in two principal ways:

1) Mechanical root support due to interconnected root systems is lost after logging. Research in Alaska, for example, indicated a time lag after clearcutting before landslide activity increased and a lack of landslide correlation with rainfall intensity. The authors believe this is due to the increased deterioration of root systems with time. Other studies similarly show that with increasing age and maturity, the effectiveness of forest cover in preventing landslides increases.

2) A denuded slope is likely to reach critical soil saturation earlier than a forested slope (since no transpiration from trees can occur). Therefore, during a large storm, it is predicted that these soils will reach a critical failure condition earlier than a forested slope would.

Impacts on tree growth and health: Soil compaction and disturbance harm trees by depriving them of moisture and nutrients (through damaged roots, restricted root growth, a loss of beneficial soil microorganisms and mycorrhizal fungi, and reduced water infiltration).

Key Finding: Soil compaction results in root damage and decreased root growth, which decrease plants' ability to access nutrients and water.

Key Finding: Soil compaction and organic matter disturbance cause a decline in mycorrhizal fungi.

Key Finding: Soil compaction results in reduced infiltration rates and increased surface erosion.

Key Finding: Soil compaction results in a loss in site productivity as measured by tree growth.

Source: Childs, S. W., S. P. Shade, D. W. R. Miles, E. Shepard and H. A. Froehlich. 1989. Soil physical properties: importance to long-term forest productivity. pp. 53-66 in Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. D. A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, R. F. Powers, eds. Timber Press, Portland, Oregon.

Damage to soil resources through soil compaction, surface disturbance, and topsoil loss is reviewed. Soil compaction results in decreased soil aeration, decreased water storage, and an increase in soil bulk density. A corresponding decrease in root growth as well as damage to roots results in a decreased ability of plants to access nutrients and water. Mycorrhizal fungi and soil microbial populations are diminished by compaction and organic matter disturbance. Nutrient availability to plants is reduced. Water infiltration rates decrease, and erosion losses of valuable topsoil layers increase. Changes in infiltration and corresponding changes in the hydrologic cycle can also degrade the site. Several studies report the effects of soil compaction as being at least several decades long.

The result of these management impacts on the soil is a loss in site productivity, such as tree height and volume. The authors also caution that the resilience of the ecosystem may be negatively affected, with a corresponding increased susceptibility to damage in the future.

Key Finding: Soil compaction restricted root growth and increased moisture stress in southern U.S. forests.

Source: Reisinger, T. W., G. L. Simmons and P. E. Pope. 1988. The impact of timber harvesting on soil properties and seedling growth in the South. Southern Journal of Applied Forestry 12: 58-67.*

The authors review research done since 1970 on the effects of logging on soil properties and productivity in a variety of soil types in the southern United States - in the Piedmont, Coastal Plain, and mountainous areas. They reported great variability in the severity of soil disturbance and compaction based on factors such as the equipment used, soil type, and soil moisture content. However, measures of compaction such as bulk density, porosity, and hydraulic conductivity were affected in all studies. For example, bulk density increases of 10%, 13%, and 20% were reported. Aeration porosity was documented to decrease by 49% in silt loam soils and by an average of 68% in loamy sands and silty clay loams. Infiltration rates also decreased in compacted soils, and a study in the Lower Coastal Plain indicated that mean infiltration rates were down to 10-22% of original rates. Skid trails and yarding corridors reportedly suffered the greatest soil compaction.

The authors also report numerous studies that indicate decreased seedling establishment and growth on compacted soils. While some compaction effects may be ameliorated over the years, research shows that compaction may persist in the lower soil horizons.

* See also key finding above.

Key Finding: Soil compaction after logging resulted in a loss of soil pore space and a 33% reduction in water to plants.

Key Finding: Soil compaction by logging reduced the movement of water through the soil (saturated hydraulic conductivity), with increases in runoff predicted.

Source: Purser, M. D. and T. W. Cundy. 1992. Changes in soil physical properties due to cable yarding and their hydrologic implications. Western Journal of Applied Forestry 7: 36-39.

Soil bulk density and saturated hydraulic conductivity (the rate at which water can move through the soil) were measured on skid trails before and after logging in the northern Cascade Mountains, Washington. The study site, a western hemlock/Pacific silver fir/western red cedar forest, was located on a steep slope, with gradients ranging from 22* to 45*. Surface and subsurface soils were sampled on four transects.

Mean bulk density values were significantly higher after logging than before. Mean of the saturated hydraulic conductivity values (Ks) was significantly lower after logging. Saturated hydraulic conductivity values (Ks) were significantly lower after logging on three of the four transects. On the fourth site, located in a hollow, sampling locations fell primarily on soil trapped behind slash, rather than the native soil, and Ks values increased.

Increased bulk density and the change in available soil pore space and hydraulic conductivity can affect water flow after rainfall events and result in surface overland flow. Surface overland flow and subsurface flow were calculated for different rainfall depths and increased runoff was predicted in the postlogging soils.

Key Finding: Soil compaction reduced growth of young ponderosa pine.

Source: Froehlich, H. A., D. W. R. Miles and R. W. Robbins. 1986. Growth of young Pinus ponderosa and Pinus contorta on compacted soil in central Washington. Forest Ecology and Management 15: 285-294.*

The authors conducted a study to determine the effect of soil compaction on the growth of natural regeneration. The two study areas (ponderosa pine and subalpine fir) were located in southern Washington, on the eastern slope of the Cascade Mountains. Multiple regression equations were developed to determine the relationship between tree growth and the variables of age, site index, overstory basal area, number of trees per plot, bulk density, and surface organic matter.

Ponderosa pine regeneration was nine to 18 years old, growing on a ponderosa pine site selectively logged 23 years earlier. The growth of 61 ponderosa pine trees was measured and soil bulk densities were obtained. Mean soil bulk density on the skid trails was found to be 15.4% higher than on undisturbed soils. Total growth of ponderosa pine as well as growth over the last five years were significantly correlated to tree age, site index, stand basal area, and percent increase in soil bulk density. Total tree height, diameter, and volume growth were reduced by 5%, 8%, and 20% respectively at the mean increase in soil bulk density. Height and diameter growth over the previous five years showed a stronger effect of bulk density, and the authors concluded that height and diameter growth may be more affected by compaction as trees develop.

Lodgepole regeneration, in the subalpine fir zone, was 10 to 13 years old, on a stand that had a group selection cut 14 years earlier. Twenty-five lodgepole pine trees were sampled. Mean soil bulk density was found to be 27.5% higher on disturbed than on undisturbed soils. No relationship was found between bulk density and tree growth. Age and organic matter presence were the most important variables correlated to lodgepole pine growth.

* See also key finding above.

Key Finding: Beneficial soil microorganisms and mycorrhizal fungi occur primarily in soil organic layers. Soil compaction and the disturbance of organic layers of the soil due to logging activities alter soil microbial activity and adversely affect mycorrhizal populations.

Source: Amaranthus, M. P., J. M. Trappe and R. J. Molina. 1989. Long-term forest productivity and the living soil. pp. 36-52 in Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. D. A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, R. F. Powers, eds. Timber Press, Portland, Oregon.

The authors review research on the functions of soil organisms, their role in site productivity, and the impacts of forest management. Organic layers, woody debris, and the upper mineral soil are the primary substrate for soil biological activity.

Soil organisms are critical for nutrient cycling, including processes such as decomposition, nutrient storage, and nitrogen fixing. Mycorrhizal fungi, important for most timber species, increase the uptake of nutrients and water. They have also been shown to protect tree species from pathogens such as Phytophthora cinnamomi, Fusarium oxysporum, and Rhizoctonia solani. Soil structure - the stability and size of pores - is maintained by mycorrhizae and other soil microbes.

Logging and site preparation have the greatest impact on soil organisms. By destroying large pores in the soil (important for oxygen and water movement), soil compaction drastically changes microbial activity. Loss of organic layers of the soil adversely affects ectomycorrhizae, which are primarily in these layers. Erosion and loss of topsoil have been shown to result in a loss of mycorrhizae and a decline in site productivity.

Key Finding: Ectomycorrhizal abundance and diversity on Douglas-fir seedlings were much lower in soils compacted by stump removal than in undisturbed soils.

Source: Page-Dumroese, D. S., A. E. Harvey, M. F. Jurgensen and M. P. Amaranthus. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Canadian Journal of Soil Science 78: 29-34.*

The authors examine the impact of stump removal, a method that is sometimes used to control Armillaria root disease in the western United States. Control (no compaction), stump-extraction treatments, and severe compaction treatments were investigated on a site in northern Idaho with an ash-cap soil. Soil bulk density increased by 15-20% to a depth of 30 cm in the compaction treatment. Stump removal increased bulk density at the 20-30 cm depth, though surface soil bulk density decreased. Soil strength increased at the 40-45 cm depth after stump removal and was similar to values in the compacted treatment. This increase in soil strength was believed to be due to equipment vibration because volcanic ash soils are apparently particularly susceptible to vibrational compaction. The authors report that increased soil strength has been shown to impede root growth.

A year after planting, Douglas-fir seedlings had reduced root volume in the soil compaction treatment. Soil compaction and stump removal also resulted in decreased ectomycorrhizal development and non-ectomycorrhizal short roots on Douglas-fir seedlings. After stump removal, there was a 70% decline in numbers of ectomycorrhizal root tips and a 63% reduction in morphological types on Douglas-fir compared to the no-compaction treatments. After three years, the height of Douglas-fir seedlings in the stump-removal plot was 20% lower and root collar diameter was 30% lower than for seedlings in the other treatments.

Western white pine seedling root volumes were not affected. They had smaller root collar diameters in the stump-removal and compaction treatments but greater height in the compaction treatment. Western white pines' numbers of non-ectomycorrhizal root tips decreased significantly, although ectomycorrhizal diversity was not affected. Seedlings' ability to capture site resources was considered to be negatively affected.

* See also key findings in Chapter 2 and above.

Key Finding: A 20% increase in soil bulk density due to soil compaction significantly reduced the numbers of root tips on Douglas-fir and western white pine seedlings.

Key Finding: Ectomycorrhizal root tip abundance and diversity in Douglas-fir seedlings were decreased by soil compaction and organic layer removal.

Source: Amaranthus, M. P., D. Page-Dumroese, A. Harvey, E. Cazares and L. F. Bednar. 1996. Soil compaction and organic matter affect conifer seedling nonmycorrhizal and ectomycorrhizal root tip abundance and diversity. Research Paper PNW-RP-494. USDA Forest Service. Pacific Northwest Research Station. 12 p.

The influence of organic matter removal and soil compaction was measured on Douglas-fir and western white pine seedlings. For Douglas-fir, moderate and severe soil compaction significantly reduced nonmycorrhizal root tip abundance. Ectomycorrhizal root tip abundance on Douglas-fir was reduced by 60% in plots with severe compaction and organic matter removal. In plots with severe compaction but no organic matter removed, ectomycorrhizal diversity was significantly reduced, with the average number of ECM types decreasing from 2.7 to 1.

For western white pine, ectomycorrhizal diversity was not affected by soil compaction or organic matter removal treatment. The number of ectomycorrhizal root tips were also not significantly affected by either kind of treatment. However, moderate and severe soil compaction significantly reduced nonmycorrhizal root tip abundance.

The authors discuss the impact of increased soil density on nonmycorrhizal root tips and indicate that a 20% increase in bulk density could significantly reduce nonmycorrhizal root tip numbers. They note that these declines could decrease the capture of site resources by seedlings. Similarly, based on studies on site productivity, the authors report that mycorrhizae are important for seedling establishment after a disturbance. Mycorrhizal diversity may also be important for forest resilience, since each type has a different function.

Key Finding: Soil erosion results in the loss of nutrients and water availability, degraded soil structure, and the loss of important soil organisms including mycorrhizal fungi.

Key Finding: Erosion of the topmost soil layers, which are the most important for nutrients, water, and soil biota, is the most damaging to site productivity.

Key Finding: Roads in mountainous areas affected site productivity upslope and downslope of the road through changes in the groundwater system and through debris slides.

Source: Swanson, F. J., J. L. Clayton, W. F. Megahan and G. Bush. 1989. Erosional processes and long-term site productivity. pp. 67-81 in Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. D. A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, R. F. Powers, eds. Timber Press, Portland, Oregon.*

The authors review various soil erosion processes and their impact on site productivity in the Pacific Northwest. Clearcutting and road construction have been reported to result in surface erosion and to

increase the frequency and extent of debris slides. The authors pinpoint surface erosion as the most likely to affect site productivity because of the large areas that can be affected and the fact that it is the most nutrient-rich layers that are lost due to soil erosion. Comparative studies showed that surface erosion was significantly higher in clearcuts than in undisturbed forest. A study in Oregon demonstrated that five years after clearcutting, surface erosion rates on a steep slope were stabilized, but still three times higher than in the forested control. Erosion was even higher in clearcut and then burned forest. The authors also report overland water flow and erosion being common where soils were compacted.

Rates of soil ravel have been reported to be high after slash burning on loamy soils, clay loams, and gravel loam soils in the Oregon coast range, particularly on slopes over 60%. Skeletal soils, widespread in the Klamath Mountains and Idaho Batholith, were also very susceptible to ravel erosion, and soil removal could progress upslope by 50 m or more from a road cut, small slide scar or stream. The greatest loss was in areas with clearcutting and hot slash burns.

The impacts of forest roads on site productivity through erosion was variable according to studies on the issue. Areas downslope of roads were affected to varying degrees by the changes in drainage, depending on species' moisture requirements. Roads can also affect upslope and downslope areas by causing debris slides and modifying the groundwater system. Debris slides due to roads can apparently occur on areas that otherwise would have little chance of sliding. These slides can experience further erosion from road runoff. The authors note that little comparative information was available on the impact of wildfires on erosion. They also stated that the long-term effects of accelerated erosion are unknown at present, and urged further study.

* See also key finding above.

Role of soil microorganisms and mycorrhizae: Soil microorganisms and mycorrhizal fungi, negatively affected by road building and logging activity, are important for nutrient cycling and the growth and survival of trees.

Key Finding: Healthy ectomycorrhizal populations are important for forest stability and recovery after a disturbance.

Source: Amaranthus, M. P. and D. A. Perry. 1994. The functioning of ectomycorrhizal fungi in the field: linkages in space and time. Plant and Soil 159: 133-140.

The authors review the importance of ectomycorrhizal fungi (ECM) to the growth and survival of trees - they take up nutrients and water, extend feeder root longevity, protect against pathogens, maintain soil structure, and can protect plants from toxic heavy metals. Furthermore, studies document that roots of different plants can be linked by commonly shared ECM fungi. Mycorrhizal hyphae supported by one plant can aid in the establishment of another plant. As a result, young seedlings can form mycorrhizae and obtain energy from an already established host tree. Extending mycelium may also help speed up regeneration in adjacent small forest openings. The authors note that ECM fungi may play a critical role during disturbance when the above-ground community dramatically changes. The existing fungi form a link between the old and new stands by aiding in the establishment of new host trees. Studies showed that tree seedling establishment was much less successful in sites without the appropriate mycorrhizae, such as on sites invaded by non-native plants, which are usually non-mycorrhizal or are associated with different mycorrhizal species.

Key Finding: Mycorrhizal fungi increase nutrient uptake in plants.

Source: Marschner, H. and B. Dell. 1994. Nutrient uptake in mycorrhizal symbiosis. Plant and Soil 159: 89-102.

The authors review the role of mycorrhizae in plant nutrition and the status of research on this topic. Mycorrhizae can increase nutrient uptake by increasing the surface adsorbing area, by excreting compounds that help take up immobile nutrients, or by modifying the soil microflora. Some ectomycorrhizal species, for example, release oxalic acid, which can mobilize phosphorus in calcareous soils where it would otherwise be sparingly soluble. Ectomycorrhizae in particular have been shown to assist in the acquisition of phosphorus, nitrogen, and potassium. There are few definite studies apparently on the role of ectomycorrhizae in the acquisition of other nutrients, particularly micronutrients. However, studies on ectomycorrhizae have also shown that they protect their host plants from excessive uptake of copper and zinc in soils high in heavy metals.

Key Finding: A healthy population of soil organisms is critical for nutrient cycling.

Key Finding: Mycorrhizae increase the uptake of nutrients and water.

Source: Amaranthus, M. P., J. M. Trappe and R. J. Molina. 1989. Long-term forest productivity and the living soil. pp. 36-52 in Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems. D. A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, R. F. Powers, eds. Timber Press, Portland, Oregon. *

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- See also key finding above.

Chapter 6

IMPACTS ON AQUATIC ECOSYSTEMS

Increases in sediment and altered streamflows: Roads and logging degrade aquatic ecosystems by increasing levels of fine sediment deposited in streams and by altering natural streamflow patterns.

Key Finding: Roads degraded stream habitat for aquatic species, including salmonids, by accelerating erosional processes and modifying natural drainage networks.

Source: Furniss, M. J., T. D. Roelofs and C. S. Yee. 1991. Road construction and maintenance. In Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19: 297-323.

The authors review research documenting the impacts of roads on stream habitat. Roads accelerate soil erosion rates due to surface erosion and mass soil movement such as slumps and earthflows, debris avalanches, debris flows, and debris torrents. High rates of stream sedimentation result from this increased erosion. Soil erosion rates (m3/hectare) were 30 to 300 times higher on forests with roads than undisturbed forest. Roads also altered streamflow rates and volumes, which along with increased sedimentation, resulted in altered stream channel geometry. Acting as new flowpaths for water, roads increased the channel network over watersheds, increasing the drainage density.

Research also demonstrated that roads degraded salmonid habitat by creating migration barriers like culverts and temporary dams caused by landslides. Erosion resulted in sedimentation of streams and declines in spawning habitat when too high a proportion of fine sediment was deposited. Macroinvertebrates, the primary food source of juvenile fish, also declined when large amounts of sediment were present.

Key Finding: Logging activities degraded stream habitat by changing the amount, quality, and timing of flowing water, increasing erosion rates, and reducing stream habitat diversity.

Source: Chamberlin, T. W., R. D. Harr and F. H. Everest. 1991. Timber harvesting, silviculture, and watershed processes. In Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19: 181-205.

The authors review the impact logging activities had on salmonid habitat through altering stream processes such as the amount, quality, and timing of flowing water, as well as changing the gravel substrate composition of the streambed, available fish cover, and food supplies. The studies reviewed show that logging altered streamflows by affecting snow accumulation rates in forests and snow melt rates. Because of vegetation removal, logging also changed evapotranspiration rates and soil water content, with resulting increases in annual runoff. Soil compaction changed infiltration rates and therefore runoff and erosion rates.

By removing streamside vegetation, logging changed stream temperatures, raising them in some cases, but lowering winter stream temperatures in more northern regions. Stream temperature was shown to affect the time required for salmonid eggs to develop and hatch. Stream channel structures were also altered after logging, with a corresponding loss of the habitat diversity required by fish populations. By accelerating erosion rates, logging increased sedimentation rates of streams. In the steep and high-rainfall forests of Oregon, Washington, British Columbia, and Alaska, for example, mass movements of soil were the dominant erosional process. Many of these mass movements originated on open areas after logging, with increases in frequency ranging from two to 31 times.

Key Finding: Soil erosion rates due to debris slides were many times higher on forests with roads, landings, and logging activity than on undisturbed forests.

Source: Amaranthus, M. P., R. M. Rice, N. R. Barr and R. R. Ziemer. 1985. Logging and forest roads related to increased debris slides in southwestern Oregon. Journal of Forestry 83: 229-233.*

The authors inventoried mass erosion events occurring over a 20-year period in the Siskiyou National Forest in the Klamath Mountains of southwestern Oregon. Aerial photos were analyzed from 24 forest sites and erosion attributed to roads, logging, or natural events. The volume of soil mass movements was estimated from the photographs, with partial field checking to confirm accuracy. Debris slides were found to be the primary type of mass erosion, accounting for about 80% of the volume of soil moved and 90% of mass erosion events inventoried. A total of almost 1.5 million yd3 of debris slide erosion occurred. Roads, occupying 2% of the area studied, were the sites for more than half the slides and 60% of the erosion volume. Clearcut areas, occupying 10% of the area studied, were the sites for 34% of the slide events and 18% of the slide volume. The authors also analyzed slides with respect to position on slopes, aspect, precipitation, and geology of study area.

* See also key finding in Chapter 5.

Key Finding: Roads were responsible for 61% of the soil volume displaced by erosion in northwestern California.

Source: McCashion, J. D. and R. M. Rice. 1983. Erosion on logging roads in northwestern California: How much is avoidable? Journal of Forestry 81: 23-26.*

The authors investigated erosion due to forest roads and logging in northwestern California. Their inventory covered 344 miles of roads in the Coast and Klamath Mountains. Roads were thinly rocked, graveled, or heavily rocked and regularly maintained logging roads. Slope, grade, aspect, cut-and-fill height, and soil volume displaced by erosion were recorded on each 1-mile road segment.

Mass erosion was the predominant form of erosion occurring in the study sites. Roads caused 152 of the 171 major erosional events inventoried (events that displaced more than 20 cubic yards of soil), and 61% of the soil volume displaced by erosion was due to these road-related events. The remainder was due to natural events and some logging-caused erosion. Road-related erosion increased with the slope traversed by the road. Seasonal roads had similar erosion rates to main-haul (and regularly maintained) roads.

In a separate study, erosion due to roads relative to logging areas was studied in 30,000 acres of commercial timberland in Six Rivers National Forest. The road network occupied less than 4% of the total logging area. Total erosion from the 30,000 acres was 137,800 cubic yards. Of this total, 40% came from the roads and 60% from the logged areas. The average erosion rate in the road rights-of-way (47 cubic yards per acre) was 17 times the average erosion rate in the logging areas (2.82 cubic yards per acre).

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Key Finding: Clearcutting increased the frequency of mass soil movements from hillsides.

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A review of the scientific literature, including research from Alaska, Utah, California, Oregon, and Japan, demonstrated that clearcutting on slopes increased the frequency of mass soil movement events (landslides, earthflows, slips, etc.). The loss of forest cover was believed to affect slope stability in two principal ways:

1) Mechanical root support due to interconnected root systems was lost after logging. Research in Alaska, for example, indicated a time lag after clearcutting before landslide activity increased and a lack of landslide correlation with rainfall intensity. The authors believe this is due to the increased deterioration of root systems with time. Other studies similarly showed that with increasing age and maturity, the effectiveness of forest cover in preventing landslides increased.

2) A denuded slope was likely to reach critical soil saturation earlier than a forested slope (since no transpiration from trees can occur). Therefore, during a large storm, it was predicted that these soils would reach a critical failure condition earlier than a forested slope would.

* See also key finding in Chapter 5.

Key Finding: During storm events in southwestern Washington, average sediment levels in runoff from forest roads ranged from 500 mg/l to 20,000 mg/l.

Key Finding: Roads were direct sources of sediment delivery to streams, with approximately 34% of road drainage points entering stream channels.

Source: Bilby, R. E., K. Sullivan and S. H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. Forest Science 35: 453-468.

The authors studied the erosion of sediment from two kinds of forest gravel roads in southwestern Washington: heavily used, valley-bottom haul roads and midslope secondary haul roads. Sampling sites were located at the downslope of each cross-drain and at ditches draining from cut slopes. Traffic use of each road was also monitored.

The sediment produced from each road segment was related to traffic rate as well as to type of road surfacing material. The majority of the sediment produced (80%) was material finer than 0.004 mm. Steeper roads produced a higher proportion of coarser material (primarily sand). Average sediment concentrations from the secondary road sites were 2,000 mg/l, with a maximum of 19,500 mg/l. Hourly concentrations from the mainline road ranged from 500-700 mg/l, occasionally exceeding 20,000 mg/l.

Delivery of this sediment to streams was investigated by carrying out an inventory of road drainage sites in three watersheds. Two thousand drainage points, along 730 km of road, were identified. Of these, 34% directly entered streams rather than draining into the forest floor.

Key Finding: Very fine sediment washed from a forest road surface directly into a stream during rainfall events.

Source: Bilby, R. E. 1985. Contributions of road surface sediment to a western Washington stream. Forest Science 31: 827-838.

The size of sediment washing from a gravel-surfaced road and its fate after entering a small stream were examined in Johnson Creek, Washington. The study stream was a fourth-order stream, tributary to the Deschutes River. Road sediment entered the creek at a large culvert under the road. Areas upstream of the bridge (upstream of the road sediment entry point) and downstream of the bridge (downstream of sediment entry) were sampled. Freeze-core samples of sediment were taken from five salmonid spawning gravel areas above and below the bridge, three times during the year. Automatic pump samplers were used to measure suspended sediment and turbidity.

During the study period, the road had an average traffic rate of 290 axles daily, primarily logging trucks. During dry weather, there was little difference in stream turbidity upstream and downstream of the culvert. After rainfall events, sediment input from the road frequently increased the levels of suspended sediment

downstream of the culvert compared to upstream levels. Maximum turbidity reached downstream was almost three times the maximum recorded upstream. Road runoff contributed a total of 20.4 metric tons of suspended sediment during the one-year study period. Sediment concentrations reached a peak during peak ditchflow and rapidly dropped off after that. Sediment was primarily very fine particles (more than 80% less than 0.004 mm in size) and was attributed to erosion from the road surface rather than roadside ditches or banks.

Key Finding: Forest road erosion was a source of fine sediment in stormflow runoff, even after mitigation measures.

Source: Swift Jr., L. W. 1984. Soil losses from roadbeds and cut and fill slopes in the Southern Appalachian Mountains. Southern Journal of Applied Forestry 8: 209-216.

The contribution of forest roads to soil erosion was investigated on a newly constructed timber sale access road in the southern Appalachian Mountains. The roadbed surface, cut slopes, and fill slopes were tested separately for soil loss. Dry weight was obtained of heavy particles deposited in collection troughs below cut and fill slopes and in stream sections ahead of each stream-gauging station. To measure lighter-weight particles, stormflow water was filtered and sediment concentrations determined by weight. Two sites were studied, one with a roadbed grade of 7% and the other with a grade of 5%.

The usual practices after road construction of grass seeding on cut and fill slopes and surfacing the roadbed with gravel were delayed for the purposes of this study. The greatest percentage of soil loss occurred during the first winter after road construction, with 42% of the total soil loss from roadbeds (tons/acre) occurring during this period, as well as 58% of the loss from fill slopes and 82% of the loss from cut slopes. Cut slopes had the highest soil erosion in the winter, due to dry ravel and frost heaving. Fill slopes had the highest erosion in early spring. Both cut and fill slopes generally experienced soil erosion of all particle sizes, while more than half the erosion from the roadbed surface was composed of finer particles. Soil erosion rates were higher on the roadbed of the steeper 7% grade site than on the 5% grade site.

After seeding and grading the road surfaces with gravel, soil loss rates were greatly reduced, especially from the grass-covered cut and fill slopes. However, some erosion from the roadbed continued. Despite the reduced erosion rates after these mitigation measures, soil loss from the entire roadway was calculated to be about 20 times the normal rate for undisturbed forest.

Key Finding: Gravel forest roads generated up to 440 tons of sediment/km/year from surface erosion.

Source: Reid, L. M. and T. Dunne. 1984. Sediment production from forest road surfaces. Water Resources Research 20: 1753-1761.

A one-year field study was conducted to determine how much sediment was generated from forest road surfaces and from ditches and cutbanks. Ten road segments were investigated in the Olympic Mountains of Washington State. Of these, eight were gravel roads and two were paved roads. Traffic use was categorized as heavy (more than four logging trucks per day), moderate (one to four trucks), light, and abandoned. During rainstorms, water discharge was measured at the mouth of each culvert and from natural lips on abandoned roads. Rainfall intensities were recorded at each sampling location.

Three factors - traffic intensity, road gradient, and road segment length - were investigated. Sediment loss was found to be related to traffic intensity and was highest on heavy-use gravel roads compared to unused roads or paved roads. Sediment yield from cutbanks and ditches alongside paved roads was less than 1% of that from gravel roads. Heavily used roads were calculated to produce 440 tons of sediment/km/yr over the period of study, compared to lightly used roads with 3.8 tons/km/yr and paved roads with 2 tons/km/yr.

Key Finding: The volume of fine sediment present in streams increased in direct proportion to logging in the watershed and stream crossings by roads.

Source: Eaglin, G. S. and W. A. Hubert. 1993. Effects of logging and roads on substrate and trout in streams of the Medicine Bow National Forest, Wyoming. North American Journal of Fisheries Management 13: 844-846.

The effects of logging and associated road construction on streams and on trout populations were studied in the Medicine Bow National Forest, Wyoming. Twenty-eight stream reaches (200 m each) were examined, with sampling conducted along transects at 4-m intervals. Trout standing stocks were estimated using a backpack electroshocker. The percentage area logged and the density of roads in areas upstream of the drainage were calculated. The density of road culverts was recorded as an index of the extent to which roads crossed watercourses within the drainage.

The amount of fine sediment in a stream reach increased, and the embeddedness of fine sediment (its coverage of large particles) in the substrate increased as the proportion of logged area increased and as the extent to which roads crossed watercourses increased. Trout standing stocks also decreased as the density of road culverts increased.

Key Finding: Logging and forest road construction led to an increase in landslides and surface erosion, disrupting the riparian vegetation along first- and second-order tributaries of a river in Oregon.

Source: Ryan, S. E. and G. E. Grant. 1991. Downstream effects of timber harvesting on channel morphology in Elk River Basin, Oregon. Journal of Environmental Quality 20: 60-72.

Aerial photos were used to investigate the downstream impacts of logging in the Elk River Basin of Siskiyou National Forest in southwestern Oregon. The river and its tributaries were reported to be good habitat for salmonid species such as chinook salmon, steelhead trout, cutthroat trout, and coho salmon.

Commercial logging in the basin began in the mid-1950s. Aerial photos from 1956, 1964, 1969, and 1979 were used to reconstruct the disturbance history of Elk River's tributaries. Openings in riparian canopies due to a disturbance were identified on first- through fifth-order channels and attributed when possible to landslides, debris flows, large floods, or excessive sedimentation from surface erosion.

In first- and second-order tributaries, the number of sections with open riparian canopies (open reaches) increased continuously through the study period. The largest increase in open reach length occurred between 1964 and 1969 after a major 1964 storm. Of the new open reaches, 74% were initiated by landslides; the majority of these were associated with clearcuts or roads. Twenty percent of the open reaches created were attributed to surface erosion; all of these were associated with clearcuts or roads.

Open reaches also occurred on higher order channels (fourth- and fifth-order) but did not show significant changes in number or size over the study period. Upslope forestry activity could not be linked, therefore, to openings downstream in these higher-order tributaries. The authors attribute this to the lack of debris flows in this system, low harvest levels before the major 1964 storm, and slope constraints.

The distribution of gravel bars in the main stem, Elk River (sixth-order), was measured to obtain a rough estimate of increases in sedimentation due to changes upstream. Overall, there was a 77% increase in the number of gravel bars over the 26-km segment of river analyzed. The authors noted that this was a qualitative indication of increased sedimentation, though their study did not demonstrate causation.

The authors note that their methods provide useful coarse-scale information on the erosional impacts of logging and roads, but only where sediment volume or management activity is extensive enough to have removed the riparian canopy.

Key Finding: Roads intercepted subsurface flow on mountainous slopes in the Idaho Batholith, converting it to surface flow.

Key Finding: Subsurface flow converted to surface flow by intercepting roads would be likely to trigger soil erosion and soil mass movement.

Source: Megahan, W. F. 1972. Subsurface flow interception by a logging road in mountains of Central Idaho. pp. 350-356 in Watersheds in Transition. Proceedings of a symposium on "Watersheds in Transition." Fort Collins, Colorado, June 19-22, 1972. AWRA. Urbana, Illinois.

The author's study site was located in the Idaho Batholith, where water in undisturbed forest rarely flows overland after a heavy rainstorm or snowmelt, but instead is primarily subsurface flow. The author measured the volume of subsurface flow intercepted by a road in two undisturbed micro-watersheds. The forest was composed primarily of ponderosa pine, Douglas-fir, and Engelmann spruce. Slopes ranged from 35% to more than 70%.

Water was collected at road cut banks where bedrock was exposed. Subsurface flow emerged on the face of the bedrock and ran down to a collection trough. Subsurface flow was therefore converted to surface flow. The author calculated that along a given length of road, the amount of subsurface flow intercepted by the road was 7.3 times greater than surface runoff from the road alone after a precipitation event.

The author discusses the impacts of converting subsurface flow to surface flow. Total watershed runoff volume probably increases. Surface flow commonly causes significant surface erosion and excess soil water can result in mass erosion. In addition, the author mentions the potential broader ecological impacts of rerouting subsurface flow from downslope habitat, such as the alteration of vegetation species composition and growth rates.

* See also key finding in Chapter 5.

Key Finding: The peak rate of subsurface flow increased by an average of 27% after clearcutting, and due to its interception by a road cut and conversion to surface flow, was believed likely to lead to increased levels of erosion from the road and the slopes below the road.

Source: Megahan, W. F. 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Resources Research 19: 811-819.

A paired watershed study was conducted on headwater watersheds in the Idaho Batholith to evaluate the effects of clearcut logging on the watersheds' hydrology. Data on inflow, storage, and outflow from three years before logging and three years after logging were analyzed. Within one year after logging a wildfire burned through both the logged and unlogged watersheds, so its effects were also included.

A logging road ran along the lower boundary of both watersheds. Subsurface flow, intercepted by the road cut, was collected in a trough at the bottom of the cut slope. Data on annual snow accumulation were also collected. In contrast to the unlogged watershed, the clearcut watershed had a highly significant increase in snow water content the year after logging, as well as a significant increase over the next two years after the wildfire. There was no detectable increase in snow water content on the unlogged watershed even after the fire. Subsurface outflow, as measured at the road cut, increased after clearcutting. Both the volume and peak rate of subsurface flow increased, the former by 96%, the latter by an average of 27%. Because this increased subsurface outflow was intercepted by the road cut, the author considered it likely that erosion due to surface flow along and below the road would increase.

Key Finding: Roads and clearcut logging increased peak stream discharges and advanced the timing of peak discharges in multiple paired watershed studies, most likely because of subsurface flow being converted to surface flow at road cuts.

Key Finding: Even after many years, roads and clearcut logging, both together and separately, resulted in significant increases in stream peak discharges.

Source: Jones, J. A. and G. E. Grant. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research 32: 959-974.

The authors studied paired watersheds in the western Cascades and examined road building, logging, and peak discharge records to compare streamflow peaks pre- and post-treatment. Records for two pairs of small basins extended over 34 years, and records for three adjacent large basin pairs extended over 50 to 55 years.

One of the small watersheds was 100% clearcut without road construction. After clearcutting, a significant number of storms resulted in higher peak discharges and volumes, and began earlier. A higher-than-expected number of runoff events had greater peaks and volumes. Sixteen to 22 years after clear-cutting, average peak discharges were still significantly higher (almost 40%) than pre-logging levels.

The second small basin provided four years of data on the impact of roads alone, before logging began. Roads occupied 6% of the watershed. After road construction, a higher-than-expected number of storm events had higher peak discharges and began earlier. After clearcutting 25% of the watershed, average peak discharge increased by 50% in the first five years, and storm discharges began an average of six hours earlier than pre-treatment. After 25 years, average peak discharges were still significantly (more than 25%) higher than pre-management levels.

Similarly, in the three large basin pairs, peak discharge increased as cumulative area logged increased. Begin times were not reported.

The authors note that the most likely mechanism for the increase in peak flow due to just roads was road cuts converting subsurface flow to surface flow, which was then routed directly to stream channels. Logging, they conclude, had an impact on streamflow due to changes in evapotranspiration and snow accumulation and melt rates.

Key Finding: Roads formed new surface flow paths to natural channels and incised new gullies, so increasing the routing efficiency of water; thereby probably explaining some higher stream peak flows.

Source: Wemple, B. C., J. A. Jones and G. E. Grant. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. Water Resources Bulletin 32: 1195-1207.

Two fifth-order basins (Lookout Creek and Blue River), in the western Cascades of Oregon, were studied to determine the mechanism by which logging roads may alter stream peak flows by changing water routing efficiency. The road density in each basin was 1.9 km/km2, and roads occupied 3% of each basin's area.

A sample of 62 km of the road network was surveyed. A total of thirty-one 2-km transects was selected, and the transects were subdivided into segments at each culvert. Study sites were distributed between valley, midslope, and ridgetop sites and among roads ranging in construction period from the 1950s to the 1990s. A subsample was also studied immediately after storm events.

Road culverts delivered water to natural stream channels at stream crossings, into new gullies incised below culvert outlets, or onto hillslopes, where water reinfiltrated the soil. The first two mechanisms of surface flow linked the roads directly to the stream channel network. More than 57% of the total road length surveyed was calculated to be connected to the stream network by these two flowpaths. Of the 436 culverts examined, 33% crossed streams and 23% were ditch-relief culverts with gullies incised below. Thirty-four percent of the road length drained to stream channels and 24% drained to gullies. Of the gully-forming culverts studied immediately after storm events, approximately half directed surface runoff to a

nearby channel or saturated area. The authors estimated that these new flowpaths due to roads resulted in an increased drainage density of 36% and 39% in the two basins, although they noted that these figures would probably vary by season and by the degree to which gullies were connected to streams.

The authors describe an earlier study in the same basins (Jones and Grant 1996), in which stream peak flows increased after road construction and logging. They hypothesize that the present study, documenting the integration of roads with stream networks and the increased drainage density, in the two basins, was a possible mechanism for increased water routing efficiency and therefore increased peak flows.

Key Finding: Almost 30 years after clearcut logging occurred, average and peak stream flows in the watershed studied were still higher than pre-logging flows.

Source: Troendle, C. A. and R. M. King. 1985. The effect of timber harvest on the Fool Creek Watershed, 30 years later. Water Resources Research 21: 1915-1922.

The Fool Creek watershed study was part of a paired watershed experiment in the Rocky Mountains started in the 1940s. More than 10 years of data on pre-logging streamflow were available. The study evaluated the effects of clearcut logging on streamflow and snowpack accumulation for a 28-year period after the first trees were cut.

Streamflows from April to September increased after logging, with the average annual increase being 40%, or 8.2 cm, higher than that expected based on pre-logging data and the control watershed. Twenty-eight years after logging, the increase observed was still high (10.2 cm). Peak mean daily discharge also increased by an average of 23%, or about 55 l3/s, after 28 years, and peak mean daily discharge occurred about 7.5 days earlier in the year. These increases were attributed to snow melting sooner in exposed, logged areas and less water being used for soil saturation. Peak water equivalent (total snowmelt) of the entire watershed increased by 9%, a significant change. The authors review other studies from sites near their watershed, showing that even partial cutting of trees resulted in an increase in the overall deposition of snow and less loss of moisture through interception by trees. The authors conclude that one thirdof the increase in streamflow may be due to increased peak water equivalent and note that vegetation regrowth over the past 28 years has had little effect.

Key Finding: Natural streamflow rates during periods of high flow were significantly altered in two watersheds after logging road construction.

Key Finding: Subsurface flow intercepted by logging roads was converted to surface flow and was the most likely cause for increases in streamflows during snowmelt runoff and heavy summer storms.

Source: King, J. G. and L. C. Tennyson. 1984. Alteration of streamflow characteristics following road construction in north central Idaho. Water Resources Research 20: 1159-1163.

The effects of logging roads on streamflow were monitored on six headwater watersheds in Nez Perce National Forest in north central Idaho, as part of the Horse Creek project. Watersheds ranged from 28 to 148 ha in size. The study was conducted after logging roads were constructed, but before the logging occurred. Daily water discharge data were collected at the mouths of the watersheds and compared with pre-road data for the same watersheds and with a control watershed that had no roads.

Two of the six watersheds showed significant changes. In one watershed, with 3.9% of its area disturbed by roads, there was an increase in the 25% exceedance flows (streamflow during snowmelt runoff and summer storms). The authors attributed this increase in streamflow to interception of subsurface flow by the roads and conversion to surface flow. A majority of the road length had cut slopes greater than 6 m in height, and being located midslope, the road had the potential to intercept upslope flow from 67% of the watershed's area. The authors observed high interception of subsurface flow along one of the cut slopes, with long periods of flow in the ditches.

Another watershed, with 4.3% of its area in roads, showed a significant decrease in the 5% exceedance flow, which represents the period of highest flow (usually snowmelt runoff). The other four watersheds showed no significant change in the any of the seven streamflow variables.

Key Finding: Stream peak flows increased significantly in a watershed with 12% of its area in roads, before any logging occurred.

Key Finding: Stream peak flows increased as the percentage of watershed area clearcut increased.

Source: Harr, R. D., W. C. Harper and J. T. Krygier. 1975. Changes in storm hydrographs after road building and clear-cutting in the Oregon Coast Range. Water Resources Research 11: 436-444.

Six small watersheds were studied in the Alsea River basin of the Oregon Coast Range. Changes in stormflow after road building, logging, and slash burning were compared to pre-logging data and to a control watershed. Storm events were monitored over three years of rainy seasons, with fall data separated out from winter data. Only one year of data was available for changes due to roads alone, before logging commenced.

After road construction, but prior to logging, peakflow volumes increased significantly in only one watershed. Average peakflows increased (by 5 ft3/s/mi2) in this watershed, which had the greatest extent of roads (12% of its area). Peakflow changes in the other watersheds were smaller and inconsistent. Data for streamflow were limited, however, since there was only one year of information.

After clearcutting, three of the five logged sites showed significant increases in peak flow, with the largest increases being in the watersheds with the greatest area clearcut. For example, fall peak flow increased (by 27 ft3/s/mi2) in the watershed that was 90% clearcut.

Key Finding: Forest roads extended the natural channel network, initiated new channels, and increased the susceptibility of steep slopes to landsliding.

Key Finding: Road cuts intercepted subsurface flow and diverted it to roadside ditches.

Source: Montgomery, D. R. 1994. Road surface drainage, channel initiation, and slope instability. Water Resources Research 30: 1925-1932.

Field surveys were conducted at three sites in the western United States to investigate road drainage and associated landsliding and channel network extension. The study sites were located in 1) the southern Sierra Nevada; 2) on Mettman Ridge in the Oregon Coast Range; and 3) on Huelsdonk Ridge on the Olympic Peninsula. Drainage area and slope were determined to be the key criteria contributing to slope instability (so leading to landslides) and initiation of new water channels. The author mapped all discharge points from the roads and estimated the contributing drainage area. In each area, average ground slopes were also measured.

In the southern Sierra Nevada site, road drainage resulted in the road surface acting as an extension of the natural channel network. Road cuts had diverted both surface and subsurface flow into ditches. Four hollows had lost natural drainage waters due to diversion by the roads. Three different hollows received extra drainage from the road system. The overall drainage density of the area studied (1.2 km2) had increased by a factor of 1.6.

Forest roads studied in Oregon and Washington were both ridgetop roads. Roads had initiated new channels. Road-associated landsliding was highest on the steepest slopes and on slopes having the greatest drainage area. Drainage density due to new water flowpaths increased by a factor of 1.23 at the Oregon study site; no figure was reported for the Washington site. Road discharge points were studied immediately

after rainfall only at Oregon site. At other sites, the author estimate that mapping accuracy of drainage areas was within +/- 30%.

Adverse impacts on aquatic species: Increased fine sediment deposition in streams and altered streamflows and channel morphology result in increased adult and juvenile salmonid mortality, a decrease in aquatic amphibian and invertebrate abundance or diversity, and decreased habitat complexity.

Key Finding: Salmonid survival rates decreased after logging and road construction as fine sediment levels in streams increased and as important habitat characteristics, including the number of pools and winter cover, decreased.

Source: Hicks, B. J., J. D. Hall, P. A. Bisson and J. R. Sedell. 1991. Responses of salmonids to habitat changes. In Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19: 483-518.

The authors review research on the effects of logging on salmonids and their stream habitat. Studies from Oregon, Idaho, British Columbia, and Alaska, for instance, showed that salmonid abundance and fry survival decreased as fine sediment levels increased after logging. Fine sediment in deposits or suspension also reduced the availability of food in streams by reducing invertebrate abundance and primary production. Suspended sediment increases were shown to affect salmonids in various ways, including avoidance, cessation of feeding, and disrupted social behavior.

The increased frequency of landslides and other mass erosion events due to logging and roads changed channel morphology, reducing pool area and depths and resulting in stream reaches that were wider, shallower, and more prone to bank erosion. Studies in British Columbia, for instance, showed that pool habitat was reduced by an average of 79% in streams affected by debris torrents and suitable winter cover was reduced by an average of 75%. Coho salmon winter survival averaged 1.8% in stream reaches affected by debris torrents compared to survival rates of 24.5% in unaffected streams.

The authors discuss studies showing salmonid abundance initially increasing after clearcutting. They note that these increases were documented only over the short term and that over the longer term (after 10 to 15 years), other research had indicated that populations could eventually decline to levels lower than those in old-growth forest.

Key Finding: Coho and chum salmon fry survival declined after logging and associated increases in fine sediment deposited in spawning areas.

Source: Scrivener, J. C. and M. J. Brownlee. 1989. Effects of forest harvesting on spawning gravel and incubation survival of chum (Oncorhynchus keta) and coho salmon (O. kisutch) in Carnation Creek, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46: 681-696.

The effect of logging practices on salmonid spawning gravel composition and fry survival was investigated in Carnation Creek on the west coast of Vancouver Island. The study included pre-logging, logging, and post-logging data. Three clearcut logging treatments were conducted at varying distances along the stream: 1) clearcutting with a strip of vegetation left along the streamside; 2) intense streamside treatment; and 3) careful streamside treatment with some shrubby vegetation left intact. Permanent survey sites were established at 3-m intervals in each study section. Streambed cores were obtained from each of these sites using a freeze-core technique, driving steel probes 30 cm into the bed. Peak flows and suspended sediment

levels were also measured. Annual egg-to-fry survival rates for coho and chum salmon were estimated by calculating egg deposition rates from adult female numbers and sizes and by counting emerging salmon fry at traps at a downstream fence.

After logging, the percentage of fine sediment increased in the streambeds, although the patterns of deposition and proportion varied among treatments and timing of logging. These fines particles appeared to originate from erosion of streambanks after the loss of living roots from streamside vegetation and the loss of large organic debris post-logging. They were transported through the creek primarily as bedload rather than as suspended sediment. Streambank erosion increases were highest in the intense streamside treatment and lowest in the treatment with a buffer strip.

After logging and a subsequent large snowmelt event, coho salmon fry survival to emergence rates declined to 16.4%, compared to a prior survival rate of 29.1%. The decline was correlated to decreasing mean particle sizes in the lower layers of the streambed cores. Survival to emergence of chum salmon fry declined from a prior rate of 22.2% to 11.5% post-logging and was correlated to decreasing mean particle size in the whole streambed core and in the top layers of the core. Peak survival occurred during years when pea gravel and sand were washed out from the top layer. The authors attribute the difference in streambed layers affecting chum and coho survival to differences in natural egg deposition depths between the two species.

Key Finding: Survival rates of coho salmon and steelhead trout fry decreased as the proportion of fine sediment in spawning gravel increased.

Source: Phillips, R. W., R. L. Lantz, E. W. Claire and J. R. Moring. 1975. Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. Transactions of the American Fisheries Society 3: 461-466.

Laboratory experiments were conducted at the Alsea Watershed Study field station to investigate the relationship between the proportion of fine sediment in spawning gravel and the survival of coho salmon (Oncorhynchus kisutch) and steelhead trout (Salmo gairdneri) fry. Six different gravel sizes were mixed in troughs to create spawning gravel similar in composition to natural coho salmon redds in Deer Creek, in the Oregon Coast Range. The proportion of fine sediment (sand 1-3 mm in diameter) was then increased by 10% increments to create eight gravel mixtures with 0-70% sand by volume. Coho salmon and steelhead fry were buried in the gravel, and their date of emergence, survival, and weight were recorded. Six replicates were tested.

As the proportion of fine sediment in the gravel mixtures increased, coho salmon fry emerged earlier and were smaller in size. Their survival rates decreased as fine sediment percentage increased, from 96% survival in the control gravel mixture to 8% survival in the mixtures containing 70% sand. Fine sediment proportions had no effect on the timing of steelhead fry emergence. However, their survival patterns were similar to those of coho salmon fry, with 99% survival for steelhead fry in the control mixture and 18% in the 70% sand mixture.

The authors note that sediment sizes smaller than 1 mm were not tested in their experiment and that total emergent fry survival could be even lower under conditions that included finer sediment. They also note that if fish were exposed to high sediment levels for a longer time period, from egg fertilization through development, mortality due to indirect effects such as low oxygen concentrations could be higher.

Key Finding: Brook trout populations declined significantly after stream sedimentation levels increased.

Key Finding: Populations of stream benthic invertebrates (the major food source of brook trout) declined significantly after stream sediment levels increased.

Key Finding: Higher fine sediment levels in a stream resulted in a loss of pool habitat, fish cover, changes in stream velocity, and higher summer water temperatures.

Source: Alexander, G. R. and E. A. Hansen. 1986. Sand bed load in a brook trout stream. North American Journal of Fisheries Management 6: 9-23.

The effects of sedimentation on populations of brook trout (Salvelinus fontinalis) and stream channel physical characteristics were investigated over a period of 15 years in Hunt Creek in the Lower Peninsula of Michigan. Trout populations were monitored for five years prior to sand deposition, for five years during which sand was introduced into the stream, and then five more years without adding sand.

The study area was divided into two 1-mile sections, with the upper section of the stream serving as a control throughout the study. For five years, sand was introduced daily into the treated section of the stream, increasing total sediment concentrations from approximately 20 ppm to 80 ppm to replicate concentrations reported for trout streams with severe streambank erosion. Cross sections were established at 100-ft intervals to document changes in stream channel characteristics. Brook trout were collected from spring through fall every year, as were samples of benthic invertebrates (their primary food source).

The volume of sand deposited on the streambed gradually increased over the study period. A significant decrease occurred in brook trout populations in the treated section of the stream, a decrease particularly evident four years after the initial introduction of sand. Total trout numbers dropped by 51%, a statistically significant change. Trout of all sizes and ages declined in number in the sand-treated section compared to the control section of the stream. There was no change in growth rates.

After sand introduction, populations of benthic invertebrates also dropped to less than half their pre-treatment populations. The insect orders of Ephemeroptera, Diptera, Coleoptera, Trichoptera, and Plecoptera showed the most significant declines. Fish stomach analyses revealed that the majority of these taxa were important food sources for brook trout.

Stream physical characteristics also changed with increased levels of sedimentation. The stream became wider and shallower, pools disappeared, and the stream bottom lost all fish cover after becoming uniformly covered by sand. Water temperatures in the summer increased. Deeper stream depths near the banks disappeared.

Key Finding: Salmonids avoided water with suspended sediment in Alaskan streams and lakes.

Source: Lloyd, D. S., J. P. Koenings and J. D. LaPerriere. 1987. Effects of turbidity in fresh waters of Alaska. North American Journal of Fisheries Management 7: 18-33.

The authors review research on the effects of turbidity (due to suspended particles) in Alaskan streams and lakes. They note that there are natural sources of particles from glacial meltwater, as well as unnatural sources from placer mining, logging, and road construction. Primary production (algae and vascular plant growth), the foundation of the aquatic food chain, was found to be positively related to the clarity of streams. The authors review studies indicating that various salmonid species, including Arctic grayling, coho salmon, chinook salmon, and rainbow trout, avoided turbid waters. This avoidance was attributed to their reduced ability to find food, as well as interference with visual cues during migration.

Key Finding: Delivery of fine sediments to streams and deposition on spawning and rearing substrate decreased after a moratorium on logging, but increased again after logging resumed.

Source: Platts, W. S., R. J. Torquemada, M. L. McHenry and C. K. Graham. 1989. Changes in salmon spawning and rearing habitat from increased delivery of fine sediment to the South Fork Salmon River, Idaho. Transactions of the American Fisheries Society 118: 274-283.

The effects of fine sediment delivery to rivers from logging and road construction were studied in habitat for chinook salmon (Oncorhynchus tschawytscha) and steelhead (O. mykiss, formerly Salmo gairdneri). Spawning and rearing areas were studied after a logging moratorium was declared in the watershed of the South Fork Salmon River, which drains part of the Idaho Batholith. The authors reported results of earlier studies indicating high levels of fine sediment present in the river due to accelerated erosion from logging, road construction, large storm events, and road washouts.

Ten transects were established at each of five chinook salmon spawning areas, and substrate characteristics were measured for 20 years. After logging ceased, there was a significant decline in the percentage of fine sediment (material <4.75 mm in diameter) on the surface of 84% of the spawning area locations. Overall sediment declines over the 20 years varied at each of the five spawning areas, but ranged from a decrease by 16.7% at one area to a decrease by 76.5% at another. The percentage of gravel and rubble correspondingly increased. Within two years of resuming logging, however, surface fine sediments increased at all five spawning areas, with overall increases of 22.2% to 83.8%.

In salmon rearing areas, transects were established at 15-m intervals at 47 sample stations. Data were collected from these areas for six years. The percentage of fines on the surface of rearing areas decreased by 73.5% over the study period. Overall, rearing areas had lower levels of fine sediment deposition from logging than spawning areas did.

Key Finding: Fine sediment deposition on cobble substrates decreased the availability of interstitial spaces (used as winter refuges), and winter densities of juvenile chinook salmon decreased correspondingly.

Source: Hillman, T. W, J. S. Griffith and W. S. Platts. 1987. Summer and winter habitat selection by juvenile chinook salmon in a highly sedimented Idaho stream. Transactions of the American Fisheries Society 116: 185-195.

The authors investigated the effect of fine sediment on juvenile chinook salmon (Oncorhynchus tschawytscha). One particular criterion they looked at was the impact of fine sediment deposition on winter survival. Two sites on Red River, Idaho, were modified in September 1985 by placing cobble in randomly located 1-m2 plots center stream and under the banks. The cobble was expected to provide more refuge areas for salmon during the winter. Fish populations were estimated by three-pass electrofishing and by snorkeling several times through the winter.

Salmon winter rearing densities increased eightfold in glide areas (slow, shallow areas) after cobble was added, compared to densities the previous year. Densities in treated areas were nine times higher than densities in untreated areas during the same period. A significantly higher density of young chinook salmon (five times higher) used interstitial spaces in the altered areas than in the unaltered areas. By March 1986, however, when the cobble had become heavily embedded with fine sediment, juvenile salmon densities had decreased by more than 90% and were similar to densities pre-alteration.

Key Finding: Chum salmon eggs were susceptible to mortality from increased streambed scour associated with logging and/or roads.

Source: Montgomery, D. R., J. M. Buffington, N. P. Peterson, D. Schuett-Hames and T. P. Quinn. 1996. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Canadian Journal of Fisheries and Aquatic Sciences 53: 1061-1070.

Spawning by chum salmon (Oncorhynchus keta) in streambed gravel was studied in a stream near Juneau, Alaska. Egg burial in summer was followed by a winter incubation period, during which the stream experienced the greatest discharge volumes due to high rainfall. The depth to which egg pockets were buried in the gravel was measured in 40 salmon redds (nests). To measure the depths to which the

streambed was scoured during winter peak flows, 104 scour monitoring chains were distributed throughout the study section of the stream.

Depths of bed scour and egg pockets varied, with scour depths ranging from 0-60 cm (mean of 13.4 cm) and egg pocket depths ranging from 9.8-48.9 cm (mean of 22.6 cm). The authors found that for the majority of egg pockets, burial depth was just enough to protect them against natural scour during the peak winter discharge. The authors indicate that this protection was most likely a result of finely tuned adaptation by the salmon to natural rates of sediment transport and scour depths.

They note research by other authors reporting that increases in scour depths were related to increases in stream discharge and velocity and increases in fine sediment transport. The authors therefore conclude that increases in scour due to increased sedimentation from logging or roads could significantly increase the mortality of buried salmon eggs.

Key Finding: Salmonid embryo survival rates decreased as the proportion of fine particles in stream spawning substrate increased and dissolved oxygen levels decreased.

Source: Chapman, D. W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society 117: 1-21.

The author reviews laboratory and field studies on salmonid embryo survival. The majority of studies showed that salmonid embryo survival rates decreased as the percentage of fine sediments in stream substrate increased. With increasing fine sediment levels, dissolved oxygen levels decreased, as did gravel permeability and pore space. Dissolved oxygen levels were found to be critical to the survival of embryos and their later development. Size of emergents was also found generally to decrease as fine sediment levels increased.

Despite the variability among studies in quantitative results, they consistently showed the adverse impacts of fine sediments on salmonid survival.

Key Finding: Adult and juvenile salmonids exposed to suspended fine sediment in streams had an increasingly negative response as concentrations and duration of exposure increased.

Source: Newcombe, C. P. and J. O. T. Jensen. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. North American Journal of Fisheries Management 16: 693-727.

The authors review 80 published studies on the response of fish to suspended sediment in streams. Data from these studies were used to develop models quantifying the response of fish to varying sediment concentrations and varying durations of exposure. This response was defined as "severity of ill effect," which included effects such as reduced growth rates, reduced fish density, reduced fish population size, and habitat damage. The data were also used to provide estimates of the onset of sublethal and lethal effects in fish.

Data were grouped into six subcategories based on species, age, and sediment size. Adult and juvenile salmonids exposed to particle sizes of 0.5-250 (m showed an increasingly negative response as sediment dose increased, and sublethal and lethal effects occurred at high doses. The equations derived for the model were tested against newer data and validated.

Key Finding: Juvenile coho salmon avoided water with high turbidity levels.

Source: Bisson, P. A. and R. E. Bilby. 1982. Avoidance of suspended sediment by juvenile coho salmon. North American Journal of Fisheries Management 4: 371-374.

An aquarium experiment was designed to investigate the effect on juvenile coho salmon of suspended sediment from logging roads. Young coho salmon were collected from a tributary of the Deschutes River, Washington, and fine sediment was collected from a catchment basin next to a heavily used, unpaved road. One group of fish was acclimatized to clear water, the other to water with a low turbidity, to replicate natural winter turbidities in this tributary. After being held for three weeks, 10 individuals from each group were placed in an aquarium with suspended sediment added to one side only. Fish could move freely and their preference for a particular side of the chamber was then monitored.

Both groups of fish avoided turbid waters once a threshold of tolerance had been reached. This threshold was lower for the salmon acclimated to clear water than to salmon acclimated to slightly turbid water. The exception was fright behavior, when, due to a lack of any other cover, fish grouped in the turbid portion of the chamber.

Key Finding: Basins with more than 25% of their area logged had lower stream habitat diversity, as measured by the number of pools and pieces of wood, than basins with less than 25% of their area logged.

Key Finding: The diversity of juvenile anadromous salmonid populations was lower in basins with more than 25% of the area logged than in basins with less than 25% logged.

Source: Reeves, G. H., F. H. Everest and J. R. Sedell. 1993. Diversity of juvenile anadromous salmonid assemblages in coastal Oregon basins with different levels of timber harvest. Transactions of the American Fisheries Society 122: 309-317.

The diversity of juvenile anadromous salmon populations was examined in relation to the extent of logging in coastal Oregon stream basins. Fourteen stream basins were sampled. Basins with 25% or less of the watershed area logged were classified as having low logging levels. Basins with greater than 25% of their area logged were classified as having high logging levels.

As an index of stream habitat complexity, pools and number of pieces of wood per 100 m of stream length were counted. This data was collected for three paired streams, selected to minimize variation in other stream characteristics. Juvenile anadromous salmon were sampled in all streams over five years by divers. Species identified were chinook salmon (Oncorhynchus tshawytscha), coho salmon (O. kisutch), steelhead (O. mykiss), and cutthroat trout (O. clarki). Counts were used to estimate relative population numbers.

In the paired comparisons, streams in low-harvest basins had higher habitat diversity than streams in high-harvest basins. Number of pieces of wood per 100 m was significantly higher (2-12 times higher) in low-harvest basins and number of pools was significantly higher in two out of three comparisons, ranging from 10-47% higher.

Salmon species dominance was used as the primary attribute of community diversity. Juvenile anadromous salmonid assemblages were significantly more diverse in low-harvest basins, with single species dominating the fish assemblage more often in high-harvest basins than in low-harvest basins. There were no differences in total mean densities of fish between different logging levels.

Key Finding: The density of all three stream amphibian species studied was lower in streams affected by sediment due to road construction than in control streams. Two of three species had significantly lower numbers in all five stream microhabitats.

Source: Welsh, H. and L. M. Ollivier. 1998. Stream amphibians as indicators of ecosystem stress: a case study from California's redwoods. Ecological Applications 8: 1118-1132.

The authors analyzed the impact of highway construction and resulting erosion on the abundance of stream amphibians in California old-growth redwood forest. A major storm during road construction resulted in large volumes of sediment from mass wasting and surface erosion entering stream channels. Five streams affected by sediment were compared with five control streams in the same basin. The three most abundant native amphibians were sampled - larval Pacific giant salamanders (Dicamptodon tenebrosus), larval tailed frogs (Ascaphus truei), and larval and adult southern torrent salamanders (Rhycotriton variegatus). Salamander densities were surveyed in transects placed throughout more than 3 km each of affected stream habitat and control stream habitat. Different habitat types were sampled, including pools, glides/runs, riffles, step runs, and step pools.

A total of 267 transects, 0.6 m wide, was sampled, with 540 individual amphibians captured. The density of Pacific giant salamanders and southern torrent salamanders was significantly lower in the sedimented than in the control streams. The density of tailed frogs was lower in their preferred riffle and step run habitat in sedimented streams as opposed to control streams, although results were not statistically significant.

Key Finding: A higher proportion of fine sediment occurred in streams flowing through forest stands with logging than streams flowing through unlogged forest stands.

Key Finding: Abundance, density, and biomass of all aquatic amphibian species studied were lower in streams flowing through logged forest than unlogged forest streams.

Source: Corn, P. S. and R. B. Bury. 1989. Logging in western Oregon: responses of headwater habitats and stream amphibians. Forest Ecology and Management 29: 39-57.

The authors compared the occurrence and abundance of amphibians in streams flowing through unlogged forest versus streams flowing through forests with prior logging in Oregon's Coast Range. Stream segments 10 m long were examined in 43 streams, which included first-, second-, and third-order streams. Stream segments were chosen partly based on their accessibility and partly on how typical they appeared of the rest of stream. Twenty-three streams were in unlogged forest stands ranging in age from 60 to 400 years old. Twenty streams were in logged stands ranging in age from 14 to 40 years old, with canopy cover having been reestablished over the streams. No study sites had road crossings upstream of them. Streams were surveyed from June to early August for two years. Stream physical characteristics were recorded and thorough searches conducted for all amphibians.

Results were analyzed for the four amphibian species reported to be the most common and the dominant vertebrates of small streams in the Oregon Coast Range: tailed frogs (Ascaphus truei), Pacific giant salamanders (Dicamptodon ensatus), Olympic salamanders (Rhyacotriton olympicus), and Dunn's salamanders (Plethodon dunni). All four species occurred more frequently and had higher density and biomass in the streams flowing through unlogged as opposed to logged forest stands. The only stream physical variable found to be significantly different between stand treatment was that streams in logged stands had more fine sediment.

Key Finding: Stream insects preferred fully exposed cobble on the streambed to cobble partly or fully embedded in fine sediment.

Source: Brusven, M. A. and K. V. Prather. 1974. Influence of stream sediments on distribution of macrobenthos. Journal of the Entomological Society of British Columbia 71: 25-32.

Aquatic insects in the orders of Ephemeroptera, Plecoptera, Trichoptera, and Diptera were studied in the laboratory and in natural streams to determine what streambed material they preferred. Five species were collected in the field (Pteronarcys californica, Arctopsyche grandis, Ephemerella grandis, Brachycentrus sp., and Atherix variegata) and introduced into artificial streams. Substrates of different particle sizes were placed in test quadrants of the stream.

All five species preferred fully exposed cobble to cobble half-embedded in fine sand. Likewise, in natural streams, four of the five species occurred in rocky streams, where they lived on the surface of coarse substrate materials or used the spaces between and below for retreat. One species, Atherix variegata, lived in a wider range of substrate habitat.

Key Finding: Adult aquatic insects were an important part of the insect community in forests adjacent to streams, and were believed to be an important part of the food web for forest animals such as birds and bats.

Source: Jackson, J. K. and V. H. Resh. 1989. Distribution and abundance of adult aquatic insects in the forest adjacent to a northern California stream. Environmental Entomology 18: 278-283.

The authors studied the distribution of adult aquatic insects in mixed evergreen forest adjacent to a stream in the northern California Coast Range. Sticky traps were set up in a 100-m section of streamside forest for 26 days, during the period of peak aquatic insect emergence from the stream. Traps were hung in oak trees that were 5, 40, and 150 m from the stream and at heights of 2, 5, and 8 m above the ground.

A total of 5,402 individuals, including insects in 27 aquatic insect taxa were collected. Near the stream, up to 40 m into the forest, adult aquatic insects represented more than 30% of the total arthropod numbers and 25% of total arthropod biomass. Further from the stream, at 150 m, aquatic insects represented 15% of total arthropod numbers and 11% of total arthropod biomass.

The authors note that adult aquatic insects are an important link between aquatic and terrestrial habitat. They were a significant part of the arthropod community even 150 m away from the stream and may be an important part of the land food web as demonstrated by research on songbird and bat diets.

Key Finding: The remaining intact watersheds in southeast Alaska are key to maintaining sustainable salmon stocks.

Source: Bryant, M. D. and F. H. Everest. 1998. Management and condition of watersheds in southeast Alaska: the persistence of anadromous salmon. Northwest Science 72: 249-267.

The authors review the history of forest management practices in the Tongass National Forest since the 1950s. They note that, although logging practices have greatly improved during the past 40 years, most logging in the Tongass occurred before riparian protection policies were in place. As a result, there is a legacy of watersheds with degraded salmonid habitat. Although there is a lack of systematic data available on salmonid populations pre- and post-logging in Alaska, the authors predicted that logged watersheds would be less resilient to environmental stresses than intact watersheds and that salmonid populations would therefore be more vulnerable to environmental disturbances such as decreased marine survival, drought, landslides, flooding, etc. They also note studies on the contribution of large trees to stream channels that have shown that stream habitat deterioration may not be apparent for decades after logging and that habitat quality is unlikely to be restored for more than 100 years after logging ceases. The authors therefore conclude that streams in unmanaged, intact watersheds of southeast Alaska are critical to maintain sustainable salmon stocks.

Key Finding: Trout standing stocks decreased as the density of road culverts (a measure of the extent to which roads crossed watercourses) increased.

Source: Eaglin, G. S. and W. A. Hubert. 1993. Effects of logging and roads on substrate and trout in streams of the Medicine Bow National Forest, Wyoming. North American Journal of Fisheries Management 13: 844-846.*

The effects of logging and associated road construction on streams and on trout populations were studied in the Medicine Bow National Forest, Wyoming. Twenty-eight stream reaches (200 m each) were examined, with sampling conducted along transects at 4-m intervals. Trout standing stocks were estimated using a backpack electroshocker. The percentage area logged and the density of roads in areas upstream of the drainage were calculated. The density of road culverts was recorded as an index of the extent to which roads crossed watercourses within the drainage. The amount of fine sediment in a stream reach increased and the embeddedness of fine sediment (its coverage of large particles) in the substrate increased as the proportion of logged area increased and as the extent to which roads crossed watercourses increased. Trout standing stocks also decreased as the density of road culverts increased.

* See also key finding above.

Key Finding: During the summer, adult chinook salmon preferred pool habitat and cool stream reaches over other kinds of stream habitat.

Source: Torgersen, C. E., D. M. Price, H. W. Li and B. A. McIntosh. 1999. Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. Ecological Applications 9: 301-319.

The distribution and behavior of adult spring chinook salmon relative to stream temperature and physical habitat was investigated in the Middle Fork and North Fork of the John Day River basin, northeastern Oregon. Salmon were counted by divers during July and August in selected stream sections, their habitat use recorded, and their location recorded using a global positioning system. Water temperature patterns were measured by remote sensing and by handheld thermometers. Temperature maps were compared with salmon locations using a geographical information system (GIS).

The total number and average density of chinook salmon was greater in the North Fork, which was relatively undisturbed, than in the Middle Fork, which had relatively intense land use including logging, grazing, and agriculture. Chinook salmon were found to use pools more frequently than riffles and in a proportion greater than the pools' availability. During this study period, 98% of the salmon were found in pools in the Middle Fork, and 82% were found in pools in the North Fork. The distribution of salmon was also strongly associated with temperature. Overall, salmon indicated a preference for stream reaches that were cooler and had greater pool volume.

Chapter 7

GENERAL REVIEW PAPERS ON THE ECOLOGICAL EFFECTS OF ROADS

Key Finding: Roads were associated with a diversity of negative effects on the biotic integrity of both terrestrial and aquatic ecosystems.

Source: Trombulak, S. C. and C. A. Frissell. In press. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology.

A review of the scientific literature reveals seven general effects of roads of all kinds on the ecosystem. 1) Road construction resulted in the death or injury of roadside plants or slow-moving animals, compacted soils, and affected water bodies at road crossings. 2) Roadkill affected the demography of numerous species. 3) Animal behavior changed due to roads, with avoidance of roads, modification of movement patterns or home ranges, changes in reproductive success, escape behavior, or physiological state. 4) Roads disrupted the physical environment by changing soil characteristics such as density, surface runoff, and sedimentation. They altered the hydrology of slopes and stream channels, created barriers to the movement of fish and other aquatic animals, and altered channel and shoreline development. 5) Roads affected the chemical environment by contributing pollutants such as heavy metals, salts, or nutrients to roadside plant and animal communities as well as to aquatic ecosystems through runoff. 6) Roads promoted the spread of exotic species. 7) Roads increased access by humans, and therefore increased poaching pressure, fishing, and passive harassment of animals.

Key Finding: Based on numerous studies on the ecological impact of roads, 15-20% of the United States land area was estimated to be affected by roads.

Source: Forman, R. T. T. and L. E. Alexander. 1998. Roads and their major ecological effects. Annual Reviews of Ecology and Systematics 29: 207-231.

The authors review the scientific literature available from North America, Europe, and Australia on the impacts of roads on plant and animal populations. Roads affected vegetative communities through facilitating disturbance-tolerant plant species and introducing exotic species. Road avoidance, barrier effects, and roadkill were documented as major factors affecting animal populations. The impacts of roads on aquatic systems were also reviewed, including altered runoff patterns, increased sediment input, disrupted hydrology, and delivery of pollutants such as heavy metals and deicing salts into streams. The authors report that the ecological effect of roads extended into the landscape beyond the road itself into a broader area that they called "the road-effect zone," based on which they estimated that 15-20% of the United States land area is affected by roads.

Key Finding: The zone of ecological effects surrounding roads averaged more than 600 m wide, and for some factors extended more than 1 km from the road surface.

Source: Forman, R. T. T. In press. The ecological road-effect zone of a Massachusetts (USA) suburban highway. Conservation Biology .

The authors investigated the area to which the ecological effects of a road can extend outward, into a zone termed the "road-effect zone." Nine components of the ecosystem were specifically examined. The authors collected data on some criteria from a 25-km stretch of highway in Massachusetts, and used information from other scientists' research for the remaining factors.

Habitat invasion by roadside exotic plants was investigated by searches through 1 ha each of 22 adjacent woodland locations. Eleven (50%) of the woodland sites showed evidence of invasion by exotic species such as privet or Norway maple up to distances of 120 m. Research by other authors showed that migration by salamanders in the spring was prevented by roads, with populations hindered from traveling several hundred meters to vernal pools on the other side of the highway. Bird communities were negatively affected by roads for hundreds of meters. This was hypothesized to be primarily due to traffic noise and its possible interference with bird communication during the breeding period. The population density of forest interior birds was reduced as far as 650 m from a road. Grassland birds were reduced in number for up to 1-2 km from a roadside. For mammals such as deer and black bears, the highway destroyed suitable habitat and interrupted natural travel corridors.

The effect of the Massachusetts highway on local streams and wetlands was calculated. Of the 13 streams and intermittent channels crossed by the 25 km of highway, almost all had been channelized upslope or downslope for distances ranging from 30-500 m. Of the nine wetlands crossed or adjacent to the highway, all showed evidence of drainage, and five wetlands were affected at distances of 100 m or more from the road. Evidence of road salt pollution was found in a reservoir 1 km away from the highway. Information collected from natural resource specialists indicated that road salt had moved into groundwater and polluted wells at other locations.

They authors note the variability of road-effect zones, with greater effects in some locations and lesser effects in others. They conclude that the average distance of direct ecological impacts was more than 300 m, with a road-effect zone therefore of more than 600 m.

Key Finding: Roads are a major cause of forest fragmentation because they divide large landscape patches into smaller patches and convert forest interior habitat into edge habitat.

Key Finding: Clearcuts and roads affected 2.5 to 3.5 times more of the landscape than the surface area occupied by the actual clearcuts and roads themselves.

Source: Reed, R. A., J. Johnson-Barnard and W. L. Baker. 1996. Contribution of roads to forest fragmentation in the Rocky Mountains. Conservation Biology 10: 1098-1106.

Fragmentation due to roads was quantified in a 30,123-ha area of the Medicine Bow-Routt National Forest in southeastern Wyoming. A geographic information system was used to analyze landscape structure. Forest patch and edge-related landscape changes were measured using several indices: the number of patches, mean patch area, mean interior area, mean area of edge influence, mean patch perimeter, total perimeter, and mean patch shape.

Roads contributed to forest fragmentation more than clearcuts in the study area since they dissected large forest patches into smaller fragments. They also converted more forest interior habitat into edge habitat. The edge habitat due to roads was 1.54 to 1.98 times the edge habitat created by clearcuts. Taking these factors into account, the authors calculated that together, clearcuts and roads affected 2.5 to 3.5 times more of the landscape than the area occupied by the actual clearcuts and roads themselves.

Key Finding: Road networks affected stream systems, increasing the frequency and/or magnitude of peak flows, debris flows, and landslides.

Source: Jones, J. A., F. J. Swanson, B. C. Wemple and K. U. Snyder. In press. A perspective on road effects on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology.

The authors review research on the impact of road networks on stream networks. They looked at two key processes influencing riparian vegetation and channel morphology: peak flows (floods) and debris flows. Fifty years of research on biophysical processes on watersheds in the H. J. Andrews Experimental Forest in Oregon provided evidence for the impacts of roads. The road network was found to be hydrologically

connected to the stream network and increased the frequency and/or magnitude of peak flows, particularly in small basins. Roads and logging together generally had a more severe effect. Debris slides, resulting in debris flows, were also frequently associated with roads. These debris flows affected the disturbance patterns of streams and transported sediment to segments of the stream. Both peak flows and debris flows influenced stream physical features such as channels, bars, and flood plains, which in turn are closely associated with riparian vegetation and aquatic communities. The authors review studies on native aquatic organisms, such as salmonids, for instance, that had evolved with historical disturbance patterns of their stream habitat.

Key Finding: Richness of plant, bird, amphibian, and reptile communities in wetlands decreased as road density within the adjacent 2 km increased, with the full impact on biodiversity not evident for several decades.

Source: Findlay, C. S. and J. Bourdages. In press. Lagged response of wetland biodiversity to road construction on adjacent lands. Conservation Biology.

The authors studied the decline in plant, bird, and herptile (amphibian and reptile) richness of wetlands due to road construction on adjacent lands within 1 to 2 km. They were particularly interested in the lagged effects of road density on biodiversity loss. Therefore, they calculated historical road densities over four decades on lands adjacent to their sample of wetlands in Ontario. Using multiple regression models, they examined how much variation in species richness was due to past and current road densities. For plants, species loss was not detectable until several decades after the original road construction. For birds and herptiles, species loss was detectable within eight years, and increasingly evident after several decades.

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