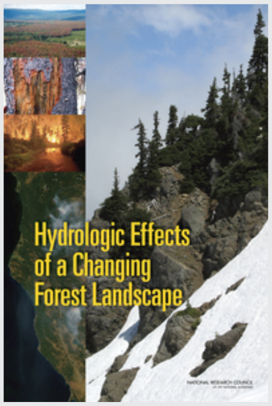

Hydrologic Effects of a Changing Forest Landscape

DETAILS

180 pages | 6 x 9 | PAPERBACK
ISBN 978-0-309-12108-8 | DOI 10.17226/12223

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3
Forest Disturbance and Management Effects on Hydrology

Forest hydrology is the study of water in forests: the movement, distribution, and quality of water as regulated by forests. Forest hydrology addresses the hydrologic processes within forested areas and the output of water resources from forested areas. Disturbances—both planned and unplanned—and management activities in forests (see Chapter 2) can significantly alter hydrologic processes. These changes can affect nearly all components of forest ecosystems, including surface erosion, slope stability, nutrient cycling, channel morphology and aquatic organisms, and the quantity and quality of water.

This chapter defines forest hydrology, describes the factors that produce change in forests, and lists the general principles of forest hydrology (Figure 3-1). The chapter then provides an overview of forest hydrology findings to date and evaluates how this science supports the management of forests for water.

FOREST HYDROLOGY SCIENCE

Forest hydrology draws on forestry, including silviculture and forest watershed management, as well as civil, environmental, and hydraulic engineering; ecohydrology; geomorphology; soil science; and water resources engineering. It combines field measurements, experiments, and modeling to characterize and predict hydrologic processes and water resources. Principal instruments include precipitation and streamflow gages; devices for collecting and measuring water in tree canopies; thermocouples and other devices to measure sap flow in trees; wells, piezometers, lysimeters, and other devices to measure soil water tension, soil water content, and water table depth; and many types of devices to characterize chemical composition of water in trees, soils, and streams. The principal questions of forest hydrology are:

- What are the flowpaths and storage reservoirs of water in forests?
- How do modifications of the forest—including both trees and forest soils—influence water flowpaths and storage? and
- How do changes in forests affect water resources from forests?

Forest hydrology science relies on watershed studies, plot studies, process studies, and modeling. "Paired watershed" studies are an important approach to forest hydrology. In a paired watershed study, stream gages are installed at the mouths of two or more watersheds, and the watersheds are manipulated to determine the effects of experimental forest treatments on streamflow or water quality. Paired watersheds are similar in size, land use or land cover, and other

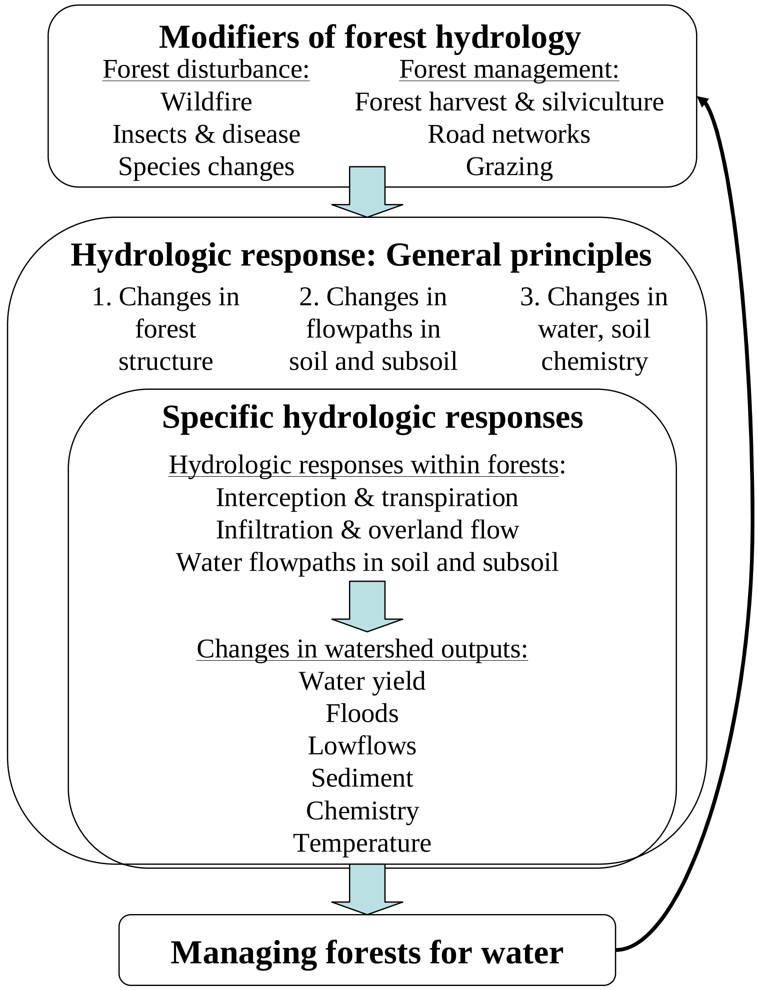


FIGURE 3-1 Forest hydrology examines the flowpaths and storage of water in forests, and how forest disturbance and management modify hydrologic responses. Hydrologic responses to changes in forests fall into three categories of general principles, as well as specific hydrologic responses, discussed in the text. The final section of this chapter evaluates the state of knowledge of forest hydrology and its implications for managing forests for water, including feedbacks to processes that modify forests.

attributes. After a reference period (usually five or more years), the "treated" watershed is subjected to manipulations (i.e., forests cutting, road building, fire, herbicides, etc.), but the "control" or reference watershed is not. The change in the relationship of streamflow and water quality between the treated and control watersheds before and after treatment is defined as the effect of the forest treatment. Most paired watershed studies in forest hydrology were begun in the 1940s through the 1960s, and many of these studies had been abandoned by the 1980s.

Field measurements from plots (segments of hillslopes), plot-scale experiments, process studies, and hydrologic modeling also are important components of forest hydrology. Field measurements from control and treated (e.g., burned, watered, cleared) forested plots have provided important insights into key hydrologic processes such as interception, transpiration, infiltration, and overland flow. Hundreds of hydrologic models have been developed to represent and predict water quantity and quality, and many of these models have been applied to forested areas; models are especially important for areas lacking field measurements and experiments.

In the twentieth century, forest hydrology science was conducted primarily in relatively small areas: segments of hillslopes ("plots") or small watersheds that ranged in size from a few square meters to 1-2 km^2. Time scales for plot-scale research commonly spanned a few growing seasons. Watershed studies have mostly been limited to one or two decades, but some, especially those in U.S. Forest Service (USFS) experimental forests and Long-term Ecological Research (LTER) sites sponsored by the National Science Foundation (NSF), have spanned periods up to 60 years. Most watershed studies occurred on publicly owned forestland, but some were conducted on privately owned land.

MODIFIERS OF FOREST HYDROLOGY

Forests are dynamic systems. Forests can be modified by: (1) fire; (2) species changes; (3) insects and disease; (4) forest harvest and silvicultural activities; (5) roads and trails, including skid trails; and (6) grazing (see Figure 3-1).

Hydrologic Effects of Fire

Record-breaking fires in recent years and projected increases in high-severity wildfires in the western United States (Fried et al., 2004; Westerling et al., 2006) have contributed to increased interest in how fire in forested systems affects water (Neary et al., 2005a). The type and magnitude of post-fire effects on runoff and water quality vary greatly with fire severity (Box 3-1), vegetation type, topography, soil type, subsequent amount and type of precipitation, and other local conditions. Despite these variances, fires can increase runoff and erosion rates by one or more orders of magnitude (Tiedemann et al., 1979; Helvey, 1980).

BOX 3-1
Fire Severity and Hydrologic Effects

Most researchers and resource managers use fire severity as the primary means to characterize and predict the hydrologic effects of fires. Fire severity differs from fire intensity. Forest fire *severity* refers to the amount of tree mortality, which is related to fire effects on the ground surface. Fire *intensity* is the heat released per unit time per unit length of flame front.

Fire severity is usually divided into three classes—low, moderate, and high. In low-severity fires the surface of the litter layer is blackened or partially consumed and some understory vegetation may be scorched or burned, but some charred or unburned litter is still present on the soil surface (Wells et al., 1979). In moderate-severity fires the litter layer is completely consumed, but the underlying mineral soil is not physically or chemically altered. High-severity fires not only burn all of the surface litter, but the greater soil heating also consumes some of the surface organic matter. This results in a disaggregation of particles in the uppermost layer of mineral soil and, depending on the soil type and amount of heating, a discoloration of the soil surface. In high-severity fires, more than 75 percent of the forest canopy is killed, and the forest floor may contain cavities where stumps and roots have been completely consumed as well as lines of white ash where coarse woody debris once covered the surface.

High-severity fires typically have a much greater hydrologic effect than low- or moderate-severity fires. The effect of wildfires on life, property, and aquatic resources means that wildfire risk is a major factor driving forest management, particularly on public lands. Approximately 45 percent of the U.S. Department of Agriculture Forest Service budget is now being devoted to fire suppression and fuels management, which is nearly double the proportion allocated in the 1980s and 1990s.

Hydrologic Effects of Changing Species Composition in Forests

The composition of forest species changes as a result of natural disturbance and forest management. During forest succession after disturbance, early successional species are replaced by late successional species, leading to changes in water yield (Swank and Crossley, 1988; Jones and Post, 2004). Forest management may modify forest species, such as replacing deciduous forest with conifer species; these changes modify water yield and timing (Swank and Crossley, 1988). In addition, wildlife management, particularly the reduction of predators, may increase native ungulates and indirectly modify forest species composition by altering the intensity of browsing (Gill and Bearsall, 2001). The hydrologic responses to these indirect effects of wildlife management are not known.

Hydrologic Effects of Insects and Diseases

A wide array of insects and diseases can be found in forest ecosystems. Insect and disease dynamics are closely coupled to climate and forest disturbances such as wind, ice, and fire. The two groups of insects of primary concern to forest managers are bark beetles and defoliators (Schmid and Mata, 1996). Bark beetles bore into the living tissue and weaken or kill trees by introducing fungi and disrupting the transport of water and nutrients between the tree crown and the roots. Recent bark beetle infestations have killed extensive areas of mature trees in short periods of time. Defoliators generally lay their eggs in the buds of trees and feed on the emerging new leaves or needles. In contrast to bark beetles, defoliators take several years of repeated, heavy attacks to kill a tree.

Large, relatively infrequent outbreaks of insects or disease in forests are often a matter of public concern; they are also ubiquitous disturbance mechanisms in forest ecosystems. Low levels are termed *endemic*, whereas a rapid increase in insect populations or the incidence of disease is termed an *outbreak.* Historical photographs and tree ring records indicate that outbreaks of native species of insects and native diseases are intrinsic processes that are a natural part of forest ecosystems. However, introduced insects and pathogens are primary drivers of forest change and have transformed forests in the United States.

Large outbreaks of native insects and dramatic forest decline due to the introduction of exotic pests and diseases fueled early interest in the effects of insects and pathogens on forest hydrology (Bue et al., 1955; Bethlahmy, 1974). Recent increases in forest area affected by insect outbreaks and possible links to fire suppression (Fleming et al., 2002; Bebi et al., 2003) have reignited scientific interest in the effects of insect and pest outbreaks on water quantity and quality. However, very few studies have been conducted on the hydrologic effects of insects and disease. The hydrologic effects of insects and disease can be extrapolated from general principles derived from studies of timber harvest and fire (MacDonald and Stednick, 2003; Uunila et al., 2006), but much remains to be understood about hydrologic effects of insects and disease.

Hydrologic Effects of Timber Management and Silviculture

Since the 1950s and 1960s, when timber harvesting expanded on federal forest lands and industrial forestry developed on private lands, an extensive literature has examined the effects of forest management. Forest hydrology studies have addressed the effects of silvicultural practices (such as site preparation, herbicide treatment, and thinning); forest protection (such as post-harvest slash burning); and timber harvest (especially removal of trees, and construction of roads and trails) on water quantity and quality. Along with fire, insects, and disease, these are the primary processes that modify forests. Most of these studies have occurred in small plots or in small, experimental watersheds. Forest management effects on water quantity, quality, and timing vary with the area treated, the type of treatment, forest type, soils, climate, and time after treatment (Hibbert, 1967; Anderson et al., 1976; Bosch and Hewlett, 1982; Swank and Crossley, 1988; Hornbeck et al., 1993; MacDonald and Stednick, 2003; Jones and Post, 2004; Brown et al., 2005; Moore and Wondzell, 2005).

Hydrologic Effects of Roads and Trails

Forest management for timber and firefighting in the latter half of the twentieth century relied heavily on trucks and other heavy machinery for skidding logs to landings, constructing fire breaks, and hauling logs to mills. Starting in the 1940s, extensive road networks were constructed on public and private forestlands in the western United States, and heavy machinery was used on forest soils throughout the country.

Obvious soil disturbances associated with mechanized harvesting equipment and conspicuous landsliding associated with forest roads led to early interest in the effects of roads and trails on forest hydrology (Megahan, 1972; Anderson, 1974; Harr et al., 1975; Swanson and Dyrness, 1975; Ziemer, 1981). Continued hydrologic and sedimentation effects of lengthy road networks combined with efforts to decommission roads have fueled continued study of the effects of roads and trails on water quantity, timing, and quality (Reid and Dunne, 1984; King and Tennyson, 1984; Wemple et al., 1996; Bowling and Lettenmaier, 2001; Lamarche and Lettenmaier, 2001; Wemple et al., 2001; Wemple and Jones, 2003; Coe, 2006). Roads affect water timing and water quality, but the magnitude of the effect depends on road design, slope steepness, soils, and the configuration of the road system relative to the stream and river drainage networks.

Hydrologic Effects of Grazing in Forests

In 1970, about half (85 million acres) of the western forests and about four-tenths (161 million acres) of the eastern forests were grazed, and about one-half of the areas grazed in eastern forests was “exploitatitve,” or beyond acceptable management (Anderson et al., 1976). Forest Service researchers (Platts, 1981) estimated that more than 800 million acres in the United States were grazed by livestock in 1970, furnishing 213 million animal unit months of forage. Overgrazing (animal densities in excess of the carrying capacity of the range) was common on forestlands and became a major research and management concern in the 1920s (Platts, 1981). Overgrazing in forests was associated with decreased infiltration capacity, increased overland flow and surface erosion, increased peak flows, and increased sedimentation in streams (Johnson, 1952; Dissmeyer, 1976; Anderson et al., 1976). In larger watersheds, overgrazing by domestic livestock is associated with ecological damage to thousands of linear miles of riparian forest cover and associated ecosystems, spurring policy statements by the American Fisheries Society (Armour et al., 1994).

HYDROLOGIC RESPONSES: GENERAL PRINCIPLES

Twelve general principles of forest hydrology (Table 3-1) describe the

TABLE 3-1 General Principles of Forest Hydrology Describing the Direct Effects on Hydrologic Processes of Changes in Forest Structure, Changes in Water Flowpaths, and Application of Chemicals

Principles of Hydrologic Response to Changes in Forest Structure	
1	Partial or complete removal of the forest canopy decreases interception and increases net precipitation arriving at the soil surface
2	Partial or complete removal of the forest canopy reduces transpiration
3	Reductions in interception and transpiration increase soil moisture, water availability to plants, and water yield
4	Increased soil moisture and loss of root strength reduce slope stability
5	Increases in water yield after forest harvesting are transitory and decrease over time as forests regrow
6	When young forests with higher annual transpiration losses replace older forests with lower transpiration losses, this change results in reduced water yield as the new forest grows to maturity
Changes in Water Flowpaths in Soils and Subsoils	
7	Impervious surfaces (roads and trails) and altered hillslope contours (cutslopes and fillslopes) modify water flowpaths, increase overland flow, and deliver overland flow directly to stream channels
8	Impervious surfaces increase surface erosion.
9	Altered hillslope contours and modified water flowpaths along roads increase mass wasting
Hydrologic Response to Application of Chemicals	
10	Forest chemicals can adversely affect aquatic ecosystems especially if they are applied directly to water bodies or wet soils
11	Forest chemicals (fertilizers, herbicides, insecticides, fire retardants) affect water quality based on the type of chemical, its toxicity, rates of movement, and persistence in soil and water
12	Chronic applications of chemicals through atmospheric deposition of nitrogen and sulfur acidify forest soils, deplete soil nutrients, adversely affect forest health, and degrade water quality, with potentially toxic effects on aquatic organisms

NOTE: These general principles are not predictions, so qualifying adjectives such as "may," "usually," etc., are omitted.

direct effects or first-order responses to changes in forest structure, changes in water flowpaths in soil and subsoil, and application of chemicals. These principles tie together the storage and movement of water in forests, how disturbance and management modify water storage and movement within forests, and how these internal changes are translated into changes in watershed outputs (Figure 3-1). These principles embody the state of knowledge of forest hydrology based on process, plot, and watershed studies conducted mostly in the second half of the twentieth century.

HYDROLOGIC RESPONSES WITHIN FORESTS

Forest disturbances and management affect the pathways of water within the forest system. Interception, evapotranspiration, infiltration, and overland (or surface) flow respond to forest disturbance and management (Figure 3-1). In turn, these changes affect watershed outputs.

Interception and Evapotranspiration

Interception is the net loss of precipitation, by evaporation, between the top of the forest canopy and the forest floor; this water is returned to the atmosphere and does not enter the soil. When forest canopies temporarily capture raindrops or suspend ice and snow, they slow the rate at which precipitation arrives at the forest floor. If this captured moisture evaporates, it effectively decreases the amount of precipitation available for soil moisture storage, transpiration, or runoff. In dispersing raindrops or suspending ice or snow, interception slows the rate at which precipitation hits the forest floor and, in doing so, effectively decreases the net effect of precipitation. Removal of trees reduces leaf area and hence, interception. Reductions in leaf area—from fire, harvest, insects, or disease—and differences in leaf area among different forest types and ages all affect hydrology in the same way (Verry, 1976; Schmid et al., 1991): a reduction in interception increases the amount of water that reaches the mineral soil. If infiltration rates are not changed, an increase in net precipitation increases soil moisture, water availability to plants, and the proportion of precipitation that is available for streamflow (Helvey and Patrick, 1965; Helvey, 1971). Reduced leaf area decreases interception rates in both rain- and snow-dominated systems; in snow-dominated systems an increase in net precipitation increases water stored in the snowpack (Neary and Ffolliott, 2005; Woods et al., 2006). Where forest canopies capture additional moisture from clouds, a reduction in leaf area can decrease net precipitation (Harr, 1982; Hutley et al., 1997; Reid and Lewis, 2007).

A reduction in leaf area also increases the amount of light reaching the forest floor, increasing energy exchange between soil or snow and the atmosphere and altering the energy budget (Figure 1-3). Increased exposure of the snowpack to solar radiation and to turbulent heat transfer by wind increases snowmelt rates relative to undisturbed forest canopies. In snow-dominated forest systems a reduction in leaf area can lead to increased snow accumulation as well as an earlier onset of snowmelt and faster melt rates (Helvey, 1980; Megahan, 1983; Hornbeck et al., 1997; Jones and Post, 2004).

The process of transferring moisture from the earth to the atmosphere by evaporation of water and transpiration from plants is called evapotranspiration. In North American forests, evapotranspiration accounts for 40 to more than 85 percent of gross precipitation. A reduction in leaf area from forest harvest, fire, or insect or disease outbreaks reduces evapotranspiration and increases water available for runoff. The magnitude and persistence of the reduction in transpiration depends on the amount and type of the vegetative canopy removed and the rate at which the vegetative cover is reestablished. However, it has only recently become possible to accurately measure transpiration in trees, and few studies have quantified transpiration rates for forest stands (but see Ryan et al., 2000; Moore et al., 2004).

Infiltration and Overland Flow

Most forests have an organic surface layer that protects the soil surface and facilitates infiltration. In most cases this water moves by subsurface pathways to the stream. Because forest soils have high infiltration rates, water rarely flows over the ground surface as infiltration excess (also called Horton overland flow). In flatter, low-lying or convergent zones, the saturated zone may rise to the surface and produce saturated overland flow.

Forest management activities and forest disturbances may remove or alter the surface layers of forest soils, and thereby reduce infiltration and increase Horton overland flow (Figure 1-1). Forest management activities and disturbances also create impervious surfaces (e.g., as roads) and modify hillslopes in ways that alter water flowpaths in soils and subsoils, shift subsurface flow to surface flow, and increase runoff and erosion rates. When organic surface layers are removed or burned, underlying mineral soil is exposed to raindrop splash and fine soil particles can accumulate on the surface, reducing infiltration and increasing overland flow. If soils are compacted to the extent that infiltration rates are lower than rainfall or snowmelt rates, the resulting overland flow can greatly increase runoff rates and surface erosion.

CHANGES IN WATERSHED OUTPUTS

Forest hydrology science describes direct changes in watershed outputs resulting from fire, timber harvest, and roads and trails (Table 3-2). These findings are summarized below.

Fire

Fire, Infiltration, and Overland Flow

Burning can greatly reduce infiltration rates and thereby increase surface runoff and erosion rates through several mechanisms: development of a water-repellent (“hydrophobic”) layer at or near the soil surface; exposure of the soil surface to raindrop impact and soil sealing; increased soil erodibility; and decreased surface roughness (Box 3-2). Large post-fire increases in runoff and erosion are often attributed to an increase in soil water repellency after burning (Box 3-2), but soil sealing may play an equal or even larger role in increased runoff and erosion in some areas.

TABLE 3-2 Magnitude and Duration of Direct Effects on Watershed Outputs of Three Sets of Processes That Modify Hydrology in Forests: Fire, Forest Harvest and Silviculture, and Roads and Trails

	Processes That Modify Hydrology in Forests		
Watershed Output	Fire	Forest Harvest and Silviculture	Roads and Trails
Water yield	High-severity fire increases annual water yields; little effect of low-severity fire	Increase water yield; magnitude and duration of response varies (see text)	Little or no effect
Peak flows	High-severity fire increases peak flows; effect is short-lived	Increase peak flows; magnitude and duration of response varies (see text)	Increase peak flows; effects may be long-lived and affect extreme events
Low flows	High-severity fire increases low flows; little effect of low-severity fire	Increase low flows in short term; deficits may develop as forests regrow	Little or no effect
Erosion, landslides, sedimentation	High-severity fire increases erosion and sedimentation in streams; less effect from low-severity and prescribed fire	Increase surface erosion, landslides, and sedimentation; effects may be long-lived	Increase surface erosion (road surfaces and gullies below culverts) and landslides; increase sedimentation in streams
Water temperature and chemistry	Increases water temperature due to riparian forest removal; fire retardants and ash affect chemistry; effects are short-lived	Increase water temperature due to riparian forest removal; effects of fertilizer mostly small and short-lived; short-lived post-harvest increases in nitrate	Deliver road chemicals (e.g. salt, oil) to streams
Research gaps	Uncertainty about effects beyond a few years; magnitude and persistence of downstream effects; effects of salvage logging	Uncertainty about effects beyond one or two decades; magnitude and persistence of downstream effects; effects on habitat and aquatic ecosystems	Uncertainty about road effects on extreme floods and in watersheds >1 km^2

NOTE: These are general effects, not predictions, so qualifying adjectives such as “may,” “usually,” etc., are omitted. See text for factors that influence when, where, and to what extent these effects apply.

BOX 3-2
Physical and Chemical Causes of Water Repellency in Soils

Many soils are water repellent without being burned, particularly in coniferous forests and xeric shrublands. Waxy and other aromatic compounds in the foliage of these vegetation types leach out and accumulate on the soil surface. Fungal hyphae also can generate very strong, localized soil water repellency near soil surfaces. In the absence of burning, these compounds are rarely sufficient to reduce infiltration rates at the hillslope scale. However, when burned at roughly 175-200ºC, these compounds vaporize and are driven by steep heat gradients down into the soil, where they condense on cooler underlying soil particles. Thus, burning can create a semicontinuous or continuous water repellent layer at or beneath the soil surface, whose depth and thickness depend on the duration and magnitude of soil heating (DeBano, 2000; Letey, 2001). Temperatures above 280-400ºC consume most waxy and aromatic compounds, so very hot fires produce a nonrepellent, disaggregated soil layer above a water-repellent layer (DeBano, 2000; Doerr et al., 2006). Coarse-textured soils are more susceptible to the formation of a water-repellent layer than fine-textured soils because of their lower surface area and greater air permeability (Huffman et al., 2001; DeBano et al., 2005).

Fire-induced soil water repellency has been well documented for certain vegetation types, particularly coniferous forests and chaparral-type ecosystems (e.g., DeBano, 2000). Fire-induced soil water repellency is spatially heterogeneous (Woods et al., 2007) and can persist for a few weeks or several years (Shakesby and Doerr, 2006). Snowmelt or prolonged rainfall may overcome water repellency until soils dry out (Doerr and Thomas, 2000; MacDonald and Huffman, 2004). Thus, burning may have less effect on infiltration and runoff during winter wet seasons or in snowmelt-dominated areas than in drier areas subjected to summer thunderstorms. Fire-induced soil water repellency breaks down by a combination of physical, chemical, and biological processes over time as plant regrowth provides a protective cover of vegetation and litter (e.g., Robichaud and Brown, 1999; Benavides-Solorio and MacDonald, 2005). Therefore, runoff and erosion rates usually return to reference or pre-fire levels within one to four years (Shakesby and Doerr, 2006).

Soil sealing refers to a reduction in infiltration as a result of breakdown of soil aggregates and rearrangement of soil particles at the surface. After moderate- and high-severity fires, rain splash can detach soil particles and reduce infiltration rates by a sealing effect at the soil surface. Combustion and the loss of organic matter also lead to a loss of soil cohesion. These effects contribute to greater overland flow (Neary et al., 1999; DeBano et al., 2005; Moody et al., 2005) and soil erodibility (Cerda, 1998; Larsen and MacDonald, 2007; Woods and Balfour, 2007).

Severe fire leads to greater reductions in infiltration and greater increases in overland flow than moderate- or low-severity fire (Shakesby and Doerr, 2006). In the Colorado Front Range, for example, summer thunderstorms with 60 mm of rainfall per hour often produce no surface runoff or erosion, but after a high-severity fire, surface rainfall intensities of only 10 mm per hour can generate overland flow (Moody and Martin, 2001; Kunze and Stednick, 2006; Wagenbrenner et al., 2006). Compared to high-severity fires, low-severity wildfires and most prescribed fires result in little or no exposure of the mineral soil surface, smaller changes in soil water repellency (Robichaud, 2000), and little effect on overland flow (Van Lear and Danielovich, 1988; Robichaud, 2000; Benavides-Solorio and MacDonald, 2005).

Salvage logging is often conducted post-fire, and although its effects on forest ecosystems are being debated (Donato et al., 2006), few studies have examined the hydrologic effects. Ground-based salvage logging generally results in more ground disturbance and less ground cover (Klock, 1975; McIver and McNeil, 2006), and extensive ground disturbance can increase soil erodibility and erosion rates. Non-ground based activities, such as the use of helicopters in logging, result in relatively little ground disturbance and may have minimal effect on post-fire runoff and erosion rates. Standard salvage logging practices are unlikely to significantly reduce or break up the water-repellent layer from a high-severity wildfire.

Fire and Water Yield

High-severity fires occur in unpredictable locations, at unpredictable times (Carpenter, 1998), which makes their study difficult and has resulted in few studies that confirm relationships between fire and water yield. By analogy to clear-cutting, high-severity fires are expected to increase water yield. Changes in interception, transpiration, and runoff processes usually lead to higher annual water yields after a high-severity fire, although the increases are highly variable between and within ecoregions (Berndt, 1971; Campbell et al., 1977; Helvey, 1980; Neary and Ffolliott, 2005; Neary et al., 2005b). Low-severity fires generally do not consume or kill enough vegetation to alter water yields significantly (e.g., Douglass and Van Lear, 1983; Gottfried and DeBano, 1990).

Fire and Peak Flows

High-severity fires can increase peak flows by one or two orders of magnitude (Scott, 1993; Moody and Martin, 2001; Neary et al., 2005b). The greatest increases in peak flows occur in areas with summer thunderstorms or fall rains, where burning has altered infiltration and overland flow processes. Reported changes in peak flows after wildfires include (1) minimal change following a high-severity burn in a snow-dominated Wyoming fir forest (Troendle and Bevenger, 1996): increase of 1.4 times in a Douglas fir forest in Oregon (Anderson, 1974); (2) increase of 6.5 to 870 times in California chaparral (Hoyt and Troxell, 1934; Sinclair and Hamilton, 1955; Krammes and Rice, 1963); and (3) increase of 20 to more than 2,000 times in ponderosa pine forests in Arizona and New Mexico (Campbell et al., 1977; Bolin and Ward, 1987; Ffolliott and Neary, 2003).

Fire and Erosion

The most important effects of fire are increases in overland flow and erosion and resulting effects on flooding and water quality. Fire can enormously increase surface erosion. Fire exposes the mineral soil and increases surface erosion; it also may increase soil moisture and landslides (Wells et al., 1979; Moody et al., 2005; Neary et al., 2005; Shakesby and Doerr, 2006). Fire-induced higher rates of erosion increase sediment delivery to streams (Helvey, 1980; Ewing, 1996; Moody and Martin, 2001; Ffolliott and Neary, 2003; Wondzell and King, 2003; Libohova, 2004; Kunze and Stednick, 2006). Low-severity and prescribed fires produce smaller effects on erosion and sedimentation in streams (Douglas and Van Lear, 1983; Van Lear et al., 1985; Van Lear and Danielovitch, 1988; Gottfried and DeBano, 1990; Wright et al., 1982). Post-fire salvage logging can further increase erosion and sediment delivery to streams (McIver and McNeil, 2006). Studies of erosion and sedimentation after high-severity fires have become more frequent in the past few decades as wildfire activity has increased on forestland in the western United States (Westerling et al., 2006).

Fire Effects on Water Temperature and Chemistry

Fire can affect a series of water quality parameters (see recent summaries by Landsberg and Tiedeman, 2000; Ranalli, 2004; Neary et al., 2005b). The effects of fire depend in large part on the pre-fire composition of organic matter and the fire intensity. The chemistry of unburned organic matter varies with plant species, underlying geology, time elapsed since the last disturbance, and atmospheric deposition of elements such as mercury and lead.

Fires usually affect water quality by the indirect pathway of increasing stream water temperature and two direct pathways, atmospheric deposition and surface runoff. Extensive burning of the riparian forest canopy removes shade, increases the amount of solar radiation, and raises stream water temperatures. Increased organic carbon and temperature in streams can reduce concentrations of dissolved oxygen (Neary et al., 2005c).

During a fire, gases and particulate matter are carried aloft and transported for varying distances before being deposited on water surfaces. In the Yellowstone fires of 1988, for example, increases in nitrogen in lakes and rivers were attributed to the diffusion of smoke into the water bodies under active fire conditions (Spencer et al., 2003).

Ash deposition can increase the pH of surface water and soil (Neary et al., 2005b). Post-fire pH values in stream water rarely exceed U.S. Environmental Protection Agency (EPA) standards (Landsberg and Tiedemann, 2000), but transient pH values of 9.5 were measured in streams after a fire in eastern Washington (Tiedemann, 1973; Tiedemann et al., 1979). Fire can cause a short-term increase in stream nitrate concentrations, and the delivery of ash and fine sediment can increase phosphorus concentrations in streams. In most cases these increases do not exceed standards for drinking water (Neary et al., 2005c).

During forest fires, chemical fire retardants are applied aerially to forests and inadvertently (perhaps unavoidably) to streams and rivers. The effects of these chemicals on water quality may be important, especially since recent studies have shown that they persist for years after application (Morgenstern, 2006). Fire retardants can contain nitrate and possibly sulfate, phosphate, and some trace elements (Landsberg and Tiedemann, 2000), which can contribute to eutrophication, especially when applied directly to streams. When these materials enter rivers, streams, and lakes, they react with sunlight to form compounds that are toxic to aquatic organisms (e.g., Buhl and Hamilton, 1998, 2000). Increased concentrations of other chemicals, such as manganese, sulfate, and mercury, also have been documented after forest fires. Elevated concentrations of both lead and mercury were detected in the post-fire runoff from the Bobcat fire outside Fort Collins, Colorado. Elevated post-fire concentrations of manganese and other constituents forced the Denver Water Board to initiate additional specialized treatments to maintain drinking water quality. In most cases the adverse effects of forest fires on chemical water quality persist for no more than two or three years.

Forest Harvest

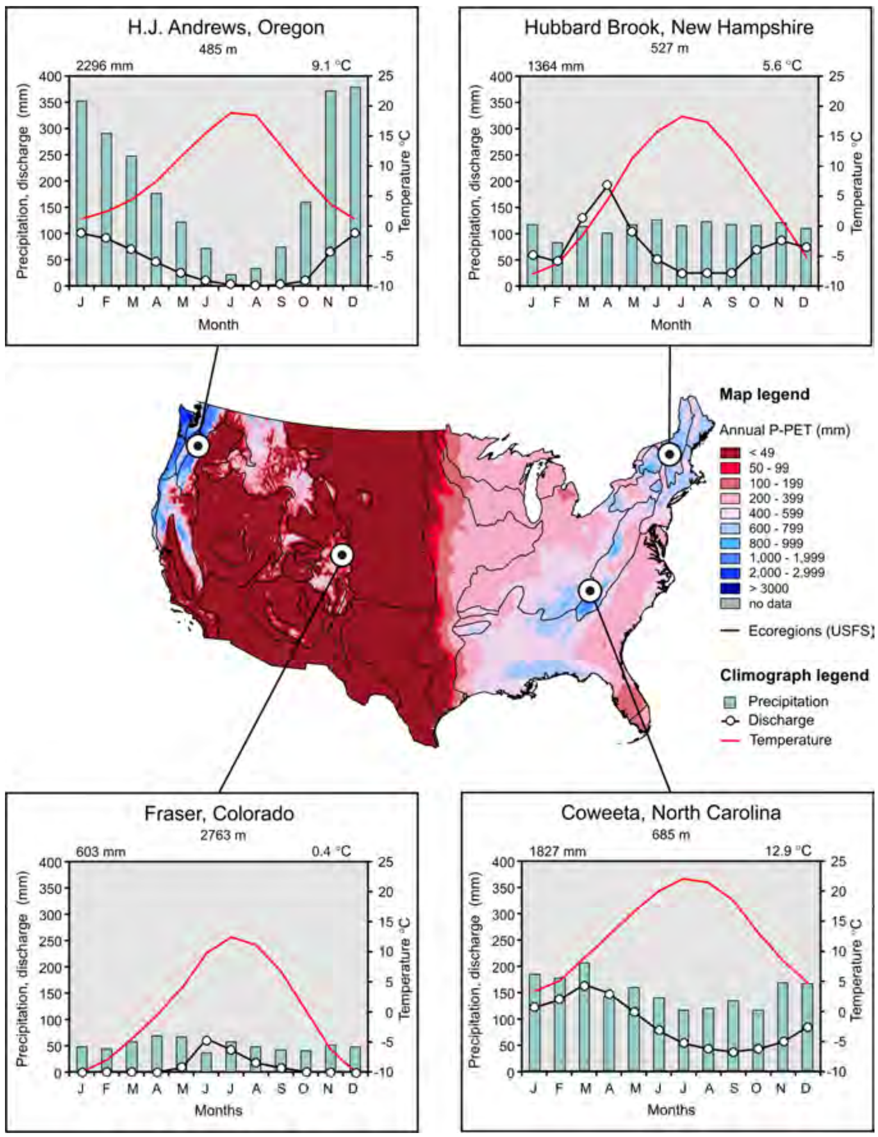
Timber Management, Silviculture, and Water Yield

Dozens of paired watershed forest harvest experiments have demonstrated that forest removal increases water yield (Bosch and Hewlett, 1982; Hornbeck et al., 1993; Ice and Stednick, 2004; Jones and Post, 2004; Brown et al., 2005). The magnitude of water yield increases can be expressed as an absolute increase (e.g., millimeters of water, Figure 3-2) or as a percentage. Water yield increases are highest after 100 percent forest harvest, and are almost always highest in the first year after forest harvest, or the wettest year in the early post-harvest period, when changes in interception and transpiration have the greatest effect on the water balance (Bosch and Hewlett, 1982; Sahin and Hall, 1996).

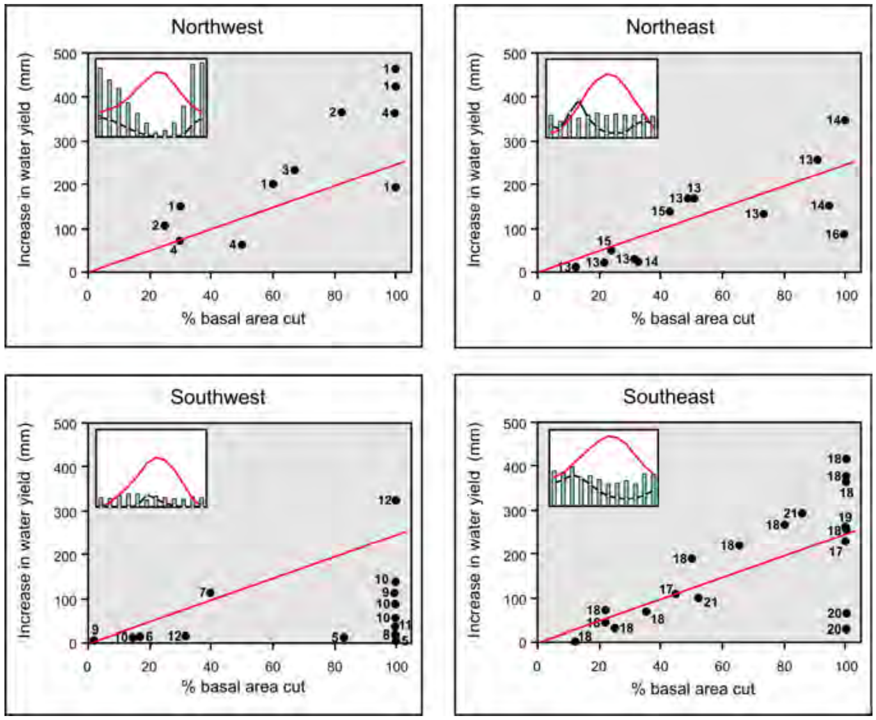
Water yield increases after forest harvest vary according to several factors:

- **Climate**. The largest absolute water yield increases have occurred after cutting of forests in climates with relatively abundant precipitation (1,500 to 2,500 mm per year) and relatively low evapotranspiration. High water yield increases (300 to 500 mm per year) have been measured in the Pacific Northwest (H.J. Andrews Experimental Forest, site 1), the Northeast (Hubbard Brook Experimental Forest, site 14), and the Southeast (Coweeta Experimental Forest, site 18) (Figure 3-2). Much smaller water yield increases have been measured in regions where mean annual precipitation is low (<500 mm per year) and

(a)


H.J. Andrews, Oregon
485 m
2296 mm
9.1 °C
Hubbard Brook, New Hampshire
527 m
1364 mm
5.6 °C
Fraser, Colorado
2763 m
603 mm
0.4 °C
Coweeta, North Carolina
685 m
1827 mm
12.9 °C
Precipitation, discharge (mm)
Temperature °C
J F M A M J J A S O N D
Month
Months
Map legend
Annual P-PET (mm)
< 49
50 - 99
100 - 199
200 - 399
400 - 599
600 - 799
800 - 999
1,000 - 1,999
2,000 - 2,999
> 3000
no data
Ecoregions (USFS)
Climograph legend
Precipitation
Discharge
Temperature

(b)



(c)

Northwest
1. Andrews, OR
2. Alsea, OR
3. Casper Creek, CA
4. Coyote Cr, OR

Northeast
13. Fernow, Wva
14. Hubbard Brook, NH
15. Leading Ridge, PA
16. Marcell, MN

Southwest
5. Beaver Creek, UT
6. Castle Creek, UZ
7. Fraser, CO
8. Natural Drainage, AZ
9. San Dimas, CA
10. Three Bar, AZ
11. Wagon Wheel Gap, CO
12. Workman Creek, AZ

Southeast
17. Alum Creek, AR
18. Coweeta, NC
19. Grant Forest, GA
20. North Mississippi, MS
21. Upper Bear Cr, Ala

FIGURE 3-2 (a) Potential annual water yield (precipitation minus potential evapotranspiration, P – PET) in millimeters for the United States, and mean monthly precipitation, temperature, and discharge at four small watershed sites in the Northwest, Northeast, Rocky Mountains, and Southeast. Mean elevation (meters), mean annual precipitation (millimeters), and mean annual temperature (degrees celsius) are shown above the graph for each of these four sites. (b) First year water yield increase (millimeters) versus percent basal area removal for 21 paired watershed forestry experiments in the conterminous United States. The trend line, shown for comparison, was taken from Figure 1 of by region were developed by Stednick (1996), which represented 95 catchments spread across similar geographic regions as shown here. (c) Locations of paired watershed sites show in (b). Black lines on map are USFS ecoregions.

potential evapotranspiration is high. In these areas, such as the interior West and Southwest, removal of forest cover is largely offset by increased soil evaporation and evapotranspiration by any remaining vegetation, and water yield increases are often <150 mm per year (Bosch and Hewlett, 1982) (Figure 3-2). Small water yield responses in the Southwest illustrate the limited potential for increasing water yields in dry forest types.

- **Seasonal timing of precipitation**. In regions where precipitation is evenly distributed throughout the year (Northeast, Southeast; Figure 3-2), water yield increases typically occur during the growing season (Martin et al., 2000; Jones and Post, 2004). In regions with dry summers and wet winters (western forests; Figure 3-2), the largest water yield increases occur in the late fall and early winter due to a reduction in transpiration and resultant increase in soil moisture carryover (Jones and Post, 2004). In snowmelt-dominated regions, most of the water yield increase occurs in spring because larger snowpacks accumulate in cutover areas (Harr et al., 1979; Troendle and King, 1985; Troendle and Reuss, 1997; Jones and Post, 2004). Thus, in both eastern and western forests, water yield increases after forest harvest often occur during seasons when water is abundant, not scarce (Harr, 1983; Troendle et al., 2001).
- **Amount of forest removed**. Forest harvest experimental treatments have ranged from 100 percent clear-cutting to partial cuts, overstory thinning, or selective harvest of a fraction of watershed area (Figure 3-2). In areas with more than 500 mm of mean annual precipitation (the Pacific Northwest, Northeast, and Southeast), water yield increases are roughly proportional to the amount of forest area cut (Hibbert, 1967; Bosch and Hewlett, 1982) (Figure 3-2). Water yield increases are difficult to detect when less than 20 percent of the basin area has been harvested (Stednick, 1996) (Figure 3-2). The spatial arrangement of cutting within a watershed also affects whether a water yield increase is detected; controlling for the amount of forest cut, there is less detectable water yield increase for thinning or selective harvests than for patch cuts (Site 4, Figure 3-2) (Perry, 2007).
- **Harvest treatments**, such as burning, herbicides, or buffer strips. Forest harvest has different effects on water yield increase depending on whether the area is burned, herbicide is applied, or the treatment is conducted in stages (compare vertical scatter of points from site 14 in Figure 3-2).
- **Storage of water in soil and snow**. Year-to-year storage of water in deep soils or poorly drained areas may offset water yield increases in areas with deep compared to shallow soils (compare site 20 versus 18, and 16 versus 14 in Figure 3-2). Post-harvest changes in snow accumulation and melt rates also can affect water yield increases after harvest (Verry et al., 1983; Troendle and Reuss, 1997; Jones and Post, 2004) (compare vertical scatter of points from site 1 or site 14 versus 13 in Figure 3-2),
- **Type and age of forest removed**. Post-harvest water yields are higher when old-growth forests with high leaf area are harvested, compared to when younger forests with low leaf area are cut (Swank and Crossley, 1988; Jones and Post, 2004). When forests of low interception (or lower annual transpiration

losses), are replaced by forests with higher interception (higher transpiration losses) the net water yield can be reduced as the new forest grows to maturity (e.g., Swank and Crossley, 1988; Jones and Post, 2004).

- **Time since harvest**, or the amount of forest regrowth. As forests regenerate after harvest, water yield increases disappear. Water yield increases have persisted for as little as a decade in some areas, but for multiple decades in other areas, depending on the type and history of the forest, soils, climate, reforestation methods, and harvest treatments (Bosch and Hewlett, 1982; Troendle and King, 1985; Swank and Crossley, 1988; Hornbeck et al., 1993; Hornbeck et al., 1997; Troendle et al., 2001; Jones and Post, 2004; Brown et al., 2005). In some cases, water yields drop below pre-harvest levels after a couple of decades of forest regrowth (Hornbeck et al., 1993; Swank and Crossley, 1988; Jones and Post, 2004; Brown et al., 2005). Many paired watershed experiments established to test forest management effects on water yield were terminated after the first 5-10 years of post-treatment, so only a few paired watersheds are still providing information about the long-term consequences of past forest management for water yield.

In summary, water yield increases from forest harvest are highly variable. The highest increases in water yield occur from 100 percent forest harvest in the first years after harvest and in areas where water is relatively abundant. Because of the inherent variability in water yield responses, the amount of forest harvest necessary to produce a water yield increase varies according to regional and site-specific characteristics (e.g., amount and type of precipitation, slope, soil thickness, silvicultural methods, harvest treatments).

There is little evidence that timber harvest can produce sustained increases in water yield over large areas. Because of high evapotranspiration relative to precipitation, and dry summers, the potential for augmenting water yield on a sustainable basis in western forests and rangelands is very low (Harr, 1983; Hibbert, 1983; Troendle et al., 2001). Water yield increases from the harvest of western forests occur in winter when water is relatively abundant, and these increases would have to be stored for up to six months to effectively augment water supplies when water is scarce in late summer (Harr, 1983). Maintaining water yield increases requires continued forest harvest or conversion of forests to other land uses such as pastures, annual crops, and urban areas. Although the potential for augmenting water yield is higher in eastern than western forests, achieving this potential would require major changes in forest management objectives and land use (Douglass, 1983).

Timber Management, Silviculture, and Low Flows

Relative to peak flows or annual water yields, few studies have examined the effects of forest harvest on low flows. Most studies show an initial increase in low flows immediately after forest harvest (Harr et al., 1979, 1982; Keppeler and Ziemer, 1990; Hicks et al., 1991; Hornbeck et al., 1997; Johnson, 1998; Swank et al., 2001; Jones and Post, 2004). Observed water increases in low flows after harvest change are often short-lived, usually persisting for less than 10 years due to the relatively rapid recovery of leaf area, interception capacity, and transpiration rates.

These short-term surpluses during the low-flow period change to deficits as forests regrow. As in the case of annual water yields, the increase in low flows often is followed by a decrease in low flows to below pre-harvest levels (Hicks et al., 1991; Hornbeck et al., 1997; Swank et al., 2001). These decreases occur when a forest with relatively high transpiration and/or interception replaces a forest with relatively low transpiration or interception, such as during (1) species conversion (e.g., deciduous to evergreen) (Swank et al.,1988); (2) regeneration of a young stand with higher water use than the mature stand it replaces (Hicks et al., 1991; Perry, 2007); or (3) establishment of different riparian vegetation with greatest water demands (Moore et al., 2004; Ice and Stednick, 2004). Because relatively few studies have examined long-term trends in low flows, there is much uncertainty about this subject.

Timber Management, Silviculture, and Peak Flows

Decreases in transpiration and interception after forest harvest increase soil moisture, and higher initial soil moisture at the beginning of a storm increases storm runoff (peak flow) (Box 3-3). Recent compilations of studies examining forest management effects of peak flows show wide variability in the magnitude of peak flow response to forest harvest (Austin, 1999; Moore and Wondzell, 2005; Grant et al., 2008). Much of this variation is explained by the differences in how peak flows were defined and analyzed, dominant hydrologic regimes (e.g., rain or snow), differences in forest management, and other differences in site conditions (Austin, 1999).

Peak flow responses to forest harvest vary according to several factors:

- **Event size**. Often, the percentage increase in peak flows after forest harvest decreases as the magnitude of the peak flow increases (Harr, 1976; Beschta et al., 2000; Grant et al., 2008). However, in many cases the absolute increase in peak flows is larger with larger storms (Box 3-4; Verry, 1986; Jones and Grant, 1996; Jones, 2000; Moore and Wondzell, 2005). As storm magnitude (the total amount of rainfall or snowmelt) increases, the proportion of precipitation that can be stored by vegetation decreases. Therefore, large peak flows often experience smaller relative increases than small peak flows. Nevertheless, small percentage increases in very large floods as a result of forest harvest (Figure 3-3) may be quite large in absolute terms; a 10 percent increase in a typical 50-year flood is the same amount of water as a 50 percent increase in a 1-yr flood. Small increases in extreme floods affect more people and may be of greater concern for managers than increases in small floods.

BOX 3-3
Does Timber Harvesting Cause Floods?

The effect of forest management on flooding has been a recurrent scientific, social, and political theme (Eisenbies et al., 2007). The notion that deforestation leads to widespread land degradation and exacerbates the risk of flooding dates to antiquity (Hillel, 1994), and the role of forest management on extreme floods is an important concern for policy makers and the public (Figure 3-3). There is little doubt that forests influence the storage and movement of water, particularly at annual and seasonal time scales. Understanding the role of forest management in moderate and large floods requires a clear definition of terms and careful consideration of the various processes by which forest management can affect the size of peak flows.

Floods are variously defined by scientists and affected populations. Floods are commonly described as flows that exceed channel capacity and result in overbank inundation (Brooks et al., 2003), which can occur as frequently as every one to two years, since channels tend to adjust their shape to accommodate more frequently occurring events (Leopold et al., 1995). Hydrologists typically define floods according to their probabilities of recurrence or return period (*e.g., the 5-year flood, the 100-year flood*). Public concerns about floods are commonly limited to the more extreme events that result in a loss of life or property.

The largest floods are associated with extreme storm events, such as tropical cyclones. Some recent assessments have attempted to link the growth in flood damage in recent decades to development in flood-prone lands and to discount the role of deforestation on large-scale extreme floods (FAO, CIFOR, 2005). Nevertheless, considerable public and political pressure tends to follow extreme floods, and forest protection is often an important element of debates and policy formulation (Eisenbies, 2007).

Logging suspect in Virginia floods

By Chris Kahn
The Associated Press

TACOMA, Va. — Life along Stony Creek has never been so rough for Ray Begley.

The creek jumped its banks last summer, tearing his living room from its foundation and carrying the tangled mess downstream. Another flood last month washed away the gravel mountain road that led to his ramshackle home.

"I'm done with this place," said Begley, 62, who grew up swimming and fishing along the creek. "I just don't trust it anymore."

This is not how it used to be.

Like many people living in the mountains of Virginia's extreme southwest, Begley suspects logging above his home has created more and larger floods than ever before.

With last year's floods still fresh on people's minds and this year's floods causing $55.7 million in damage, environmentalists, hunters and residents want to stop a proposed timber harvest on 700 acres in the Jefferson National Forest, about 100 miles northeast of Knoxville, Tenn.

Local activists handed Rep. Rick Boucher, D-Va., a petition with 5,000 signatures in November condemning the proposal. In response, Boucher, who represents southwestern Virginia, has asked the U.S. Forest Service to suspend the timber sale until a panel of forest professionals and environmentalists can examine the region's timber practices.

"The flooding calls everything into question," said Blain Phillips with the Southern Environmental Law Center in Charlottesville, which represents the activists.

Bill Damon, supervisor for the George Washington and Jefferson National Forests, said his agency has tried to be responsive to public concern, cutting the proposed harvest in half from 1,413 acres. Damon said he has trouble understanding why there is such resistance to logging on just a few hundred acres in a forest of 1.76 million acres.

Damon would not say if he believes logging contributes to flooding, deferring to Boucher's advisory committee, which started meeting in February.

The panel, which includes local officials, activists, the Forest Service, U.S. Fish and Wildlife, the Army Corps of Engineers and lumber industry representatives, is expected to make its recommendations by summer.

In September, however, the Forest Service concluded in a field study that July's floods on Stony Creek would have happened no matter what.

"That was a big flood," said Gary Kappesser, a Forest Service hydrologist. "Any management within the watershed would have made little difference."

Similar complaints have been raised in other parts of Appalachia, with many people suggesting that the coal mining practice of cutting away mountaintops has also made floods more dangerous.

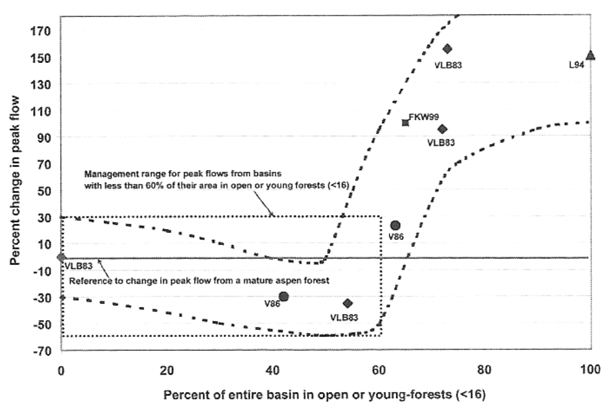
Michael Gillen, a hydrologist with the National Weather Service in Blacksburg, said flooding has increased all along the Appalachian range, but he is not sure why. The effects, however, are increasingly visible as more people move to rural areas, he said.

"You've got more people living along these streams because they're so beautiful when they're not flooded," Gillen said, "and when you clear-cut property, you reduce its ability to absorb runoff."

FIGURE 3-3 Public perception of flooding is often linked to land use activities. SOURCE: Reprinted, with permission, from Associated Press (2002). Copyright 2002 by Associated Press.

BOX 3-4
Regional Variability in Peak Flow Response: Northern Lake States

The effect of timber harvesting (or forest clearing for other uses) on the timing of peak flows varies regionally, as illustrated in the northern Lake States, particularly where snowmelt dominates the annual hydrograph. In mountainous areas, snowmelt is naturally desynchronized by the heterogeneity of terrain features such as slope, aspect, and elevation. The snowpack generally melts first at low elevations and last at high elevations, more quickly on south slopes than on east and west slopes, and most slowly on north slopes. Differences in forest canopy type and density (e.g., dense, even-aged conifers versus sparse, deciduous stands) also change the timing and rate of snowmelt. In the relatively flat terrain of the northern Lake States the effect of topography on energy exchange is minor in comparison to the influence of forest cover. Therefore, when timber harvesting (e.g., patch or strip cuts) changes the energy balance and microclimate of a watershed, it tends to desynchronize snowmelt (Figure 3-4). In effect, forest harvest changes the snowmelt hydrograph from one peak to two, with the first peak coming from the harvested openings and the second peak from the remaining mature forest. As the proportion of the harvested area within a watershed increases (e.g., greater than ~70 percent open), snowmelt occurs earlier and at a more rapid rate.



NOTE: Dashed lines are theoretical envelope curves started at ±30 percent on the left but expanding to include all of the data to the right. They are an estimated mean response first proposed in Verry (1986). Data points (author and year of publication) are from paired watershed experiments (Verry, Lewis, and Brooks 1983 — Marcell Experimental Forest), double mass curve historical evaluations (Verry 1986 — Upper Mississippi above St. Paul, Minnesota), historical geomorphic and modeling analyses (Fitzpatrick, Knox, and Whitman 1999 — North Fish Creek near Ashland, Wisconsin), and modeling of complex upland/peatland watersheds (Lu 1994 — Marcel Experimental Forest). Several state, county, and river basin groups use the 60 percent open and young forest condition to guide watershed cover condition.

FIGURE 3-4 First-year increase in peak discharge versus percent forest clearing for watersheds in the northern Lake States. SOURCE: Reprinted, with permission, from Ice and Stednick (2004). Copyright 2004 by the Society of American Foresters.

- **Rain versus snow**. Storm events involving rain respond differently to forest harvest than those involving snow. In rain events, forest harvest affects peak flows directly through changes in soil water. In events involving snow, the effect of forest harvest on peak flows depends on how forest harvest changes snowpack size and snowmelt, as well as soil moisture (Verry et al., 1983; Troendle and King, 1985; Jones, 2000; MacDonald et al., 2003; MacDonald and Stednick, 2003; Schnorbus and Alila, 2004).
- **Season**. Peak flow increases after forest harvest are proportionately larger in spring, summer, and fall compared to winter, because soil moisture levels are sensitive to transpiration by forest vegetation in spring, summer, and fall. However, peak flow increases (in millimeters) after forest harvest are absolutely (see Figure 3-2) larger in winter than in spring, summer, or fall, because peak flows are higher in winter, and reductions in transpiration in previous seasons carry over into winter (Jones, 2000; MacDonald and Stednick, 2003).
- **Proportion of area harvested**. The larger the proportion of area harvested, the greater is the increase in peak flows (Jones, 2000; Moore and Wondzell, 2005). Peak flow increases have been detected after only 25 percent harvest of a small watershed (Harr et al., 1979, 1988; Jones and Grant, 1996; Caissie et al., 2002).
- **Topographic relief and elevation**. The effect of forest harvest on the energy balance, and resulting changes in snow accumulation and melt, vary with elevation and aspect. Forest harvest may increase peak flows during rain-on-snow events in the Pacific Northwest (Harr, 1981; Harr, 1986). In the flatter topography of the northern Lake States, harvesting 20 – 50 percent of the watershed desynchronizes snowmelt and reduces annual snowmelt peak flows by as much as 40 percent, while harvesting over 60 percent of a basin can increase the size of snowmelt peak flows by more than 140 percent (Box 3-4 and Figure 3-4) (Verry, 1986).
- **Time since harvest**. As forests regenerate, peak flows return to preharvest levels (Troendle and King, 1985; Jones, 2000).
- **Roads and skid trails**. Many studies of forest harvest effects on peak flows include some roads and skid trails, which can accentuate the effect of harvest on peak flows (Jones and Grant, 1996). Because roads and trails influence different components of the water balance, they are discussed separately below.

Timber Management, Silviculture, and Erosion, Mass Movement, and Sedimentation

Many studies have shown that timber harvest practices greatly increase surface erosion (summarized in Dunne and Leopold, 1978; Brooks et al., 2003). Overland flow and surface erosion are rare in undisturbed forests, but logging operations expose surface soils and lead to surface erosion. Multiple studies have shown that surface erosion is most significant in areas of soil disturbed by cable yarding and skidding of cut logs to landings (e.g., Johnson and Beschta, 1980). Many forestry regulations govern surface erosion and sediment production. The effects of skid trails and unpaved roads on surface erosion are described below in the discussion of roads and trails.

In steep landscapes, extreme storms trigger landslide events and the associated input and transport of bedload and woody debris (MacDonald and Coe, 2007). Portions of the Pacific Northwest, northern Rocky Mountains, and central Appalachians are especially prone to shallow landslides. After forest harvest on steep slopes, decreasing root strength and increased soil moisture and pore water pressures contribute to decreased slope stability and can increase the likelihood of shallow landslides (debris avalanches) during precipitation events. Higher soil moisture (from reduced interception and transpiration) increases the forces generating slope movement. Higher soil moisture also increases pore pressures and reduces soil cohesion; combined with loss of root strength after harvesting, these factors reduce the forces resisting slope movement (Swanson and Dyrness, 1975; Sidle et al., 1985; Montgomery et al., 2000; Miller and Burnett, 2007). A number of studies have documented increased landslides from forest harvest relative to undisturbed forested areas (Swanson and Dyrness, 1975; Sidle and Ochiai, 2006). Forest clearcutting may increase the landslide erosion rate by two to nine times relative to undisturbed areas (Montgomery et al., 2000; Sidle and Ochiai, 2006; Miller and Burnett, 2007). Sediment and woody debris delivered to stream channels by landslides can be transported downstream by debris flows, which may create debris dams and exacerbate flooding in lowland settings, causing extensive property damage. Steep forestlands also are prone to deep slow-moving earthflows. During large storms, these earthflows may contribute material to streams, including fine clays, which may create persistent turbidity in downstream reservoirs and water supply systems (Bates et al., 1998).

Many studies have shown that fine sediment contributed to streams by surface erosion from exposed soils or landslides can greatly increase suspended sediment in streams, adversely affecting aquatic habitat, especially in steep, coarse-bedded streams (e.g., Campbell and Doeg, 1989). Suspended sediment levels may remain elevated for many years or decades after timber harvest (Grant and Wolff, 1991).

Timber Management, Silviculture, Water Temperature, and Chemistry

Removal of riparian vegetation along streams causes peak water temperatures to increase as a result of increased solar radiation. The largest stream temperature increases occur in the summer (Levno and Rothacher 1967, 1969; Beschta and Taylor, 1988; Binkley and Brown, 1993a; Johnson and Jones, 2000). As streamside forests regenerate and provide shade, temperatures usually return to pretreatment levels (Johnson and Jones, 2000; Ice et al., 2004). Maintaining streamside forests of sufficient width to shade streams helps mitigate temperature increases from forest harvest (Stednick, 2000; MacDonald and Coe, 2007), but groundwater contributions and hyporheic flow also mitigate stream temperature increases (Story et al., 2003; Johnson, 2004).

In silviculture, fertilizers, herbicides, fungicides, insecticides, and fire retardants are used to protect and enhance tree growth. Plant available nitrogen and phosphorus are occasionally added to forests as fertilizer if one or both of these nutrients are limiting growth. Generally, increases in stream concentrations after fertilization are minimal because forest soils efficiently retain nutrients, and because fertilizer that is not absorbed is often volatilized (Binkley et al., 1999; NCASI, 1999; Stednick, 2000). If fertilization increases stream nitrogen concentrations, the maximum value is usually reached within two to four days, and concentrations decrease rapidly thereafter (although a return to pre-treatment conditions could take six to eight weeks). Greater effects on stream nutrient concentrations occur when fertilizer is applied directly to the stream, applied during rainy periods (Stednick, 2000), or applied to sites already affected by nitrogen pollution from non-fertilizer sources (Fenn et al., 1998). Relatively few studies have addressed the effects of fertilizer at large watershed scales or over the long term (Anderson 2002; McBroom et al., 2008).

When pesticides are applied according forestry regulations, they are unlikely to impair water quality (Michael, 2000; Dent and Robben, 2000 [from Ice et al., 2004]; Tatum, 2003, 2004). If pesticides enter streams, they are usually at low concentrations and only remain for a short period of time (Ice et al., 2004). Nevertheless, members of the public, nongovernmental organizations (NGOs), and the scientific community remain concerned that risk assessments are incomplete and that manufacturers funded most studies. Concerns focus on (1) chemicals that have yet to be investigated; (2) synergistic, cumulative effects of mixtures in the environment; (3) effects of degradation products in the long term through transformation and transport in groundwater (Michael, 2000); and (4) inadequate tests of how stream ecosystems might react because native amphibians may be more sensitive than laboratory animals (Tatum, 2003).

Most forests are naturally nitrogen-limited, and stream concentrations of nitrogen are lowest in young forests and increase as forests mature (Edwards and Helvey, 1991; Swank and Vose, 1997; Vitousek, 1997). Decades of elevated atmospheric deposition of nitrogen (and sulfur, in the eastern United States) have greatly altered the nitrogen dynamics of eastern forests (Likens et al., 1977, 1996; Lovett and Kinsman, 1990; Likens and Bormann, 1995; Fenn et al., 1998) and increasingly, western forests (Riggan et al., 1985; Binkley, 2001). Resulting nitrogen saturation of soils and streams (Aber, 1992), as well as soil acidification and loss of basic cations, has affected forest growth and tolerance to cold stress, elevated stream nitrogen concentrations, and acidified streams, especially in the eastern United States (Adams et al., 1993; Lovett and Lindberg, 1993; Flum and Nodvin, 1995; Rustad et al., 1996; Lawrence et al., 1997; De Hayes et al., 1999; Lawrence and Huntington, 1999; Lovett et al., 2000; Baldigo and Lawrence, 2001). Riparian forest buffers have been adopted to mitigate these effects (Lowrance et al., 1997).

After forest harvest, concentrations of nitrate-nitrogen (nitrate-N), one of the most mobile nutrients in disturbed forests, typically increase in streams as soil moisture content and subsurface flow rates increase (Likens et al., 1970; Miller and Newton, 1983; Martin and Harr, 1989; Binkley and Brown, 1993; Martin et al., 2000). Elevated stream nitrogen concentrations return to pre-harvest levels within a few growing seasons or less as young forests grow on a harvested site (Likens et al., 1970, 1977; Martin and Harr, 1989; Likens and Bormann, 1995; Martin et al., 2000; Swank et al., 2001). The duration of elevated post-harvest nitrogen in streams varies among sites according to soil nitrogen levels and microbial activity, atmospheric deposition, and forest regrowth (Swank, 2000). A review of more than 40 studies found that nitrate-N on averaged doubled in concentration to 0.44 mg/L for one to five years after harvest on 75 percent of the locations, but the remaining studies could not detect increases and a few (5) even had 24-95 percent declines (Binkley et al., 2004).

Elevated peak flows and surface erosion after forest harvest may increase phosphorus delivery to streams. Phosphorus export occurs most during stormflow events that mobilize the fine particulate matter to which phosphorus is sorbed (Hobbie and Likens, 1973; Meyer and Likens, 1979). Riparian forest buffers have been successful in reducing particulate phosphorus (phosphorus attached to sediment) by minimizing overland flow but less effective in removing dissolved phosphorus (de la Crétaz and Barten, 2007; Stednick, 2000).

Roads

Roads, Trails, Infiltration, and Overland Flow

Roads and skid trails modify surface and subsurface flowpaths of water (Figure 3-5). Forest roads alter runoff processes in two ways **(**Figure 3-5) (Megahan, 1972; Wemple and Jones 2003**)**. First, roads and skid trails (compacted soil surfaces) generate overland flow because they have very low infiltration rates (Johnson and Beschta, 1980; Luce and Cundy, 1994; Ziegler and Giambelluca, 1997). Cutslopes above roads and hillslopes below roads also often have lower infiltration rates than forest soils, and they also may generate overland flow. Roads constructed on steep slopes also can intercept water flowing in the subsurface, further increasing overland flow (Megahan, 1972; Wemple and Jones, 2003). During precipitation or snowmelt events, water flows on road surfaces or in ditches that are connected to streams, so the road network delivers this water directly to the stream network.

Roads also increase overland flow by intercepting water flowing in subsurface flowpaths at cutbanks on steep hillslopes (Figure 3-5) and converting this water to surface flow, which the road network then delivers to streams (Wemple

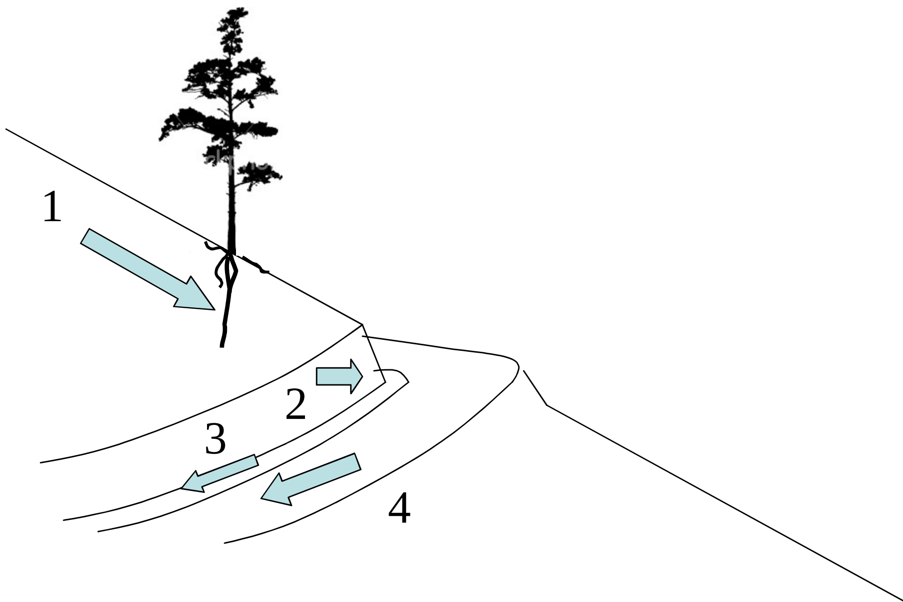


FIGURE 3-5 Schematic diagram of how roads modify water flowpaths in soils and subsoils. Roads generate Horton overland flow and intercept subsurface flow: 1 = shallow subsurface flow in the hillslope; 2 = subsurface flow intercepted by the roadcut; 3 = water flowing in roadside ditch; 4 = Horton overland flow on impervious road surface. Adapted from Wemple et al. (1996).

and Jones, 2003). The greater the depth of the soil profile exposed by the cutbank, the greater is the potential for subsurface flow interception (see photo below). With these two effects, roads convert relatively slow moving subsurface flow to overland flow, which has higher flow velocities.

Roads, Trails, and Water Yield

Roads have their greatest impact on hydrologic effects on infiltration and overland flow (see preceding section). Neither in empirical studies nor in modeling studies have roads been identified as having significant effects on annual water yields in forested systems.

An unpaved forest road in steep terrain with a large cutslope. Photo courtesy of B. Wemple.

Roads, Trails, and Peak Flows

Roads redistribute water locally and alter flow routing. Roads can contribute to an increase in the size of peak flows by increasing the amount of surface runoff from impervious surfaces, intercepting subsurface stormflow, and speeding the delivery of this runoff to the stream network through ditches or gullies (Megahan, 1972; Wemple et al., 1996; Wemple and Jones, 2003). The percentage of unpaved roads that are connected to the stream network is directly proportional to mean annual precipitation and decreases with the presence of engineered road drainage structures such as waterbars, rolling dips, and relief culverts (Coe, 2006). Through the combination of increasing the amount of surface runoff and delivering this runoff more rapidly to the stream channel, roads can produce detectable changes in peak flows at the small watershed scale (Harr et al., 1975; Ziemer, 1981; King and Tennyson, 1984; Wright et al., 1990, LaMarche and Lettenmeier, 2001). Modeling studies have replicated measured road effects on peak flows (Bowling and Lettenmeier, 2001; LaMarche and Lettenmeier, 2001; Tague and Band, 2001; Cuo et al., 2006).

It is debated how much roads affect very large peak flows in small or large watersheds (Jones and Grant, 1996; Megahan and Thomas, 1998; Beschta et al., 2000; Jones, 2000; Jones and Grant, 2001a, 2001b). A small number of studies designed to test road effects and a lack of long-term records that capture extreme floods contribute to uncertainty about the magnitude of road effects on very large floods or in large watersheds. Very few experimental studies have been conducted with road-only treatments, but many paired watershed forest harvest experiments include roads. Very few large watersheds lack roads, and fewer of these have streamflow records. Hence peak flow responses to forest harvest often include the effects of forest removal, the effects of roads, and the interaction between them (Jones and Grant, 1996).

Roads, Trails, Erosion, Mass Movements, and Sedimentation

High rates of overland flow along unpaved road surfaces entrain sediment, erode road surfaces, and contribute fine sediment to forest streams (Reid and Dunne, 1984). Overland flow on road surfaces and in roadside ditches and culverts concentrates soil moisture on oversteepened fillslopes below roads and cutslopes above roads, increasing susceptibility to landslides (Swanson and Dyrness, 1975; Larsen and Parks, 1998; Wemple et al., 2001; May, 2002). Forest roads can increase the landslide erosion rate by 30-300 times relative to undisturbed areas (Sidle and Ochiai, 2006), much more than the effects of forest harvest. Road fills and cutslope areas are subject to landslides during storm events, and these can contribute large volumes of sediment to downstream receiving waters (Swanson and Dyrness, 1975; Wemple et al., 2001). Landslides contribute fine sediment to streams, which can be detrimental to water quality and aquatic habitat, as well as coarse sediment and large pieces of wood, which are important structural elements for stream ecosystems but also can exacerbate downstream flooding and serve as tools for damaging roads and bridges.

In addition to their effects on landslides, compacted road surfaces, cutslopes, fillslopes, ditches, and areas below culverts are exposed to chronic surface erosion as a result of the generation and concentration of overland flow; roads deliver much of this fine sediment directly to streams, where it may become suspended sediment (Reid and Dunne, 1984; Bilby 1985). Suspended sediment is the most ubiquitous nonpoint pollution source from forests (Landsberg and Tiedemann, 2000) and can degrade aquatic ecosystems by reducing water clarity, reducing interstitial flow and dissolved oxygen levels, and altering stream channel morphology (Waters, 1995; Stednick, 2000; Swanson et al., 2000). Sediment-laden water increases water treatment costs, reduces water storage facility storage volume and life span, and interferes with disinfection processes (NRC, 2000; Scatena, 2000; Stednick, 2000). Sediment particles also can bind with and become a transportation vehicle for contaminants such as nutrients, metals, organic compounds, and pesticides.

MANAGING FORESTS FOR WATER

Forest hydrology principles elucidate direct effects of forest management and disturbance on hydrologic processes. Direct effects of forest management and disturbance on hydrology include increased net precipitation, temporary increases in water yield, and increased suspended sediment concentrations. General principles of forest hydrology science indicate that increased water yield is one of the direct effects of forest harvest (Tables 3-1 and 3-2). Increases in water yield occur locally and may last up to a few decades after forest harvest.

Although in principle forest harvest can increase water yield, in practice a number of factors make it impractical to manage forests for increased water. Water yield increases from vegetation removal are often small and unsustainable, and timber harvest to augment water yield may diminish water quality. Increases in water yield tend to occur at wet, not dry, times of the year, and tend to be much smaller in relatively dry years. In addition, harvesting enough area to achieve a sustainable increase in water yield will have potential effects on wildlife fisheries and aquatic ecosystems

Forest hydrology principles also describe **indirect** and **interacting** effects of forest management on hydrologic processes. Indirect effects are responses to forest management that are displaced in time or space, such as fire suppression leading to insect outbreaks that affect forest hydrology. Interacting effects occur when two or more management practices coincide, such as when post-salvaging logging and road building have a different collective effect on forest hydrology than their individual effects. The state of knowledge of forest hydrology provides a strong foundation for knowledge of the **direct** effects of forest management and disturbance on hydrology. Contemporary forest management and disturbance processes raise issues that require extending the science from these principles to prediction, including indirect and interacting effects of changes in forest landscapes. These research needs are discussed in Chapter 4.