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14 Effects of Fire on Soil Erosion

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Executive Summary

Erosion is the product of complex interactions among geomorphic processes, climate, vegetation, soils, and landforms. The energy derived from falling or flowing water and gravity dominates erosion processes in Pacific Northwest forests. Rainfall causes splash erosion of exposed soil, and flowing water may cause sheet, rill, and gully erosion. Freezing water occasionally loosens soil by frost heaving for subsequent transport by water. Gravity causes soil and rocks to move down steep slopes as ravel, the slow creep of the soil mantle downslope; and mass wasting includes various types of landslides. Channel erosion adds material directly to streams.

Disturbance of Pacific Northwest forest ecosystems generally accelerates erosion processes, alters the transport and storage of sediment within watersheds, and increases export of material from watersheds relative to undisturbed forested lands. The frequency and severity of wildfire, a major forest disturbance, affects the magnitude of accelerated erosion. Prescribed fire in managed forests can also accelerate erosion and alter the dominant forms of erosion.

Fire increases the potential for accelerated erosion primarily through its effects on vegetation and soil. As fire increases in severity, more vegetation is killed, more forest floor is consumed, and it becomes more likely that the physical properties of the soil and watershed are changed. These changes increase the potential for erosion by exposing mineral soil to erosion processes.

The potential for prescribed fire to increase erosion increases with fire severity, soil erodibility, steepness of slope, and intensity or amount of precipitation. The magnitude of fire-accelerated soil loss from forest land in the Pacific Northwest is usually minor because the times and situations when these four factors occur concurrently are rare.

Hydrologic and other soil physical properties are particularly important factors affecting the potential for surface erosion. Coarse-textured soils low in organic matter are most susceptible to surface erosion; these soils are much less common in the Pacific Northwest than elsewhere in the western United States. Most undisturbed forest soils in the region have a high porosity which, coupled with the low intensity of most rainfall events, seldom result in overland flow. Prescribed fire can increase soil movement by ravel on steep slopes, but has a negligible effect on mass wasting.

Accelerated erosion from prescribed fire usually has a minor effect on long-term forest productivity in the Pacific Northwest. The potential for

prescribed fire to affect productivity, however, increases if fires are severe, soils are highly erodible, and prescribed fires are more frequent than past wildfires. The potential for prescribed fire to cause accelerated erosion decreases with the severity and frequency of its use.

Introduction

Fire changes forest ecosystems and interacts with geomorphic processes, climate, and landform in a variety of ways to alter the landscape and temporarily increase the potential for erosion (Fig. 14-1). Soil erosion in Pacific Northwest forests is typically low when the soil is protected by litter and the site is covered by a closed forest canopy. Disturbance of forests by wildfire, harvesting, road construction, and site preparation (including prescribed burning) increases the potential for erosion.

Fire affects erosion processes by exposing readily erodible material and in some cases, increasing hydrologic energy available to move it. Exposure of erodible material depends on how the severity of fire affects vegetative cover, the organic forest floor, and soil. Following a fire, landform, soil properties, and climate interact to determine the dominant geomorphic processes that move material downslope and into stream channels. The hydrologic characteristics of the soil and drainage network control many erosional processes, but on steeper slopes gravitational processes become increasingly important.

In presettlement time, wildfire was an important factor affecting geomorphic processes and forest communities in the Pacific Northwest (Chapter 3; Swanson 1981). In many respects, the effects of prescribed burning on geomorphic processes are similar to wildfire, although the severity of prescribed fires is often less than that of wildfires. However, the effect of harvesting and road construction either supercede or dominate many erosion processes in managed forests, particularly when prescribed burns are not severe.

This chapter begins with a discussion of fire-induced changes in vegetation, soil physical properties, and hydrology that may alter geomorphic processes and accelerate erosion. The direct effects of fire are followed by a discussion of the three types of accelerated erosion which may follow—surface erosion, mass wasting, and stream channel erosion. Where appropriate, changes following prescribed burning are contrasted with those following a wildfire or the interactions o prescribed burning with other management prac tices. Finally, the potential for erosion from prescribed burning to affect forest productivity is ad dressed.

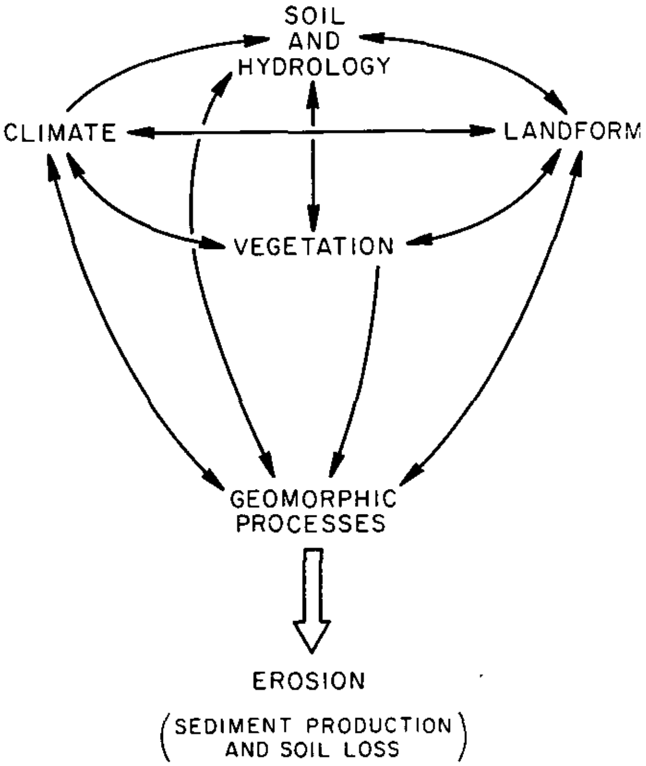


Figure 14-1. Fire and other disturbances interact with climate, landform, and vegetation to shape the landscape b a variety of geomorphic processes. The interaction o these factors determines the type and rate of soil loss b erosion.

Fire Effects on Vegetation

A combination of harvesting and prescribe burning in managed forests temporarily leave most sites with little, if any, vegetative cover. Th temporary removal of vegetation detrimental t reforestation efforts is an important objective o using prescribed burning for site preparatio (Chapter 6); however, several species that aggressively invade newly burned sites or require fire fo germination may ultimately become more competitive with newly planted seedlings than existing vegetation (Chapter 4). In contrast to prescribed fire, the effect of a wildfire on vegetation is often more dependent on fire severity. Low-severity wildfires generally burn slowly through the understory and have little direct effect on overstory vegetation. At higher fire severities, trees may be killed by heat. Under the most severe conditions, entire crowns and portions of the stem may be burned. If the crowns do not burn, dead foliage often falls to the ground and covers some of the exposed soil (Megahan and Molitor 1975).

Pioneer species or sprouts of residual species that have adapted to disturbance by fire rapidly occupy most burned sites (Chapter 4; Dyrness 1973, Gholz et al. 1985). Although the cover provided by vegetation is not as effective at protecting the soil as that provided by the forest floor, newly established vegetation produces litter to replace that burned.

Fire Effects on Soils

Depending on severity, fire may change several forest floor and soil properties which affect the movement of water into or over the soil surface and the susceptibility of exposed soil to erosion processes. The forest floor is the organic horizons covering soil and comprises litter, duff (partially and completely decomposed organic material), and woody debris. Retention of a portion of the forest floor generally protects the soil from the adverse effects of fire.

Forest floor

The forest floor buffers the soil from extremes in temperature and moisture and protects it from surface erosion. The bulk density of forest floors is typically 20 percent or less of the underlying soil horizons (Wooldridge 1970). The low bulk density results from the lower particle density of organic particles; the high porosity of these layers causes the forest floor to have much higher hydraulic conductivities than soil.

The thickness and natural variation in density of forest floors depend on the age and type of forest ecosystem (Gessel and Balci 1965). Forest floors are often less than an inch thick in drier climates and young forests (Amaranthus and McNabb 1984, Edmonds and Hsiang 1987), but are much thicker in more mesic or older forests (Little and Ohmann 1988).

The thickness and density of forest floors also affect physical properties, such as temperature and moisture gradients, that limit or slow their consumption by fire (Sandberg 1980). Thin forest floors dry quickly and are most susceptible to consumption by fire (Amaranthus and McNabb 1984). Forest floors greater than about 2 inches in thickness typically dry from the surface downward, resulting in a dry surface layer over a much wetter layer (Little and Ohmann 1988). While the dry surface layer may be readily consumed by a fire, the wet layer is much less susceptible to consumption (Sandberg 1980, Little and Ohmann 1988). As more of the surface layer dries in late summer, more of the forest floor may be consumed by a fire.

Moisture content of the forest floor also affects its ability to change temperature; high moisture contents slow changes in temperature and help limit the consumption of forest floor materials. Forest floors with a high moisture content are difficult to burn without an external source of heat, such as the burning of woody fuels (Sandberg 1980). Dry forest floors, however, are often consumed during a fire because less water must be evaporated before the temperature for combustion is reached; this condition is most likely to occur during a severe late summer wildfire or an early fall prescribed fire.

Water repellency and infiltration capacity

When forest floors burn, some of the organic compounds may be partially volatilized (Chapter 16). Most of these are lost to the atmosphere in smoke, but some move downward into the soil by convection where they condense on the surfaces of cooler soil particles. Compounds of long-chain aliphatic hydrocarbons are believed to cause water repellency when they condense on soil particles (DeBano 1981). The development of a water-repellent layer reduces the infiltration capacity of the soil and increases the potential for overland flow. The infiltration capacity is the potential maximum rate at which water enters soil. The infiltration capacity of soil is not constant but decreases as soil becomes wetter and the wetting front moves deeper into the soil. Some water repellency of soil is a natural phenomenon in unburned soils of the Pacific Northwest (Singer and Ugolini 1976, Johnson and Beschta 1980, McNabb et al. 1989).

An increase in water repellency of soil following prescribed burning or wildfire has been reported for several locations in the Pacific Northwest (Megahan and Molitor 1975, Dyrness 1976, Johnson and Beschta 1980, McNabb et al. 1989). Water repellency induced by a low-to-moderate-severity prescribed fire is usually of short duration. In southwest Oregon, repellency resulting from a late spring prescribed burn returned to near natural levels soon after the fall rains began (McNabb et al. 1989). Following a late summer wildfire in the Oregon Cascade mountains, however, repellency of volcanic ash soils did not return to nonburn levels for about 6 years (Dyrness 1976).

Water repellency and its persistence are affected by differences in soil moisture, soil texture, severity of the fire, and quantity and composition of the litter (DeBano 1981). Water repellency is more common in coarse-textured soils because the soil temperature gradients that affect volatilization and condensation during burning are often greater and the soil has less surface area on which volatilized compounds may condense. Coarse-textured soils include soils derived from pumice and other volcanic ash, glacial till, and granite. Fortunately, these soils are generally less common in the high-precipitation zones of western Oregon and Washington, have high porosities, or tend to weather to finer-textured soils.

Water repellency at the soil surface is most likely to occur when fire severity and duration cause moderate increases in soil temperatures (DeBano 1981). Severe fires producing high soil temperatures force the water-repellent layer to form deeper in the soil. Reducing the severity of prescribed burns, retaining forest floor, and burning when soil moisture is high are effective techniques for keeping soil temperatures low and minimizing water repellency.

Water repellency is less likely to cause surface erosion if the reduced infiltration capacity of the soil is higher than precipitation intensity. In southwest Oregon, an increase in water repellency reduced the infiltration capacity of the surface soil from greater than 4 inches per hour to an average of 3.5 inches per hour following a late spring prescribed burn; the lowest infiltration capacity measured was 2 inches per hour (McNabb et al. 1989). Despite this decrease, the lowest capacity still exceeded, by a factor of two, the maximum storm intensity expected in a 25-year period.

A water-repellent layer forming below the soil surface is likely to cause more erosion than such a layer at the surface. The infiltration capacity of the soil over a water-repellent layer is much higher than the hydraulic conductivity of the underlying water-repellent layer. As a consequence, the surface soil is easily saturated by even low-intensity rainfall events, which can cause overland flow or loss of the surface soil in a shallow debris flow above the water-repellent layer (DeBano 1981).

Water repellency has been measured in numerous studies, but only a few have also measured the infiltration capacity of the soil (Megahan and Molitor 1975, McNabb et al. 1989). The high porosity of most forest soils in the Pacific Northwest (Dyrness 1969, Harr 1977), coupled with the low to moderate intensity of most rain events, normally preclude overland flow except immediately after a severe fire or other site disturbance. Overland flow is more likely to occur because the lower hydraulic conductivity of subsoil horizons and underlying rock causes the upper soil horizons to become saturated during large storms; this can cause overland flow unrelated to fire (Dyrness 1969, Beasley 1976). The hydrologic properties of the subsoil are not affected by fire.

Porosity and soil structure

Only the most severe fires are likely to alter soil properties sufficiently to directly affect soil porosity and structure (Dyrness and Youngberg 1957). These conditions may occur where large concentrations of dry fuel are burned over a dry forest floor and soil.

Soil structure improves the macroporosity of soil responsible for the high infiltration capacity typical of forest soils of the Pacific Northwest (Dyrness 1969, Harr 1977). It is altered when fire burns the organic matter that helps bind soil particles together (Dyrness and Youngberg 1957). The breakdown of soil structure frees individual soil particles, making them more susceptible to transport by raindrop splash and overland flow. Smaller soil particles may also move downward into the macropores of the underlying aggregated soils, effectively blocking the macropores, sealing the soil surface, and reducing the infiltration capacity.

Following a severe fall prescribed burn, soil structure was affected over less than 8 percent of a severely burned site in the Oregon Coast Range (Dyrness and Youngberg 1957). But further destruction of soil aggregates may occur from raindrops falling on exposed soil (Packer and Williams 1973).

The most severe fires may occasionally raise soil temperatures enough to alter clay mineralogy and fuse silicate minerals together into cinder-like rocks (Dyrness and Youngberg 1957). Fusion of soil particles is less common than the loss of soil structure and is generally confined to areas with the highest concentration of woody debris, such as near landings. Current burning prescriptions, more complete utilization, and removal of other woody debris generally prevent the high fire severities that cause fusion of soil particles.

Soil temperature

All fire may cause some changes in the thermal properties of soil, but large changes in soil temperature usually result from the loss of vegetation and forest floor. The forest floor is a heat sink when wet and acts as an insulator when dry; both attributes help minimize soil temperature fluctuations.

Burning can alter soil color and the ability of the soil to absorb heat. Charred or blackened surfaces absorb more heat than unburned litter layers or lighter colored soil. As a consequence, burning often results in higher soil temperatures, and greater diurnal temperature fluctuations and extremes (Isaac and Hopkins 1937, Neal et al. 1965). These changes may slow the rate at which vegetation is reestablished and increase the period when soil is more susceptible to erosion processes.

Increased frequencies of low temperatures can cause repeated freezing and thawing of soil exposed following burning of the forest floor. Ice layers forming in soil may destroy soil structure, separate soil aggregates, and uproot shallow-rooted plants as the surface soil is heaved upward. A single frost heave cycle may temporarily raise the surface soil by several inches. Heaving of soil is accomplished by the transfer of soil water from deeper in the soil profile to the freezing front (Chalmers and Jackson 1970, Heidmann 1976). Maximum heaving occurs when the heat lost from freezing water is balanced by the transfer of warmer water deeper in the soil profile to the freezing front. Frost heaving is most severe in moist, medium-textured soils with relatively high rates of unsaturated hydraulic conductivities.

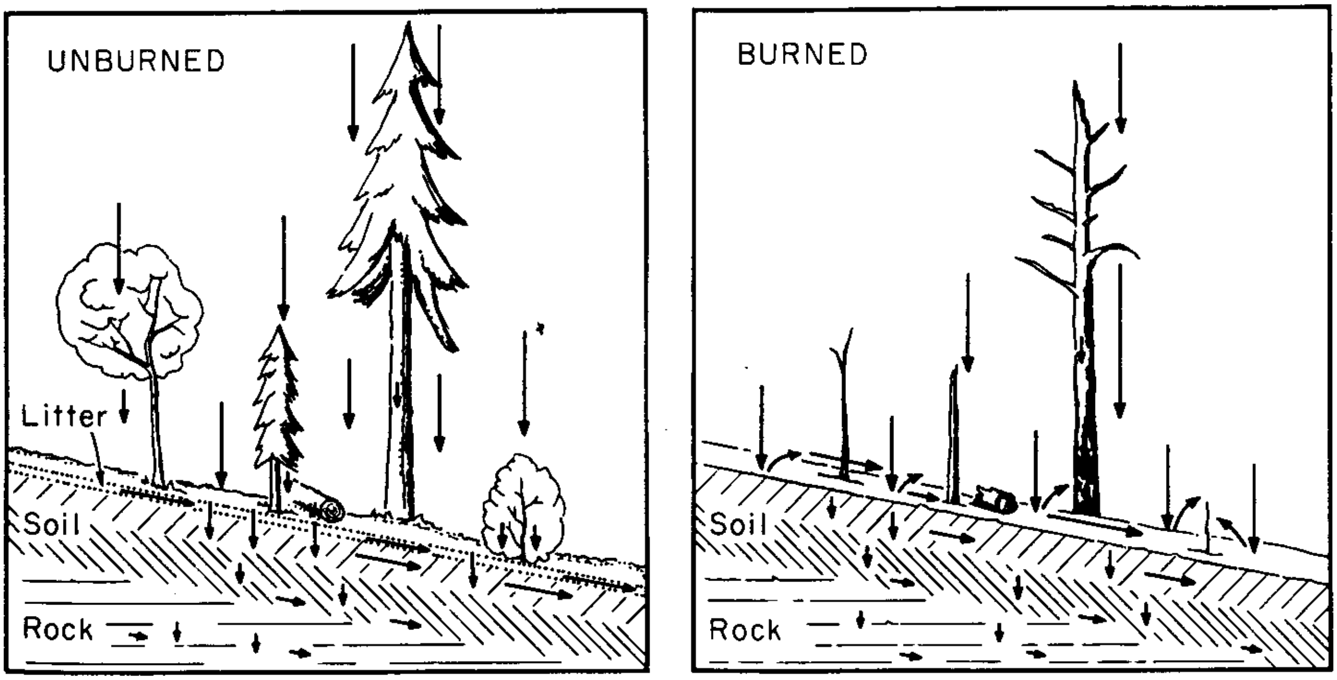


Figure 14-2. Vegetation and the forest floor reduce the energy of water flowing through the litter and reaching the soil. Length of the shaft on the arrow suggests the relative energy of the raindrop or flowing water. A severe burn increases the energy of rain striking the ground and of flow across exposed soil. The flow of water into and through the surface may also be reduced.

Fire Effects on Hydrology

Fire-induced changes in vegetation, forest floor, and soil properties may alter the movement of water over as well as into the soil. The reduction or loss of the forest floor has the greatest potential for altering hillslope hydrology but is often confounded by the concurrent loss of vegetation by fire and harvesting. The largest changes in hillslope hydrology are likely to occur following changes in soil properties but are generally limited to small areas where fire was severe. Changes in hillslope hydrology will ultimately cause some changes in channel hydrology and erosion processes.

Hillslope hydrology

Vegetation intercepts precipitation and alters the energy of falling raindrops striking the ground (Fig. 14-2). Although some intercepted precipitation may evaporate or flow down the stems of plants to the soil surface, the changes in the energy of droplets striking the ground have a major impact on erosion of surface soil.

Vegetation killed by fire no longer transpires soil water, resulting in reduced on-site storage of water during subsequent precipitation events. Changes in soil moisture are least during the winter when transpirational rates are low but low transpiration causes soil moisture to be higher for a longer period of the year and increases the annual yield of water (Chapter 17; Harr 1976, Klock and Helvey 1976, McNabb et al. 1989).

The loss of tree cover following a severe wildfire may increase snow depths and affect melt rates. Changes are similar to those following clearcut harvesting. Snowpacks in openings will melt faster as a result of direct radiation and contact with a more turbulent, warm air mass. In the Pacific Northwest, heat exchange and air turbulence during rain events accelerate the melt of thin snowpacks; this is most likely to occur on middle elevation sites with intermittent snowpacks (Harr 1981, Berris and Harr 1987). Increased melt rate increases the potential for surface erosion, mass wasting, and stream channel changes.

The loss of vegetation will have minimal effect on erosion of surface soil if the forest floor remains relatively undisturbed, because the forest floor is more effective at adsorbing the impact of falling raindrops. In addition, the forest floor stores water, slows the flow of water over the soil surface, helps maintain the porosity of the surface soil, and reduces the transport of sediment by surface water.

Depending on thickness, the forest floor may hold up to 2 inches of water (Gessel and Balci 1965); however, the amount of water that can be stored in the forest floor during a precipitation event will depend on the initial water content. Following a severe slash fire in the Oregon Coast Range, Dyrness et al. (1957) estimated that the destruction of a 2-inch-thick forest floor reduced soil water storage by 0.75 inch of water. More importantly, the forest floor temporarily detains precipitation for later infiltration into the soil or slows the flow of water over the surface (Dyrness 1969). The forest floor protects the soil from raindrop splash that decreases porosity and increases the potential for overland flow (Packer and Williams 1973).

Fire has a minor effect on the ability of the soil profile to hold water. The water storage capacity of the surface 2 inches of soil was reduced by 0.25 inch following a severe broadcast burn in the Oregon Coast Range but the loss was observed to occur only over a small percentage of the site (Dyrness et al. 1957). The importance of this loss is minor compared to the overall water-holding capacity of soils capable of holding 6 or more inches of water and temporarily detaining nearly an equal amount (Dyrness 1969).

Deeper soil horizons, with lower permeabilities, can cause a temporary rise in the water table during rainfall/snowmelt (Harr 1977). The water table may eventually reach the soil surface during storms of moderate to high intensity and long duration; this condition may produce overland flow, increasing the potential for surface erosion. Fire may cause overland flow on sites where it normally does not occur by reducing the permeability of the surface soil that would normally be adequate to transport water throughout the slope (Packer and Williams 1973). This is the most likely cause of overland flow on sites having thin surface soil horizons, well-developed subsurface horizons of low permeability, high percentage of coarse fragments, or a shallow soil over bedrock.

Overland flow is also less likely on undisturbed forest slopes of the Pacific Northwest coast because most winter storms are of low intensity. Summer thunderstorms over the high mountains of the region, however, may produce higher-intensity storm events of shorter duration (1.5 inches in

30 minutes) than winter storms (Helvey 1973). These storms are generally local events whose frequency of occurrence has not been measured. In contrast, much higher rates of sustained precipitation occur in Midwest and Eastern forests where large thunderstorms are common (Orr 1973, Patric 1981).

The potential for overland flow also increases for a specific rainfall intensity if the soil profile is nearly saturated from a previous storm event or results in rapid melt of snowpack (Meeuwig 1971, Harr 1981, Berris and Harr 1987). This is an important factor increasing runoff from small watersheds in the Pacific Northwest where rain-free periods are often short during the wettest months of the year (Istok and Boersma 1987).

Channel hydrology

The reduction in transpiration increases annual water yield from a few inches in forests east of the Cascade crest to approximately 20 inches in western Oregon forests (Chapter 17; Helvey 1972, Harr 1976, Klock and Helvey 1976). Increases in flow are most noticeable in early fall, although flow also remains higher through the summer months; these increases have little effect on channel erosion west of the Cascade crest because the flows generally remain below those necessary for significant sediment transport. Changes in spring snowmelt following wildfire in high elevation and eastside forests, however, may result in increased peak flows (Helvey et al. 1976). Winter peak flows in westside forests seldom are affected by fire unless it changes soil physical properties sufficiently to cause overland flow (Chapter 17; Harr 1976). Although overland flow can speed the movement of surface water to streams, thereby increasing peak flows, it is not known to what extent higher sediment yields may be attributed to such changes in flow.

Fire Effects on Erosion Processes

Erosion is an important factor shaping the landscape of the Pacific Northwest and, historically, disturbance of forest ecosystems by fire has been a major factor affecting geomorphic processes. As a result of disturbance, geomorphic processes and accompanying erosion vary both temporally and spatially (Swanson 1981). In addition to the complex factors affecting natural rates of erosion (Fig. 14-1), forest operations such as road construction, harvesting, and site preparation also influence erosion, making it more difficult to allocate erosion to a specific type of disturbance, such as prescribed fire.

Although the literature on the direct effects of fire on vegetation and soil is voluminous (Chapters 4, 12, and 13; Wells et al. 1979, Feller 1982), a conceptual framework for estimating erosion has not been formulated for all types of erosion processes affected by fire. Several watershed studies have been installed in the past few decades that provide valuable information as to the direct effects of fire on larger areas, but the complexity of the erosion processes involved requires careful review before extrapolating to other sites. Studies of erosion at the level of forest ecosystems and on the timescale of repeated disturbances are extremely rare because of their greater complexity and the longer periods of time necessary to observe changes (Swanson 1981).

The following is an overview of soil erosion processes—surface erosion, mass wasting, and channel erosion. Changes in hillslope and channel hydrology dominate most forms of erosion but gravity becomes increasingly important on steeper slopes. Erosion processes and transport of sediment are seldom constant but typically accelerate in response to ecosystem disturbance.

Surface erosion

Vegetation and soil properties altered by fire affect surface erosion in a variety of ways. Splash, sheet, rill, and gully erosion caused by changes in hillslope hydrology, frost heaving caused by changes in the soil temperature regime, and ravel from the gravitational movement of material downslope all contribute to surface erosion. The interaction of geomorphic processes, soil and hydrologic properties, climate, and landform determine the relative importance and magnitude of these processes on a specific site.

Splash erosion occurs when raindrops strike exposed mineral soil with sufficient force to dislodge soil particles and small aggregates. Vegetation and the forest floor generally protect the soil from splash erosion. Splash erosion on exposed soil is least under low shrubs, forbs, and grasses because of the short distance intercepted raindrops must travel to the soil. Interception of raindrops by foliage and stems of tall trees, including fire-killed trees without needles or leaves, generally increases drop size and subsequent splash erosion (Herwitz 1987).

Precipitation intensity and slope steepness affect splash erosion less than the size of the soil particles or aggregates (Farmer 1973, Yamamoto and Anderson 1973). Fine sand-sized particles (less than 0.004 to 0.01 inch diameter) are most easily transported in droplet splash; larger particles of single-grained soils are more easily displaced than those in clayey soils (Farmer 1973).

When soils are saturated, splash erosion increases markedly; part of the increase is from a 2-fold increase in the size of material susceptible to detachment by raindrop impact (Farmer 1973). In addition, when raindrops strike saturated soil they cause positive hydrostatic pressures in the surface soil from the soil deforming under their impact. These positive pressures are transmitted outward and upward from the point of impact, aiding particle detachment (Al-Durrah and Bradford 1982). This process is an important factor responsible for a significant increase in splash erosion of finer-textured, single-grained soils.

Splash erosion is an underrated and often misdiagnosed surface erosion process in the Pacific Northwest. It has not been measured in this region as it has elsewhere (Farmer and Van Haveren 1971). It is often confused with sheet erosion because the saturated soil conditions most conducive to splash erosion often cause the overland flow responsible for sheet erosion. Splash erosion is generally uniform across a slope but sheet erosion results in more variable loss of soil and produces deposits of sediments in depressions and behind obstructions.

Splash erosion generally occurs whenever soil is exposed; however, exposure of rock fragments in some soils will eventually protect the underlying soil from raindrop impact. Partial retention of the forest floor during prescribed burning is critical to reducing splash erosion. The relative importance of splash erosion as a geomorphic process increases if prescribed fires that expose soil become more frequent than past wildfires.

Sheet and rill erosion. Once soil particles are detached by splash erosion, they are more easily transported in overland flow. The hydraulic energy of water flowing over the soil also has the ability to detach soil particles. Transport is often as sheet erosion where water flow is not concentrated into small channels (Meeuwig 1970).

Sheet erosion increases exponentially with increasing slope steepness and as the clay content of the soil increases (Meeuwig 1970). Organic matter has a variable effect on sheet erosion; coarse-textured soils become more erodible as organic matter increases while fine-textured soils become less erodible. In general, soils with a relatively high percentage of sand particles (0.002 to 0.08 inches in diameter) are the most erodible. These include many soils derived from granite, sandstone, and volcanic ash.

Sheet and splash erosion are most severe immediately following exposure of the soil to rain or snowmelt. These forms of erosion decrease rapidly after the first year, primarily because of reestablishment of vegetative cover, but also because of "armoring" of the surface by larger particles and aggregates (Megahan 1974). Armoring may be the dominant process reducing erosion of gravelly surface soils (soils with greater than 35 percent rock fragments). Reports of sheet erosion following prescribed burning are rare. Some transport of sediment in overland flow on burned sites occurred during snowmelt in western Montana, but the rate was less than 200 pounds per acre per year and only lasted 2 years (DeByle and Packer 1972).

Rill and gully erosion are less common in forest soils than in agricultural soils because of greater surface roughness, more rock fragments, and absence of tillage that regularly mixes and loosens soil horizons. Rill erosion has been reported on erodible soils following a severe wildfire in unburned logging slash, although rilling was not evident in adjacent uncut timber killed by the wildfire (Megahan and Molitor 1975). Gullies are uncommon in undisturbed forest ecosystems (Heede 1975).

Frost heaving increases the downslope movement of soil when the ice lenses supporting soil particles melt, allowing the soil to drop vertically to the surface. Rapid warming or rain also can cause frost-heaved material to slide or flow down the slope, particularly if the underlying soil remains frozen. Furthermore, the loosening of soil particles by frost heaving makes the individual particles more susceptible to transport by other surface erosion processes.

Fire increases the potential for accelerated erosion by frost heaving when it consumes the forest floor and exposes mineral soil. The contribution of frost heaving to accelerated surface erosion, however, depends on the texture of the soil, landform, and climate. Daily, or periodic, freeze-thaw cycles in temperate climates are most likely to increase erosion from frost heaving. Frost heaving is generally less in cold climates because the freezing front moves progressively deeper into the soil, and thawing is infrequent or snow cover insulates the soil.

Ravel. The movement of soil particles and organic debris down steep slopes in response to gravity is a geomorphic process accelerated by fire. This process is often referred to as "dry ravel," but movement may occur during any season (Anderson et al. 1959); referring to surface erosion by gravity as ravel is a more encompassing term. The material moving may include soil, gravel, cobbles, boulders, and organic debris (Figure 14-3). Detachment can occur by drying and shrinking of the soil particles, frost heaving, animal disturbance, and decomposition or burning of supporting organic debris. Because transport is by gravity, substantial ravel occurs only on slopes exceeding the angle of repose—approximately 35 degrees (Mersereau and Dyrness 1972, Bennett 1982).

Ravel is a natural process occurring on steep forest slopes, but rates are often low because vegetation, forest floor, and other woody debris slow or stop the movement. Burning initially disturbs or eliminates many of the organic structures holding loose material on the slope. As a result, large increases in ravel are observed during and immediately following a burn. In the Oregon Coast Range, two-thirds of the ravel measured the first year following prescribed burning occurred in the first 24 hours (Bennett 1982). Part of the accelerated ravel from burning of harvested sites, however, may be material initially dislodged by movement of logs and equipment over the soil surface during harvesting (McNabb and Crawford 1984). Slash and other woody debris remaining after harvesting trap loose material that is released by burning.

Figure 14-3. Ravel is the downslope movement of surface soil, rock fragments, and organic debris. Rates increase exponentially as slopes exceed 60 percent.

Locally, ravel is an important geomorphic process that is responsible for talus slopes and scree (gravel layers) that may bury soil horizons on steep slopes. Rates of ravel following prescribed burning are several hundred times greater on slopes greater than 60 percent than on less steep slopes (Mersereau and Dyrness 1972, Bennett 1982). Also, vegetation is established more slowly on slopes with high ravel; consequently, ravel continues at elevated rates for a longer time (more than a decade). Ravel deposited directly in streams is readily transported from the watershed by fluvial processes (DeBano and Conrad 1976).

Mass wasting

Rain, snow, and rain-on-snow events may trigger the downslope movement of one or more soil horizons, parent material, and sometimes the underlying rock, by mass wasting. Mass wasting includes debris flows, debris slides, debris avalanches, earthflows, slumps, and creep, depending on the landform, and the depth, rate, and properties of the material moving (Burroughs et al. 1976). In the Pacific Northwest, steep slopes, high rainfall, a history of tectonic uplift, and rapid weathering of weak rocks combine to make mass wasting a dominant erosion process.

Fire leads to an apparent reduction in soil strength following the decay of root systems of fire-killed vegetation (Burroughs and Thomas 1977). Live roots increase the stability of shallow soils on steep slopes by binding the soil mantle across potential failure surfaces (Ziemer and Swanston 1977). The root component of soil strength is less significant in deeper soils where the root zone occupies a smaller percentage of a landslide zone of failure.

The potential for shallow mass wasting increases for several years during the period when dead roots decay and before the roots of new vegetation become fully established (Burroughs and

Thomas 1977). Soil strength is reduced more when conifers are killed because most conifers cannot sprout and maintain a viable root system, as do many hardwood tree and shrub species.

Soil creep is generally a slow process in which the soil mantle may move downslope only a few hundredths of an inch to a few inches annually. The rate is thought to be affected by the length of time a soil remains wet (Gray 1973, Harr et al. 1979). Soil creep contributes to accelerated erosion along stream banks as the banks encroach on stream channels. Devegetation lengthens the seasonal period when soil moisture is high (Chapter 17; Rothacher 1973), which may increase the annual rate of soil creep.

On steep slopes at high elevations, fires may kill vegetation and consume organic debris that help anchor snowpacks and prevent or limit the extent of snow avalanches (Swanson 1981). The loss of vegetation may also increase snow accumulation and hence the risk of avalanches. Avalanches may entrain soil and rocks by scour and uproot trees, including unburned vegetation in the runout area. Avalanche tracks can be slow to revegetate because of repeated avalanches.

Of the several forestry operations that can affect mass wasting, the effect of prescribed burning is usually minor. Most of the potential for the root systems of trees to reduce the risk of mass wasting is lost when the trees are harvested. Road construction and harvesting, rather than prescribed burning, are the dominant factors contributing to increased mass wasting in managed forests (Swanston and Swanson 1976). Wildfires that kill vegetation can have an equivalent or greater effect on mass wasting than harvesting, but the amount of road constructed to harvest fire-killed timber will have an important effect on the overall rate of erosion.

Channel erosion

Fluvial transport is the main mechanism moving soil and nutrients from watersheds. This process is discussed in Chapter 17 but part of the fluvial transport process involves channel erosion, which is relevant here.

Streambank cutting is primarily aided by encroachment of streambanks into channels from creep and other mass wasting processes (Fig. 14-4). Of lesser importance are effects due to increases in peak flow. Changes in hillslope hydrology often result in an expanded network of perennial and intermittent streams which transport water only following major forest disturbances or extreme peak flows (Fig. 14-5). Seldom used and intermittent stream channels are susceptible to erosion because they are less likely to be armored with rock (Helvey et al. 1985).

Figure 14-4. Material which encroaches upon stream channels by surface erosion, creep, or mass wasting may become unstable when supporting vegetation or debris is consumed by fire.

Fire increases channel erosion as a result of altered hydrology and sediment availability (Chapter 17; Helvey et al. 1985, Berris and Harr 1987). These conditions may occur when loss of cover affects snow accumulation or melt, water yield is a small percentage of the total precipitation, or loss of transpiring vegetation temporarily increases stream flow.

Wildfires are far more likely than prescribed burning to increase channel erosion. Prescribed fires, in addition to typically being less severe, are generally separated from larger channels by an uncut, unburned buffer strip. Wildfires generally consume all the vegetation and fuels along streams, and the topography along intermittent streams is likely to cause the most severe fire.

Accelerated erosion

Erosion is the consequence of numerous geomorphic processes. Much of the material moving on hillslopes in Pacific Northwest forests is temporarily stored on slopes or in stream channels. Some material is stored for very long periods of time, sometimes centuries in small watersheds

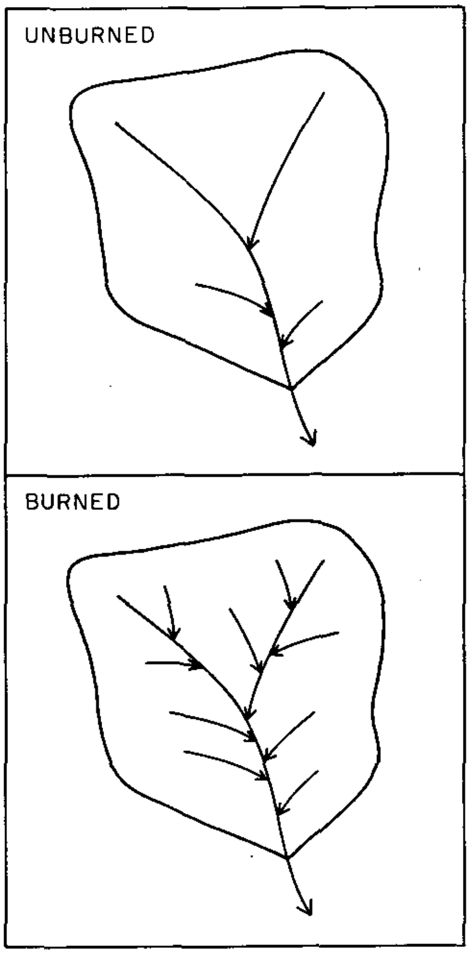


Figure 14-5. Severe fires which remove vegetation and alter soil properties may increase runoff and expand the stream network into smaller, less frequently used channels. Fluvial transport of sediment from the new channels may be high because organic debris which stored sediment was consumed by fire, and the channels generally are not armored.

and longer in larger basins. Noticeable movement generally awaits severe disturbances. The frequency and severity of disturbance such as wildfire, windthrow, road construction, harvesting, and site preparation can affect the balance between the relatively low baseline erosion of the undisturbed forest and the accelerated erosion triggered by disturbance of vegetation (Swanson 1981).

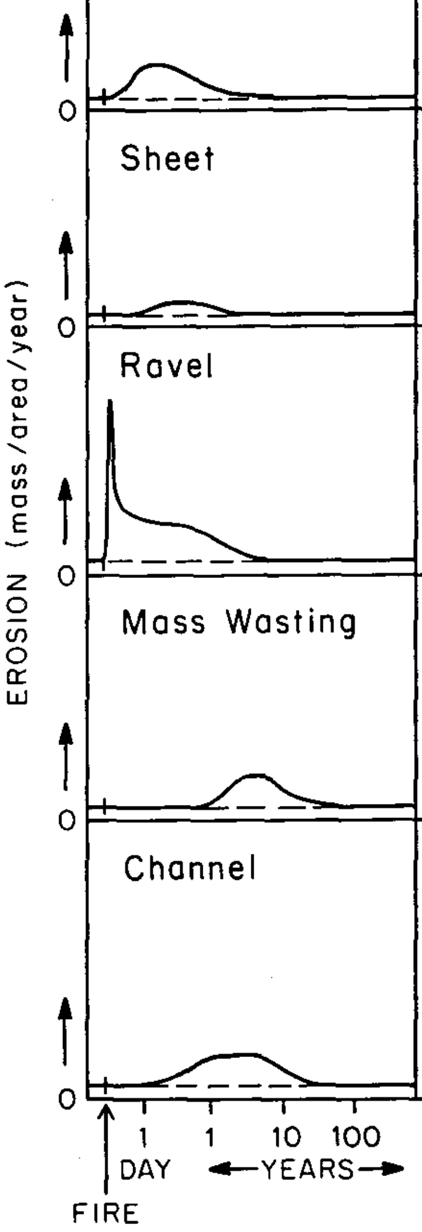
Although the baseline rate of erosion provides a reference for measuring accelerated erosion from natural forest disturbances, the average long-term rate of erosion is an integration of the baseline and accelerated rates of erosion. The long-term rate of erosion is higher than baseline and can only be estimated over a timescale of multiple disturbances. In many forest ecosystems of the Pacific Northwest, the historical frequency of vegetation disturbance resulting in accelerated erosion is presumed to be closely associated with the frequency of wildfire. In regions with a long interval between fires, accelerated erosion is a smaller percentage of the long-term average rate of erosion than in regions where natural disturbance is more frequent (Swanson 1981).

Forest management affects both the frequency and severity of disturbance that, in turn, may alter the accelerated, baseline, and average rates of sediment production. The effects of prescribed burning on these rates can only be assessed by knowing how forest management practices affect the frequency of fire and how fires in managed forests affect erosion. In general, prescribed fire increases erosion less than associated forest practices or severe wildfire in the Pacific Northwest, particularly when burning results in partial retention of the forest floor. The risk of detrimental erosion increases when burning fails to leave some of the forest floor.

Soil Loss Following Fire

In a hypothetical analysis, Swanson (1981) suggests that accelerated erosion following a major forest disturbance in a small watershed in the western Oregon Cascades may persist as long as two to three decades and account for 25 percent of the total long-term sediment yield, assuming major disturbances occur at an average interval of 200 years. Accelerated erosion accounts for a higher percentage of the total long-term erosion when disturbances are more frequent. More frequent disturbances are likely to increase surface erosion and mass wasting because mineral soil is exposed and root contribution to soil strength is reduced for a larger percentage of the time. Increased erosion is likely because of the greater probability that a site may be susceptible when a storm capable of causing major erosion occurs.

Estimates of accelerated erosion are highly variable because of the complex interaction of various factors that affect erosion processes (Fig. 14-



Erosion Process	Major Factors Affecting Erosion Processes	
	Amplitude of Peak	Timing of Peak
Splash	Soil exposure Soil texture Slope Amount of rainfall Intensity of rainfall Loss of vegetation	Formation of forest floor Rate of revegetation
Sheet	Soil exposure Infiltration capacity Armoring of soil surface Amount of rainfall Intensity of rainfall Antecedent precipitation	Armoring of soil surface Formation of new forest floor Timing of major storm events
Ravel	Soil exposure Slope steepness Type of material exposed Position on slope Removal of supporting organic debris Other disturbances	Rate of revegetation Other disturbances
Mass Wasting	Slope Amount of rainfall Antecedent precipitation Loss and importance of root strength Road construction/harvesting	Major storm events Revegetation (root strength)
Channel	Size and stability of channel Armoring of channel Amount of rainfall Antecedent precipitation Rain or snow Removal of organic debris	Major storm events Mass wasting Revegetation

Figure 14-6. The interaction of numerous factors affects erosion processes. Important factors which affect both the amplitude and timing of specific types of erosion are listed in conjunction with the relative effect on erosion rate: inherent to all factors is the effect of fire.

6). For example, ravel is high immediately following a prescribed burn (Bennett 1982), but also includes ravel dislodged by harvesting and stored in slash (McNabb and Crawford 1984), and elevated rates of ravel can persist for years on steep slopes if revegetation is slow (Mersereau and Dyrness 1972). Other forms of surface erosion will most likely be greatest during the first few years following a fire, depending on how quickly the site is revegetated and the surface becomes armored. The potential for severe mass wasting is generally highest 4 to 7 years after disturbance (Burroughs and Thomas 1977, Ziemer and Swanston 1977), but can occur sooner or later depending on precipitation events and rates of decomposition and reestablishment of root systems.

Erosion directly attributable to prescribed burning is rarely considered a serious problem in the Pacific Northwest (Swanston and Swanson 1976, Wells et al. 1979, Helvey et al. 1985). Where fire-related erosion has been observed, the prescribed fires were locally severe or were confounded by harvesting disturbance (Fredriksen et al. 1975, Beschta 1978, Bennett 1982). Direct measurements of erosion specifically resulting from prescribed fires are invariably confounded by erosion from road construction and harvesting (Swanston and Swanson 1976).

The potential for increased erosion from prescribed fire in a managed forest is primarily a function of the frequency and severity of prescribed fire relative to that of past wildfires. The greater the difference in frequency or severity, the more likely that rates of erosion will differ between natural and managed forest conditions. Surface erosion will likely increase in managed forests unless the intensity of prescribed burning is such that a portion of the forest floor is retained. On the other hand, managed forests will most likely have lower fuel loads which should result in less severe burns.

Erosion following prescribed burning in the Pacific Northwest is different from other regions in the United States where burning may be as frequent as every other year, soils are more erodible, or burning vegetation releases compounds which cause the soil to be water repellent (Ralston and Hatchell 1971, Megahan 1974, DeBano and Conrad 1976). A combination of thick forest floors, high soil infiltration capacities and hydraulic conductivities, complex slope configurations, and low-intensity precipitation events results in fewer opportunities for serious erosion in the Pacific Northwest.

Effects of Soil Loss on Forest Productivity

Soil erosion decreases forest productivity when the rate at which that soil is lost exceeds the rate of soil formation (Swanson et al. 1989), but forest productivity may be affected by other fire-induced changes in soil than erosion (Chapter 12 and 13). A net soil loss can reduce the volume of soil available for root occupancy, soil moisture storage, and availability of nutrients. The ratio of soil loss to soil formation by weathering provides a relative index of the sensitivity of forest ecosystems to the effects of forestry practices on productivity. For a number of reasons, such tolerance indices (the amount of soil loss a site can withstand without having productivity impaired) either have not been developed or are highly speculative estimates for Pacific Northwest forest ecosystems (Wischmeier 1974, Pierce et al. 1984). Furthermore, existing tolerance indices are based on soil lost by sheet and rill erosion, which are relatively minor forms of erosion in forests of the Pacific Northwest, except on severely disturbed sites (Swanson et al. 1989).

Loss of soil from some forest ecosystems is more critical than others (Klock 1982, Swanson et al. 1989), and the history of past site disturbance is important to interpreting these differences among sites (McNabb 1988). Losses of forest floor and soil are more critical on sites where the potential for transpiration by vegetation is high, precipitation is low, and evaporation of water from exposed soil is significant (Flint and Childs 1987). Increased plant moisture stress caused by excessive evaporative and transpirational losses generally have greater influence on revegetation and plant growth than the direct loss of soil water-holding capacity.

Locally, mass wasting may substantially reduce the productivity of the failed portion of a site (Miles et al. 1984), but prescribed burning has a minor effect on mass wasting. Reduced forest productivity from soil loss following sheet or rill erosion has not been measured; but where soil has been removed mechanically, forest growth has been reduced significantly (Glass 1976). Surface erosion rarely causes a critical loss of soil in Pacific Northwest forests because of high infiltration rates and relatively low precipitation intensities (Wells et al. 1979). With the possible exception of highly erodible soils such as granitic soils, or the possible formation of a water-repellent layer below the soil surface following an unusually severe fire, surface erosion is unlikely to reduce forest productivity in the region (Swanson et al. 1989). Prescribed burns which leave a portion of the forest floor covering the soil can minimize all forms of surface erosion.

The loss of nutrients during a fire is much more likely to reduce the productivity of Pacific Northwest forests than is erosion of surface soil (Chapter 12). Significant reductions in site nutrients and the associated forest floor and woody debris, however, can reduce soil organic matter and affect soil biology over an extended period of time (several rotations). Reduced soil organic matter will cause detrimental changes in soil physical properties that could substantially increase surface erosion. Thus, using prescribed burning techniques which minimize the loss of nutrients will lessen the risk of future soil erosion.

Managing Prescribed Burning to Reduce Erosion

Based on the few studies of wildfires and severe prescribed burns, accelerated erosion is greatest on sites with steep slopes and highly erodible soils prone to overland flow (Megahan and Molitor 1975, Helvey et al. 1985). Retention of some forest floor over all soil until postfire vegetation begins to replace lost forest floor materials, particularly in the riparian zone, is an important method of reducing surface erosion (Brown and Krygier 1971). The thickness of forest floor which should be left to achieve this objective varies by forest ecosystem because of differences in decomposition rate and hydrology. In addition, maintaining some vegetation in intermittent stream courses with poorly defined channels may also be an effective technique for reducing erosion when the stream network expands during major storm events.

Using prescribed burning techniques which leave a portion of the forest floor covering the soil (Chapter 22) prevents detrimental changes in soil properties. Of the many burning techniques available, burning when the forest floor is moist is particularly effective for retaining some forest floor. Retention of a portion of the forest floor is least likely to occur during late summer and fall burns because the forest floor remains dry even after several inches of precipitation.

Grass seeding sometimes speeds revegetation of severely burned sites after a late summer wildfire. Seeding generally has minimal impact on deterring surface erosion in the Pacific Northwest because most soils are generally well aggregated, seldom subject to overland flow, and revegetate quickly (Dyrness et al. 1957, Helvey and Fowler 1979, Wells et al. 1979). Grass seeding may successfully reduce the immediate risk of surface erosion in riparian zones, soil disturbed by construction of fire lines, and areas with particularly steep slopes and erodible soils. Grass seeding for erosion should be used judiciously, however, to avoid jeopardizing the reforestation and natural revegetation of burned sites. Grass seeding may hinder the establishment of native vegetation on burned sites (Taskey et al. 1989) and increase the risk of mass failures on steep slopes in later years.

All prescribed burning practices that minimize nutrient losses and protect soil biota are compatible with reducing the potential for soil erosion. Practices that burn fuels when the forest floor is dry are incompatible with minimizing impacts on soil erosion and forest productivity.

Conclusion

Severe wildfires have been, and potentially remain, a dominant factor that temporarily accelerates several erosion processes, including mass wasting, surface erosion, and ravel, in the forest ecosystems of the Pacific Northwest. Wildfires increase erosion by removing part or all of the vegetation canopy, consuming the forest floor, and causing detrimental changes in surface soil properties. In contrast, prescribed fire alone is less likely to cause as much erosion, because harvesting rather than fire removes most of the vegetation, and the intensity of the burn can be controlled to reduce its severity. It is possible, and common, to prescribe burn a site while leaving a portion of the forest floor covering the soil and not to affect soil physical properties.

Retention of some forest floor covering the mineral soil and rapid revegetation of burned sites effectively prevent or limit most accelerated surface erosion. Therefore, the thickness and areal coverage of forest floor remaining after a prescribed burn is the most important measure of the potential for surface erosion. Protection of the forest floor is more difficult in the managed forests of northwestern Oregon and western Washington because the planned rotation length in these forests is less than the natural fire frequency. Increased frequency of burning results in thinner forest floors that will require greater adherence to burning prescriptions designed to minimize consumption of the forest floor. Elsewhere in the region, retention of the forest floor is no less important. Although rotations may be longer than the interval between wildfires, slower forest growth and slower production of a new forest floor will require greater retention of forest floor to sustain its protective role.

Surface erosion caused by prescribed burning has seldom been measured in the Pacific Northwest because it is not perceived to be a major cause of erosion from forested lands. Road construction and harvesting are more serious causes of erosion, particularly mass wasting on steeper slopes. Furthermore, erosion by these practices often obscures erosion caused by prescribed burning. Measurement of surface erosion processes, however, will become more important in the future because forest floors in managed forests will be thinner and more difficult to protect from burning, particularly if other constraints such as concern for air quality or fire hazard reduction result in burning when fuels and forest floor are dry.

The judicious use of prescribed burning in most forest ecosystems of the Pacific Northwest is not anticipated to cause sufficient erosion to adversely affect long-term forest productivity, although the productivity of a few highly erodible soils may be reduced if burned frequently or severely.

Literature Cited & Key References

Al-Durrah, M.M., and J.M. Bradford. 1982. Parameters for describing soil detachment due to single waterdrop impact. Soil Sci. Soc. Am. J. 46:836-840.

*Amaranthus, M., and D.H. McNabb. 1984. Bare soil exposure following logging and prescribed burning in southwest Oregon, p. 234-237. *In* New Forests For A Changing World. Proc., 1983 Soc. Amer. For. Nat. Conv., Portland, OR. 640 p.

Anderson, H.W., G.B. Coleman, and P.J. Zinke. 1959. Summer slides and winter scour . . . dry-wet erosion in southern California mountains. USDA For. Serv. Pac. Southwest For. Rge. Exp. Sta., Berkeley, CA. Tech. Pap. PSW-36. 12 p.

Beasley, R.S. 1976. Contribution of subsurface flow from the upper slopes of forested watersheds to channel flow. Soil Sci. Soc. Am. J. 40:955-957.

Bennett, K.A. 1982. Effects of slash burning on surface soil erosion rates in the Oregon Coast Range. M.S. thesis, Oregon State Univ., Corvallis, OR. 70 p.

Berris, S.N., and R.D. Harr. 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the Western Cascades of Oregon. Water Resour. Res. 23:135-142.

Beschta, R.L. 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resour. Res. 14:1011-016.

Brown, G.W., and J.T. Krygier. 1971. Clear-cut logging and sediment production in the Oregon Coast Range. Water Resour. Res. 7:1198-1198.

*Burroughs, E.R., Jr., and B.R. Thomas. 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. USDA For. Serv. Intermt. For. Rge. Exp. Sta., Ogden, UT. Res. Pap. INT-190. 27 p.

Burroughs, E.R., Jr., G.R. Chalfant, and M.A. Townsend. 1976. Slope stability in road construction, a guide to the construction of stable roads in western Oregon and northern California. USDI Bur. Land Manage., Portland, OR. 102 p.

Chalmers, B., and K.A. Jackson. 1970. Experimental and theoretical studies of the mechanism of frost heaving. U.S. Army, Cold Regions Res. and Engr. Lab., Hanover, NH. Res. Rep. 199. 23 p.

*DeBano, L.F. 1981. Water repellent soils: a state-of-the-art. USDA For. Serv., Pac. Southwest For. Rge. Exp. Sta., Berkeley, CA. Gen. Tech. Rep. PSW-46. 21 p.

References marked by an asterisk are recommended for general information.

DeBano, L.F., and C.E. Conrad. 1976. Nutrients lost in debris and runoff water from a burned chaparral watershed, p.3:13-27. *In* Proc., 3rd Fed. Inter-Agency Sediment Conf., Denver, CO. U.S. Water Resources Council, Washington, DC.

*DeByle, N.V., and P.E. Packer. 1972. Plant nutrient and soil losses in overland flow from burned forest clearcuts, p. 296-307. Nat. Symp. Watersheds in Transition, Amer. Water Resour. Assoc., Colorado State Univ., Ft. Collins, CO. 405 p.

Dyrness, C.T. 1969. Hydrologic properties of soils on three small watersheds in the Western Cascades of Oregon. USDA For. Serv. Pac. Northwest For. Rge. Exp. Sta., Portland, OR. Res. Note PNW-111. 17 p.

Dyrness, C.T. 1973. Early stages of plant succession following logging and burning in the western Cascades of Oregon. Ecol. 54:57-69.

Dyrness, C.T. 1976. Effect of wildfire on soil wettability in the High Cascades of Oregon. USDA For. Serv. Pac. Northwest For. Rge. Exp. Sta., Portland, OR. Res. Pap. PNW-202. 18 p.

*Dyrness, C.T., and C.T. Youngberg. 1957. The effect of logging and slash-burning on soil structure. Soil Sci. Soc. Amer. Proc. 21:444-447.

Dyrness, C.T., C.T.Youngberg, and R.H. Ruth. 1957. Some effects of logging and slash burning on physical soil properties in the Corvallis watershed. USDA For. Serv. Pac. For. Rge. Exp. Sta., Portland, OR. Res. Pap. PNW-19. 15 p.

Edmonds, R.L., and T. Hsiang. 1987. Forest floor and soil influence on response of Douglas-fir to urea. Soil Sci. Soc. Amer. J. 51:1332-1337.

Farmer, E.E. 1973. Relative detachability of soil particles by simulated rainfall. Soil Sci. Soc. Amer. Proc. 37:629-633.

Farmer, E.E., and B.P. Van Haveren. 1971. Soil erosion by overland flow and raindrop splash on three mountain soils. USDA For. Serv., Intermt. For. Rge. Exp. Sta., Ogden, UT. Res. Pap. INT-100. 14 p.

*Feller, M.C. 1982. The ecological effects of slashburning with particular reference to British Columbia: a literature review. British Columbia Ministry of Forests, Univ. of British Columbia, Vancouver, B.C. Land Manage. Rep. 13. 60 p.

Flint, L.E., and S.W. Childs. 1987. Effect of shading, mulching and vegetation control on Douglas-fir seedling growth and soil water supply. For. Ecol. Manage. 18:189-203.

*Fredriksen, R.L., D.G. Moore, and L.A. Norris. 1975. The impact of timber harvest, fertilization, and herbicide treatment on streamwater quality in western Oregon and Washington, p. 283-313. *In* Bernier, B., and C.H. Winget, (eds.) Forest Soils and Forest Land Management. Proc., 4th North Amer. For. Soils Conf., Laval Univ., Quebec. 675 p.

Gessel, S.P., and A.N. Balci. 1965. Amount and composition of forest floors under Washington coniferous forests, p. 11-23. *In*: Youngberg, C.T. (ed.) Forest-Soil Relationships North America. Proc., 2nd North Amer. For. Soils Conf., Oregon State Univ., Corvallis. 532 p.

Gholz, H.L., G.M. Hawk, A. Campbell, K. Cromack, Jr., and A.T. Brown. 1985. Early vegetation recovery and element cycles on a clear-cut watershed in western Oregon. Can. J. For. Res. 15:400-409.

Glass, G.G., Jr. 1976. The effects from rootraking on an upland piedmont loblolly pine (*Pinus taeda* L.) site. Sch. Forest Resour., North Carolina State Univ., Raleigh, NC. Tech. Rep. 56. 44 p.

Gray, D.H. 1973. Effects of forest clearcutting on the stability of natural slopes—results of field studies. Report for National Science Foundation GK-24747. Dept. Civil Eng., Univ. Michigan, Ann Arbor.

*Harr, R.D. 1976. Forest practices and streamflow in western Oregon. USDA For. Serv., Pac. Northwest For. Rge. Exp. Sta., Portland, OR. Gen. Tech. Rep. PNW-49. 18 p.

Harr, R.D. 1977. Water flux in soil and subsoil on a steep forested slope. J. Hydrol. 33:37-58.

Harr, R.D. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. J. Hydrol. 53:277-304.

Harr, R.D., R.L. Fredriksen, and J. Rothacher. 1979. Changes in streamflow following timber harvest in southwestern Oregon. USDA For. Serv. Pac. Northwest For. Rge. Exp. Sta., Portland, OR. Res. Pap. PNW-249. 22 p.

Heede, B.H. 1975. Stages of development of gullies in the west, p. 155-161. *In* Present and Prospective Technology For Predicting Sediment Yields and Sources. Proc., Sediment-Yield Workshop, USDA Agr. Res. Serv., Oxford, MS. ARS-S-40, 1972. 285 p.

Heidmann, L.J. 1976. Frost heaving of tree seedlings: A literature review of causes and possible control. USDA For. Serv., Rocky Mt. For. Rge. Exp. Sta., Ft. Collins, CO. Gen. Tech. Rep. RM-21.

Helvey, J.E. 1972. First-year effects of wildfire on water yield and stream temperature in north-central Washington, p. 308-312. *In* Nat. Symp. on Watersheds in Transition, Amer. Water Resour. Assoc., Colorado State Univ., Ft. Collins, CO. 405 p.

Helvey, J.D. 1973. Watershed behavior after forest fire in Washington, p. 403-422. *In* Proc., Irrigation and Drainage Division Specialty Conf. Amer. Soc. Civil Engr., New York, NY. 808 p.

Helvey, J.D., and W.B. Fowler. 1979. Grass seeding and soil erosion in a steep, logged area in northeastern Oregon. USDA For. Serv., Pac. Northwest For. Rge. Exp. Sta., Portland, OR. Res. Note PNW-343. 11 p.

*Helvey, J.D., A.R. Tiedemann, and T.D. Anderson. 1985. Plant nutrient losses by soil erosion and mass movement after wildfire. J. Soil Water Conserv. 40:168-173.

*Helvey, J.D., A.R. Tiedemann, and W.B. Fowler. 1976. Some climatic and hydrologic effects of wildfire in Washington State. Tall Timbers Fire Ecol. Conf. Proc. 15:201-222.

Herwitz, S.R. 1987. Raindrop impact and water flow on the vegetative surfaces of trees and the effects on streamflow and throughfall generation. Earth Surf. Processes Landf. 12:425-432.

Isaac, L.A., and H.G. Hopkins. 1937. The forest soil of the Douglas-fir region and the changes wrought upon it by logging and slash burning. Ecol. 18:264-279.

Istok, J.D., and L. Boersma. 1987. Effect of antecedent rainfall on runoff during low-intensity rainfall. J. Hydrol. 88:329-342.

*Johnson, M.G., and R.L. Beschta. 1980. Logging, infiltration capacity, and surface erodibility in western Oregon. J. For. 78:334-337.

Klock, G.O. 1982. Some soil erosion effects on forest soil productivity, p. 53-66. *In* Determinants of Soil Loss Tolerance. Proc., Symp. Soil Sci. Soc. Amer., Aug. 5-10, 1979, Am. Soc. Agron. Fort Collins, CO. Spec. Pub. 45. 153 p.

Klock, G.O., and J.D. Helvey. 1976. Soil-water trends following wildfire on the Entiat Experimental Forest. Tall Timbers Fire Ecol. Conf. Proc. 15:193-200.

Little, S.N., and J.L. Ohmann. 1988. Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/western hemlock clearcuts. For. Sci. 34:152-164.

McNabb, D.H. 1988. Interpreting the effects of broadcast burning on forest productivity, p. 89-103. *In* Lousier, D., and G.Stills (eds.) Degradation of Forest Lands—Forest Soils at Risk, Proc., Tenth British Columbia Soil Sci. Workshop, Feb. 20-21, 1986. British Columbia Ministry of Forests and Lands, Land Management Report 56. Victoria, B.C. 331 p.

McNabb, D.H., and M.S. Crawford. 1984. Ravel movement on steep slopes caused by logging and broadcast burning, p. 263. *In* Agron. Abstr., 76th Annu. Mtg. Amer. Soc. Agron., November 25-30, 1984, Las Vegas, NV. 285 p.

McNabb, D.H., F. Gaweda, and H.A. Froehlich. 1989. Infiltration, water repellency, and soil moisture content after broadcast burning of forest site in southwest Oregon. J. Soil Water Conserv. 44:87-90.

Meeuwig, R.O. 1970. Sheet erosion on intermountain summer ranges. USDA For. Serv. Intermt. For. Rge. Exp. Sta., Ogden, UT. Res. Pap. INT-85. 25 p.

Meeuwig, R.O. 1971. Soil stability on high-elevation rangeland in the intermountain area. USDA For. Serv. Intermt. For. Rge. Exp. Sta., Ogden, UT. Res. Pap. INT-94. 10 p.

Megahan, W.F. 1974. Erosion over time on severely disturbed granitic soils: a model. USDA For. Serv. Intermt. For. Rge. Exp. Sta., Ogden, U. Res. Pap. INT.156. 14 p.

*Megahan, W.F., and D.C. Molitor. 1975. Erosional effects of wildfire and logging in Idaho, p. 423-444. *In* Watershed Management Symp., Aug. 11-13, 1975. Irrig. Drainage Div., Amer. Soc. Civil Engr., Logan, UT.

*Mersereau, R.C., and C.T. Dyrness. 1972. Accelerated mass wasting after logging and slash burning in Western Oregon. J. Soil Water Conserv. 27:112-114.

*Miles, D.W.R., F.J. Swanson, and C.T. Youngberg. 1984. Effects of landslide erosion on subsequent Douglas-fir growth and stocking levels in the western Cascades, Oregon. Soil Soc. Amer. J. 48:667-671.

Neal, J.L., E. Wright, and W.B. Bolen. 1965. Burning Douglas-fir slash: physical, chemical, and microbial effects in the soil. For. Res. Lab. Res. Pap. 1. Oregon State Univ., Corvallis. 32 p.

Orr, H.K. 1973. The Black Hills (South Dakota) flood of June 1972: impacts and implications. USDA For. Serv. Rocky Mt. For. Rge. Exp. Sta., Fort Collins, CO. Gen. Tech. Rep. RM-2. 12 p.

*Packer, P.E., and B.D. Williams. 1973. Logging and prescribed burning effects on the hydrologic and soil stability behavior of larch/Douglas-fir forests in the northern Rocky Mountains. Tall Timbers Fire Ecol. Conf. Proc. 14:465-479.

Patric, J.H. 1981. Soil-water relations of shallow forested soils during flash floods in West Virginia. USDA For. Serv. Northeastern For. Exp. Sta., Broomall, PA. Res. Pap. NE-469. 20 p.

Pierce, F.J., W.E. Larson, and R.H. Dowdy. 1984. Soil loss tolerance: Maintenance of long-term soil productivity. J. Soil Water Cons. 39:136-139.

*Ralston, C.W., and G.E. Hatchell. 1971. Effects of prescribed burning on physical properties of soil, p. 68-85. *In* Proc. Prescribed Burning Symp. USDA For. Serv., Southeast For. Exp. Sta., Asheville, NC. 160 p.

Rothacher, J. 1973. Does harvest in west slope Douglas-fir increase peak flow in small forest streams? USDA For. Serv. Pac. Northwest For. Rge. Exp. Sta., Portland, OR. Res. Pap. PNW-163. 13 p.

Sandberg, D.V. 1980. Duff reduction by prescribed underburning in Douglas-fir. USDA For. Serv. Pac. Northwest For. Rge. Exp. Sta., Portland, OR. Res. Pap. PNW-272. 18 p.

Singer, M.J., and F.C. Ugolini. 1976. Hydrophobicity in the soils of Findley Lake, Washington. For. Sci. 22:54-58.

*Swanson, F.J. 1981. Fire and geomorphic processes, p. 401-420. *In* Proc., Fire Regimes and Ecosystems Conf., December 11-15, 1979, Honolulu, HI. USDA For. Serv., Washington, DC. Gen. Tech. Rep. WO-26. 594 p.

*Swanson, F.J., R.L. Fredriksen, and F.M. McCorison. 1982. Material transfer in a western Oregon forested watershed, p. 233-266. *In* Edmonds, R.L. (ed.), Analysis of coniferous forest ecosystems in the western United States. US/IBP Synth. Ser. No 14. Hutchinson Ross Publ. Co., Stroudsburg, PA. 419 p.

*Swanson, F.J., J.L. Clayton, W.F. Megahan, and G. Bush. 1989. Erosional processes and long-term site productivity, p. 67-81. *In* Perry, D.A., R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, and R.F. Powers (eds.), Maintaining the Long-term Productivity of Pacific Northwest Forest Ecosystems. Timber Press, Portland, OR. 257 p.

*Swanston, D.N., and F.J. Swanson. 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest, p. 199-211. *In* Coates, D.R. (ed.) Geomorphology and Engineering. Hutchinson Ross Publ. Co., Stroudsburg, PA. 360 p.

Taskey, R.D., C.L. Curtis, and J. Stone. 1989. Wildfire, ryegrass seeding, and watershed rehabilitation, p. 115-124. *In* Symp., Fire and Watershed Management. USDA For. Serv. Pac. Southwest Res. Sta., Berkeley, CA. Gen. Tech. Rep. PSW-109. 164 p.

*Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Fredriksen, E.C. Franklin, R.C. Froelich, and P.H. Dunn. 1979. Effects of fire on soil. USDA For. Serv. Washington, DC. Gen. Tech. Rep. WO-7. 34 p.

Wischmeier, W.H. 1974. New developments in estimating water erosion, p. 179-186. *In*: Land Use: Persuasion or Regulation. Proc., 29th Annu. Mtg. Soil Conserv. Soc. Amer., Aug. 11-14, 1974, Syracuse, New York.

Wooldridge, D.D. 1970. Chemical and physical properties of forest litter layers in central Washington, p. 151-166. *In*: Youngberg ,C.T., and C.B. Davey (eds.) Tree Growth and Forest Soils. Oregon State Univ. Press, Corvallis, OR.

Yamamoto, T., and H.W. Anderson. 1973. Splash erosion related to soil erodibility indexes and other forest soil properties in Hawaii. Water Resour. Res. 9:336-345.

Ziemer, R.R., and D.H. Swanston. 1977. Root strength changes after logging in southeast Alaska. USDA For. Serv. Pac. Northwest For. Rge. Exp. Sta., Portland, OR. Res. Note PNW-306. 10 p.