Chapter 6.

Cumulative Effects of Fuel Treatments on Channel Erosion and Mass Wasting

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Introduction

Controversy over fuel treatments on public forestlands often focuses on the potential for such treatments to contribute to cumulative watershed impacts. If a fuel treatment project modifies the production or transport of water, sediment, or woody debris through a channel network, downstream habitats and aquatic resources may respond adversely to the changes. If these changes augment impacts from previous or on-going activities, the fuel treatment project will have increased the overall level of impact—the cumulative impact—to downstream resources.

As currently applied, "fuel treatments" include a variety of practices, such as prescribed burning, removal of sub-canopy "ladder fuel" and downed wood, thinning of canopy trees, thinning of understory trees, conversion of fire-susceptible stands, clearing of shaded fuel breaks, post-fire salvage logging, and logging of insect-damaged or at-risk stands. Many of these activities are not economically self-supporting, so they are often bundled with standard timber sales to offset costs. Such projects tend to be subjected to particularly intense public scrutiny, and questions are often raised concerning the extent to which fuel treatments influence erosion.

Considerable research has been carried out on channel erosion and mass-wasting processes, but few studies explore the effects of fuel treatments on such processes. Wondzell (2001) reviewed the literature available as of 2001. However, the scarcity of literature that specifically addresses the issue is not a critical problem. Fuel treatments influence factors controlling process rates in ways similar to activities (such as logging) and events (such as wildfires) that have been more widely studied. If erosion process mechanisms are understood, a large body of literature becomes applicable to the problem. This chapter describes characteristics of channel erosion and mass-wasting processes, describes the environmental factors that most strongly influence erosion processes, discusses the mechanisms by which fuel treatments can influence those controlling factors, outlines strategies for determining whether such influences will occur, and describes how erosion evaluations might be incorporated into a cumulative impact analysis. The erosion processes discussed here include channel-bank erosion, gullying, soil creep, landsliding, and related processes. Sheetwash erosion is considered in chapters 5, 8, and 13.

Characteristics of Erosion Processes

The erosion processes considered in this chapter often occur downstream or downslope of the triggering land use activities. Consequently, they not only can contribute to off-site cumulative watershed impacts, but also can themselves be influenced by multiple upslope or upstream activities. The potential influences of each process on downstream environments can be inferred through an understanding of

1. the factors affecting the distribution and rates of these erosion processes,
2. the kinds of sediment likely to be produced by each, and
3. the likely distribution of sediment inputs in time and space.

Channel-Bank Erosion

Bank erosion generally occurs by direct tractive erosion of a raw bank face or by undercutting and toppling or slumping. At sites where activities impinge on banks, direct disruption can also be important. The rate, mode, and distribution of channel-bank erosion are strongly influenced by bank materials, vegetation on the bank, pore pressures in the bank, channel flows, near-bank activities, and in-channel deflections. Hooke (1979), Thorne and Tovey (1981), and Couper and Maddock (2001) describe processes of bank erosion and evaluate factors that control the erosion rate.

Tractive erosion is most active on sparsely vegetated banks formed of non-cohesive materials such as sand and gravel. Repeated wetting and drying or freezing and thawing of bank materials can reduce their cohesion, contributing to "dry ravel" of the banks and increasing their susceptibility to tractive erosion. Banks formed from cohesive clays are more resistant to tractive erosion but can spall off in sheets when subjected to wet/dry or freeze/thaw cycles. Tractive erosion usually is negligible on bedrock banks unless the rock is poorly indurated. Bank erosion rates at a site generally increase if the duration of inundation increases, and more of the bank face is susceptible to tractive erosion for longer periods if hydrologic changes lead to increased channel flows.

Tractive erosion sources generally are distributed along the channel network—rarely is input dominated by erosion at a single site. Potential rates of tractive erosion are expected to increase downstream with increasing discharge and increasing prevalence of fine-grained bank materials. However, this general downstream trend may be reversed in low-gradient, lowland rivers with banks formed of cohesive materials (Lawler and others 1999). At a reach scale, erosion tends to be most rapid at the downstream outer edge of bends, where high-velocity flow impinges on banks. Often, erodible banks are inundated for only a small fraction of the year, so sediment inputs may be restricted to high-flow events.

Tractive erosion generally produces fine-grained sediment that remains mobile after entering the stream (table 1). Larger clasts are also contributed to the extent that they are present in the bank, but they are usually dislodged by undermining rather than by traction.

Bank failures are often triggered by undercutting, so rates of bank erosion by toppling and slumping depend in part on rates of tractive erosion. Toppling is most pronounced where floodplain- or terrace-surface deposits are cohesive. Roots increase cohesion even in inherently non-cohesive materials, and banks along incised grassland channels are often characterized by toppling failures.

In contrast to tractive erosion, bank failures tend to occur as high flows recede because

1. the susceptible material is then at its highest bulk density due to saturation,
2. pore pressures in the bank are high, and
3. the undercut soil mass is no longer partially supported by the hydrostatic force from inundation (Thorne and Tovey 1981).

Table 1. Selected characteristics of major channel erosion and mass-wasting processes.

Erosion process	Grain size	Sediment input timing	Location	Potential influences [a]
Bank erosion	fine to medium	high flows after high flows	of most concern in moderate to large channels	altered woody debris altered riparian vegetation altered channel form increased channel migration
Gully erosion	fine to medium	periods of runoff early season flows	hillslopes small to medium channels below diversions	altered site productivity lowered water table accelerated runoff more hillslope sediment delivery increased bank erosion altered channel form reduced floodplain connectivity
Soil creep	fine to medium	chronic	pervasive	increased bank erosion
Shallow slides	fine to coarse	high-intensity rain onto wet ground	inner gorges hillslope swales undercut banks certain bedrocks	altered site productivity flow deflection altered woody debris
Debris flows	fine to coarse	high-intensity rain onto wet ground	steep swales certain bedrocks	altered channel roughness flow deflection altered woody debris channel blockage
Deep-seated slides	fine to very coarse	very wet seasons	certain bedrocks	flow deflection
Earthflows	fine to very coarse	very wet seasons	certain bedrocks	flow deflection altered site productivity

[a] All erosion processes can also contribute to aggradation, turbidity, altered bed material, and altered bed stability.

Because bank failures often produce blocks of cohesive sediment and often occur after the flow peak, the sediment introduced may remain close to its source. Tractive erosion during lower flows then gradually mines away the sediment. In forested areas, bank failures often contribute woody debris to channels.

Undercutting can also trigger large streamside landslides that affect more than just bank materials. Such slides can be found wherever channels encroach on valley walls, and they frequently occur along the "inner gorges" (Kelsey 1988) characteristic of many tectonically active areas. Although undercutting usually contributes to the instability, these failures are also susceptible to the same kinds of influences as other landslides. Some streamside landslides initiate at the toe of a slope and propagate upslope over time, while others fail as a single unit.

Streamside landslides can produce large quantities of extremely coarse sediment. Their deposits may remain in place for long periods and can modify the course and character of the channel both upstream and downstream. Where slide deposits deflect channel flows, additional landslides can be triggered by undercutting of new sites, thereby propagating the impacts even farther downstream. The largest slides may create temporary dams, sometimes resulting in dam-release floods capable of scouring and widening channels for long distances downstream.

Direct disruption of channel banks and beds can occur through trampling by animals or people and by land use activities that impinge on stream channels, such as in-stream mining and yarding of logs across channels. The distribution and rates of erosion from direct disruption depend strongly on animal and human use patterns and on the original morphology of the banks. Sites where banks are low, for example, tend to be selected as crossing points. Initial sediment inputs from these sources usually occur during low-flow seasons, when disruptive activity levels are often highest. But because the resulting channel modifications tend to be unstable during higher flows, storm flows usually mobilize additional sediment as they rework the unstable deposits.

Inputs from direct bank disruption are often relatively fine-grained and can be an important source of turbidity during low-flow periods, when natural turbidity levels are low. Such unseasonal sediment inputs can be disproportionately important if they contribute to additional stress on organisms already challenged by low flows or high temperatures.

If a channel reach is not aggrading, incising, or changing form, bank erosion rates along the reach are expected to be roughly equivalent to rates of sediment resupply to those banks (Dietrich and Dunne 1978). Channels can supply fine sediment to banks through overbank deposition, while coarser channel-bed sediments can be incorporated into banks through bar accretion and associated channel migration. Where channels abut hillsides, hillslope sediment transport processes, such as soil creep and landsliding, also can contribute sediment to channel margins. Over a long period, slight imbalances in rates of erosion and deposition lead to the gradual down-wasting of the landscape, while over a short period, larger imbalances lead to temporary, localized changes in channel and bank form. Over an intermediate period, however, conditions tend to average out in most undisturbed settings. An undisturbed headwater channel is expected to look much the same today as it did a hundred years ago, despite relatively continuous bank erosion along the channel.

Under some conditions, bank erosion can occur quite rapidly and may lead to extreme changes in channel character. Major floods or debris flows can significantly widen channels, and sudden or episodically high inputs of sediment can fill channels, leaving flow to spread across the valley bottom in multiple “braided” flow strands. If the aggraded sediment is erodible, each strand then mines the new deposits, gradually shifting the load downstream. Braided channels are typical of glacial outwash plains and alluvial fans.

Unless sediment input remains high or a channel is freely migrating, accelerated bank erosion is usually self-limiting. Banks begin to stabilize once a channel has widened enough that flow becomes too shallow—or impinges on banks too infrequently—to remove eroded sediment.

Gully Erosion

Gully erosion is a particular kind of rapid channel erosion that forms incised, steep-walled channels. Rapidly incised channels small enough to be eliminated by plowing are referred to as “rills,” which are considered a component of sheetwash erosion. In forested settings in North America, gullies are usually of most concern along headwater channels and in meadows. In the semi-arid west, gullying is also important farther downstream, where incision of gullies known as “arroyos” has strongly altered valley-bottom conditions over the past 150 years (Cooke and Reeves 1976). Factors expected to influence susceptibility to gullying include channel gradient, substrate, vegetation cover, and peak-flow regimes. Bull and Kirkby (1997) and Oostwoud Wijdenes and Bryan (2001) discuss gully erosion processes and factors that influence rates of gully erosion.

Gullies can form in unchanneled settings by upslope migration of channel heads, collapse of subsurface soil pipes, or incision of scour holes along previously stable drainageways. Generalized incision or headcut migration can also form gullies along existing channels. Widespread gullying is most often associated with anthropogenic changes, such as introduction of cultivation or livestock. However, gullying can also be triggered by natural events that reduce vegetation cover (such as wildfires), deposit erodible material (such as volcanic eruptions), or generate extreme surface runoff (such as intense thunderstorms). Stratigraphy of valley-bottom deposits in the southwestern United States suggests that climatic shifts have triggered several episodes of arroyo formation over the past 4,000 years (Waters and Haynes 2001).

Gullies commonly grow by upstream retreat of a near-vertical headwall. Water falling over the headwall excavates a plungepool at its base, undercutting the headcut and sidewalls. Undercutting promotes toppling failures, allowing the gully to widen and to progress upstream. Seepage at the base of a headcut can also increase rates of undercutting and in some areas can be the dominant mechanism for headcut retreat (Higgins and others 1990). A depositional lip typically forms at the downstream end of the plungepool, and the channel downstream is often graded to the level of the lip. Channel-fill sediment downstream of a migrating headcut and its associated plungepool may thus represent the upstream progress of deposition on the plungepool lip.

Gully cross sections are modified by the types of bank erosion processes described in the previous section. Often, gully width increases and wall gradient decreases as a function of the distance downstream of a headcut, reflecting progressively longer periods of recovery since passage of the headcut. Upstream headcut migration may halt if a headcut encounters non-erodible material or if the contributing area becomes too small to generate erosive flows.

Gullying most commonly forms intermittent or ephemeral channels, where "intermittent" refers to channels that carry water seasonally, while "ephemeral" usually implies that water is present only during storms. Sediment often accumulates in gullies during dry periods through trampling, dry ravel, and spalling of banks. The first flows after a dry period may then carry particularly high sediment loads as the accumulated sediment is flushed out (Crouch 1990). Gullying tends to be suppressed where soils contain coarse sediment because the coarse clasts can armor the bed and banks and restrict further erosion. Consequently, gullying is generally associated with fine-grained substrates, and sediment produced by gullying usually is readily transportable by channel flows.

Some areas of steep terrain and poorly consolidated bedrock are susceptible to rapid formation of gullies large enough and steep enough that gully-wall failures begin to generate debris flows. At this point, expansion no longer depends on channel flow, and the gully network can form an amphitheater-shaped basin that extends to the ridgeline. These gully-landslide complexes are referred to as "gully slips" in New Zealand, where they formed after conversion of forest to pasture in some regions (Betts and others 2003). Reforestation of gullied watersheds has halted the growth of many New Zealand gully slips, although the forms remain present.

Recovery from a gullying episode tends to be slow, and evidence of gullying may persist for centuries in the form of terraces. Gullies may continue to produce sediment from headcut retreat and wall erosion long after the conditions that initially triggered gully formation have been reversed. Sediment redeposited downstream of actively incising reaches may remain in storage for long periods. Moody and Martin (2001), for example, expect that much of the sediment produced by channel incision after a fire in Colorado will remain in the watershed for several hundred years.

Soil Creep

Soil creep is a gradual mass wasting process that occurs within the soil mantle on most hillslopes. Transport can occur through plastic deformation of the soil mass in some clay-rich soils, but more common is transport by displacement of individual soil particles through root growth, animal burrowing, wetting and drying, and freezing and thawing. These soil disturbances tend to move particles preferentially downslope because of the influence of gravity, and incremental transport of individual particles combines to gradually displace the entire soil profile. Saunders and Young (1983) provide a tabulation of measured creep rates. More recent work (such as Heimsath and others 2002) adds to the measurement record and provides further discussion of creep mechanisms.

Although rates of soil creep are slow, the process is influential because it occurs over most of the landscape. The nature of the motion and its slow rate make measurement difficult, so transport rates are generally estimated by other means. In many quasi-steady-state systems, soil creep is the major source of sediment resupply to stream banks abutting hillslopes, so long-term measurements of bank erosion can provide estimates of creep rates.

Creep rates are expected to depend on hillslope gradient, soil texture, soil moisture, biological activity within the soil, and vegetation, but little is known about the relative influences of these factors because measurement is difficult. Changes in hillslope conditions that increase soil moisture or soil disturbance are likely to increase creep rates, but such effects have not yet been documented in a controlled setting.

Shallow Landsliding

"Shallow landsliding" is a commonly used term that is not recognized in the widely adopted landslide classification system presented by Cruden and Varnes (1996). Some apply the term to any slide that involves only colluvial material, thus corresponding to the "debris" material category of Cruden and Varnes (1996). Others use the term to indicate that the depth to the failure plane is markedly less than the length or width of the slide, corresponding roughly to the "translational" motion category of Cruden and Varnes. Under this second usage, a 5-m deep slide might be considered "shallow" if it is 50 m long or "deep-seated" if it is only 10 m long. When used in forestry related literature, "shallow landsliding" appears to most commonly refer to translational slides. Although these often consist primarily of surficial deposits, some may include significant bedrock. Saunders and Young (1983) compiled measurements of landsliding rates, and many more recent studies provide additional measurements.

Shallow failures generally occur during periods of high-intensity rain that falls onto already wet soils. Relations between slide occurrence and various measures of rainfall intensity have been developed at many sites (for example, Crosta 1998; Crozier 1999; Finlay and others 1997; Nilsen and others 1976; Reid and Page 2003). Slide frequencies are also influenced by hillslope gradient, root cohesion, soil moisture, lateral slope convergence, bedrock type, soil depth, and soil texture. Shallow slides occur most frequently on steep portions of the landscape into which subsurface flow is concentrated, such as headwater swales and inner-gorge slopes. Failure planes of small slides are often within the rooting depth of forest vegetation. Increased landsliding rates are sometimes noted several years after logging, after dead roots have decayed but before new roots have matured (Bishop and Stevens 1964; Swanston 1969). A variety of analytical tools have been developed to identify sites susceptible to shallow sliding (for example, Montgomery and Dietrich 1994).

Shallow slides often mobilize both soil and partially weathered bedrock, so most slide deposits contain a wide range of grain sizes. In forests, deposits usually include woody debris. The proportion of landslide debris reaching a channel tends to decrease with increasing distance between the landslide scar and the stream. However, even distant slides may contribute sediment where slopes are steep or when slides are generated by intense storms. At such times, overland flow generated from the new slide scar can act as a temporary extension to the downstream channel, allowing sediment delivery directly to the stream. Shallow landslides generally occur during periods of intense rain and high flow, so some portion of the landslide sediment reaching a channel is usually transported downstream during the triggering storm.

Once a shallow slide has occurred, the bared scar continues to contribute sediment through surface erosion and gullying until vegetation regrows (Larsen and others 1999). Sediment inputs can be further prolonged as streams rework temporarily stored landslide deposits, contributing both suspended sediment and bedload (Sutherland and others 2002). Because of the relatively slow transport rates for bed material, decades may be required before debris from a major landslide-generating storm is fully evacuated from a moderate-sized channel (Madej and Ozaki 1996). Meanwhile, aggradation from the downstream transport of landslide debris can deflect stream flow into banks, causing secondary failures at downstream sites.

Debris Flows

Shallow failures often displace saturated material, and pore pressures at some failure sites are high enough that landslide debris can lose all cohesion and flow as a liquid. If debris moves as a fluid, the event is referred to as a "debris flow." Field evidence suggests that some debris flows can initiate within channel deposits, and flows have occasionally been found to originate high on slopes without evidence of an initiating landslide (J. McKean, personal communication).

Debris flows in steep forestland channels can entrain large volumes of channel deposits and woody debris (May 2002). Wood-bearing debris flows often come to rest where the wood becomes jammed or the channel gradient decreases to the point that material can no longer flow. These conditions are often present where an affected tributary joins the mainstem channel (Benda and Cundy 1990), so landscapes characterized by debris flows commonly exhibit debris fans at tributary mouths. Debris flow deposits are recognized as unstratified mixtures of diverse grain sizes.

Debris flows and less dense, sediment-laden "hyperconcentrated flows" can also form through rapid incision and entrainment of in-channel deposits (Cannon and others 2001; Cannon and Reneau 2000). In some areas, such flows are common after high-intensity fires that generate hydrophobic soil layers. After a debris flow has occurred, the scoured channel and debris deposits remain subject to accelerated erosion until they are revegetated or become armored by coarse sediment. Log jams formed by debris flows at tributary junctions can accumulate considerable volumes of bed material from both the affected tributary and the mainstem. When the jam eventually fails, a portion of the trapped sediment is released to resume its downstream transport.

Deep-Seated Landsliding and Earthflows

The term "deep-seated landslide" is also not recognized by the Cruden and Varnes (1996) classification system. The term is variously used to refer to landslides having failure surfaces within bedrock or to slides that are deep relative to their length and so have moved by rotation along a curved failure plane (slumps). In the forestry literature, the term is used primarily for rotational slides, though it also often encompasses non-rotational bedrock failures if they seem unlikely to have been influenced by near-surface pore pressures.

Large, deep-seated landslides tend to be more responsive than shallow slides to seasonally high rainfall accumulations and respond less to high-intensity rain bursts or individual storms. The failure surface is often deep enough that root cohesion is inconsequential. The largest features remain visible on the landscape for millennia, and only ancient examples are present in many areas. Controversy persists over the extent to which long-stabilized slides can be reactivated by land management activities.

Once mobilized, large deep-seated slides can remain active for decades or longer. Slide surfaces are often irregular and hummocky, and a depression or sag-pond may be present at the base of the headwall scarp. In some cases, the progressive motion is slow enough that it is most readily recognized by haphazard orientations of mature tree trunks, disruption of road surfaces, or distortion of fences. In other cases, the entire failure may occur over minutes or days, with subsequent activity limited to erosion of the disrupted slide mass and bared scarp. The toes of old slumps often form over-steepened slopes that are now susceptible to shallow landsliding. Sediment contributed by deep-seated slides can include grain sizes ranging from weathered clays to large blocks of intact bedrock.

In some terrains, materials initially mobilized by deep-seated slumps continue to move downslope as earthflows. Earthflows are plastically deforming masses of unconsolidated material that remain active over long periods, ordinarily moving from several centimeters to tens of meters each year. More rapid flows that occur as discrete events are termed "mudflows" or "debris flows." Earthflows generally occur in areas of clay-rich, mechanically weak bedrock, such as shale or argillite. In areas susceptible to earthflows, evidence of past activity is often visible as hummocky terrain, and active earthflows may appear as patches of grassland in otherwise forested areas.

Earthflows are most active during seasonally wet periods. Activity may cease during the dry season or in years with low rainfall and resume when water tables have again risen to a threshold level. On large flows, variations in velocity generally are not associated with individual storms. Flageollet and others (2000) describe the three-dimensional structure of a major earthflow, and Iverson and Major (1987) describe patterns of motion for a similar flow over a 3-year period.

Many large earthflows are bounded by streams at their toes. Activity of the slide can then strongly control the form and sediment load of the stream channel, while channel erosion, in turn, repeatedly undercuts and reactivates the slide mass. A year of rapid motion may constrict the stream, while years of lesser activity may allow the stream to reexcavate its characteristic channel.

Earthflow toes are often the site of intensive surface erosion and shallow landsliding. Consequently, periods of high sediment production are associated with individual storms even though motion of the earthflow itself often is not. Earthflow surfaces often support gullied drainage networks that contribute additional sediment during storms. Because earthflows generally form in areas with weak, clay-rich bedrock, even the coarser blocks tend to be rapidly broken down once introduced to a channel. The largest sediment blocks remain stranded in channels until worn away, while finer sediments can contribute to chronically high suspended sediment loads.

Related Erosion Processes

A variety of other channel erosion and mass-wasting processes can be strongly influenced by fuel management activities and may be important in some settings even though they rarely dominate the sediment supply. Of particular note for forested areas are subsurface channel erosion (tunnel erosion or piping; Jones 1981; Uchida and others 2001), tree throw (Schaetzl and others 1989), and animal burrowing (Gabet and others 2003). Several other processes, such as dry ravel and sheetwash erosion, frequently occur on sites bared by channel erosion and mass-wasting processes and prolong sediment inputs from the primary sources.

Tunnel erosion is common in unchanneled swales in many areas, though its presence is often unnoticed. The process can usually be detected by examining channel heads for soil pipe outlets. Pipeflow is generated primarily by subsurface drainage during storms, though some pipe networks can continue to flow long into the dry season. Pipeflow tends to remain relatively clear of sediment even during storms. Surficial erosion processes do not contribute directly to pipeflow sediment loads unless the pipe's roof is breached upslope. Instead, most tunnel erosion sediment is generated by bank erosion processes and tractive erosion within the pipe. Tractive erosion of the pipe circumference increases with increasing discharge.

Piping is often present in unchanneled swales that are subject to periodic debris slides. In a quasi-steady-state system, soil-creep input of sediment to these swales is largely balanced by the combined activity of tunnel erosion and landsliding. At a smaller scale, pipe diameters are expected to remain relatively constant over time, so erosion of sediment from pipe walls evidently keeps pace with the tendency for pipes to constrict due to soil creep. Tree throw or cave-ins can unroof pipes, temporarily increasing sediment loads and diverting flow to the surface. It is likely that pipe roofs can be reestablished by bridging with forest floor litter and small woody debris, though descriptions of the recovery process have not been published.

Tree throw can contribute appreciable sediment to streams where forested banks or valley walls are steep. At such sites, it may be difficult to distinguish tree-throw events from landsliding because both contribute a mixture of woody debris and sediment and leave similar scars. The distinction rests on the cause of the failure: did a landslide topple the trees, or did falling trees destabilize adjacent soils?

Tree throw is most prevalent during high winds that occur while soils are saturated and trees are in full foliage. Although blowdown of snags is common after fires, such falls often occur by stem breakage and thus do not contribute directly to sediment loads. Whether a tree is likely to break or uproot also varies by species (Veblen and others 2001).

Under most conditions, animal burrowing is an implicit component of soil creep, so creep rate estimates generally account for displacement by burrowing. However, burrowing can also influence sediment production by exposing unvegetated soils to overland flow or by directly contributing sediment to streams where burrow tailings are deposited within the high-flow stream margin. In the Pacific Northwest, for example, mountain beaver burrows often are associated with headwater streams. Populations of burrowing animals vary with stand age, and young stands may provide food sources to support large populations of burrowing rodents.

"Dry ravel" of surface sediments occurs when grains are transported downslope in the absence of flow. Cohensionless particles can be dislodged downslope by even minor disturbances, so dry ravel is common on landslide scars and eroding banks of non-cohesive sediments. Particles on a bare surface can be loosened by cycles of wetting and drying or freezing and thawing, and fire often promotes dry ravel by baring mineral soils and by burning out small woody debris that has trapped sediment on stream banks and hillslopes. After fires, ravel can be an important source of sediment delivery to low-order streams, where the accumulated sediment can then be easily remobilized by wet-season flows (Roering and Gerber 2005).

Factors Influencing Erosion Processes

Although many environmental characteristics can affect erosion processes, several are particularly influential for multiple processes. The distribution of erosion processes, their rates of sediment production, and the timing of sediment inputs are largely controlled by topographic setting, materials, surface conditions, hydrologic conditions, and vegetation. Each of these factors also exerts influence on the others. An understanding of these controlling factors and of how they may be influenced by management activities provides the link needed to evaluate the effects of specific land use activities on erosion processes.

Topography

The susceptibility of a site to various erosion processes can often be inferred from its topographic setting. On hillslopes, local gradient, lateral convergence, and distance from the ridge-top strongly influence which erosion processes will be active. Once processes are activated, their influence depends in part on how far the mobilized sediment travels. Topographic conditions downslope of an eroding site strongly affect the proportion of the mobilized sediment that reaches a channel. Particularly influential are gradient and lateral convergence downslope, presence of topographic irregularities along the travel path, and distance to the stream.

In channels, local topography strongly influences the shear stress imparted by flows on the bed and banks. Deep, high velocity flows on steep slopes develop the highest shear stresses—these are the sites most likely to incise. Along a channel, variations in gradient and channel width can control the distribution of aggradation and incision.

Topographic setting is also important because management-related topographic changes can trigger a variety of erosion processes. On forested hillslopes, most topographic modifications are associated with road construction. Excavation of over-steepened road-cuts, emplacement of fills, construction of stream crossings, excavation of road-side ditches, and deposition of unstable side-cast material can all contribute to increased erosion risk.

Topographic modifications in channels also often result from road construction. Banks may be realigned and armored to protect riparian roads, and levees are sometimes constructed to reduce flooding. Bridges or culverts modify channel cross sections, sometimes restricting passage of woody debris or coarse sediment. Stream crossings on steep slopes are particularly vulnerable to failure because drainage structures can be blocked by woody debris, allowing flow to pond behind the unconsolidated road fill. Overtopping can then lead to rapid gullying, while increased pore pressures within the fill can trigger landslides. At some sites, in-stream structures have been built to divert flow for low-head hydroelectric power generation or to pond water for livestock. Such changes can alter sediment delivery and channel erosion rates downstream. At a larger scale, dams are major controls on downstream channel forms and processes and can strongly influence the effects of upstream activities on downstream environments.

Materials and Surface Conditions

Material characteristics—particularly grain size and cohesion—also influence which processes are likely to be active and how far eroded sediment can move. Coarse-grained sediment tends to have low cohesion and thus is susceptible to dry ravel, but bedrock that weathers to coarse material is not likely to support earthflows. Clays, in contrast, are extremely fine-grained and cohesive. Earthflows usually occur in areas with clay-rich bedrock, but cohesive clay soils are resistant to tractive erosion and ravel. Coarse sediment requires high shear stress for in-stream transport and so may be mobile only during high flows. Coarse sands, gravel, and cobbles thus generally form the bed material in upland streams, while clays and silts are readily transported in suspension and contribute little to the bed material.

Surface characteristics can strongly influence the susceptibility of hillslope or channel materials to erosion. Removal of readily transported fine-grained sediment often leaves a lag of coarse sediment that armors hillslopes or stream beds, impeding further erosion. Soil surface characteristics change radically after fires. Erodible mineral soils are often exposed when protective organic material is burned off. At some sites, fire can generate a surficial hydrophobic layer (DeBano 2000a, b), resulting in rapid runoff and increased surface erosion during subsequent rains. The increased runoff may trigger debris flows, gullying, and increased bank erosion downstream. Ground-disturbing activities can also modify the susceptibility of swales to gully incision by exposing erodible soils.

Hydrologic Conditions

Water affects most types of erosion and sediment transport on hillslopes, and the largest sediment inputs usually occur during major storms. The occurrence of shallow landslides is particularly responsive to the timing and spatial distribution of high pore pressures, which in turn are influenced by soil surface topography, bedrock surface topography, subsurface drainage paths, location along a slope, hydraulic conductivity of soils and bedrock, and the amount of water contributed to the site by precipitation or surface and subsurface drainage. These factors generally control the routing of water down hillslopes and so influence the distribution of gullying, tunnel erosion, debris flows, deep-seated slides, and earthflows.

Shear stress at a channel cross section increases with discharge, thus increasing rates of sediment transport and channel erosion. Because of this dependence, and because sediment inputs from hillslopes also respond to water, most of a stream's annual sediment transport may occur during a few major storms. Changes in the timing, amount, and duration of runoff change the timing, amount, and duration of in-channel erosion, sediment transport, and aggradation.

Land use activities or natural events that modify hillslope hydrology can influence rates of shallow landsliding. Hillslopes may become wetter after logging or wildfire due to decreased transpiration and rainfall interception. The presence of roads often influences hillslope hydrology by rerouting shallow subsurface flows and by diverting road drainage onto hillsides.

Vegetation

Vegetation strongly affects erosion processes by influencing soil strength, surface materials, and hydrology. Root networks in both forest (Schmidt and others 2001) and grassland (Preston and Crozier 1999) can provide additional cohesion to soils of low inherent strength. In some areas, the distribution of shallow landslides reflects this influence. Roering and others (2003), for example, found that slides in their study area were located at some distance from the nearest trees.

Forest-floor litter strongly affects the characteristics of near-surface soil horizons. Organic-rich horizons often have relatively open textures, resulting in high infiltration rates and high moisture storage capacities. Overland flow is uncommon where deep litter has accumulated, and litter shields mineral soils from surface erosion and gully initiation. Removal of a litter layer through mechanical disruption or fire can increase the incidence of overland flow, thus increasing rates of downstream channel erosion.

Channel erosion rates can be particularly sensitive to vegetation changes because of the influence of vegetation on hydrology. Plants use large quantities of water, drawing it from the soil through their root systems and transpiring it into the atmosphere through their leaves. Conversion of vegetation to a community with lower water use increases runoff (Bosch and Hewlett 1982), thereby increasing the potential for channel erosion. Plants also trap rain and snow on foliage, increasing the evaporative loss of water during and after storms (Calder 1990). In areas where cold-season storms can include either rain or snow, warm rainstorms falling onto well-developed snowpacks can generate large flood flows that are often associated with significant in-channel erosion. In these settings, snow accumulations are highest and melt most rapidly in cleared areas, so presence of a forest cover moderates the runoff rate (Marks and others 1998).

Forest stand characteristics in the western United States are changing in response to earlier fire management strategies and on-going global climate change. Given the strong influence of vegetation on erosion processes, erosion regimes are expected to change in response. But even though vegetation change can strongly influence short-term sediment yields, influences on sediment yield over the long term may not be as great because the long-term average soil erosion rate must balance the long-term average soil formation rate if soil depths do not perpetually increase. The soil formation rate, in turn, is influenced by soil depth, erosion processes, and vegetation, and soil depths are controlled by erosion processes and soil formation rates. Because these factors are interdependent and all are influenced by vegetation, a vegetation change alters the balance between them. Where forest was converted to grassland in parts of the East Cape region of New Zealand, for example, deep forest soils are being removed by widespread shallow landsliding (Reid and Page 2003). Over time, a transition to shallower soils typical of grasslands is likely at these sites. The net erosion rate might eventually be nearly the same as before the vegetation change as erosion once again becomes constrained by soil formation rates, but the transition period is characterized by extreme erosion as the volume of sediment stored on hillslopes is rapidly reduced (see also Gabet and Dunne 2003). Such short-term readjustments on hillsides can lead to profound long-term changes downstream, where channels may be choked and floodplains inundated by the sudden influx of new sediment.

Potential Influences of Fuel Treatments on Erosion Processes

Once the factors controlling erosion process rates are understood, the potential influences of various fuel treatments can be inferred by examining their effects on the controlling factors. Forest fuel treatments can be grouped into four categories on the basis of their potential effects on hillslope and channel erosion processes: managed burning, mechanical treatments, logging, and strategic stand design. These activities are supported by the transportation infrastructure and, in some cases, require modification of existing road networks. General patterns of influence are summarized in table 2.

Managed Burning

Fire can be used to reduce ground fuel over wide areas at relatively low cost, whether it is applied through prescribed burning or by allowing wildfires to burn unhindered in particular areas. Activities associated with managed burning often include road use and construction of fire breaks. A small proportion of managed burns escape control or burn more severely than planned, leading to erosional conditions typical of more intense wildfires. Many publications describe the effects of wildfire on erosion processes (for example, Wondzell and King 2003).

Table 2. Potential influences on major channel erosion and mass-wasting processes.

			Treatment[a]				
Process	**Influential attributes**	**Mechanisms of change**	**Brn**	**MT**	**Log**	**Sal**	**Rd**
Bank erosion, gullying	peakflow, runoff	interception, transpiration	+		++		
	“	road, skid trail drainage		+	+	+	++
	“	hydrophobicity	++				
	“	compaction		+	+	+	++
	direct disruption	trampling, trafficking		+	+	+	++
	soil-pipe collapse	trampling, trafficking		+	+	+	++
	rooting density	trampling, trafficking		+	+	+	
	“	canopy removal			+		
	“	burning of groundcover	++				
	surface armoring	burning of litter	++				
	“	less ground-cover vegetation	++	+	+		
Soil creep	soil moisture	interception, transpiration	+		++		
	soil disturbance	trampling, trafficking		+	+	+	+
	rooting change	burning of groundcover	+				
	“	canopy removal			+		
Shallow slides, debris flows	antecedent wetness	interception, transpiration	+		++		
	increased drainage	road, skid trail drainage		+	+	+	++
	“	hydrophobicity	++				
	“	compaction		+	+	+	++
	“	interception, transpiration	+		++		
	undercut toe	disruption		+	+	+	++
	undercut by flow	road, skid trail drainage		+	+	+	++
	“	hydrophobicity	++				
	“	compaction		+	+	+	++
	material	emplaced fill					++
	“	less woody debris	+		++	++	
	root cohesion	canopy removal			+		
Slumps, earthflows	seasonal wetness	interception, transpiration	+		++		
	“	road, skid trail drainage		+	+	+	++
	root cohesion	canopy removal			+		
	undercut toe	disruption		+	+	+	++
	undercut by flow	road, skid trail drainage		+	+	+	++
	“	hydrophobicity	++				
	“	compaction		+	+	+	++

+ indicates a likely influence, and ++ indicates that the influence is likely to be strong.

[a] Treatments and associated activities: *Brn* = Managed burning; *MT* = Mechanical treatment; *Log* = Green-tree thinning; *Sal* = Salvage logging; *Rd* = Road construction or use.

Burning strongly affects soil surface characteristics, ground-cover vegetation, and organic debris on the forest floor, while construction of associated roads and firebreaks mechanically disrupts soils. Depending on the soil type, vegetation type, and burn intensity, burning may induce hydrophobicity in soils (DeBano 2000a, b; Huffman and others 2001; Robichaud 2000). Rain falling on hydrophobic soil may run off as overland flow instead of infiltrating, increasing the likelihood of gully erosion, channel incision, channel-bank erosion, and in-channel debris flows. These processes are also accelerated by burning of soil-surface litter and in-channel woody debris, and by removal of ground-cover vegetation. Canfield and others (2005) describe channel incision after a fire, and Istanbulluoglu and others (2003) describe post-fire gullying. In general, the potential for accelerated erosion is expected to increase with burn intensity (Wondzell and King 2003). Hillslopes may be particularly susceptible to other influences after burning. In one case, for example, trafficking after a low-intensity burn triggered incipient gullying (Saynor and others 2004).

Burning of ground-cover and understory vegetation may reduce transpiration and increase soil moisture. However, these vegetation components usually have shallower roots than overstory vegetation, so the effect is expected to be insignificant by the end of the dry season in areas characterized by seasonal drought. Similarly, changes in rainfall interception would be small unless a significant proportion of the vegetation burns.

If large portions of a landscape are treated, managed fire will burn through small channels and riparian zones. In-channel erosion rates are likely to increase where channels have burned. Sediment in low-order channels is often held in place by small pieces of woody debris. When these burn, trapped sediments are free to move downstream Loss of protective litter in unchanneled swales may allow gullying to progress at these sites, and burning of bank vegetation can increase susceptibility to bank erosion. It may be possible to burn during seasons when naturally high moisture levels might deflect burns from riparian areas or moderate their intensity, but unseasonal burns may defeat faunal strategies for coping with typical wildfires. Spring burns, for example, may disproportionately impact amphibians that are seasonally dispersed across the landscape (Pilliod and others 2003).

Mechanical Treatments

Accumulations of dead wood on the forest floor can be removed mechanically, along with sub-canopy trees that form “ladder fuel” capable of carrying a ground fire to the forest canopy. Dense understories of suppressed conifers form ladder fuel at many sites. Such wood usually is not merchantable and may be treated on site by chipping or chunking, with the pieces then spread as mulch. Alternatively, debris may be piled and burned or marketed for wood chips. Occasionally, logging of the smaller trees (thinning from below) produces stems large enough to be marketable as saw logs or fence posts. In each case, associated activities include road use and may involve road construction.

The primary erosional influences of mechanical understory treatments are likely to be associated with direct disruption to soils through yarding or by high-intensity fire effects under burn piles. Effects are particularly likely where these activities impinge on unchanneled swales or low-order channels. Spreading of chipped materials as mulch may promote infiltration on hillslopes, reducing the potential for increased erosion in swales.

Mechanical treatments are expected to influence hydrology primarily by compaction and disruption of soils due to yarding or other trafficking. Increased surface runoff from compaction may increase the potential for gullying, both in previously unchanneled swales and in downstream channels. Changes in live vegetation density are unlikely to be large enough to significantly influence transpiration or interception unless a high density of green ladder fuel is removed.

Logging

A number of timber sales recently have been categorized as fuel treatments, either because they accomplish canopy thinning (thus reducing the likelihood of spread of a crown fire) or because they remove dead or at-risk stems after wildfires or insect outbreaks. In the case of green-tree removal, such activities entail the same types of erosional consequences as ordinary timber sales, and such effects have been widely studied (for example, Chamberlin and others 1991). McIver and Starr (2000) summarize literature on the effects of post-fire logging on erosion.

After logging, decreased transpiration and interception may lead to increased pore pressures and reduce slope stability. Reduced interception is likely to be the more important of the two mechanisms in the coastal Pacific Northwest, where high interception rates have been measured even during the high-intensity winter rainstorms that generate most sediment in the region (Reid and Lewis 2007). Reduced interception increases effective rainfall, directly increasing the geomorphic impact of individual storms as well as contributing to increased seasonal groundwater levels. In contrast, transpiration changes are most influential during the growing season and so may be most important in areas where the major sediment-producing storms do not occur in winter. Decreased transpiration does not directly increase effective storm rainfall but can augment pore pressures by slowing the reduction of soil moisture and groundwater levels after storms so that antecedent conditions are wetter than usual at the onset of the next storm. Reduced interception and transpiration can thus increase both the activity of deep-seated slides and the risk of shallow landslides and debris flows.

The risk of shallow sliding is further enhanced by reduced root cohesion after green-tree logging. Debris flows may be more mobile if the entrained woody debris does not include boles, which are most likely to lodge in channels and halt the flow. Logging has also been associated with increased activity of existing deep-seated landslides (Swanston and others 1987), and earthflow velocities under forest vegetation in New Zealand were found to be several orders of magnitude lower than in deforested terrain (Zhang and others 1993). Such differences may reflect changes in both hillslope hydrology (Reid and Lewis 2007) and the mechanical behavior of the root-laden soil (Zhang and others 1993). Each of these effects will vary in importance with the proportion of trees logged. Miller and Sias (1998) modeled the effect of altered forest canopy on the stability of a deep-seated landslide.

In areas where rain-on-snow flooding occurs, clearcut logging can increase flood frequencies and magnitudes by allowing deeper snow accumulation and increasing the melt rates. Selective logging is expected to have a lesser effect. At sites where logging has been extensive enough to modify runoff characteristics, small channels with erodible beds and banks are likely to adjust to altered flow regimes through bank erosion, incision, and downstream aggradation. The extent of the adjustment depends in part on the magnitude and persistence of flow changes.

Assessment of the erosional consequences of salvage logging requires consideration of two issues that are not relevent for green-tree logging. First, erosion processes reflect interactions between the salvage logging and conditions left by the disturbance because a site's sensitivity to logging-related impacts may have increased due to the initial disturbance. Hillsides and small channels can become more susceptible to erosion if the litter layer and small organic debris have burned or if surface runoff has increased due to burn-induced hydrophobicity.

Second, removal of dead or dying trees modifies the erosional response to the initial disturbance. Fires and other stand-killing disturbances themselves increase erosion rates. Landslide rates may increase due to reduced transpiration, interception, and root cohesion, and surface erosion increases where mineral soil is exposed. But after disturbance, newly downed wood can trap eroded sediment by adding roughness to slopes and channels, and woody debris may reduce landslide debris mobility by promoting debris jams. Downed wood also can provide soil moisture reservoirs that hasten regrowth. To the extent that post-disturbance management reduces the supply of woody debris, these inherent recovery mechanisms may be impaired relative to an unmanaged condition.

Strategic Stand Design

A fourth fuel reduction approach employs landscape-level design of forest stand distributions to restrict the spread of individual wildfires or to modify fire intensity in critical areas (Graham and others 1999). This strategy arose because there is far more at-risk forest present than can be treated in the near future using the approaches described above. However, if such approaches are used strategically to control future fire behavior at specific locations, the areal extent or overall effects of wildfires might be controllable. For example, one of the methods previously described might be used to establish strips of fire-resistant forests, called "shaded fuel breaks," along ridgelines. Fires originating within a watershed would then be more likely to go to ground upon reaching the fuel break and thus be more readily managed.

Similar strategic planning can be used to protect at-risk structures and communities by concentrating fuel management activities around the area to be protected. Because these approaches are limited in scope, they are less likely to entail widespread erosional consequences than is a more extensive implementation of fuel treatments.

Use of strategic stand design introduces a need to understand the implications of landscape-scale distributions of erosion processes. Local effects can be evaluated on the basis of the particular practices used, while the broader-scale effects reflect the distribution of treatments (in time and space) and the nature of process interactions within and downstream of particular watersheds. At this scale, an understanding of in-stream sediment transport becomes particularly important.

Other Activities Associated with Fuel Treatment

Each fuel treatment approach described above is associated with additional activities such as road use and, in some cases, road construction. Roads are often a major source of management-related sediment through road surface erosion, gullying, landslides, and stream crossing failures. Effects of roads on erosion are described in Chapter 5.

Maintenance of an extensive, functioning road network is sometimes justified in part by the need for ongoing fuel treatment. To the extent that a road network supports fuel treatment, a sediment budget would associate the road-related sediment production with the fuel treatment efforts. For example, if 50 percent of the erosion-generating activity on a road is in support of fuel treatment, then 50 percent of the road-related sediment can be attributed to fuel treatment activities.

Strategies for Evaluating Influences

The previous sections describe how various fuel treatments *could* influence erosion processes. Whether such influences are likely to occur in a particular instance depends on the setting, treatment, and weather. Evaluation of the potential for erosion usually entails

1. examining the landscape to be treated to identify erosion processes already active at the site,
2. examining similar sites over a broader area to identify the less common processes that might occur, and
3. examining similar areas that have undergone similar treatments to identify the types of changes likely.

The questions to be addressed for each erosion process are

1. *In what settings* can the process occur? and
2. *Under what conditions* is it likely to occur in those settings?

Different erosion processes need different strategies for evaluation, require examination of different portions of the landscape, and are most usefully addressed at different spatial and temporal scales. Strategies are described here for evaluating channel-bank erosion, gullying, shallow landsliding, and deep-seated sliding. Similar strategies would be used to evaluate other channel erosion and mass-wasting processes if they are of concern at a project site.

Channel-Bank Erosion and Gullying

Evaluation of in-channel and gully erosion relies on information obtained by examining channel systems at several spatial scales. First, the types of channels and settings at and downstream of the project site are described. This work identifies past and current styles of channel behavior to answer the questions:

- Is there evidence of recent or older changes in channel plan-form?
- Is there evidence of recent or older channel aggradation or incision?

- Is there evidence of recent or older gully activity upslope of the current channel heads?
- Do banks show evidence of recent or older erosion?

If such evidence is found, the spatial and temporal patterns of the occurrences would be identified. Evidence of past episodes of gullying might take the form of bank-like scarps upstream of channel heads in otherwise unchanneled swales, uncharacteristically low width-to-depth ratios along small streams, or the presence of exposed tree roots in banks. If gullying was active in the past, the stream network may be particularly sensitive to small changes in factors promoting channel incision.

The next scale of inquiry examines sites outside of the project area that (1) are likely to be most susceptible to increased channel or gully erosion because of their history or setting and (2) have bedrock and topography similar to those of the project area. For in-channel erosion, these might include channels downstream of road drainage inputs or sites downstream of pervasively logged watersheds. Off-site examinations for gully erosion might focus on burned swales or sites where unprotected ditch-relief culverts empty into steep swales or headwater channels.

This portion of the evaluation describes potential mechanisms of influence on the processes, defines the tolerance of the landscape to change, and identifies the changes in controlling variables to which local erosion processes are sensitive. For example, if channels appear stable at the project site, but similar channels show extensive bank erosion below road surface drainage inputs, the effects of the proposed activities on runoff become a concern. Interpretation of the field observations requires evaluation of the storm history in the area. If no large storms have occurred since a road was constructed, lack of evidence for downstream destabilization cannot be considered evidence that destabilization is unlikely.

Field examination next turns to sites at which the proposed activities—or similar activities—have already been carried out. Here, too, evidence of channel destabilization and gullying is sought, as is evidence for influences on the controlling factors found to be important elsewhere. For example, if gullying was found at sensitive sites, treated sites would be examined for evidence of changes in swale-surface erodibility and surface runoff. In this case, too, sites for which challenging events have not occurred are not particularly useful.

The series of observations described above is intended to document the logic trail needed to support a diagnosis. Information presented might include:

1. descriptions of channel types in the area and downstream,
2. observations of those channel types in potentially erosive settings,
3. discussion of likely destabilization mechanisms at sites where erosion was observed,
4. description of channels and of any evidence for disruption at sites of analogous activities, and
5. description of evidence for the effects of the analogous management activities on conditions likely to influence the mechanisms in (3).

If evidence for an effect is found, or if information from elsewhere suggests that influences are possible, those effects would be further analyzed for the project site. Likely changes in runoff might be estimated through modeling, for example, and this change could then be compared to that present at sites where road drainage has destabilized channels. Particularly important issues for channel and gully erosion often include altered runoff, woody debris, and surface conditions.

In some cases, the weather conditions that provoke erosion may not have occurred recently enough to provide evidence of potential changes. Most channel changes occur during large floods, so conclusions will be weak if a geomorphically significant flood has not occurred in the past decade or so. Similarly, if the combination of disturbances and fuel treatment prescriptions are unprecedented for an area, evidence from past landscape behavior provides a weaker conclusion than it would had analogous conditions existed in the past.

Landsliding

Analysis of shallow landsliding requires special care because

1. such landslides often occur at sites where no evidence of previous destabilization is visible,
2. significant landsliding often occurs only with major storms,
3. the areal density of landslides is usually low even after landslide-generating storms,
4. even a few landslides can cause major impacts in downstream channels, and
5. the process is often of great public concern because it is frequently the most visible erosion process associated with land management activities.

Shallow landslides associated with forest management usually occur because management activities modify conditions at previously stable sites, destabilizing them. Consequently, site inspections cannot reliably reveal whether specific sites will become unstable after activities occur. The diagnosis instead must be made by identifying the site types present at the proposed activity site, assessing the inherent susceptibility of those site types to landsliding, and determining whether the proposed activities will increase that susceptibility. This strategy is essentially the same as that described for assessing susceptibility to channel-bank and gully erosion.

Shallow landsliding is generally associated with particular landscape features such as inner gorges and steep hillslope swales. Such associations simplify the analysis by allowing efficient stratification of the landscape into landslide-prone and stable areas. Analysis is also simplified because, in contrast to gullying and channel erosion, large slides are often visible on aerial photographs. Analysis usually begins with a broad-scale, air-photo-based evaluation of landslide distribution across the landscape using photos that pre-and post-date a major landslide-generating storm. Associations between landslide distribution and landform are first evaluated, then areal landslide densities are calculated for each landform type in areas that had undergone different types or ages of management activities at the time of the storm. Comparison between these values for different management activities provides estimates of the relative influence of the activities on landsliding for particular landforms.

In the hypothetical example shown in table 3, recent logging is associated with an overall landslide frequency 2.5 times that of unlogged areas, and most of the increase results from destabilization of headwater swales. Data for the same 1994 to 1997 storms for older logging suggest that the older sites are largely restabilized, showing only a 22 percent increase relative to unlogged sites. In most locales, the area of remaining old growth forest is too small to allow comparison between unlogged and logged areas, so changes relative to naturally occurring rates cannot be directly calculated. In such cases, definition of the recovery trend as a function of disturbance age can provide an estimate of the minimum change likely, or a simple comparison of rates in older and younger stands (such as the comparison between less than 15-year stands and greater than 15-year stands in table 3) might indicate a minimum likely change if management practices did not differ greatly between the periods.

Susceptibility to shallow sliding can be strongly influenced by hydrologic changes, and such changes can be generated by activities occurring upslope from potentially unstable sites. For example, concentration of road drainage onto a hillside can trigger failures downslope. It may thus be useful to test for relationships between downslope landslide frequencies and upslope activities.

Human activities can also influence characteristic landslide size, and landslides of different sizes often have different effects on impacted resources. If management activities increase landslide frequency and decrease landslide size, for example, biological responses may be important due to the altered spatial and temporal distribution of impacts even if the average rate of sediment input is unchanged (Chapter 12).

Once the association of landslides with particular landforms is defined and the relative susceptibility of those landforms to destabilization is understood, the project

Table 3. Hypothetical example of a rate calculation for shallow landsliding

Landform	Area of landform (ha)	Number of slides[a] 1994-97	Rate (slides/km^2)	Ratio to unlogged	Ratio to >15 yr logging
Unlogged					
Planar slope	1900	3	0.16	1	0.83
Headwater swale	210	2	0.95	1	0.69
Inner gorge	430	4	0.93	1	0.62
Other[b]	450	1	0.22	1	--
Total	*2990*	*10*	*0.33*	*1*	*0.82*
Logged within 15 years					
Planar slope	6300	19	0.30	1.91	1.59
Headwater swale	510	23	4.51	4.74	3.27
Inner gorge	1410	36	2.55	2.74	1.69
Other[b]	1510	3	0.20	0.89	--
Total	*9730*	*81*	*0.83*	*2.49*	*2.04*
Logged before 15 years ago					
Planar slope	3700	7	0.19	1.20	1
Headwater swale	290	4	1.38	1.45	1
Inner gorge	730	11	1.51	1.62	1
Other[b]	680	0	0	0	--
Total	*5400*	*22*	*0.41*	*1.22*	*1*
Grand total	18120	113			

[a] Only slides greater than 100 m^2 are tabulated to provide uniform resolution in different vegetation types.
[b] "Other" includes inherently stable sites such as ridge-tops and floodplains.

area—and areas downslope—can be examined for presence of the types of landforms found to be most important. The change in susceptibility can be estimated as the ratio between rates per unit area of the given landform on forested and treated sites (for example, table 3). The level of concern would be particularly high if the landforms of interest already show evidence of destabilization.

Examination of sites that have undergone analogous treatments is primarily intended to evaluate the types of influences the planned activities may have on controlling variables. Rarely would the sample area be large enough, and the storm history suitable enough, that influences on landslide frequency could be directly estimated on the basis of a site examination.

As with shallow landsliding, it is useful to begin an analysis of deep-seated landsliding with a broad-scale air-photo survey to identify patterns in the distribution of the process. If deep-seated slides are not already present in settings with bedrock and topography similar to those at the project site, they are not likely to be of concern unless significant earthwork is planned.

If deep-seated slumps and earthflows are present in similar settings, the broad-scale survey can be used to detect patterns in their activity levels. In particular, evidence can be sought to determine whether existing features can be reactivated or accelerated by management activities occurring on or upslope of the features. Remobilization of a dormant slump might be recognized by opening of new tension cracks at the base of the headscarp or by increased rates of shallow sliding from the toe. Temporal variations in activity level for earthflows can often be detected by using sequential aerial photographs to track the displacement of surficial features such as trees or roads.

The project site itself is then examined to determine whether deep-seated slumps or earthflows are present and evaluate their current activity levels. If either active or dormant features are present, activities that increase water inputs to the features would tend to increase their activity level. Evaluation of deep-seated features must usually be qualitative rather than quantitative.

Evaluating Cumulative Impacts

The preceding sections focused on understanding and evaluating the influences of fuel treatments on the distribution and rates of channel erosion and mass-wasting processes. Such analyses can provide estimates of the extent to which management activities might increase the erosion risk. However, increased erosion is of concern only if an increased risk of erosion is accompanied by an increased hazard to a resource or entity of concern. It is at this point that evaluation of the cumulative impacts of altered erosion becomes necessary.

From the point of view of an impacted resource, the effects of a land use activity on individual processes are not nearly as important as the overall effect of changes caused by the full distribution of activities through time and across the landscape. These cumulative effects are important to understand in two respects. First, the combined influences on a particular process must be understood if the net change in process rate is to be evaluated. For example, rates of shallow landsliding might increase because of both decreased rainfall interception and decreased root cohesion after canopy thinning. Second, the combined effects of all influences on a potentially impacted resource must be understood if the actual severity of the impact is to be evaluated. For example, increased flood damage caused by heightened rain-on-snow runoff may be further augmented by reduced channel conveyance due to landslide-related aggradation.

The Council on Environmental Quality (CEQ) has provided guidance (CEQ 1997) for preparation of cumulative impact analyses for documents prepared under the National Environmental Policy Act (NEPA), and federal courts have clarified standards for analysis through their opinions on cases involving such analyses (Chapter 14). Both the CEQ and the courts indicate that analysis is intended to evaluate the net impacts on particular resources. Consequently, a cumulative impact analysis for a fuel treatment project would need to assess the extent to which erosion rates influenced by the project might affect the nature and severity of impacts on specific resources.

The CEQ (1997) describes the analytical steps useful for cumulative impact analysis (table 1, Chapter 14), and these are readily applied to analysis for cumulative impacts associated with channel erosion and mass wasting. The procedure first defines impacted resources of potential concern in the area, as well as the resources, values, or issues of importance in the area that may not yet show impacts (step 1). Issues that might necessitate evaluation of erosion processes could include concerns over salmonid populations, downstream flooding, water quality, reservoir sedimentation, or any other impact that can be affected by altered sediment load or channel form.

For each entity of concern, the mechanisms through which impacts might occur are then identified. Potential interactions between impacts and sediment load may begin to become evident at this stage, though identified mechanisms need not directly involve erosion processes. Because the analysis is of *cumulative* effects, the broader context in which sediment-related influences occur must be evaluated. In the case of concerns over increased downstream flooding, for example, potential mechanisms of interest that are not directly related to a project's sediment inputs might include increased peakflows, reduced channel conveyance due to vegetation encroachment, changes in reservoir management strategies due to increased irrigation demands, and increased residential development on floodplains. Sediment-related mechanisms could include reservoir sedimentation and reduced channel conveyance due to aggradation.

An understanding of the distribution of the resources of interest and of the nature of relevant impact mechanisms then allows definition of the spatial and temporal scales needed to analyze impacts on each resource (steps 2 and 3). Because different impacts are expressed at different sites and over different time scales, analysis scales will differ for each kind of impact, and sometimes for each impact mechanism. For example, most influences on flood hazard need to be evaluated over the watershed upstream of sites susceptible to flooding, but prediction of the contribution of changes in reservoir management strategy to flood hazard requires consideration of socio-economic influences over a much broader scale.

At this point, a general overview is useful of the types of activities that have occurred in each relevant analysis area and that may affect the resources of concern (step 4). Evaluation of the nature and timing of past changes is facilitated if the distribution and timing of past agents of change are known. An assessment of cumulative impacts on flood hazard, for example, might evaluate the history of vegetation change in the upstream watershed and assess the timing and distribution of activities that can influence rates of sediment production.

Examination of recent legal opinions suggests that defining the significance of environmental changes is particularly challenging (Chapter 14), and the next analysis steps outline a strategy for addressing this problem. First, the types of coping strategies or responses to each potential impact are described for each resource (step 5). This information provides a basis for evaluating how much of a change is tolerable before a resource becomes impaired. Impacts on some issues of concern, such as municipal water supplies or transportation infrastructure, can be assigned economic values. In other cases, regulations may have established particular thresholds of significance. At this stage, examination of natural disturbance patterns can be very useful. Many resources of concern (such as endangered species) developed in the context of the spatial and temporal variations in conditions that occurred before Euro-American settlement. For these, deviations from the natural patterns define the levels of stress currently experienced (step 6). In some cases, attempts have been made to place current conditions in the context of very-long-term averages for sediment inputs obtained by cosmogenic isotope work. However, if the "range of natural variability" is found to have included an extreme sediment-generating event 2,000 years ago, that event did not occur in the context of the other changes that are present today. If such major events are found to have occurred naturally, the impact assessment would need to evaluate the cumulative effect of the modern land use activities on the ability of impacted resources to recover from such an event.

The CEQ then suggests that baseline conditions be described (step 7), and explains that "*the baseline condition of the resource of concern should include a description of how conditions have changed over time and how they are likely to change in the future without the proposed action*" (CEQ 1997, p. 41). In this context, establishing the baseline requires description of the pre-Euro-American conditions, comparison of those to today's conditions, and description of the current trajectory of conditions. Of these tasks, description of the pre-Euro-American conditions is usually the most challenging because undisturbed conditions are rarely available for comparison. Instead, those conditions generally must be inferred from (1) observation of sites with *relatively* undisturbed conditions, (2) an understanding of the history of change in an area (step 4 above), and (3) historical evidence, including old snapshots, early aerial photographs, oral histories, and so on. For the flood hazard example, baseline conditions would be established for flood frequencies at susceptible sites as well as for the conditions influencing those frequencies. Baseline channel conveyance, for example, might be established by using historical aerial photographs to evaluate changes in channel form and bank vegetation, and old surveyed cross sections may be available from bridge construction sites.

At step 8, the cause-and-effect relations between human activities and impacts are identified. For increased flooding, anthropogenic effects on peakflows and channel conveyance would be evaluated at this stage. Most impacts are influenced by a variety of mechanisms, many of which do not involve sediment production. Anthropogenic effects on channel conveyance, for example, might include vegetation management on channel banks or construction of levees.

Past and on-going land use activities would then be evaluated to determine the extent to which they influence conditions that affect impact levels. The existing cumulative impact on a resource is the overall impairment caused by the combined mechanisms (step 9). At this stage, the potential influences of a proposed activity would be examined to determine whether they could contribute to the identified impacts. The first eight analysis steps outlined potential impact mechanisms relevant to the particular setting, thus narrowing the scope of the portion of the analysis relating specifically to erosion processes. It now becomes possible to match the potential changes likely to be associated with altered erosion (for example, column 5 in table 1) with the types of changes relevant to the impacts of concern. Many potential influences would be discarded at this stage if they are found not to be relevant in the particular system being evaluated.

To evaluate impacts associated with erosion processes, the proposed activities would first be analyzed to identify their potential influences on particular processes (table 2). Each of the impact mechanisms identified for flood hazard, for example, could then be evaluated to determine whether the potential influences from the relevant erosion processes (table 1, column 5) can affect the impact mechanism. For example, a project involving road construction for salvage logging in steep terrain might be expected to generate shallow landsliding (table 2), which could contribute to aggradation (table 1). If analysis has suggested that reduced channel conveyance is of concern, for example, potential changes in aggradation could contribute to a cumulative impact on flood hazard.

The final steps outlined by the CEQ allow for use of the analysis to redesign or mitigate the project (step 10) and for monitoring and modification of the project after it is implemented (step 11). The preceding analysis steps provide much of the information needed to design efficient and effective mitigations and monitoring projects.

Impact analysis under NEPA also requires analysis of the cumulative impacts associated with the "no action" alternative. In the case of salvage activities, such analysis would ordinarily consider impacts of the disturbance event and any rehabilitation work associated with the event. Analysis of the project's effects on channel erosion and mass wasting would need to address how changes from the project would modify the effects of the event on those processes in the absence of the project. At some sites, for example, woody debris contributed to small streams by a fire might trap large volumes of sediment eroded from burned slopes, and salvage of the wood could increase the downstream sediment flux relative to the effect of the fire alone. In addition, if Euro-American management practices influenced the extent or character of the infestation or fire, some aspects of the initial disturbance are themselves anthropogenic, and those influences would need to be evaluated as a component of cumulative impacts.

Analysis of the role of fuel treatment projects in cumulative impact generation will also be required during impact evaluation for future projects of other kinds. At that time, the erosional consequences of past fuel treatment projects—even if carried out under categorical exclusions under NEPA—would need to be evaluated since they will have become "past projects" that provide the context for newly planned projects.

Cumulative impact analysis is necessarily an interdisciplinary exercise. Here we consider effects on mass-wasting and channel erosion processes, but similar analyses would be carried out for effects on hydrology, vegetation, wildlife, and so on. In the real world, all of these influences interact. As analysis proceeds for each of these environmental components, linkages between components are identified and incorporated into the analysis. For example, when likely hydrological changes are identified, their influences on erosion processes can be evaluated. Influences on the impact mechanisms from other previous and potential future activities would also be analyzed using a similar approach. In particular, implications of the combined influence of past and proposed activities in prolonging the duration and spatial extent of the impacts would need to be considered. Interdisciplinary analysis is also important because a change in erosion rate is of interest in cumulative impact analysis only insofar as it influences an impact of concern, so evaluation of the significance of erosional changes may require an understanding of fisheries biology, riparian ecology, structural engineering, or any of a number of other fields.

As in many areas of human endeavor, forest management decisions must be made even though knowledge of the likely outcomes of those decisions is incomplete. Even if knowledge of erosion processes were perfect, precise outcomes could not be predicted because future weather conditions are unknown. The challenge for cumulative impact analysts is to use knowledge from a broad range of disciplines as effectively as possible to allow adequately informed decision-making.

Conclusions

The broad range of potential fuel treatment practices can influence channel erosion and mass-wasting processes in a variety of ways, so the erosional outcome from a particular project depends strongly on the nature and setting of the project. Thus, each application must be evaluated in its own right to assess potential impacts. Even though the effects of particular fuel treatment activities on erosion rates have not been widely studied, information from a variety of other studies is applicable to the problem if the factors controlling the distribution and rates of erosion processes are understood and the effects of particular fuel treatment practices on those factors can be determined. In general, fuel treatment activities that modify soil conditions, hydrologic conditions, vegetation, or hillslope or channel morphology are likely to influence the rates and distribution of channel erosion and mass-wasting processes.

If the resulting influences adversely affect an entity that is experiencing impacts from other sources as well, the fuel treatment project will have contributed to the cumulative impact on that entity. If the relevant impact mechanisms are understood, the potential effect of erosion from a planned fuel treatment project on the cumulative impact can be evaluated by determining the extent to which the types of erosion that are likely to be associated with the project will influence those impact mechanisms.

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