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11. Landscape Patterns, Disturbance, and Management in the Pacific Northwest, USA

Frederick J. Swanson, Jerry F. Franklin, and James R. Sedell

The ecology of landscape-scale processes is richly expressed in forested mountain landscapes of western Oregon and Washington in northwestern North America (Figure 1). The mosaic of landscape patterns is especially dynamic in these geomorphically active areas of high relief, heavy precipitation, and frequent disturbance by fire, wind, and other processes. Indeed, the time scales of geomorphic and ecosystem change overlap in these areas of active volcanism, unstable hillslopes, and long-lived trees. Mount St. Helens in Washington State, for example, has had eruptive episodes over the last 2500 years, interspersed with dormant periods lasting 200 to 700 years (Mullineaux and Crandell, 1981). The eruptions have altered the surrounding conifer forests, dominated generally by Douglas fir *(Pseudotsuga menziesii),* which can live well beyond 1000 years.

Only a few decades ago, much of the Pacific Northwest was blanketed with forests that originated after wildfires during the twelfth through the early nineteenth centuries. This was before nonaboriginal peoples entered the area (about A.D. 1800) or had significant effect on fire ignition (beginning about 1840) and suppression (beginning about 1910). Aboriginal people may have influenced fire history during much of the Holocene Epoch, but their influence is mostly unknown and may not have been widespread in the massive, generally wet forests west of the crest of the Cascade Range (Morris, 1934; Burke, 1979; Teensma, 1987) (Figure 1).

Today, privately owned forest lands have been almost entirely cut over, and extensive tracts of Federal forest land are now being logged and converted to

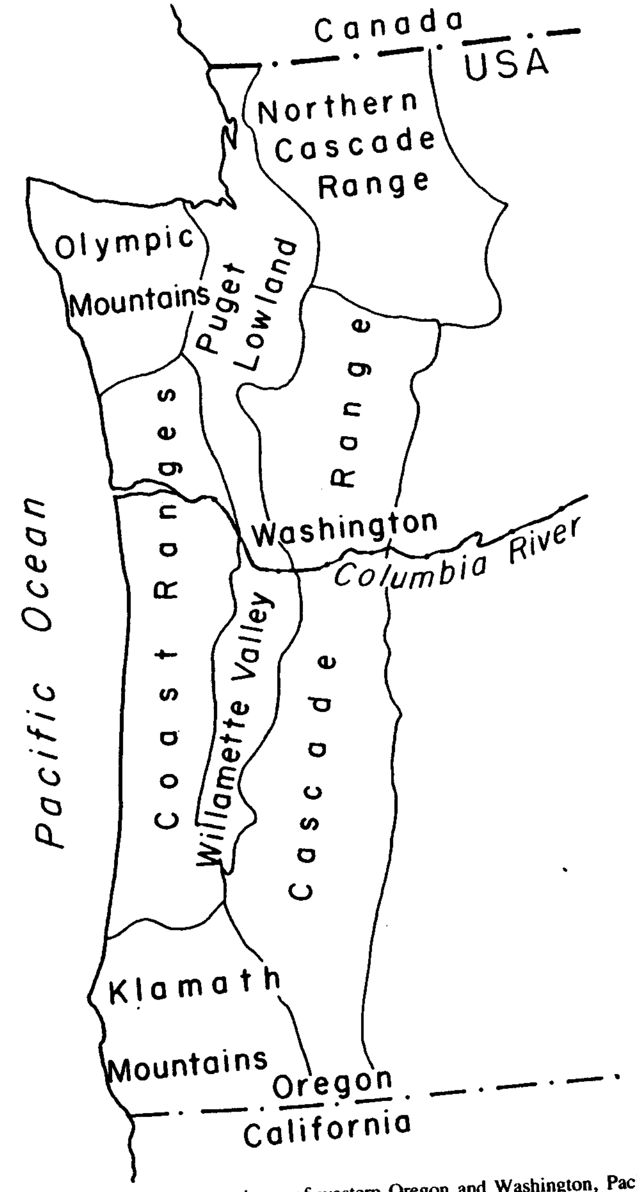


Figure 1. Physiographic provinces of western Oregon and Washington, Pacific Northwest, United States.

managed forests. Despite recent forest cutting, the natural patchwork of forest stands before the influence of nonaboriginal people and the history of disturbances over the past 500 to 800 years can be reconstructed from aerial photographs and dendrochronological records. The patterns can be compared with the landscape pattern imposed by management activities. Many current, politically charged issues in forest management concern the degree to which altered landscape structure and forest fragmentation influence wildlife, hydrology, water quality, and susceptibility of forests to catastrophic disturbance by agents such as wind, fire, and pests.

In this chapter, we present several examples of key landscape-ecology processes operating in forest and stream systems of the Pacific Northwest before and after the conversion from wildland to managed forest land. We do not offer a general model for these landscapes, but instead examine some of the elements that might go into such a model. We discuss in particular the relation among forest and flowing-water ecosystems, disturbances, and geomorphology. Geomorphology concerns both landforms and the geomorphic processes that sculpt them.

Landscapes of the Pacific Northwest

The ecological, physiographic, and geologic complexities of the Pacific Northwest (Franklin and Dyrness, 1973) have created highly varied landscapes. The landscape pattern is strongly influenced by environmental factors that vary spatially either as discrete patches or as broad gradients. Discrete variation in landscape pattern is controlled primarily by land use, wild disturbances (i.e., by natural processes as distinguished from management-imposed disturbance), and geology. Rock types on opposite sides of knife-sharp geologic contact may contrast may strongly in physical and chemical properties, thereby causing abrupt changes in vegetation composition and in dominant geomorphic processes that can trigger disturbances. Superimposed on this geologic template are gradients of important environmental variables: (1) precipitation, which varies with elevation, latitude, and mountain-created rain-shadow effects; (2) snowpack accumulation and timing of snowmelt which, in turn, control the timing and magnitude of flood flows; (3) wildfire, which is controlled primarily by effects of climate on vegetation type, fuel mosaic, ignition, and spread; (4) high winds, including frequency, magnitude, and seasonal timing; (5) glacial imprints on topography and soil; and (6) volcanism, which produces zones of air-fall tephra and mudflow deposits extending outward from stratovolcanoes in the Cascade Range.

Topography changes conspicuously across the region. At one extreme are areas with long, steep slopes in highly glaciated, hard-rock terranes in the northern Cascade Range and Olympic Mountains of Washington (Figure 1). In these areas, landform relief (height of ridge crest above adjacent valley floor) may exceed by 20 times the typical heights (50 to 70 m) of the once widespread old-growth forest. The unglaciated Coast Ranges of Oregon and Washington, underlain by moderately indurated Tertiary sedimentary rock, have low relief (landform relief of two to six old-growth tree heights in many areas), although slopes may be steep and cut by a high density of stream channels. Broad inland valleys—e.g., the Willamette Valley and the Puget Lowland (Figure 1)—and coastal marine terraces are among the landforms of lowest relief in the region. Major landforms are mainly the result of erosion, but the Quaternary stratovolcanoes in the Cascade Range exceeding 2300 m in elevation are imposing features of constructional origin (Figure 2).

Disturbance regimes, influenced in part by landforms (Swanson et al., 1988), also differ across broad gradients in the region. Climate creates a great diversity of wildfire regimes. Essentially fire-free ecosystems occur along a narrow coastal strip from Washington to southeastern Alaska. At the other extreme, a complex regime of frequent, low- to high-severity fires of highly variable patch sizes is characteristic of southern Oregon and northwestern California. The Cascade and Coast Ranges of Oregon and Washington experience an intermediate fire regime that includes large (100,000-ha) stand-replacing fires (Teensma, 1987). The importance of wind as an agent of disturbance is greatest near the coast and through the Columbia River Gorge (Franklin, in preparation). Landslides create fewer but larger disturbance patches in the Cascade Range than in the highly dissected Coast Range of southern Oregon (Swanson and Lienkaemper, 1985). Snow avalanches are common at higher elevations of the Cascade Range but do not occur in the Coast Ranges.

Figure 2. High-relief landscape on the southeast flank of Mount Rainier, Washington. Near the northern end of the Cascade Range (Figure 1).

Flowing-water and valley-floor ecosystems of the region also show great variation; they range from headwater channels a few meters wide flowing among 70-m-tall conifer trees to broad, multichanneled rivers bordered by shrubs and hardwoods that are frequently disturbed by floods. Bedrock outcrops and landslides from hillslopes create constrictions—local sites of narrow, steep channels—and alter the magnitude of shading, litter production, and other effects of streamside vegetation on stream ecosystems. Channel reaches along valley floors that are free of these constraints may be meandering or braided; lateral channel migration is common, and floodplain forests can significantly affect the dominant processes and food base of the aquatic ecosystem. Geologic conditions, including the resistance of rock to erosion and the rate and recency of uplift, affect the type and geographic arrangement of constrained and unconstrained stream reaches.

This diversity in landform and disturbance regimes has created a complex natural mosaic of forest patches ranging from less than 0.1 to 100,000 ha. Fire, wind, landslides, snow avalanches, patches of root-rot mortality, changes in river channels, and other natural processes are responsible for the mosaic of disturbances. Further complexity in the form of environmental-resource patches (Forman and Godron, 1986) is created by extremely shallow soil, bedrock outcrops, wetlands, talus fields, and other nonforested sites that persist through forest disturbances.

Forest cutting, road construction, and maintenance of forest vegetation for stream protection and other purposes are creating new patchworks that differ markedly in their structure and rate of creation. On U.S. Government land, for example, a *staggered-setting* or dispersed-patch approach to timber harvest uses clear-cut areas of about 15 ha dispersed through the forest (Figure 3). In this system, cutting occurs progressively over the entire rotation (time between successive complete harvests of a site). The rotation in Douglas fir is commonly 50 to 100 years. The staggered-setting system is an effort to disperse the effects of management activities across time and space (Franklin and Forman, 1987). On private industry lands, on the other hand, cut areas commonly form much larger patches, and an entire drainage basin of hundreds of hectares may be cut within a few years; consequently, management activities are altering landscape patterns over large areas and in dramatically different ways with little regard for the natural landscape mosaic or the processes that created it.

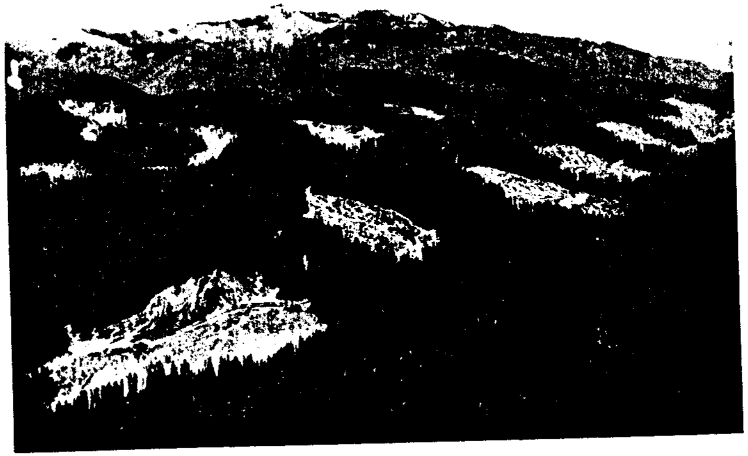


Figure 3. Early stage in the staggered-setting or dispersed-patch system of forest cutting used on U.S. Government land.

Concepts of Landscape Ecology

Existing landscape concepts emphasize terrestrial landscapes as a system of patches of different types, shapes, and functions and also the interactions among patches (Forman and Godron, 1986). This perspective has great use in analyzing landscapes of forested mountain regions. Further useful landscape-ecology concepts include: (1) the effects of landforms on ecosystem patterns and processes, such as disturbance and the dynamics of terrestrial mosaics (Swanson et al. 1988); (2) link between terrestrial and aquatic systems; (3) models of flowing-water ecosystems from small to large channels; and (4) structure and function of landscapes that are constantly changing as a result of forest management. We now explore these concepts in sequence.

Effects of Landforms on Ecosystem Patterns and Processes

Many aspects of landscape pattern in mountainous areas reflect the influence of landforms on disturbance and resources for ecosystem development. Landform

effects on ecosystems can be viewed as occurring in four ways (Swanson et al., 1988):

1. Slope gradient, elevation, and aspect affect the quantity of solar energy, water, nutrients, pollutants, and other materials received by a site.
2. Landform position and slope gradient affect the flow of materials (water, dissolved material, organic and inorganic particulate matter), organisms, propagules, and energy across landscapes by their influence on gravitational gradients, by guiding flowpaths of wind, and by forming barriers to movement.
3. Landforms and slope gradient influence the frequency, spatial pattern, and intensity of disturbances, such as fire and wind, which are strongly and positively influenced by the presence of vegetation.
4. Landforms influence the spatial pattern and frequency or rate of disturbance by geomorphic processes.

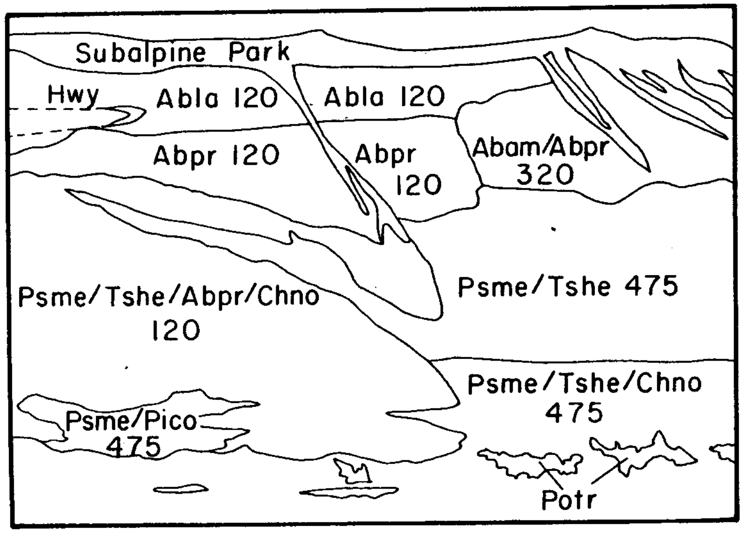
The first three of these classes of landform effects assume topography to be static; only the fourth class accommodates the dynamic geomorphic character of many mountain landscapes.

Patterns in most landscapes represent superimposed effects of several classes or all four classes of landform influences. At Mount Rainier in Washington State, for example, repeated volcanic activity and glaciation have formed a steep, high-relief landscape with slope lengths locally exceeding 1000 m (figures 2 and 4) (Hemstrom, 1982; Hemstrom and Franklin, 1982). Vegetation habitat types therefore occur in zones defined by altitude, because of strong effects of temperature and moisture (class-1 effect) (Figure 4). Downslope movement of moisture and nutrients superimposes a pattern of higher productivity on lower slope locations (class-2 effects). Frequency, size, and geographic patterns of fire appear to be significantly affected by landforms (Hemstrom, 1982). Major ridges and valley bottoms impede fire movement. Snow avalanches repeatedly sweep along bedrock-controlled paths, thereby creating treeless areas that may serve as fire breaks. In addition, all major valleys that drain the mountain have had mudflows that began on the upper flanks of the mountain (class-4 effect).

The resulting landscape mosaic at Mount Rainier is complex but predictable to a degree. Gross landforms are relatively invariant on a time scale of several thousand years; where landforms strongly control the pattern of disturbance, boundaries between patches along ridge lines and valley floors are likely to persist through disturbance. Other segments of boundaries between patches may be ephemeral and readily overridden by subsequent disturbances. This process may occur in midslope positions where fire boundaries have been determined by shifts in wind direction or the onset of rainy weather. Landscape dynamics can be analyzed in terms of the persistence of boundaries between patches, based on the degree of landform control on boundary locations as a measure of ecotone stability.

The influences of landforms on disturbance patterns (class-3 and class-4 effects) pose interesting questions about the importance of the relative scales of

(A)



(B)

vegetation and landforms. We hypothesize that in steep mountain landscapes where landform relief does not exceed several tree heights, disturbance agents such as fire and wind can readily move through the forest with little regard for topography. Landforms may have greater effect on the spread of disturbance and mosaic structure (i.e., patch size and edge location with respect to landform feature) where relief substantially exceeds tree height.

Links Between Terrestrial and Aquatic Systems

Major ecological links occur where terrestrial and aquatic systems meet in the riparian zone, the three-dimensional zone of interaction between terrestrial and aquatic systems (Swanson et al., 1982). Analyses of landscapes containing aquatic systems should consider both terrestrial and aquatic components and their zone of interaction. The riparian zone is a distinctive element of the landscape commonly subject to disturbances characteristic of both fluvial and terrestrial systems and having mosaic structure and some species not found in either terrestrial or aquatic areas.

From a biological point of view, forest–stream interactions include transfers of organic matter and nutrients and the regulation of energy flow. In steep lands with narrow valley floors and wet climates, the dominant direction of influence is from forest to aquatic system. The composition of aquatic communities and rates of stream ecosystem processes are strongly influenced by the structure and composition of streamside vegetation. The vegetation produces litter and shading, which regulates water temperature and light available for instream primary production. The opposite interaction (from stream to forest) may dominate in areas of broad floodplains and especially in arid and semiarid areas where streamwater flows outward into the groundwater system, recharging it. In virtually any system bordered by forests, large woody debris from adjacent stands can influence the structure of aquatic habitat and the ability of the aquatic system to retain organic detritus, making it available for consumption by aquatic organisms (Harmon et al., 1986).

The interactions between riparian vegetation and aquatic ecosystems differ in response to disturbance history, vegetation succession, and geomorphic setting. A key factor is the height of vegetation relative to the widths of valley-floor geomorphic surfaces. We are now studying these relations in valley floors of

Figure 4. Photograph (A) of mosaic of forest stands on Sunrise Ridge in the White River drainage of Mount Rainier. This east-southeast facing slope extends from 900 to 1800 m elevation. Drawing (B) shows forest-stand types and ages reflecting landform influences on environment and disturbance. Snow avalanche tracks cut through the upper elevation forests. The White River (bottom of photograph) has experienced major mudflows generated on Mount Rainier and extensive lateral channel migration. Tree species dominating stands are: Abla = *Abies lasiocarpa*, Abam = *Abies amabilis*, Abpr = *Abies procera*, Psme = *Pseudotsuga menziesii*, Tshe = *Tsuga heterophylla*, Chno = *Chamaecyparis nootkatensis*, Pico = *Pinus contorta*, Potr = *Populus trichocarpa*. Numbers indicate the stand age in years.

third- to fifth-order (stream-ordering system of Strahler, 1957) mountain streams to determine the rates and patterns of change in stream-habitat structure and streamside vegetation in response to disturbance by fire, channel change during floods, streamside landslides, and debris flows from tributaries. This analysis recognizes a critical hierarchy of structural scales in the fluvial system: (1) single particle; (2) subunits, such as a patch of like-sized particles; (3) channel units (e.g., pool or riffle); (4) reach type (defined below); (5) sections composed of multiple reaches (e.g., high-gradient mountain streams, meandering rivers in major valleys); and (6) the full drainage network (Figure 5). Furthermore, in forested mountain systems some individual scales are not sharply distinguished from adjacent scales. Single particles, for example, can be as large as whole, fallen old-growth tree stems, which are the size of and control formation of channel units two scales larger.

To interpret and predict the long-term (centuries to millennia) ecosystem behavior of valley-floor environments, scientists are examining the geomorphic structure and behavior of the fluvial system across the first five scales. These channel conditions must be interpreted in the context of their valley-floor (floodplain, terrace, alluvial fan) and valley-wall environments (landslide, earthflow, bedrock, soil-mantled slope). A key to predicting long-term valley-floor dynamics is to understand the geomorphic behavior of reach types. Reach types are defined in terms of the type and degree of constraint on the stream system by factors exogenous to the mainstem river system. Three reach types common in mountain streams are: (1) reaches with passive constraint by bedrock exposed in the bed and bank of the channel, (2) reaches with active constraint of slow-moving landslides (termed earthflows) from a hillslope (Figure 5), and (3) areas free of these constraints where the channel has greater opportunity for lateral shifting. We think that fluvial disturbances in bedrock-confined areas will be infrequent and limited in areal extent. Reaches constricted by earthflows have frequent, small, streamside slides (Swanson et al., 1985) that create a fine-scale mosaic of stands of streamside vegetation in various successional stages. Areas free of these constraints have larger, elongated disturbance patches where recent channel changes have provided fresh substrates for establishment of streamside vegetation. Many ecosystem characteristics differ among these reach types, including channel-habitat structure, the spatial distribution and geomorphic functions of large woody debris, and valley-floor wildlife habitat.

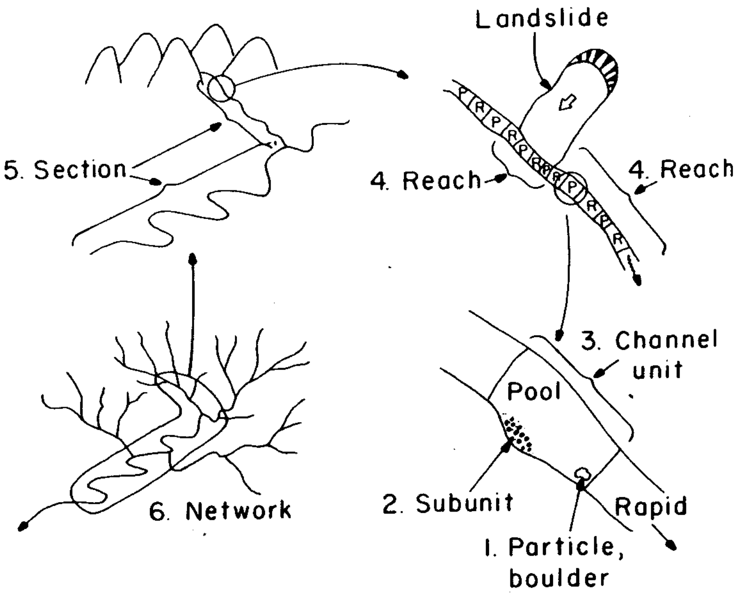


Figure 5. Six scales of the hierarchical structure of river systems from single particle to drainage network. Scales are numbered from the single particle (1) to the full drainage network (6). At the channel-unit (3) and reach (4) scales, P = pool and R = riffle. Scale 5, the section, shows mountain and lowland valley examples.

In the high-gradient, fourth- and fifth-order mountain streams of the western Cascade Range in Oregon, broad valley floors occur predominantly upstream of earthflow constrictions because of a local damming effect (Figure 6). These areas may be several hundred meters wide, several kilometers long, and contain a

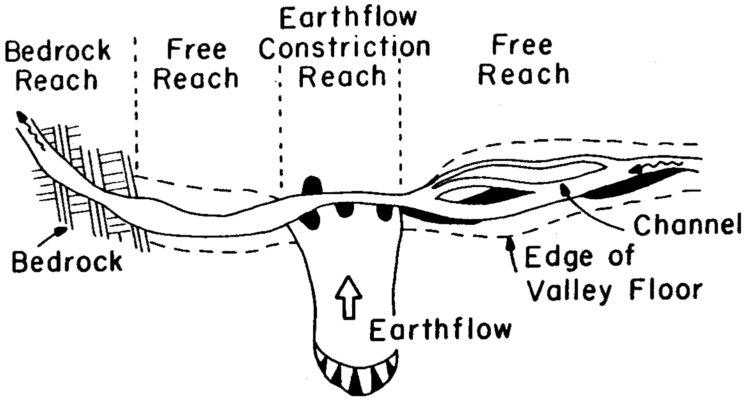


Figure 6. Stream reach types near an earthflow constriction. Dark patches are areas of recent disturbance caused by channel change (in the free reach upstream) and by streamside slides (in the earthflow reach). Interactions between terrestrial and aquatic systems are greatest in the upstream free reach.

complex braided network of perennial, intermittent, and ephemeral channels flowing through shrub and forest stands of different ages (Vest, 1988). The extent of floodplain inundation at high discharges, and hence interaction between terrestrial and aquatic systems, is greatest in these unconstrained reaches.

The size and extent of patches created by disturbances in riparian zones differ by type of disturbance and the type of reach. In French Pete Creek, a wilderness stream drainage in the western Cascade Range in Oregon, a major 1964 flood with associated debris flows in disturbed patches of streamside forests (Grant, 1986) now characterized by stands of alder *(Alnus rubra)* established after that event. The width of these patches is greatest where debris flows from tributaries entered stream reaches free of bedrock and earthflow constraint (Figure 7). Along the free reaches unaffected by debris flows in 1964 and in an earthflow-constricted reach, more than 70 percent of the channel length is bordered by vegetation patches of 1964 origin that are less than 10 m wide (Figure 7). The effects of patch width on forest–stream interactions is determined in part by the ratio of patch width to tree height. These disturbed areas along French Pete Creek are generally narrow in relation to the heights of the alders established after the 1964 flood and to the 100- to 500-year-old conifers on the adjacent, older surfaces (Figure 7). This low ratio of disturbance-patch width to tree height results in continuity of shading and some litter input to streams through fluvial disturbances of riparian vegetation. Periodic disturbance maintains a narrow streamside band of deciduous vegetation bordered by taller coniferous forest. This mosaic of stands produces a mixture of coniferous and deciduous litter for the stream.

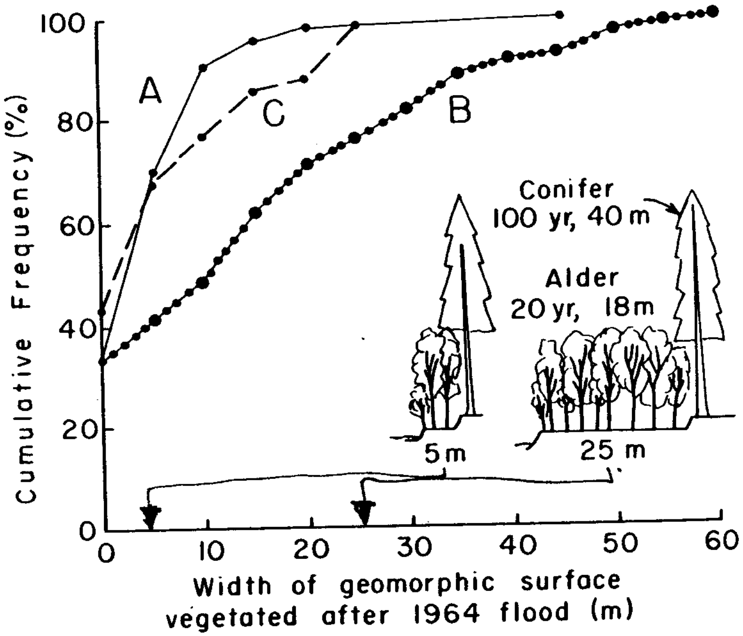


Figure 7. Widths of streamside geomorphic surfaces with vegetation dating from a major flood in 1964, distinguished by type of stream reach. A = reach free of earthflow and bedrock constraints; B = same type of reach, but affected by debris flow in 1964; and C = reach constricted by earthflow. Distance is measured perpendicular to the channel axis. Sketches show relations between surface width and stand structure 20 years after establishment of an alder stand.

The rate of geomorphic and, hence, ecological change of valley-floor ecosystems differs greatly between high-gradient, gravel-bed streams and low-gradient rivers (Table 1). Along the steep, straight mountain channels of French Pete Creek, Oregon, and North Boulder Creek, Colorado, fluvial and debris-flow events in the past century have disturbed vegetation in an area equivalent to 1.0 times the channel width or less (Furbish, 1985; Grant, 1986). In contrast, lateral channel migration of a reach of the low-gradient, meandering Little Missouri River in North Dakota, USA, reset floodplain vegetation over an area of 5.9 channel widths over the past century. Lateral channel change in mountain streams is limited by high gradients, coarse sediment, bedrock outcrops, and hillslope movement into channels. These contrasting disturbance regimes are manifest in the age distributions of streamside forests. Streamside stands along the Little Missouri have a broad spectrum of ages up to 300 years, and all are primary stands established on deposits resulting from channel migration. Forest stands along the steep channel of French Pete Creek are of only a few age classes as a result of establishment after wildfire, floods, and debris flows.

In summary, the structure, function, and disturbance regime of valley-floor

Table 1. Extent of valley floor disturbance, expressed as even-aged patches of trees less than 100 years old, in two high-gradient, straight mountain streams (French Pete Creek, Oregon [Grant, 1986] and North Boulder Creek, Colorado [Furbish, 1985]), and a low-gradient, meandering river (Little Missouri River [Everitt, 1968]).

		Extent of valley floor disturbance in previous 100 yr	
Site	Mean stream channel slope (m/m)	Hectares per km of valley length	Channel widths (mean disturbance width divided by mean channel width)
French Pete Creek	0.042	1.5	1.0
North Boulder Creek	0.030	<0.05	<0.1
Little Missouri River	0.00085	54	5.9

ecosystems are best analyzed within a geomorphic context. The type and degree of geomorphic constraints, including reach-level phenomena, strongly influence landscape dynamics and forest–stream interactions.

Models of Flowing-Water Ecosystems

River networks and their riparian zones are integral parts of many landscapes. The river-continuum concept (Vannote et al., 1980; Minshall et al., 1985) is useful for integrating flowing-water systems at the drainage-network scale into analyses of landscapes. The initial river-continuum concept predicted downstream changes in physical and biological properties of stream systems based on increased discharge and depth and decreased influence of streamside vegetation. Challenges to the simple predictions of the concept have come where geomorphic conditions, such as changes in channel and valley-floor slope, have caused changes in the degree of interaction between streams and floodplain vegetation. Changes in bedrock type, for example, may cause a river valley to change abruptly from a bedrock-confined gorge to a broad floodplain with multiple channels and extensive exchange of organic matter between terrestrial and aquatic systems. Major changes in the biological properties of the aquatic system at the section or reach scales may disrupt network-scale patterns predicted by the river-continuum concept (Minshall et al., 1985; Sedell et al., in press). Landscape ecology would benefit from further development and incorporation of concepts such as the river continuum.

Management-Created Landscapes and Landscape Management

Management practices in the Pacific Northwest are creating new landscapes with little regard for the ecological design of management at a landscape scale. Issues of landscape management are emerging rapidly through litigation, legislation, and growing concerns of managers and the public. The cumulative effects of management activities is an important issue (which must be assessed for significant U.S. Government actions as stipulated in the National Environmental Protection Act). Cumulative effects can be considered as resulting from: (1) effects of multiple actions through time at a site, and (2) downstream, off-site effects of multiple activities at one or more sites within a drainage basin or airshed. This second case—cumulative watershed effects—is most fruitfully examined in the context of landscape ecology.

A decade ago, when water quality was the major concern in watershed management in the United States, the pivotal issue in forestry was *how* to manage individual patches of land to meet water-quality objectives. New issues are now centered on the *where* and *when* aspects of management activities.

Many major issues in forest land management in the Pacific Northwest today concern landscape-scale problems, such as the effects of clear-cutting on floodplains, designing old-growth forest reserves to protect a rare owl and other old-growth-dependent species, the interaction between management-caused landslides and fish, and maintaining a management strategy in the face of disturbances by wind, fire, and other processes. Brief discussions of these issues pinpoint some applications of the perspectives of landscape ecology in forested mountain ecosystems.

Hydrology of Rain-on-Snow Systems

Warm, wet snow has a major role in the hydrology of the Cascade Range. Much of the Cascades is in a transient snow zone extending from 350 to 1200 m in elevation in Oregon. In this zone, snow accumulates and melts several times each year, mainly during rain-on-snow events when water stored in the warm, transient snowpacks melts during heavy rainfall (Harr, 1981). Precipitation at lower elevations falls mainly as rain, and a seasonal snowpack accumulates at higher elevations. The major floods in basins draining the Cascade Range have resulted from such rain-on-snow events, which are particularly important in the transient snow zone (Harr, 1981; Christner and Harr, 1982).

Harr (1981) argues, based on theoretical considerations, that changing forest structure in the snow zone by clear-cutting increases snow accumulation and also the rate of melt during rain-on-snow events. Warm snow falling in forested areas may catch in the canopy and melt during the snowfall, whereas in nearby clear-cut areas snow accumulates in a pack. During rainy periods, energy exchange between the air mass and snow surface is greatest in nonforested areas because of greater wind speed and turbulence. These relations were observed in field studies contrasting the snow hydrology of adjacent forest and clear-cut patches in the transient snow zone (Berris and Harr, 1987). Runoff records from small experimental watersheds suggest that the size of flows caused by rain-on-snow events is increased by clear-cutting (Harr, 1986). Furthermore, Christner and Harr (1982) observed increases in size of peak streamflow in fourth- and fifth-order basins; they interpret these increases to be the result of the hydrologic effects of clear-cutting in the transient snow zone.

The observations suggest that the timing and location of clear-cut areas in drainage basins within the transient snow zone can affect peak streamflow at downstream points. A high rate of cutting in the transient snow zone could have a major, near-term impact on size of peak flows. These impacts might be minimized by distributing cutting units across a range of elevations.

Landslides and Fish

The practice of forestry in unstable, landslide-prone areas is a major challenge in landscape management in the Pacific Northwest. Landslides are common in forested areas, and their occurrence may be increased by clear-cutting and road construction. Landslides may cause direct and indirect impacts on fish and their habitat many kilometers away from the site of landslide initiation. Therefore, forestry–landslide–fish interactions must be examined in a landscape context.

This can be approached by zoning landscapes in terms of the natural frequency of slides and the magnitude of increased incidence of sliding in response to clear-cutting and road construction (Swanson and Dyrness, 1975). Slope steepness, soil properties, and slope form, as they affect the concentration of water at slide-prone sites, are principal variables in evaluating hillslope stability. Clear-cutting is believed to increase sliding primarily by causing a period of reduced root strength after logging (Ziemer, 1981). The main effect of roads on slope stability is the alteration of surface and subsurface hydrology. In most areas of the Pacific Northwest, road rights-of-way have a substantially higher frequency of landslides than do clear-cut or forested areas (Swanson et al., 1987).

An important consideration in managing landslides is the geographic and temporal distribution of activities that reduce slope stability. Good management in the near term ideally would minimize landslides associated with clear-cutting and roads. This could be accomplished by first cutting land with low susceptibility to sliding; however, this strategy leaves the most unstable land until late in the cutting cycle, when practically all cutting and road construction would be on unstable land. From this perspective, good land management distributes cutting and road construction in the most slide-prone lands through time, which means cutting some unstable sites every decade, even though a recognized high probability of sliding exists. Another alternative is to cut no forest at all in the most unstable areas; this is the practice in parts of the Oregon Coast Range where landslide incidence and fisheries values are particularly high.

Many of the effects of landslides on fish habitat are obvious and adverse; however, some effects of landslides may be beneficial. The evaluation of landslide effects must be done at a landscape scale and with the recognition that fish in the Pacific Northwest have evolved in an environment with frequent and diverse disturbances. Scientists and managers face a tough challenge in distinguishing effects of human actions from those of natural events.

The negative effects from management-induced landslides on habitat of anadromous fish are a major land use issue (Kessel, 1985). Slides from roads and freshly clear-cut slopes enter streams, commonly forming debris flows that move rapidly down channels. Debris flows, typically containing several thousand cubic meters of soil, alluvium, and organic matter, affect fish habitat by altering channel structure, damaging riparian vegetation, and blocking fish passage.

Assessing the effects of landslides on fish habitat involves: (1) the distribution of slide-prone areas in a drainage basin, (2) the probable travel path of debris flows through the stream network, (3) the geomorphic effect of debris-flow deposits at the terminal deposition site, and (4) the response of fish to altered habitat along the path of the slide and at the site of final deposition. Slide-prone areas can be identified by topographical criteria: steep, concave slopes have high susceptibility to sliding. Slides from these sites can enter channels and flow downstream as debris flows, entraining additional soil, vegetation, and alluvium along the flow path. Debris flows tend to stop where the channel gradient decreases to about 4 to 6 degrees and at abrupt changes in channel direction (Benda, 1985). These two conditions are commonly met at the junction of small (first- to third-order) and large (third- to fifth-order) streams. The effects of debris-flow deposits on fish habitat in the receiving stream depend on the relation of volume of debris-flow material to the size of the channel. Small streams may be blocked by deposits; large streams may wash the debris-flow material downstream. Intermediate-size streams may be partially blocked by the debris-flow deposit and a pool may form, benefiting fish habitat in basins where fish production is limited by the quantity and quality of pool habitat. In the 52-km^2 Knowles Creek basin in the Oregon Coast Range, for example, two pools representing just 0.5 percent of the available habitat provided overwintering habitat for over 40 percent of the coho salmon *(Oncorhynchus kisutch)* smolts in one winter (Rodgers, 1986).

This type of analysis of slide potential, debris-flow-runout characteristics, and fish habitat for a drainage basin has led to landscape-scale zoning of basins (Swanson et al., 1987). Such a landscape/drainage basin perspective is essential in planning cost-effective efforts to mitigate management-induced slides. These management activities represent one form of synthesis of the spatial patterns of processes that propagate cause-effect relationships across landscapes.

Forest-Cutting Patterns

The creation of new forest patchworks in the natural landscapes of the western United States is a major management issue. Cutting patterns are creating new, managed mosaics that contrast markedly with the natural forest patterns in types and sizes of patches. In managed landscapes, a strong tendency exists for uniformity in patch sizes and homogeneity of structure within forest patches. The patch patterns created during the first cycle of forest cutting will have long-term consequences because they will be perpetuated through subsequent rotations.

Landscape issues that are consequences of specific forest-cutting patterns are increasingly being recognized. The issues include how cutting patterns affect susceptibility of forests to damaging agents (e.g., wildfire, wind, and pests and pathogens), overall ecological diversity, production of game and other wildlife species, fish production, water yields, flood levels and frequencies, and sediment yields. All are related to the rate and arrangement of forest cutting.

A theoretical analysis was done of the effects of the dispersed patch system of clear-cutting that is widely used in northwestern North America (Franklin and Forman, 1987). In the dispersed-patch system, 10- to 20-ha patches are interspersed with areas of uncut forest and older harvest units (Figure 2). The objective is to delay cutting adjacent forest patches for as long as possible. Forest regeneration, residue disposal, and development of road systems were considerations in the selection of this system (Smith, 1985).

The dispersed-patch-cut model results in some distinctive geometric patterns when the model is systematically applied to a forested grid (Franklin and Forman, 1987). Rapid changes in the average size of remnant forest patches occur between the 30- and 50-percent cutover points, as the forest matrix becomes increasingly fragmented by continued cutting (Figure 8). After the

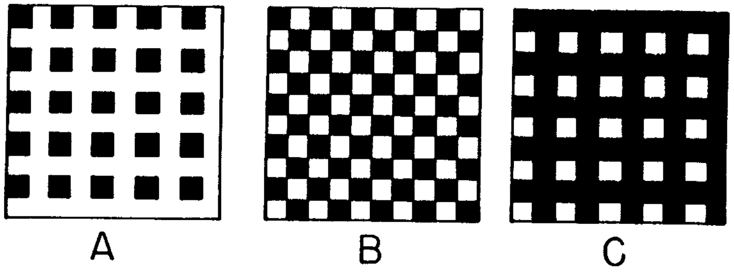


Figure 8. Progression of clear-cutting in a grid pattern using the dispersed-patch model, in which areas are selected for cutting so as to be regularly distributed through the landscape. Shading indicates the (A) 25 percent, (B) 50 percent, and (C) 75 percent cutover points.

50-percent cutover point, all remaining forested patches are the size of the grid segments (10 ha in the hypothetical model). This may effectively eliminate forest interior environments in these tall forests, where edge effects penetrate substantial distances, perhaps two to three tree heights, into a stand. The amount of edge or forest-cutover ecotone is maximized in this system as compared with most other standard cutting patterns.

The dispersed-patch-cut system affects many ecological characteristics of the landscape, such as species diversity, game populations, and abundance of species requiring interior forest conditions (Franklin and Forman, 1987). For example, consider some effects of developing a landscape dominated by the old-growth forests (generally conifer-dominated stands more than 200 years old) that were widespread in the region a few decades ago. When cutting begins, an initial loss of species is predicted because of fragmentation of an old-growth forest and the resulting loss of large blocks of interior forest environment and the species dependent on such blocks, such as the northern spotted owl *(Strix occidentalis)*. A second episode of loss of animal species is predicted when the last patch of old-growth forest is cut. Old-growth-related species, such as some salamanders with very small home ranges, that could survive in a 10-ha forest patch but not in a young, managed forest will be lost. Dead-wood structures (i.e., standing dead trees and fallen logs) are keys to the survival of many species; the magnitude of total species loss will depend on whether such structures are maintained in the managed landscape.

The forest patterns created with a dispersed-patch-cut system contribute substantially to increased risk from damaging agents (Franklin and Forman, 1987). Windthrow potential increases dramatically in the partially cutover landscape because of high densities of forest edge and long wind fetches in cleared areas. The potential for ignition and spread of wildfire in residual forest patches also increases as dispersed patches are progressively cut. Responses of pests and pathogens are highly variable depending on the distribution and abundance of suitable forest patches (e.g., specific ages of forest) and the biology of the particular pest or pathogen (e.g., method and dispersal).

Indeed, patch-cut landscapes do demonstrate high susceptibility to disturbance by agents, such as wind and fire. In the 37,000-ha Bull Run River management unit in western Oregon, for example, 482 and 899 ha of old-growth forest blew down in 1973 and 1983 windstorms. In these blowdown events, 48 and 81 percent, respectively, were directly associated with clear-cuts and road clearings. Similarly, many of the larger wildfires in this and neighboring areas have been associated with escaped slash burns.

Managers can select their cutting methods to achieve specific landscape-spatial patterns and consequent ecological effects (Franklin and Forman, 1987). For example, progressive strip clear-cutting can be used to reduce the amount of edge and therefore the potential for catastrophic windthrow. Forest patch sizes can be altered to fit the needs of interior species. What is essential is that the long-term, landscape-scale consequences of specific cutting programs be considered when plans are developed.

Wildlife and Habitat Fragmentation

Production of wildlife has always tended to be a landscape issue because many wildlife species are wide ranging and make use of several habitats. Large ungulates and many top predators range over large areas of diverse vegetation and topography, and many game species make heavy use of edge or ecotonal habitats.

An emerging global concern is maintaining nongame wildlife species. In northwestern North America, the focus has been primarily on the wildlife species associated with specialized habitat, such as old-growth forest. Such concern is legally mandated in the United States by legislation such as the National Forest Management Act (on National Forest lands) and the Endangered Species Act (on all land).

The northern spotted owl is an outstanding example of the many species identified as old-growth related and requiring a landscape approach to habitat management. This species appears to be strongly dependent for its survival on the special conditions in old-growth forest patches of 400 to 1200 ha per pair of owls, the area varying among physiographic provinces (Carrier, 1985; Forsman and Meslow, 1985). Some scientists believe the owl is potentially endangered by the reduction and fragmentation of this habitat (Gutierrez and Carey, 1985; National Audubon Society, 1986). Measures taken to preserve this bird have important ecological and economic consequences.

Maintaining viable populations of the northern spotted owl involves biological questions from the levels of the gene and population to the landscape (Marcot and Holthausen, 1987; Ruggerio et al., 1988). Critical landscape questions include the size of old-growth forest patch needed to maintain a pair of breeding birds, and the geographic arrangement of the patches across the bird's range. Island biogeographic concepts have been useful but do not address the central issues of spatial configuration in a changing mosaic. The viability of patches, especially their susceptibility to damage and to penetration of edge influences (e.g., microclimate effects), are also critical because the owl and other old-growth-related species are basically interior-forest species. Indeed, the interspersing of clear-cut patches within an old-growth forest matrix may alter habitat in favor of a competing owl species. Landscape issues in maintaining the northern spotted owl are complex and must go beyond most current thinking on habitat fragmentation.

Several management proposals have been developed; all involve some level of old-growth forest-patch preservation. One plan under consideration by Forest Service land managers would establish a network of 400- to 1200-ha old-growth patches (the size varying between physiographic provinces) where timber harvest is prohibited. These habitat patches would be arranged in a network with 10- to 20-km spacing.

Harris (1984) developed an innovative proposition for protecting old-growth forest patches, based partially on island biogeographic concepts. It involves identifying and protecting reserved old-growth islands that are surrounded by much larger buffer areas, and using riparian zones as corridors. The buffer areas would be managed on long cutting rotations (250 years) and cut in such a way that only a small segment of the edge of an old-growth island would be exposed to a clear-cut opening.

In summary, managing many animal species requires a landscape perspective. However, the science and application of landscape ecology are in early, exploratory stages.

Conclusions

To address critical ecological issues in forested mountain lands, it is essential to move from the traditional scales of research on forest plots and stands to mosaics, and from pools, riffles, and stream reaches to the drainage network. This is the perspective of landscape ecology. A further challenge is to integrate landscape-scale views of upland, riparian, and aquatic systems. In physically dynamic, forested, mountain land, the analysis of landscape ecology must be placed in the context of geomorphology. Geomorphic and nongeomorphic processes frequently change the landscape patchwork in upland and stream corridor environments. Landforms constrain the location and areal extent of disturbance and produce predictable spatial patterns in terrestrial, riparian, and aquatic systems. These considerations lead to many questions about the long-term development of landscapes in the face of change imposed by land management, acid deposition, climate change, and other factors.

Steep, forested landscapes present many opportunites to further the science and application of landscape ecology. Major issues in forest management are increasingly centered on landscape-scale problems—the cumulative effects of landscape modification on watershed conditions and functions (e.g., hydrology and sediment production) and on wildlife and stream habitat. These legislatively mandated concerns of forest managers are pushing land management to become landscape management.

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