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Geomorphology and Ecosystems

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INTRODUCTION

Natural ecosystems develop through the interplay of physical and biological factors. Biological factors have traditionally been emphasized because most ecologists have life science backgrounds. The purpose of this paper is to explore the significance of earth science perspectives in understanding ecosystems. Particularly in mountain landscapes and along streams and rivers, geomorphic processes and landforms have important roles in the development and geographic distribution of plant and animal communities. Geomorphologists and ecologists working in these dynamic landscapes have long relied on insights from each other's discipline to interpret causes and patterns of ecologic and geomorphic change. The full richness of geomorphic-biologic interactions really emerges from programs of ecosystem analysis where earth and life scientists work closely together on common topics, sites, and time frames.

In the pre-twentieth century era of naturalists, the mixing of earth and life science perspectives was common. In this century, there has been parallelism and interchange in the evolution of general models in geomorphology, plant ecology, and animal ecology (Drury and Nisbet, 1971). William Morris Davis' cyclical model of long-term (10^7–10^8 years) landform development set the stage for the views of vegetation development put forth by Clements (1936) and Braun (1950). The interpreted vegetation and landforms as progressing together toward a common end point--the peneplain with deep mature soils and "climax" vegetation on a nearly level landscape.

Gilbert (1880), Gleason (1926), and Hack and Goodlett (1960) put forth alternative concepts of landform-vegetation relations based on dynamic short-term (immediate) interactions among vegetation, soils, water, and landforms in an open system and on a variety of time scales. Hack and Goodlett (1960) argue that the landscape and vegetation development models of Davis and Clements are incorrect in their application to the Appalachian Mountains where they were initially developed. A model involving steady state in an open system has greater explanative power and heuristic value in Hack and Goodlett's view. A system may be shifted from steady state by a variety of disturbances ranging from short-term events such as flash floods to long-term changes in climate or relief. Those components of the system, whose rate of response is fast relative to disturbance frequency, react to produce a new steady state.

This view of a dynamic landscape-ecosystem with the potential for biotic-geomorphic interaction over a broad range of time scales is the subject of this paper. First, I will discuss time scales of geomorphic and ecosystem variation and consider the importance of a broad time perspective in analyzing landscape and ecosystem development. From this perspective, I will briefly examine an array of interactions among fauna, flora, landforms, and geomorphic processes, concluding with a more detailed analysis of soil and sediment movement through forest watersheds and the role of vegetation in regulating material transfer and storage.

TEMPORAL PERSPECTIVES

How one perceives interactions between geomorphic and ecosystem factors depends not only on the particular landscape and ecosystem in question, but also on the time scale used for viewing the system. Types and intensities of interactions between plants and landforms, for example, on the long-time frame of landform development and biologic evolution contrast with the short-term interaction of daily operation of geomorphic processes and growth response of individual plants. Thus, in order to examine physical-biotic relationships in natural ecosystems, it is useful to recognize the full range of temporal scales of variation in both physical and biological parts of the system and then compare system behavior at appropriate time scales.

To help clarify this point, let us look at an example from the Douglas-fir/western hemlock forest ecosystem in the Cascade Mountains of Oregon (Table 1). This charting of temporal scales of landscape-ecosystem change is an outgrowth of the process of earth scientists and biologists learning to work together in an interdisciplinary research team, the Coniferous Forest Biome (CFB) of the U.S./International Biological Program. In early 1970, I began working with CFB as a geologist mapping bedrock in the H. J. Andrews Experimental Forest, a primary CFB study site. Although working side by side with terrestrial and aquatic ecologists, we had little in common, because our time frames were disjunct. I was mapping formations no younger than 3.5 million years old; the time period of major concern to the ecologists was the annual scale of nutrient budgets and physiological behavior of plants and animals. These differences in time perspective raised questions about the sorts of geomorphology-ecosystem interactions that occur over the full range of time scales from days to millions of years. Where is the common ground for interaction between geomorphologists and ecologists?

Major exogenous events affect ecosystems and landscapes over a broad range of frequencies of occurrence (Table 1). These events include climatic and geologic processes as well as major disturbances of vegetation such as fire for which ignition may be considered exogenous, but intensity and areal extent of burns may be controlled by endogenous vegetation and landscape factors. Some of these events are regular and cyclical in occurrence, while others are episodic and their frequency would be considered here in terms of average return period.

Geomorphic factors vary over this time scale, ranging from relatively frequent changes in rates of geomorphic processes to the long-term development of the physiographic province as a whole. Development of progressively larger landforms occurs on progressively longer time scales. Geomorphic response to the most frequent exogenous events listed does not lead to development of landforms attributable to an individual event. At intermediate time scales, landforms of intermediate spatial scale, such as terraces, fans, and moraines, form in response to exogenous events. On still longer time frames, landform elements of greater geographic extent develop as the sum of all higher frequency geomorphic responses to exogenous events.

Vegetation also responds in various ways across this broad time range. Individual plants have physiological response to daily and seasonal fluctuation of moisture and temperature regimes. On the scale of centuries, vegetation (secondary) succession occurs following major ecosystem disturbances such as fire, landslides, and extensive blowdown events. Primary succession, shifts in the range of species and plant communities, and microevolution occur, in part, in response to and on the time scale of major climatic change. Most significant macroevolution takes place over still longer time periods.

To some extent, Table 1 is arranged in a hierarchical structure. Geomorphic and vegetative changes on each time scale involve response to exogenous events at that time scale as well as to the sum of all higher frequency variation in that system. For example, formation of terraces and alluvial fans may be facilitated by climate change and glaciation on the scale of 10^3 to 10^4 years, but the actual constructional processes occur as more frequent "base flow" erosion and pulses of accelerated sedimentation at the scales of decades and centuries.

One aspect of hierarchially organized systems is that system behaviors are "nearly decomposable," such that system behavior at one level or frequency may be isolated from scales of variation of higher and lower frequencies (Simon, 1973; Monk et al., 1977). Many studies of natural systems focus on one organizational level, assuming that lower frequency variations of the system are so slow that they can be considered constant and higher frequency behaviors are so rapid "that only their steady state properties appear in the system description" (Monk et al., 1977). However, CFB research in natural systems has revealed many problems with this common assumption. A notable example arose when aquatic ecologists began to compile an annual carbon budget for a small stream ecosystem. After sampling two successive years and finding two very different budgets, they quickly realized that the annual scale of behavior of this system depended strongly on streamflow characteristics for the sample period. Inputs exceeded output by about 40% in a dry year, but were nearly balanced in the wetter year, although no major peak flows occurred (Triska et al., in press).

Table 1. Geomorphic and vegetative variation and exogenous events affecting ecosystems and landscapes on an array of time scales (example from Douglas-fir/western hemlock forests in Cascade Mountains, Oregon)

Event frequency (yrs)	Exogenous events	Geomorphic variation	Vegetation variation
10^{-2} to 10^{-1}	Precipitation-discharge event	"Base-flow" erosion by noncatastrophic processes	Physiologic response of individual plants
10^0 to 10^1	Annual water budget, moderate storms		
10^2	Extreme storms, major disturbances of vegetation (e.g., fire)	Periods of accelerated erosion--slide scars, channel changes, etc.	Secondary succession
10^3 to 10^4	Climate change, glaciation	Intermediate-scale landforms; terraces, fans, moraines, etc.	
10^6	Episodes of volcanism	Gross morphology of major drainage and constructional (volcanic) landforms	Primary succession, migration, microevolution
10^7 to 10^8	- - - - - - - - -	Development of physiographic province as a whole	Macroevolution

Furthermore, the system had a good memory for detrital input and channel flushing events in earlier years. It is necessary to place annual budgets in the context of broader temporal variability of the system (the 10^2 yr scale of Table 1).

Geomorphology-ecosystem interactions are most dramatic on intermediate time scales--decades and centuries (Table 1). On longer and especially shorter time frames, geomorphic setting is commonly viewed as a passive, invariant stage on which evolution and plant physiologic behavior take place. But on the intermediate scale of secondary succession, change in plant community composition, vigor, and structure can profoundly affect rates of geomorphic processes. Geomorphic events may, in turn, set the stage for succession by creating fresh substrates and may determine to some extent the rate and type of plant community development that follows a major ecosystem disturbance.

The detailed character of geomorphology-ecosystem interactions vary from one landscape-ecosystem type to another. This interaction is particularly dynamic in the coniferous forest ecosystems of the steep Cascade terrain, where vegetation is important in regulating soil and sediment movement down slopes and streams. Historically, these forests and landscapes experienced widespread wildfire, floods, landslides, and windstorms, which caused profound fluctuations in sedimentation. Today, the major process of stand and landscape disturbance is clearcut logging and associated road construction and slash disposal.

Over the course of CFB and subsequent research projects, earth scientists and biologists in our group have developed a common focus on questions at the intermediate time scale of system behavior such as ecosystem response to disturbances like logging, wildfire, and geomorphic events. The overriding concern is to understand how nature has "managed" forests, streams, and landscapes on a variety of time scales to set a basis for evaluating and directing man's management programs.

GEOMORPHIC-BIOTIC INTERACTIONS

Interactions between physical and biological realms of ecosystems offer many unexplored but interesting and fruitful research topics that tend to fall between disciplines (Fig. 1). Much of geomorphology concerns the long-term effects of geomorphic processes in sculpting landforms and the ways that landforms determine spatial distribution of geomorphic processes in the short term. Many studies in geo-

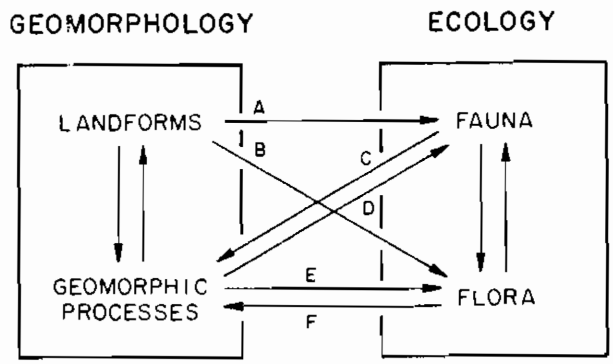

Figure 1. Relationships among landforms, geomorphic processes, fauna, and flora. A. Define habitat, range. Effects through flora. B. Define habitat. Determine disturbance potential by fire, wind. C. Affect soil movement by surface and mass erosion. Affect fluvial processes by damming, trampling. D. Sedimentation processes affect aquatic organisms. Effects through flora. E. Destroy vegetation. Disrupt growth by tipping, splitting, stoning. Create new sites for establishment and distinctive habitats. Transfer nutrients. F. Regulate soil and sediment transfer and storage.

morphology benefit from biological information derived by methods such as dendrochronology that have been exploited to only a limited extent. Fields of ecology center on relations between fauna and flora, including herbivore, habitat structuring, and the like. Ecologists have a long tradition of using information on the physical environment to interpret biological factors, but there are still many instances where ecological understanding would be enhanced by improved appreciation for the role of physical factors in ecosystems.

Linkages among geomorphic processes, landforms, fauna, and flora are manifold. Figure 1 shows interactions of major importance in forest and stream ecosystems in geomorphically active landscapes. Many of the following examples of these interactions have emerged as a result of interdisciplinary ecosystem research. We begin with landform effects on flora and fauna, then move to flora and fauna interactions with geomorphic processes, ending with regulation of geomorphic processes by vegetation, the latter probably having greatest significance to land managers.

Effects of Landforms on Flora

On the time scale of secondary succession and related major disturbances of vegetation, landforms are relatively invariant templates on which mosaics of vegetation develop. Actual patterns of vegetation types and age classes over landscapes are determined by the interplay of landforms and flora. Effects of landforms on vegetation development at a site are generally mediated by microclimatic, edaphic, and hydrologic factors. Elevation slope, and aspect, for example, are elements of landform whose main effects on vegetation are through microclimate. Slope steepness, the product of long-term landform development, influences erosion potential of soil and soil texture and nutrient capital. Narrower ridge tops and steeper slopes generally experience greater soil turnover and nutrient depletion by physical processes than more gentle topography. These effects can often be recognized in chlorotic condition of young conifer stands on these physiograph sites. Both slope steepness and soil texture determine drainage characteristics of a soil.

Soil properties are profoundly influenced by geologic factors, mainly bedrock type, and geomorphic factors that control accumulation, redistribution, and mixing of soil. In the Pacific Northwest, volcanic ash falling from the sky is an important, widespread type of soil parent material that can blanket diverse landscapes from distant sources. More typical depositional soils (alluvial, colluvial, and aeolian) commonly form the deepest, most fertile soils.

Landforms also influence vegetation by affecting the potential for disturbance of vegetation at a site. This vegetation-physical process-landform set of relationships is obvious where recurrences of the physical process have shaped the landform as well as the vegetation community. An example is the role played by floodwater in inundation and sediment deposition, which form floodplain features and associated vegetation patterns. Both the magnitude of flood impact on channel form and time for recovery of channel form depend strongly on the character of streamside vegetation (Wolman and Gerson, 1978).

Landforms play a more subtle role in determining vegetation conditions where the vegetation disturbance mechanisms are wind and fire rather than geomorphic processes. Slope position and valley configuration are important variables affecting windthrow potential of a site (Ruth and Yoder, 1953). Topography can channel and funnel winds and create intense turbulence on the lee side of ridges. Since windthrow potential is a function of tree size and shape and stand structure, topography and wind may conspire at some sites to repeatedly blow down stands as they reach a certain stage of development.

Frequency and intensity of fire at site is also regulated by landforms in several ways (Swanson, in press). In many landscapes and storm types, topography influences geographic distribution of lightning strikes. Once ignition has occurred, type and rate of fire spread are determined by fuel conditions, wind, and topography (Brown and Davis, 1973). Faster, more intense burning occurs on steeper slopes in response to convective winds and preheating of fuels uphill of a fire front. Steep, sunny slopes have dryer fuels than flatter slopes or slopes of other aspect. The role of topography in channeling winds also affects the geographic patterns of fire regime.

Landforms also influence fire pattern by creating natural firebreaks. Completely forested but sharp ridges may be effective firebreaks where upslope mountain winds prevent fire from moving down lee slopes. Lakes, streams, talus fields, snow avalanche, and landslide tracks form more conspicuous firebreaks. Effectiveness of these landscape elements as firebreaks depends on fire intensity and direction of fire spread relative to the "grain" of topography (Swanson, in press). Landforms are more effective as firebreaks during lower intensity fires burning perpendicular to drainage pattern or other potential firebreaks.

The net effects of landforms on soil formation, geomorphic processes, vegetation disturbance regime, and light, water, and nutrient availability at a site result in systematic variation in vegetation with respect to topographic position, slope, and aspect. These effects are most pronounced in steep terrain where topographic shading and ridgetop to channel soil moisture gradients are important. Resulting vegetation patterns include more mesic communities along streams, more xeric types on ridges, and greater extent of mesic types on slopes facing away from the afternoon sun. Hack and Goodlett (1960) interpret this pattern at a site in the central Appalachians principally in terms of variation in soil water-holding capability as determined by soil texture and soil-forming geomorphic processes. A similar vegetation pattern in the Cascade Range of Oregon has been interpreted more in terms of microclimate and topographic shading (Hawk, 1979).

Effects of Landforms on Fauna

Landforms affect fauna by determining the geographic distribution of habitats and by forming special habitats. The major influence of landform on fauna is a result of landform effects on vegetation patterns, since vegetation structure and distribution determine habitat and range for most forest-dwelling animals. Many examples come to mind, especially with respect to migratory large mammals whose annual ranges cover diverse vegetation types. Distribution of this vegetation, associated snow conditions, and other habitat factors are commonly strongly influenced by landforms. Floodplains and valley bottom vegetation, for example, provide winter range, connectors between diverse terrestrial habitat types, and corridors for migration (Thomas et al., 1979). Vegetation analysis of the type done by Whittaker (1956) in the Smokies and elsewhere illustrate strongly the multiple effects of landform on community pattern.

In a more special sense, distinctive landforms provide special habitat opportunities, termed "geomorphic habitats" by Maser and others (in press). Caves, talus, and cliff faces may be utilized by animals of a great variety of sizes and habits depending on size, stability, and accessibility of nesting, denning, perching, and other types of sites (Maser et al., 1979). In the Basin and Range physiographic province cliffs and associated talus slopes formed along river canyons, glaciated valley walls, and fault scarps support rich fauna in terrain with little other large-scale habitat density. The character of these geomorphic habitats is determined in part by rock type, overall topography, and mode of origin. Type of bedrock influences the size of talus blocks shed from a cliff and shape and size of cavities in cliffs. Cliff height, shape, and aspect affect localized wind currents and utilization by birds, particularly raptors (Craighead and Craighead, 1969). Canyon walls cut by rivers provide less talus and more cliff types of habitats, because the river carries away many of the talus blocks. Proportion of talus to cliff habitat is higher on fault scarps and walls of U-shaped glaciated valleys where talus accumulates for long periods of time.

These examples of rather obvious influences of landforms on flora and fauna suggest an infinite complex of more subtle physical-biological interactions running through all large-scale natural ecosystems. At successional and higher frequency time scales most landforms can be viewed as the stage or template on which geomorphic-biologic process interactions occur.

Effects of Fauna on Geomorphic Processes

Animal activities increase the rate of geomorphic processes by directly moving soil or by altering soil properties, hydrology, or vegetation with the result of accelerating subsequent erosion at a site. Soil that is moved by burrowing animals ranging in size from earthworms to small mammals can be a significant component of soil creep (Carson and Kirkby, 1972). Excavation of burrows usually involves downslope soil movement, as does subsequent burrow collapse and erosion of bare soil on burrow mounds (Imeson, 1976; Imeson and Kwaad, 1976). Charles Darwin (1881) observed in detail downslope movement of earthworm castings during dry, rainy, and windy periods and attempted to quantify the role of earthworms in overall landscape denudation. Few studies since have carefully documented rates of soil movement by animals, but qualitative observations are common. Evidence of downslope soil movement by large mammals, particularly elk, is conspicuous where population densities are high. Grazing livestock accelerates erosion especially where stock concentrate in streams and riparian zones, trampling banks and stirring up sediment. Fluvial geomorphic processes are also affected by dam construction, harvest of riparian vegetation, and bank burrowing by beaver.

Many impacts of animals on geomorphic processes are the result of indirect effects of altered vegetation, soil properties, and hydrology. Reduced litter due to browsing and increased compaction as a result of trampling can cause accelerated surface erosion, but these effects are not likely to occur in forest ecosystems where grazing intensities are low. Other subtle effects of animal activity may occur. Pierson (197?) suggested that mountain beaver (Aplodontia rufa) burrows in areas of the Oregon Coast Ranges may pipe water rapidly into mass movement prone areas, thereby increasing the potential for soil mantle failure. Kelsey (1978) and others have discussed the possibility that introduction with livestock of short-rooted, annual grasses to prairies and oak savanna, earthflow areas of northwestern California may have led to accelerated earthflow movement since the late 1880's. They hypothesize that earthflow activity was less when native deep-rooted, perennial species provided greater evapotranspiration and root strength.

Although these examples are of a very anecdotal nature, collectively they indicate that effects of fauna on geomorphic processes are probably significant in many forest ecosystems.

Effects of Geomorphic Processes on Fauna

Most effects of geomorphic processes on fauna occur indirectly as a result of influences of geomorphic processes on flora and landforms, discussed in other sections. Direct effects in terrestrial environments are minimized in part by the mobility of animals. In stream ecosystems, on the other hand, sedimentation processes can have immediate and direct impacts on aquatic organisms. Microenvironments within a stream reach are shaped by the interplay of hydraulic processes, sediment characteristics, organic debris, and bedrock. Resulting channel geometry at the scales of gravel fabric, pool-riffle sequences, and downstream decreases in gradient provide a great variety of microhabitats. The many species and functional groups (Cummins, 1974) of aquatic organism are precisely distributed over this physically defined array of microhabitats (Hynes, 1970).

Stream water velocity, for example, is a critical factor in determining distribution of organisms (Hynes, 1970). Leaf and needle processing organisms such as caddis flies reside in the relatively quiet water of eddies behind boulders and logs and in pools where organic detritus collects. Many collector organisms (Cummins, 1974) build their tiny nets on stable substrates like large pieces of wood or in interstices between rocks where the current carries sufficient organic detritus to support the organisms, but does not flow at such high velocity that it destroys the nets.

Increased sediment availability, transport, and deposition causes a variety of disruptions of aquatic organisms in these habitats. A thin film of clay and silt-sized sediment deposited over organic detritus can render this food and case-building material unusable by clogging mouths and gills of shredder organisms. The nets of organisms collecting fine organic detritus from the water column may become filled with inorganic sediment. Accumulation of fine sediment in interstitial areas of spawning sites restricts flow of oxygenated water to eggs and decreases the opportunity for alevins to move through the gravel to open stream water once they have hatched.

Extremely high streamflow events can reshape stream channels and change the distribution of aquatic microhabitats. Major abrupt geomorphic disruptions commonly have a surprisingly small, short-lived impact on aquatic organisms (Hoopes, 1974). Organisms survive major floods by finding protected sites in gravel, behind logs, amongst roots and flooded vegetation, and in the lower portions of low gradient tributary streams. Many insects have life cycles with terrestrial phases during periods of high potential for major flooding. Streams are rapidly recolonized following a major flood by organisms from these terrestrial and aquatic refugia.

Thus, the mobility of animals is a cause of weaker linkage between geomorphic processes and fauna than between geomorphic processes and flora, the latter being very important.

Effects of Geomorphic Processes on Flora

Geomorphic processes affect vegetation in all stages of development. In the context of succession on bare mineral soil, geomorphic processes may initially "filter" the species of plants established on a site. Surface erosion processes may move seeds of some species off the site, while species with other seed characteristics or reproductive strategies may become established. Established seedlings may be lifted out of the soil by frost heaving and growth of needle ice. Geomorphic processes disrupt growth of established trees by tipping, splitting, and moving soil and stones against them. Disrupted growth of trees that form regular annual rings commonly provides excellent records of geomorphic activity at a site (e.g., Potter, 1969; Schroder, 1978; Carrara, 1979).

These disturbances to individual plants alter overall stand composition and structure. On an earthflow in a coniferous forest (Swanson and Swanston, 1977), for example, areas of open ground cracks indicative of differential ground movement have complex stands with numerous holes in the canopy where many of the heavily leaning trees have been blown down. Opening of the canopy has resulted in extensive development of understory vegetation and a multilayered forest. Adjacent stands not subject to recent earth movement have complete, single-level canopies and no significant understory due to heavy shading.

Geomorphic processes such as streambank cutting and landslides completely remove vegetation, but in the process create fresh sites for establishment of new plant communities. Less destructive events such as overbank deposition of fine sediment may suppress herbs for a period of time, but also allow establishment of species which root on disturbed bare mineral soil. Geomorphic disturbances can selectively affect specific components of a plant community like other disturbance processes such as fire and harvest.

At the whole ecosystem level physical processes have important roles in nutrient cycling regimes. This is most clearly recognized in the case of stream eocsystems where the biota resides in flowing water--the principal sediment transport medium. The analogous transience and mobility of the physical environment of terrestrial ecosystems are not so easily recognized because soil movement is accomplished by a mix of slow and episodic processes. But on a broad time perspective and in steep terrain the soil mantle and its accompanying terrestrial ecosystem are moving inexorably downslope. Consequently, nutrient capital of a site reflects the long-term balance of nutrient input and output processes. Physical transport of nutrients in steep terrain is an important factor in nutrient cycling and may limit accumulation of nutrients in an ecosystem (Sollins et al., in press).

The importance of geomorphic processes as nutrient transfer vectors needs further consideration in analysis and comparison of nutrient cycling regimes of diverse ecosystems. Nutrient cycling studies typically assess storage sites and transfers for only a few years or less. Such studies run the risk of failing to account for episodic events with return periods of many years, but which accomplish in a few minutes or days the results of many "average" years (Swanson et al., in press). Debris avalanches and windthrow are two potentially dominant processes that are readily overlooked in short-term studies.

Effects of Flora on Geomorphic Processes

Vegetation regulates the movement and temporary storage of soil and sediment on hillslopes and in small to intermediate-sized streams. To appreciate the importance and variety of vegetation effects it is useful to first describe a soil/sediment routing system typical of forested mountainous terrain (Fig. 2). This model is simplified from systems defined by Dietrich and Dunne (1978) and Swanson and others (in press).

Soil moves down hillslopes by a variety of mass movement and surface erosion processes. Once in the channel, this material, now termed sediment, is moved downstream by another set of transfer processes. A single particle of material moves through a watershed from one temporary storage site to another in a series of steps by different transfer processes, and it may move by several processes simultaneously.

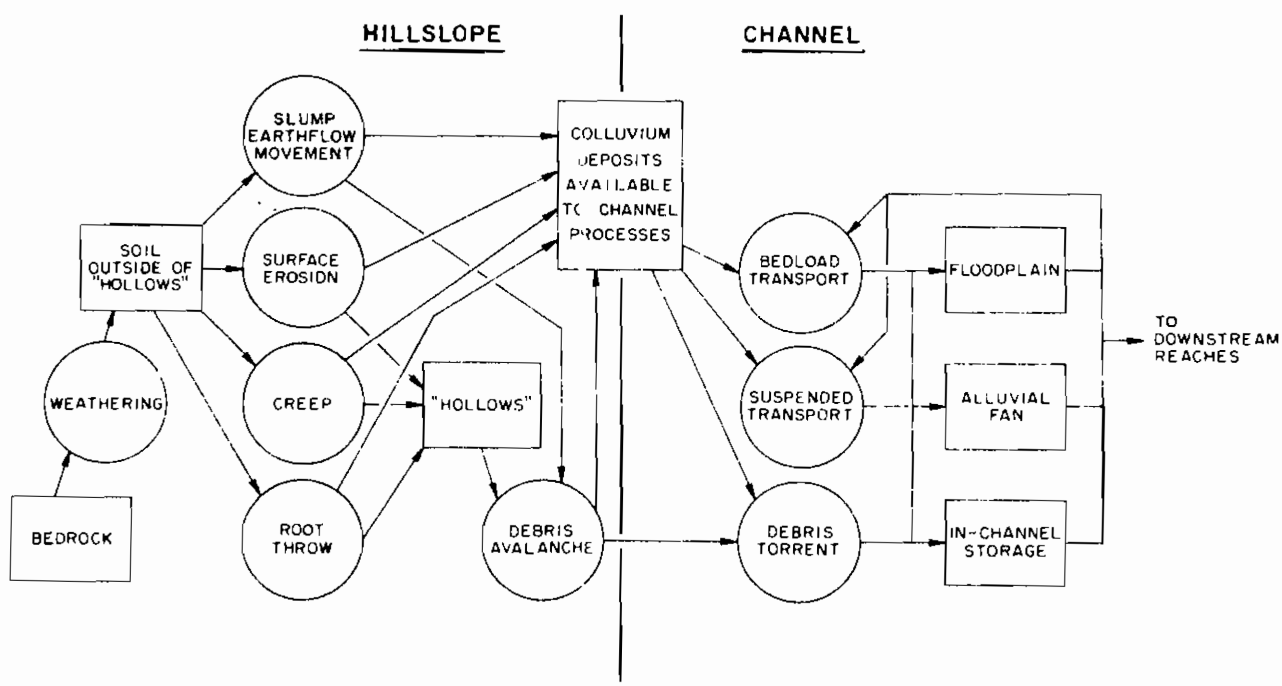

Figure 2. A model of soil and sediment movement through steep, forested watersheds. Transfer processes are circled. Storage areas are denoted by rectangles.

The soil mantle, for example, has several components subject to different sets of processes. All the soil surface is susceptible to surface erosion processes, and the entire soil mantle moves by the subtle group of processes termed "creep," including rheological soil deformation and root throw. Portions of a landscape subject to slump and earthflow movement also experience creep and surface erosion. These processes move soil directly to streams, where it may reside temporarily in deposits of colluvium until it is eroded during high streamflow events. Surface erosion, root throw, and creep also move soil into "hollows," linear depressions in the bedrock surface oriented downslope (Dietrich and Dunne, 1978). Periodically during conditions of extremely high soil moisture, soil stored in hollows fails and moves rapidly downslope as debris avalanches. Debris avalanches that enter small steep channels may maintain their momentum and continue to move rapidly downstream, picking up alluvium, colluvium, and organic material along the way.

Bedload and suspended sediment transport processes move particulate matter through channels. Sediment is stored in floodplains, alluvial fans, and a variety of in-channel sites, including point bars and deposits associated with large organic debris, such as logjams. Storage behind large organic debris is most important in headwater channels, whereas floodplain and non-debris-related storage sites are progressively more significant in larger channels (Swanson and Lienkaemper, 1978).

Forest vegetation strongly influences nearly all elements of the soil/sediment routing system on slopes and in small streams (Swanson et al., in press). Organic litter protects the soil surface by dissipating the energy of throughfall and raindrops and increasing the infiltration rate, thus decreasing the potential for overland flow. Evapotranspiration functions of vegetation reduce soil moisture which may significantly affect seasonal rates of creep and slump-earthflow movement (Gray, 1970). At many sites root throw associated with blowdown of trees is the major mechanism of soil movement. Roots increase soil strength, thereby decreasing the potential for shallow rapid soil mass movements (Swanston, 1969, 1970; O'Loughlin, 1974). Root systems contribute up to 40% of soil shear strength in some key landslide-prone areas (Dietrich and Dunne, 1978). Removal of material in solution in ground and stream waters is regulated in part by rate of nutrient uptake by vegetation (Likens et al., 1977). Sediment storage capacity of small channels is greatly influenced by the presence of large organic debris.

As a result of these and other effects of vegetation on geomorphic processes, sediment yield from small steep watersheds typically increases dramatically, but temporarily, following severe disturbance of vegetation by processes such as wildfire and clearcutting. Accelerated sedimentation commonly results more from increased availability of sediment for transport than from increased availability of water to transport sediment. Clearcut logging, for example, can trigger increased sediment yield by (1) input of soil and organic detritus to channels during timber felling, bucking, and yarding operations, (2) release of sediment stored in channels by removing large organic debris that trapped sediment prior to logging, and (3) reduction of ground cover, nutrient uptake, evapotranspiration, and root strength, all of which accelerate soil erosion following logging.

Erosion rates from disturbed sites recover to pre-disturbance levels partly as a result of revegetation and re-establishment of the various controls of vegetation on geomorphic processes. Because each erosion process is regulated by a different set of vegetation factors, recovery rates differ from process to process (Swanson et al., in press). On many sites, for example, invading herbs and residual vegetation rapidly reduce nutrient losses in solution, but redevelopment of a substantial network of woody roots may take a decade or more.

Consequently, erosion, sediment yield, and soil/sediment routing in steep forest land must be viewed in terms of succession and stand history, since the relative importance and absolute rates of geomorphic processes vary significantly on this time scale. In evaluating the geomorphic effects of man's activities in forest ecosystems, it is essential to contrast the frequency and erosion consequences of major vegetation disturbances in natural and managed systems.

SUMMARY AND CONCLUSIONS

Geomorphic factors, both processes and landforms, play important active and passive roles in forest ecosystems. Many influences of geomorphic processes and landforms on vegetation are mediated by physical, nutritional, and hydrologic properties of soils. Landforms principally determine the geographic distributions of fauna and flora. Landform effects on terrestrial fauna are mainly the result of landform-flora interactions. Geomorphic processes and flora interact strongly in steep terrain and along streams and rivers.

Live and dead vegetation regulates rates of geomorphic processes, which, in turn, destroy vegetation, create new opportunities for establishment, and influence the development of plant communities.

In considering the evolution of concepts of ecosystem development, a major contribution of geomorphology has been to provide time limits and temporal perspectives on ecosystem change. Clearly, forest ecosystem development on many time scales involves the interplay of physical and biological factors, particularly in mountainous regions. The physical sciences should be well represented in any major ecosystem study.

LITERATURE CITED

Braun, E. L. 1950. Deciduous Forests of Eastern North America. Philadelphia, Pa.: Blackiston.

Brown, A. A., and K. P. Davis. 1973. Forest Fire Control and Use, 2nd ed. New York: McGraw-Hill Co.

Carrara, P. E. 1979. The determination of snow avalanche frequency through tree-ring analysis and historical records at Ophir, Colorado. Geol. Soc. Amer. Bull., Pt. 1, 90:773-780.

Carson, M. A., and M. J. Kirkby. 1972. Hillsope Form and Process. London: Cmabridge University Press.

Clements, F. E. 1936. Nature and structure of the climax. J. Ecol. 24:252-284.

Craighead, J. J., and F. C. Craighead. 1969. Hawks, Owls, and Wildlife. New York: Dover Publ., Inc.

Cummins, K. W. 1974. Structure and function of stream ecosystems. BioScience 24:631-641.

Darwin, Charles. 1881. The formation of vegetable mould through the action of worms with observations on their habits, reprint (1945). London: Faber and Faber, Ltd.

Dietrich, W. E., and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. Zeit. für Geomorphol. Suppl. Bd. 29:191-206.

Drury, W. H., and I. C. T. Nisbet. 1971. Inter-relations between developmental models in geomorphology, plant ecology, and animal ecology. In Yearbook, Soc. Gen. Syst. Res., edited by L. von Bertalannfy and A. Rapoport, pp. 57-68.

Gilbert, G. K. 1880 (2nd ed.) Report on the geology of the Henry Mountains, U.S. Dept. Interior, Geographical and Geological Survey of the Rocky Mountain Region. Washington, D.C.: U.S. Govt. Printing Office.

Gleason, H. A. 1926. The individualistic concept of the plant association. Bull. Torrey Bot. Club 53:7-26.

Gray, D. H. 1970. Effects of forest clear-cutting on the stability of natural slopes. Bull. Assoc. Eng. Geol. 7: 45-66.

Hack, J. T., and J. C. Goodlett. 1960. Geomorphology and forest ecology of a mountain region in the central Appalachians. U.S. Geol. Surv. Prof. Paper 347.

Hawk, G. M. 1979. Vegetation mapping and community description of a small western Cascade watershed. Northwest Sci. 53:200-212.

Hoopes, L. 1974. Flooding as a result of hurricane Agnes and its effect on a macroinvertebrate community in an infertile headwater stream in central Pennsylvania. Limnol. Oceanogr. 19: 853-857.

Hynes, H. B. N. 1970. The Ecology of Running Waters. Ontario: University of Toronto Press.

Imeson, A. C. 1976. Some effects of burrowing animals on slope processes in the Luxemborg Ardennes, Part 1: The excavation of animal mounds in experimental plots. Geografiska Ann. 58A:115-125.

Imeson, A. C., and F. J. P. M. Kwaad. 1976. Some effects of burrowing animals on slope processes in the Luxembourg Ardennes, Part 2: The erosion of animal mounds by splash under forest. Geografiska Ann. 58A:317-328.

Kelsey, H. M. 1978. Earthflows in Franciscan melange, Van Duzen River basin, California. Geology 6:361-364.

Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton, and N. M. Johnson. 1977. Biogeochemistry of a Forested Ecosystem. New York: Springer-Verlag.

Maser, C., J. M. Geist, D. M. Concannon, R. Anderson, and B. Lovell. Geomorphic and edaphic habitats in managed rangelands--their importance to wildlife. In Wildlife Habitats in Managed Rangelands--The Great Basin of Southeastern Oregon, edited by J. W. Thomas and C. Maser. USDA Forest Service (in press).

Maser, C., J. E. Rodick, and J. W. Thomas. 1979. Cliffs, talus, and caves. In Wildlife Habitats in Managed Forests--the Blue Mountains of Oregon and Washington, edited by J. W. Thomas, pp. 96-103. USDA Handbook 533.

Monk, C. D., D. A. Crossley, Jr., R. L. Todd, W. T. Swank, J. B. Waide, and J. R. Webster. 1977. An overview of nutrient cycling research at Coweeta Hydrologic Laboratory. In Watershed Research in Eastern North America, edited by D. L. Correll, pp. 35-50. Washington, D. C.: Smithsonian Institution.

O'Loughlin, C. L. 1974. A study of tree root strength deterioration following clearfelling. Can. J. Forest Res. 4:107-113.

Pierson, T. C. 1977. Factors containing debris flow initiation on forested hillslopes in the Oregon Coast Range. Ph.D. thesis, University of Washington, Seattle.

Potter, N., Jr. 1969. Tree-ring dating of snow avalanche tracks and the geomorphic activity of avalanches, northern Absaroka Mountains, Wyoming. In United States Contributions to Quaternary Research, edited by S. A. Schumm and W. C. Bradley, pp. 141-165. Geol. Soc. Amer. Spec. Paper 123.

Ruth, R. H., and R. A. Yoder. 1953. Reducing wind damage in the forests of the Oregon Coast Range. USDA Forest Service Paper No. 7. Pacific Northwest Forest and Range Expt. Sta., Portland, Oregon.

Schroder, J. F. 1978. Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. Quat. Res. 9: 168-185.

Simon, H. A. 1973. The organization of complex systems. In Hierarchy Theory, edited by H. D. Pattee, pp. 3-27. New York: George Braziller.

Sollins, P., C. C. Grier, F. M. McCorison, K. Cromack, Jr., R. Fogel, and R. L. Fredriksen. The internal element cycles of an old-growth Douglas-fir stand in western Oregon. Ecol. Monogr. (in press).

Swanson, F. J. Fire and geomorphic processes. In Fire Regime and Ecosystem Properties, edited by H. A. Mooney, T. M. Bonnicksen, N. L. Christensen, J. E. Lotan, and W. A. Reiners. USDA Forest Service Gen. Tech. Rep. (in press).

Swanson, F. J., R. L. Fredriksen, and F. M. McCorison. Material transfer in a western Oregon forest ecosystem. In The Natural Behavior and Response to Stress of Western Coniferous Forests, edited by R. L. Edmonds. Stroudsburg, Pa.: Dowden, Hutchinson, and Ross, Inc.

Swanson, F. J., and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA Forest Service Gen. Tech. Rep. PNW-69.

Swanson, F. J., and D. N. Swanston. 1977. Complex mass-movement terrains in the western Cascade Range, Oregon. Geol. Soc. Amer. Rev. Engineering Geol., Vol. 3, pp. 113-124.

Swanston, D. N. 1969. Mass wasting in coastal Alaska. USDA Forest Service Res. Paper PNW-83. Pacific Northwest Forest and Range Expt. Sta., Portland, Oregon.

Swanston, D. N. 1970. Mechanics of debris avalanching in shallow till soils of southeast Alaska. USDA Forest Service Res. Paper PNW-103. Pacific Northwest Forest and Range Expt. Sta., Portland, Oregon.

Thomas, J. W., C. Maser, and J. E. Rodick. 1979. Riparian zones. In Wildlife Habitats in Managed Forests--the Blue Mountains of Oregon and Washington, edited by J. W. Thomas, pp. 40-47. USDA Handbook 533.

Triska, F. J., J. R. Sedell, and S. V. Gregory. Coniferous forest streams. In The Natural Behavior and Response to Stress of Western Coniferous Forests, edited by R. L. Edmonds. Stroudsburg, Pa.: Dowden, Hutchinson, and Ross, Inc. (in press).

Whittaker, R. H. 1956. Vegetation of the Great Smoky Mountains. Ecol. Monogr. 26:1-80.

Wolman, M. G., and R. Gerson. 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes 3:189-208.