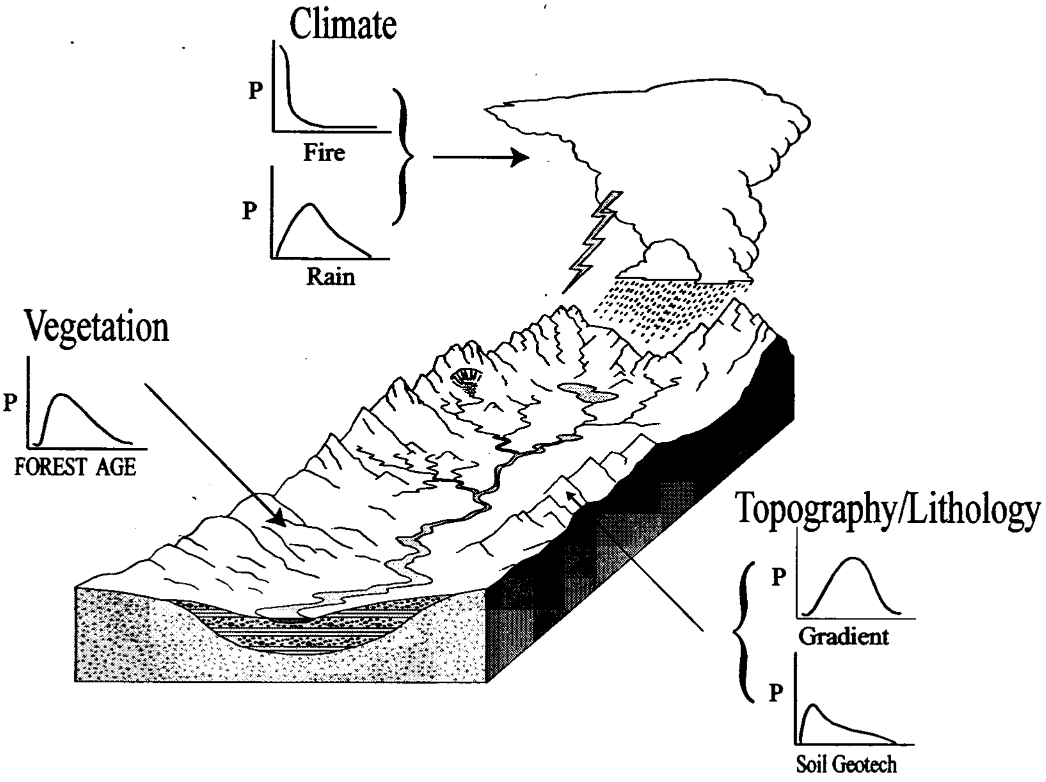
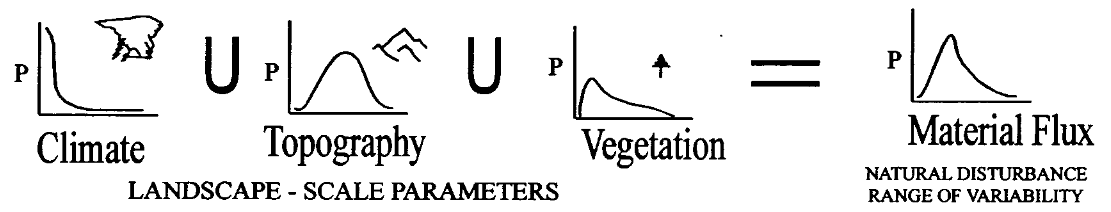
GENERAL LANDSCAPE THEORY OF ORGANIZED COMPLEXITY





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INTRODUCTION

Formation of aquatic and riparian habitats depends on the supply of inorganic and organic materials that originate from terrestrial sources. Complex interactions among large numbers of climatic, geomorphic, hydrologic, and vegetative processes govern the transfer of material to riverine environments. A stochastic climate exerts a degree of randomness in the supply of sediment and organic debris to channel networks; topography and channel-network geometry imposes a spatially determined organization in the routing and storage of those materials. Hence, aquatic and riparian habitats have both stochastic and deterministic origins. Studies that have incorporated stochastic effects have been referred to as 'disturbance ecology' (Pickett and White, 1985; Reeves et al., 1995), temporal hierarchies (Frissel et al., 1986), 'pulses' (Junk et al., 1989), and 'landscape dynamics' (Benda et al., 1998). Studies focusing on deterministic aspects are described in terms of 'continuums' (Vannote et al., 1985), spatial hierarchies (Frissel et al., 1986), 'ecotones' (Naiman et al., 1988), and classification systems (Rosgen, 1995; Montgomery and Buffington, 1997). Despite a sustained interest in ecological processes over a range of scales (Swanson et al., 1988; Naiman and Bilby, 1998), it has proven difficult to develop general principles on how deterministic and stochastic landscapes factors, in combination, govern ecosystems.

One consequence of the absence of general theoretical principles is the continuing inability to define natural disturbance regimes, including the range of variability in aquatic and riparian environments (Naiman et al., 1992 Benda et al., 1998). This problem has created a dependence on provincial case studies that have often focused on unique attributes of landscapes rather than on general principles (Benda, 1999). Moreover, the absence of parameters and theory at large scales discourages hypothesis testing and commensurable research (similar things measured in similar ways), and potentially increases the difficulty of landscape-scale and environmental problems.

Development of theoretical principles applicable at large dimensional scales is required for the orderly and progressive study of landscapes. This applies to research in the vegetative, geomorphic, hydrologic, and biotic sciences, in natural resource management, and in restoration and conservation biology. Our objective is to identify how universal attributes of landscapes, including climate, topography, lithology, vegetation, channel geometry, and spatial scale (drainage area) impose overarching constraints on the probability distributions and spatial patterns of fluxes of sediment and organic debris from terrestrial through aquatic environments. Landscape theory requires landscape-scale parameters in the form of temporal distributions of climatic, hydrologic, and geomorphic processes, and spatial distributions that characterize the attributes of large numbers of landscape elements (Benda et al., 1998; Dunne, 1998). Probability or frequency distributions, by definition, define the frequency and magnitude components of natural disturbance regimes in aquatic and riparian environments. Moreover, they offer an alternative approach to the study of landscape processes at smaller scales.

The general form of the theory is initially outlined in the form of conceptual figures to simplify its presentation to a diverse and interdisciplinary readership. Specific quantitative applications are presented at the end of the paper. We begin by reviewing how previous scientific efforts have tackled the study of systems comprised of large numbers of elements that have both deterministic and stochastic properties.

THE STUDY OF LARGE NUMBERS OF INTERACTING LANDSCAPE PROCESSES OVER TIME

The spatial scale that defines a 'landscape' depends on the questions that are posed. Questions involving aquatic and riparian ecology often range in scale from less than a hectare to watersheds of 10^4 km^2 and larger. Similarly, the time scale dictated by ecological questions often depends on how vegetation affects erosion, sediment transport, supply of organic debris, and channel form (Swanson et al., 1988). Vegetation death and growth typically span several decades to a few centuries (Spies et al., 1988; Agee, 1993), a time scale that also reflects the occurrence of large storms and floods that cause erosion and episodically transport sediment (Reid and Dunne, 1996). In addition, landslides occur with frequencies ranging from a few years to a few centuries (Benda and Dunne, 1997a). Hence, case studies of landscape processes are hindered by large temporal scales (i.e., uncertainties in basin history) and by large spatial scales (i.e., incomplete information on all the spatial attributes of watersheds).

Clues for developing inductive and deductive theories at large scales are found in the disciplines that have tackled problems involving large numbers of elements. One proven strategy is to represent interactions of many small-scale processes by larger-scale parameters. Application of analytical mechanics to landslide prediction, for example, views soil as a 'continuum', even though soil is composed of many individual grains. Continuum mechanics represents the multitude of millimeter-scale, grain-to-grain interactions into meter-scale parameters such as soil cohesion, bulk density, and soil friction angle. [A similar approach has been applied to problems involving turbulent fluid flow (e.g., fluid mechanics)]. Analytical mechanics is most effective when dealing with problems at relatively small spatial and temporal scales and it runs into difficulty when applied at larger scales. For example, calculating the behavior of thousands of meter-scale unit volumes of soil during rainstorms over centuries would tax even the fastest computers. The use of a one-dimensional, infinite slope model is an example of simplifying the interactions of multiple three-dimensional unit volumes of soil involved with landsliding.

Statistical mechanics provides another technique for predicting the behavior of exceedingly large numbers of randomly behaving elements using parameters. A purely statistical approach can describe the behavior of gases that contain vast numbers of randomly colliding molecules (Maxwell (1831-1879) and Boltzmann (1844-1906)). To calculate the macro energy state of a gas in response to applied energy fields, molecules are parameterized by probability distributions of energy states. The energy states of gases are measured in terms of the parameters of temperature, pressure, etc. Regarding landscape behavior, however, there are large differences between the statistical mechanical approach that depends on concepts of energy equilibrium and average conditions, and the non-equilibrium and transient conditions manifest in hydrologic and geomorphic processes that are of interest to scientists and resource managers (Dooge, 1986).

In the context of these approaches, landscapes contain too many components to be treated strictly deterministically and too few to be treated purely statistically. Environmental systems that fall between the end members of determinism and stochastism, but that exhibit both characteristics have been referred to as 'intermediate number systems', or systems of 'organized complexity' (Weinberg, 1975). This characterization has also been extended to ecological and geomorphological systems (Allen and Starr, 1982; Graf, 1988). To deal with systems of organized complexity, systems theory has been developed (Von Bertalanffy, 1968). Application of systems theory relies on building comprehensive computational models to scale up analytical descriptions of processes at small-scales to predict the macro behavior of a system of such processes over larger space and time scales. This so-called 'upwards approach' has been applied to the study of certain hydrological problems (Smith and Bretherton, 1972; Rodriguez-Iturbe and Valdes, 1979; Roth et al., 1989). Because of the large number of interactions involved, some simplification in mathematical representation of process is usually necessary. In addition, parameters must be developed to represent the system behavior of the many small-scale processes that occur in landscapes.

GENERAL LANDSCAPE THEORY OF ORGANIZED COMPLEXITY

Landscapes: Random and Organized Behavior

Landscapes contain both random and deterministic elements over a range of spatial and temporal scales that have made them both difficult and interesting to study. The concept of ‘organized complexity’ (sensu Weinberg, 1975) is proposed here as a framework for unifying the study of stochastic and deterministic attributes of landscapes, in particular the flux and routing of sediment and organic debris in terrestrial and aquatic environments. Randomness refers to behavior that is not predictable in detail but can be described in probabilistic terms. For example, the fundamentally stochastic nature of climate yields a strong random component to the timing and magnitude in the flux of sediment and organic material from hillslope to channels (Benda et al., 1998). Organization refers to spatial regularities or patterns in a landscape that don't vary over the time scale of interest (i.e., 10^2 years) and that are responsible for time-invariant patterns in the long-term routing and storage of materials in channels and valley floors. Spatial organization refers to laws of stream ordering and bifurcation (Horton, 1945; Strahler, 1952) and to systematic variations in network geometry, such as decreasing channel gradient and increasing channel width with increasing drainage area (Leopold et al., 1964). Topography, including channel networks, however, are typically characterized by spatial irregularities, including abrupt changes in channel gradients and drainage areas at tributary confluences and spatial variability in gradients and valley width due to mass wasting and other geological controls. A general landscape theory must address all large scale spatial and temporal patterns in a landscape.

The concept of organized complexity proposed for the development of landscape theory is commensurable with the science of complex and adaptive systems where problems at large scales have recently been tackled in a number of disciplines (Kellert, 1993; Waldrop, 1992; McIntrye, 1998). Descriptions of large-scale patterns of behavior, even in the absence of a mechanistic understanding for all of the observed processes, is a hallmark of the study of systems exhibiting both stochastic and deterministic behavior (Gell-Mann, 1994). The study of complex systems has highlighted a form of knowledge that is characterized by. (1) Contextual relationships between large-scale properties of systems and long-term patterns of behavior. (2) Descriptions of processes and interactions by temporal and spatial frequency distributions. (3) Statistical or descriptive understanding of processes with intractable physics. This form of knowledge characterizes the general landscape theory of organized complexity presented below.

Parameterizing Landscape Behavior

Landscape theory requires landscape-scale parameters. Landscape attributes, such as forests, erosion sources, and channel segments, reflect the interactions of numerous abiotic and biotic factors over time. Hence, populations of landscape attributes must be represented in the form of spatial distributions of landscape elements. Time must be represented in the form of temporal distributions of climatic, hydrologic, and geomorphic processes (Benda and Dunne, 1997a,b; Dunne, 1998). Hence, the flux and storage of sediment and wood, and associated channel and valley morphologies, also must be expressed in the form of distributions (Benda et al., 1998).

Describing and predicting habitat formation at smaller scales has proven to be difficult because of the inherent complexity and variability of natural systems. Use of distribution-based parameters that describe the flux rate of mass from terrestrial through fluvial environments offers an alternative to analyses at smaller scales. Distribution parameters, by definition, define the frequency and magnitude characteristics of natural disturbance regimes and the range of variability. They also provide information on the frequency and magnitude of riparian and aquatic habitat formation. General forms of distributions can often be inferred based on first principles about climate and topography. Detailed representations of distributions, however, will likely require extensive field surveys in combination with computational modeling (Benda and Dunne, 1997a,b). Both approaches are illustrated in this paper.

Different types of probability distributions represent different relationships between event magnitude and frequency, hence they are useful measures for considering the role that different processes play in generating variability and landforms (Figure 1). For example, an exponential distribution is characterized by a high probability of low magnitude processes that may have little morphological effect, and a low probability of high magnitude events that have large morphological effects with long legacies (Benda and Dunne, 1997b). The degree of skewness of a distribution represents the larger magnitude fluxes of sediment that are responsible for fan and terrace formation. More symmetrical distributions, in contrast, are characterized by more frequent occurrences of intermediate to low magnitude processes (Figure 1).

Theory Postulates

The general form of the landscape theory of organized complexity is based on three postulates:

(1) Differences among mixtures of climate, topography, lithology, and vegetation will result in differences in forest cover and erosion processes, and therefore, in the frequency, magnitude, and spatial distribution of sediment supply to channel networks. The supply of sediment to a channel network is partly non-uniform and non-steady because of spatial heterogeneity of topography and the stochastic nature of the climate. Differences in erosion regimes and sediment flux to channels can be expressed by the changing shapes of probability distributions. Similarly, wood supply to streams is episodic and will vary systematically with changes in forest ages (i.e., climate as represented in fire and wind frequency etc.), vegetation type (age, species, density), topography (i.e., erosion process), and rates of mortality, growth, and decay. Long-term patterns of wood flux can also be expressed in the form of probability distributions.

(2) Pulses of sediment and wood enter a hierarchical and convergent network and they combine with materials from other sources at tributary junctions. Spatial and temporal heterogeneity of erosion will result in an evolution of the long-term distributions of sediment flux and storage downstream in a network, a process reflecting the central limit theorem. Distributions of sediment are also transformed during routing because of particle attrition and storage in channels, fans, and terraces. Tributary confluences represent abrupt transitions of different probability distributions of material fluxes.

(3) The morphology of channels and valley floors reflects both stochastic and spatially deterministic origins that can be expressed in the form of a probability distribution. Distribution

shape indicates both the mean morphological state and its variance. Forms of the probability distributions of channel and valley floor morphological states will depend on climate, topography, lithology, vegetation, and position in the network (e.g., postulates #1 and #2). The distribution parameter, by definition reflects the natural disturbance regime and the range of variability.

The general form of the landscape theory of organized complexity is presented below in five parts. (i) Dynamic vegetation; (ii) Erosion and sediment supply;
(iii) Changing downstream variability in sediment supply and storage; (iv) Dynamics of woody debris; and (v) Stochastic and spatially organized channel and valley floor morphological states. The general form of the theory outlined below specifies the overarching constraints that physiographic attributes impose on the general shapes of probability distributions of material fluxes. More detailed predictions of those interactions are described through numerical analysis presented later in the paper. Although in-stream hydrology is not formally incorporated into the theory at the present time, the importance of natural flow regimes on ecosystems have been pointed out elsewhere (Poff et al., 1997) and could be added at a later date.

A Dynamic Climate and Vegetative Cover

Climate interacting with topography and other physical and biological factors dictate the species composition, density, and age distribution of vegetation in landscapes. Vegetative cover in any physiographic region varies systematically with latitude and elevation because of climatic and topographic gradients. In addition, the age distribution of vegetation varies stochastically over time because of fire and wind disturbances (Van Wagner, 1978; Agee, 1993). Hence, vegetation has both random and spatially organized components.

Coniferous forests in the Pacific Northwest are used in the present discussion. Wildfires with recurrence intervals over the last millennium of between one and four centuries (Agee, 1993) created a mosaic of forest ages that varied with time and location. Fires create a long-term probability distribution of vegetation ages that are positively right skewed and exponentially shaped (Van Wagner, 1978; Reed, 1994). The right skewness of the age distribution (Figure 2) arises because of a decreasing probability of developing very old vegetation in conjunction with an approximately equal susceptibility of fires across all age classes. This forces the highest proportion of vegetation to occur in the youngest age class and a gradual and systematic decline in area with incrasing age. In an exponential distribution of forest ages, the mean is equivalent to the mean fire cycle or recurrence interval (Johnson and Van Wagner, 1984).

Topographic effects on fire regimes include more frequent fires on south-facing hillslopes and ridges and lower fire frequency on larger valley floors (Morrison and Swanson, 1990; Benda et al., 1998, Figure 11.5). Hence, probability distributions should vary with topographic position, although the positive skewness would be similar across all locations (Figure 2). Theories of fire disturbance and associated stochastic models have been outlined by Van Wagner (1978), Johnson and Van Wagner (1984), and by Reed (1994). Spatial distributions of forest age in a landscape will vary year to year depending on the history of fires and other stand-replacing disturbances (Spies et al., 1988; Teensma, 1987; Morrison and Swanson, 1990).

Dynamics of Erosion and Sediment Supply to Channels and Valley Floors

Erosion is a product of a suite of landscape factors. These include interactions among fire, rain, and wind, topography, lithology, and vegetation. Long-term patterns of storms and fires in a landscape can be represented in the form probability distributions (Figure 3). Additionally, spatial patterns of topographic, soil, and vegetative attributes of a watershed can also be expressed in the form of distributions. Interactions between the long-term patterns of climate and topographic attributes of a watershed will yield a time series of erosional events that are expressed in the form of a probability distribution (Figure 3). Some of the pertinent distribution functions may cross correlate, such as fire and rain because of large-scale interactions that may be known or unknown (i.e., regional climatic patterns). Other factors may be independent of one another, such as slope gradient and fire, particularly over century-long time scales.

Probability distribution of erosion and sediment supply should vary across landscapes with different combinations of climate, topography, and vegetation (Dunne, 1998). Distributions for three idealized erosion regimes are illustrated below. The first one covers landscapes where periodic intense fires and rainstorms trigger spatially concentrated erosion. Intense erosion often depends on a threshold being exceeded, such as in rainfall-triggered landsliding (Caine, 1990), or in sheetwash and gullying that is dependent on soil hydrophobicity (Heede, 1988). In North America, concentrated erosion of these types has been documented in the southern coastal chaparral (Rice, 1973), Cascade humid mountains (Swanson et al., 1982), Pacific coastal rainforests (Hogan et al., 1995; Benda et al., 1998), Appalachian Mountains (Hack and Goodlett, 1960), and in the intermountain and highland arid regions (Meyer et al., 1995; Wohl and Pearthree, 1991; Robichaud and Brown, 1999). Intense erosion is often associated with a convergence of low probability climatic events, such as a fire followed by a large rainstorm (Klock and Helvey, 1976). Moreover, landslide and gully erosion often depends on soil availability that is governed by time since the last major erosion event (Dunne, 1991). Lag times in soil availability decrease the frequency of concentrated erosion (Benda, 1994).

In environments with episodic and concentrated erosion, soil flux is usually depressed during inter-mass wasting periods (i.e., erosion dominated by soil creep and bank sloughing). Extended periods of low erosion rates punctuated by high magnitude releases of sediment can be expressed by a strongly right-skewed or even exponential probability distribution, at the scale of a single hillslope or small basin (Benda and Dunne, 1997a) (Figure 4). Moreover, punctuated erosion would also lead to positively skewed distributions of sediment storage on hillslopes, characterized by sharply bounded patterns of soil depths that would reflect historical patterns of fire and storm induced erosion. The degree of skewness of sediment flux will depend on unique mixtures of climate, topography, lithology, and vegetation. Positively skewed distributions of erosion or sediment supply may typify many montane drainage basins that are characterized by threshold erosion processes (Benda and Dunne, 1997a). A pattern of relatively long periods of low sediment supply interrupted by episodic and short periods of high supply also has a corollary in sedimentology, referred to as “punctuated aggradation cycle” (Goodwin and Anderson, 1980). Episodic sedimentation in the depositional record has also been described as “long periods of boredom and brief periods of terror” by Ager (1980). An example of how field measurements in combination with simulation modeling are used to refine estimates of probability distributions of erosion is presented later.

In landscapes with more gentle topography, bank sloughing may dominate the erosion regime. Bank erosion depends on erodibility of banks and flood frequency and magnitude. Erodibility of stream banks depends on particle size of the bank material and reinforcement by roots (Hooke, 1980). Bank erosion is typically greatest in actively migrating portions of channel networks and least in upper portions of networks where banks may be comprised of bedrock, or boulders and cobbles. Under this condition, the magnitude of bank erosion should be approximately proportional to flood magnitude, assuming unlimited sediment availability. In areas of spatially uniform bank sloughing, the probability distribution of erosion should mimic the probability distribution of floods, even if bank erosion rates increase downstream. Since stream flows often follow a log normal distribution, the distribution of sediment fluxes to streams by bank erosion should be more symmetric, reflecting more frequent but smaller to moderate sediment releases (Figure 4). Moreover, a landscape dominated by bank erosion should have different spatial distributions of slope gradients, reliefs, and soil properties compared to a landscape dominated by mass wasting.

Very large and very infrequent landslides characterize the third idealized erosion regime. Very large landslides, either generated by rainfall, earthquakes, or volcanism are common in certain lithologies, including in marine sedimentary and volcaniclastic rocks (Sidle et al., 1985). In such environments, the probability distribution of erosion may contain several modes to account for the rare occurrence of slides of increasing magnitude (Figure 4). A complete distribution of landslide sizes ranging from very small to very large may occur in some landscapes with slide magnitude negatively correlated with frequency. A range of landslide sizes that can be scaled by a power law represents a form of self-organized criticality (Bak, 1996); such relationships have been detected in rockfalls and in landslides. In landscapes that have a full distribution of landslide sizes, the probability distribution of erosion will be characterized by a continuous extension of the right tail of the distribution.

Once soil is eroded from hillslopes it must enter streams and valley floors to have an effect on aquatic and riparian ecology. The degree of connectivity between hillslopes and the channel network will dictate the volumetric flux rate of sediment to channels. A high sediment delivery ratio (volume delivered to channels/total eroded volume), typical of steep terrain with narrow valley floors, will result in a sediment supply distribution (at fan margins) that mimics the erosion distribution (Figure 5). In landscapes with wide valley floors, in contrast, much of the sediment will be stored in fans and along toes of hillslopes. The stored sediment will be eventually remobilized by bank erosion, yielding a more symmetric distribution of lower magnitude fluxes (Figure 5).

Probability distributions of erosion or sediment supply can be viewed at any spatial scale. In the previous discussion, erosion and sediment supply to channels pertained to individual hillslopes or small basins. If topography and climate remain homogenous at larger watershed scales, then the distribution of total erosion or sediment influx will simply shift towards the right wall into higher volumes while retaining the overall distribution shape. However, in landscapes with topographic and climatic heterogeneity, a combination of erosion processes will yield a derivative distribution of sediment supply, different than the idealized ones depicted in Figure 4.

Dynamics of Fluvial Sediment Transport and Storage

Soil that enters stream channels by various erosion sources consists of a mixture of grain sizes ranging from clay to boulders. Upon entering channels these grains are sorted by the flow such that finer particles (less than fine sand) are washed downstream and quickly exit the watershed. This material is referred to as wash-load, and it effects water turbidity and related aspects of habitat conditions, but it is not well represented in the sediment of the channel bed and bars. In contrast, coarser material settles to the channel bed and travels intermittently downstream as bed load during high flows. A portion of bed material is reduced in size and is converted to fine material through abrasion during transport. Between periods of transport, bed material is stored in the channel bed, bars, and in the floodplain. It is the bed material that is shaped by flood flows, together with obstructions such as fans, boulders, and woody debris, which create channel habitats. Thus, the amount of bed material available in a reach of valley floor, and the rate at which it is flushed downstream, are important controls on the amount, nature and rate of change of channel habitat.

The volume and caliber of sediment stored in a channel segment reflect the supply of sediment that enters it from upstream and which enters along channel banks and intersecting tributaries. The discussion that follows pertains to bedload-size material only, although similar principles can be applied to suspendible load (Benda, 1994). Over long time periods, the probability distributions of sediment flux and storage in channels reflect the probability distribution of supply acted upon by the probability distribution of sediment transport capacities. Sediment transport is a function of sediment size, channel geometry (gradient and width), and flood regimes (Parker et al., 1989). Channels also alter their slope and width in response to changing sediment supply (Gilbert, 1917). Since variation in sediment supply is an intrinsic property of most landscapes, sediment transport will vary over many time scales. In many mountain drainage basins, however, channel gradients and transport capacities are sufficiently high to transport available sediment without long-term aggradation (Reneau and Dietrich, 1991). Under that condition, the distribution of sediment transport should approximately mimic the long-term in-channel distribution of supply at any point in the network. Obstructions, such as fans, boulders, and large organic debris, can locally alter transport capacities resulting in short-term aggradation, a process discussed later.

Channel networks, over long time periods, obtain sediment from the probability distributions of sediment supply from individual hillslopes and tributary basins. The number of hillslope and channel sediment source areas and their probability of releasing stored sediment increase incrementally downstream, with larger increases occurring abruptly at tributary confluences (Benda and Dunne, 1997a). Releases of sediment in a basin may be synchronous and correlated in time, such as may occur with bank erosion during floods. Such correlated erosion is more likely to occur in smaller watersheds where storm size is typically equal to or greater than basin size. In landscapes with correlated erosion, the long-term probability distribution of sediment flux and storage at any point a channel network should approximate the hillslope distribution of sediment supply (Figures 3 and 4).

Erosion may also occur asynchronously or be uncorrelated in time. In the case of bank erosion, if the characteristic storm size is significantly smaller than the size of the basin, different sub watersheds may produce bank erosion at different times. Moreover, because of the dominance of mass wasting in many mountain drainage basins (Swanson et al., 1987), asynchronous erosion and hence sediment supply is likely a rule, rather than the exception in those terrains. Sampling from numerous independent and identically distributed random sediment supplies over sufficiently long time periods should yield a sum (of samples of flux and storage) with a distribution that approaches a normal shape, a consequence of the central limit theorem (Figure 6). Because storms or fires may trigger erosion over large areas, however, sediment supply from individual hillslopes or tributary basins is not likely to be truly identically and independently distributed. The distribution of sediment flux (or storage), however, should evolve from positively skewed (in environments with punctuated erosion) to more symmetrical forms downstream simply because sediment sources increase and they do not release sediment at the same time (Figure 6). The geometric pattern of a channel network (i.e., stream ordering and bifurcation ratio) should affect how a distribution evolves because it governs the rate at which sediment sources combine in a channel. Simulation modeling will illustrate the process of evolving distributions later in the paper.

The evolving shape of the probability distribution of in-channel sediment flux and storage reflects the frequency and magnitude of supply fluctuations and therefore provides clues to the nature of disturbance or variability in channels and riparian areas (Figure 1). Landscapes with a positively-skewed distribution of sediment supply in low-order portions of a network will be characterized by long periods of low variability interrupted by infrequent and large perturbations, typically of short duration (Benda and Dunne, 1997b). With increasing drainage area in terrains with a degree of asynchronous erosion, fluctuations will become more frequent but of a lower magnitude. At even larger drainage areas, sediment supply fluctuations may become damped due to mixing with large stores of sediment, attrition, and storage in floodplains (Benda and Dunne, 1997b). This implies that mid-portions of a network may have the highest probability of perturbations of a magnitude that can be readily detected by observers and that will likely have ecological significance.

Probability distributions of in-channel sediment will also reflect attrition, or the breakup of bedload into smaller particles during transport. Stronger lithologies (i.e., igneous or volcanic rocks) have lower attrition rates compared to weaker rocks (Benda, 1994). Hence, lithology affects the rate of change of bedload to suspended load and thereby influences the volume of gravelly bedload found at any point in a network (Figure 6). High rates of attrition will lead to lower volumes of bedload and therefore the probability distribution of storage will shift towards the left wall (Benda and Dunne, 1997b). As a result, the evolution of sediment supply and flux distributions to more symmetrical forms will be accompanied by a leftward shift of the distribution. In contrast, in landscapes with igneous or volcanic rocks, the distribution of supply and flux should shift towards the right wall into higher sediment volumes. The rightward shift may, in part, reflect the propagation (and survival) of sediment perturbations in the form of waves.

Channel systems are not a gradual continuum of gradients but are characterized by abrupt and transient discontinuities in gradients and widths. Dramatic reductions in gradients and hence transport capacities occur due to earthflows (Grant and Swanson, 1995), landslide and debris flow deposits (Benda, 1990), rockfalls, boulder accumulations (Wohl and Pearthree, 1991), and large woody debris jams (Keller and Swanson, 1977). Lower transport capacities upstream of such obstructions can lead to aggradation over years to decades. In channel segments with numerous and persistent obstructions and increased storage, the long-term probability distribution of sediment storage can shift towards the right wall (Figure 7). Moreover, the volume of storage should vary over time depending on the creation of obstructions and on sediment supply (Benda et al., 1998). Many obstructions also create sharply steepened gradients downstream that have exceptionally high transport capacities and chronically low sediment storage.

Tributary Junctions: Dynamics Governed by Mergers of Probability Distributions

A convergent and hierarchical channel network is characterized by abrupt mergers between different types of probability distributions of sediment supply and transport regimes at tributary junctions. Merger of two different probability distributions will be characterized by differences in the magnitude, frequency, and composition of sediment flux. These factors have the potential to affect the nature of the depositional landforms that form at junctions. The size of alluvial and debris flow fans reflect the magnitude of sediment supply from a source tributary and the ability of the receiving channel to erode it away (Ritter, 1996). Hence, in the context of the theory, more frequently occurring small fluxes of sediment represented by a log normal or normal distribution may be more easily eroded by the receiving channel leading to smaller fans. In contrast, large episodic influxes of sediment (indicative of exponential or positively-skewed distributions) may create larger fans with longer perimeters and higher relief that push the receiving channel further against the opposite valley wall (Figure 5-A). This may slow erosion of the fan by the receiving stream, although erosion would also be governed by valley width and the composition of the fan. Hence, the tail of the probability distribution of material fluxes may strongly influence fan formation in certain landscapes. In addition, larger influxes of sediment may also cause transient or permanent deposits to form in the receiving channel upstream and downstream of a fan. An in-channel sediment storage distribution that is shifted towards the right wall has the potential to bury fans.

Dynamics of Wood Supply and Storage

Woody debris in streams creates storage reservoirs for coarse sediment (Heede, 1972; Megahan and Nowlin, 1976) and for dissolved and particulate matter (Bilby, 1981). Logs also form pools (Swanson et al., 1976; Lilse and Kelsey, 1982) and create spawning areas (Keller and Tally, 1979). Variation in the amount and diversity of aquatic habitat should occur with certain types of disturbances that control wood abundance (Reeves et al., 1995). Hence, the general landscape theory of organized complexity addresses wood recruitment and storage in streams because of its importance to aquatic ecology.

Similar to sediment, the supply of wood to channels has both random and organized components. Wood recruitment is inherently stochastic due to fires, wind, floods, and landslides that recruit wood to streams (Keller and Swanson, 1977). Spatially organized components include stream-adjacent recruitment and an increasing channel size with drainage area that results in increasing bank erosion and wood transport. The general theory examines how climatic, topographic, and vegetative processes impose constraints on the general shapes of distributions on wood supply and storage.

Stand-replacing fires or windstorms govern the age and specie composition of forests in many landscapes. Fires, driven by droughts and lightning storms, lead to two distinct states of wood supply: a concentrated toppling of dead trees within a few decades, followed by gradual mortality as a forest stand ages over decades to centuries. Infrequent toppling of trees during fires or hurricane-force windstorms insures that the probability distribution of wood flux will be positively skewed. The degree of skewness will depend on the frequency and magnitude of episodic tree death. Because above ground woody biomass generally increases over time (Spies et al., 1988), longer inter-arrival times of fire or wind will lead to larger punctuated releases of wood. Hence, disturbances that occur more infrequently will result in a higher degree of right skew (Benda and Sias, 1998) (Figure 8). Conversely, the probability distribution of flux will shift left due to an increase in perturbation frequency (leading to lower biomass levels). The volumetric importance of episodic disturbances on the long-term wood mass balance will increase with increasing frequency of fires or wind (Figure 8).

Bank erosion is another effective wood recruitment agent because trees that are undercut tend to fall towards the channel (Murphy and Koski, 1989). Because rates of bank erosion generally increase downstream in a drainage basin (Hooke, 1980), the amount of woody debris recruited from bank erosion should increase systematically downstream. The frequency of floods capable of causing bank erosion is higher than the frequency of stand-replacing fires and wind. This will result in variation of the probability distribution of wood recruitment downstream to more symmetrical forms as the proportion of wood recruitment by bank erosion increases (Figure 8). The tail of the distribution, governed by large-scale episodic disturbances, should diminish in importance downstream because of increasing bank erosion (Figure 8).

Mass wasting constitutes another disturbance that recruits trees to streams in mountain environments. Landslides and debris flows that scour standing trees and the accumulated dead wood along hillslopes or in small channels (i.e., as debris flows) have the potential to be the highest point loading of wood to aquatic environments. Therefore, in mass wasting environments, the far right tail of the distribution of wood loading will be governed by the frequency and spatial distribution of landsliding (Benda and Sias, 1998) (Figure 8). Low frequencies of landslides and debris flows estimated in some field studies (order of centuries; Swanson et al., 1982; Benda and Dunne, 1997a) combined with annual decay rates of 1.5 to 6% (Spies et al., 1988), will tend to limit the long-term contribution of wood recruitment by of mass wasting. However, mass wasting can dominate wood loading where there exists a high spatial density of erosion sources areas or where landslide frequency is high (McGarry, 1995; Miller and Benda, 1999). The long-term, landscape-wide contribution of wood from mass wasting will depend on the spatial density of sites, process frequency, and wood decay rates.

Floods often redistribute pieces of wood that fall into streams. Fluvial transport of wood becomes increasingly important in larger channels where piece length is less than channel width (Nakamura and Swanson, 1993). If the wood piece size distribution remains similar throughout a channel network and channel width increases systematically downstream, there should by a systematic downstream increase in wood transport. This will impose patterns on wood storage including an increase in inter-jam spacing downstream and a corresponding increase in jam volume (Benda and Sias, 1998) (Figure 8). A specific quantitative application of wood theory to a humid temperate landscape is presented later in the paper.

Wood storage is dependent on wood recruitment minus wood loss through decay and abrasion. Decay is governed by temperature, humidity, precipitation, and the size and specie of woody debris (Means et al., 1985). Submergence of wood in streams or its burial in sediment can delay decomposition and reduce the rate of wood loss. Increasing decay rates will shift the distribution to the left wall while decreasing decay will have the opposite effect.

Stochastic and Spatially Organized Channel and Valley Morphology

Stochastic and deterministic landscape processes, in combination, govern the storage of sediment and wood and, hence, channel and valley morphology. Predictable, deterministic patterns of sediment storage include increasing volumes downstream and sediment stored behind local obstructions (Figure 9). Positively skewed distributions of hillslope supply and therefore supply-limited conditions should characterize steep (approximately greater than 4%), low-order channels in mountain environments. Boulder-floored or bedrock channels are indicative of low supply environments (Benda, 1990). Sediment supply typically increases downstream in conjunction with decreases in transport capacity. In channels of moderate gradient (1-4%), increasing stores of alluvium promote a morphology that varies from cascade and step pool, to pool – riffle, depending on sediment supply (Montgomery and Buffington, 1997; Benda et al., 1998). In very low-gradient reaches (<1%), large sediment stores are typified by meandering or braiding channels (Schumm, 1977; Morisawa, 1968).

Unpredictable, stochastic effects include transient increases in sediment supply due to punctuated erosion processes. In steeper reaches with higher transport velocities, pulses of sediment will be short lived and a supply-limited, coarse substrate or bedrock morphology should dominate (Benda and Dunne, 1997b). In reaches of moderate-gradient, accumulations of sediment from numerous sources can lead to the formation of sediment waves. Sediment waves can range between 10^2 - 10^3 m in length and 0.5 - 4 m in height (Griffiths, 1979; Pickup et al., 1983; Roberts and Church, 1986; Nakamura, 1986). A passage of a sediment wave can convert a step-pool or meandering channel to respectively a meandering or braided one (Miller and Benda, in press). In lower-gradient channels (<1%), sediment pulses may be damped because they mix with larger sediment stores in wider channels with floodplains. Exceptions include basins with weak lithologies where high attrition rates lead to lower volumes of stored coarse sediment with increasing drainage area (Benda and Dunne, 1997b).

Alluvial and debris flow fans, boulders, and organic debris can slow the routing of sediment and cause alluvial beds to form. A migrating pulse of gravelly bedload may cause expansion and contraction of stored sediment at fan margins, thereby creating a stationary wave of sediment (sensu Benda and Dunne, 1997a,b) (Figure 9). Stationary sediment waves may also form in association with boulders and woody debris, or form as point bars at meanders. The spatial extent and depth of stationary waves will depend on sediment supply; as supply increases the sediment wedge that forms upstream of fans, for example, should extend upstream and thicken (Figure 9). Expansion and contraction of a stationary wave or the passage of migrating wave can also create coarse-textured, cut and fill terraces (Benda, 1990; Nakamura, 1986; Roberts and Church, 1986; Miller and Benda, in press). Formation of terraces by fluctuating sediment supply has the potential to influence the distribution and species of riparian vegetation (Trimble, 1981). Sediment supply and storage fluctuations that are defined as migrating or stationary waves allows the use of spectral analysis or other Fourier transforms, similar to the analysis of other geophysical signals (Benda and Dunne, 1997,b).

The stochastic and deterministic characteristics of channel and valley morphology are reflected in the probability distributions of sediment and wood storage. This concept is illustrated for a landscape with an asynchronous sediment supply from mass wasting (Figure 3). An exponential or positively skewed distribution in the upper portions of a network indicates that bedrock- and boulder-floored, step-pool or cascade morphology will dominate (Benda and Dunne, 1997b). Large pulses of sediment that occur infrequently will be of short duration but they have the potential to form fans and terraces (Figure A in Figure 1). Moving downstream into segments with increasing distribution symmetry of sediment supply, channels are more likely to oscillate between step-pool and meandering forms (at times braided) due to changing sediment supply (B in Figure 1). A portion of the increased sediment storage may occur in association with obstructions. Cycles of aggradation and degradation will form extensive terraces. Further downstream in lower-gradient areas (<1%), relatively stable valley trains of sediment may be characterized by other perturbations, such as floods and bank erosion (C in Figure 1). Stochastic landscape processes yield a variable morphology over time at a single channel location, a pattern parameterized by probability distributions? Asynchronous occurrence of storms and fires will also lead to a spatial variability of channel conditions across a population of segments at any one time (Figure 10).

Magnitude and Frequency of Aquatic and Riparian Habitat Formation

The formation of aquatic and riparian habitats is dependent on the flux and storage of sediment and organic debris in channels and along valley floors. In landscapes where supplies are punctuated, habitat features, such as terraces, fans, gravel beds, pools, and large woody debris may form rapidly in the course of a single storm. Moreover, large fires and floods may also shape much of the riparian and aquatic ecosystem by controlling the influx of materials. Punctuated releases or episodic movement of materials have commonly been referred to as 'disturbances' (Pickett and White, 1985; Swanson et al., 1988). The term disturbance is defined in *Websters* as, "an outbreak of disorder", "to interfere with" "to hinder" and "to trouble". Clearly, the term disturbance arose with the recognition that landscape dynamics play an important role in ecosystems, but it originated in the context of a steady state paradigm. The term was appropriate for its time. However, the term is no longer adequate when considering landscape behavior in terms of probability distributions of process rates or environmental states. Perhaps, the term dynamics is more appropriate since it does not contain the negative connotations of disorder, trouble, etc.

Dynamic landscape processes, or those process rates contained in the right tail of a probability distribution (such as floods, erosion, sediment transport, woody debris, etc.) often destroy preexisting habitats. New, and perhaps more extensive and rejuvenated riparian and aquatic habitats may evolve after large fluxes of materials in channels and valley floors (Swanson et al., 1988). This seemingly incongruous duality of landscape processes is an inherent property of ecosystems, a property reflected in probability distributions. This aspect of ecosystems can only be understood over long time and large spatial scales (i.e., landscapes over decades to centuries). This refers to a single site over long time periods, or many sites over a short period

(Figure 10). Dynamic landscape processes cannot be evaluated or understood over small scales (reaches over a few years), which is why it has proven difficult to articulate the concept of 'disturbance' other than as a "concept" (Vannote et al., 1980; Minshall et al., 1985; Frissel et al., 1986; Naiman et al., 1988).

It is difficult to extend the general theory or its applications to the spatial scale of aquatic or riparian habitat units at the present time. These sciences will need to develop a compatible suite of parameters at larger spatial and temporal scales to couple with general landscape theories. In addition, it may be necessary to link ecological field studies with hydrologic, geomorphic, and vegetative analyses that measure landscape attributes in ways that are consistent with the general theory. The probability distribution approach has already been applied conceptually to ecological issues (Reeves et al., 1995).

APPLICATIONS OF THE GENERAL THEORY

The general landscape theory of organized complexity has a potential range of applications in the area of natural sciences, and in resource management, regulation, restoration and conservation biology.

(1) Organizing Framework For Field Studies. Similar to theories at smaller scales (e.g., slope stability, sediment transport), landscape-scale theory would promote a framework that would encourage commensurability in data collection and in model building across disciplines and regions. This would include providing a common set of parameters that could guide the collection of field data, test hypotheses, and modify and refine theories. The objective would be elucidation of general principles rather than provincial case studies.

(2) Defining Natural Disturbance Regimes and Range of Variability. The distribution parameter, by definition, defines the frequency and magnitude of process rates and morphological states, and therefore provides an index of natural disturbance and the range of variability.

(3) Conducting Environmental Assessments/Regulation. The absence of landscape-scale theory has led to a preference for single process rates and environmental states by many scientists, resource managers, and regulators (Benda, 1999). Because of the inherently stochastic nature of climate, a distribution of values is a more appropriate index of the state of the environment, either over time or over space (at a single time).

(4) Conducting Restoration and Monitoring. Naturally functioning ecosystems may require the occurrence of low-frequency processes, or extreme events. Probability distributions of process rates can provide information on this aspect of ecosystems. Moreover, monitoring programs need to consider variability in space and time, information that is embodied in frequency or probability distributions.

The applications listed above may require detailed theoretical predictions in contrast to the generalized distributions sketched in Figures 1-8. The theory can be applied to specific geographic areas through numerical analysis to generate quantitative estimates of input and output probability distributions. Three examples are briefly summarized below. (1) Changes in forest ages over time in western Washington; (2) Erosion by landsliding and debris flow and its effects on fluvial sediment routing in the Oregon Coast Range. (3) Effects of five universal landscape processes on the abundance of large organic debris in streams in the Pacific Northwest.

Geographically-Specific Quantitative Modeling (1): A Dynamic Forest Cover

To investigate the role of wildfire on landsliding and on variations in recruitment of large wood to streams, an analysis of forest dynamics was conducted in western Washington. Data on forest age classes obtained from 1939 aerial photography over a 1000 km^2 area were used to develop a topographically-based probability of fire occurrence (Benda et al., Figure 11.5). In conjunction with a fire behavior model (Benda, 1994), the changing age class distribution of forests in space and time was predicted over a several thousand year period. The analysis assumes a stationary climate and fire regime. The stochastic nature of fire resulted in forests that fluctuated over time, depending on topographic position (Figure 11). Variability in forest ages was predicted to increase with decreasing basin area as the average fire size approached basin size. For example, in small basins a large fire could reset the entire forest to zero age but it was also likely that small basins would be missed by even large fires, leading to exceedingly old forests (>800 years).

Although the long-term probability distribution of forest ages predicted by the model was positively skewed, in accordance with existing theory (Johnson and Van Wagner, 1984) and as illustrated in Figure 2, distributions of forest ages varied with topographic position or stream size. The distributions for forest ages up to year 200 for a range of channel sizes in western Washington indicated that there was a higher likelihood of younger age classes in the smallest, steepest streams and landslide sites (Figure 12). An increasing amount of the probability distribution of age classes shifted right into older forests with increasing stream size. This was due to a higher fire frequency in steeper hillslope positions compared to more humid, lower gradient and wider valley floors. The simulations indicate that natural forests cannot be represented adequately be a specific age class but rather by a distribution of values, the shape of which varies with region and topographic position. The role of fire in forests has major consequences for mass wasting and recruitment of woody debris (see following two sections).

Geographically-Specific Quantitative Modeling (2): Erosion and Sediment Routing in the Oregon Coast Range

The general landscape theory was applied to the central Oregon Coast Range to examine how the mixture of infrequent stand-replacing fires, periodic intense rainstorms, and steep, landslide-prone topography govern the probability distribution of sediment flux to channels and valley floors. A further objective was to investigate how the sediment supply distributions affected sediment transport and channel and valley morphology.

The central Oregon Coast Range is comprised of relatively weak Tertiary marine sandstone rocks that have been sculpted into steep, low relief hills by shallow landsliding in bedrock hollows and debris flows in first- and second-order channels. Coniferous forests of Douglas fir, western hemlock, and western red cedar thrive under 2200 mm of precipitation falling mostly as rain in the winter. Infrequent large Pacific low pressure systems cause intense rain, floods, and concentrated landsliding. In addition, stand-replacing fires with cycles of 200 to 300 years (Agee, 1993) reduce rooting strength and lead to accelerated landsliding and debris flows (Benda and Dunne, 1997a).

In the model, the temporal and spatial patterns of landsliding and debris flows were predicted to be an outcome of: 1) probability distributions of storm intensity and duration; 2) fire size distribution; 3) distributions of topographic and geotechnical properties; 4) deterministic thickening of colluvium in landslide sites; 5) deterministic trajectories of rooting strength; and 6) debris flow scour of first- and second-order streams (Benda and Dunne, 1997a). The model predicts that episodes of concentrated sliding occur within burned areas during rainstorms for a decade to two after a wildfire, with few landslides at other places and times (Figure 13). Frequency of failures is low in small watersheds because of the low frequency of fires and relatively small number of landslide sites. Landslide frequency and magnitude increases with increasing drainage area because of increasing number of landslide sites and an increasing probability of storms and fires. At a basin area of 200 km^2, landsliding occurs almost every year (Figure 13).

The simulation model in the Oregon Coast Range predicts that the frequency distributions of landsliding and debris flows at all drainage areas are sharply right skewed, partly reflecting the non correlation of erosion (Figure 13). This distribution reflects a pattern of low erosion rates (dominated by few slides and soil creep) in most years and concentrated landsliding occurring during large storms and fires. With increasing drainage area, the probability distribution of landsliding shifts towards the right into higher numbers of slides.

The effects of spatial and temporal patterns of erosion on sediment routing and channel morphology required, in addition to probability distributions of erosion, the incorporation of network topology, channel geometry, particle attrition, and an estimated probability distribution of transport capacities. Predictions included the effect of non correlated erosion and basin scale on the spectra of sediment transport and storage, a process represented in the gradual evolution of the shape of the sediment flux and storage distributions downstream (Figure 14). In upper parts of the network, distributions are predicted to be positively skewed reflecting the hillslope distribution of sediment supply and few other upstream channel sources of sediment. Frequency distributions of supply and storage become approximately log normal to normal downstream because of the integrating effects of the converging, hierarchical network that combines sediment from many different sources in a watershed (Benda and Dunne, 1997b). The shapes of long-term distributions of sediment flux and storage yield theoretical insights into the frequency and magnitude of terrace development and channel changes (Benda et al., 1998; Figure 11.9). Other predictions include that the size and duration of pulses of fine sediment and gravelly bedload (sediment waves) depend on the magnitude of sediment flux, the scale and topology of the network, particle attrition, and sediment transport processes (Dunne, 1998).

Several of the theoretical predictions are in accord with field measurements and observations. The predicted potential for catastrophic sedimentation in the Oregon Coast Range is verified by aerial photography of spates of landsliding following stand replacing fires in the mid twentieth century (Benda et al., 1998; Figure 11.4). Evidence for watershed and landscape-scale channel sedimentation leading to formation of alluvial terraces also exists in the Oregon Coast Range (Personius et al., 1993). The theoretically-based model provides a process-based explanation for the spatially varying ratio of sediment supply to transport capacity that is exhibited in the observed spatial and temporal patterns of bedrock and boulder floored channels. Moreover, high particle attrition rates of the weak sandstone bedload (measured by tumbling experiments, Benda, 1994), lead to a compressed and left-shifted probability distribution of sediment volumes and depths (Figure 14). That pattern is in accordance with the bedrock-dominated channels and sand-dominated terraces found at large drainage areas in the Oregon Coast Range.

Developing General Qualitative Principles: Landscape Controls on Large Wood in Streams

The general landscape theory was applied to the problem of defining the range of variability of wood abundance in streams. The effect of two end member fire regimes on variability in wood loading was examined: a 500-year cycle associated with the wettest forests and a 150-year cycle associated with drier areas in the southern and eastern parts of the Pacific Northwest region. The analysis of fire kill and subsequent forest growth applies a series of simplifications to reduce complexity. (1) Increases in forest biomass over time during dominance by even-aged stands can be represented as a linear function (Borman and Likens, 1979), a pattern consistent with the linear rate of coarse woody debris accumulation on forest floors up to about year 500 in coniferous forests in the Pacific Northwest (Spies et al., 1988); (2) Mortality in mature coniferous west-side forests averages about 0.5% annually (Franklin, 1979); (3) Significant mortality of large conifer trees does not begin until about year 100 (Spies et al., 1988), at which time the majority of tree height is attained (McCardle et al., 1961); and (4) Fire-killed trees topple over a period of several decades (Agee and Huff, 1987). Time trends and probability distributions of flux of wood for the two fire cycles were predicted based on a geometric random fall model (Van Sickle and Gregory, 1990), piece size distributions (Heimann, 1988; Veldhuisen, 1990), and specified toppling periods of fire-killed trees (Agee and Huff, 1987). In pursuit of general quantitative principles, in-stream woody debris was expressed in arbitrary units of wood volume.

Role of Mortality Versus Fire

The magnitude of wood recruitment associated with chronic stand mortality is significantly higher in the 500-year cycle because a constant rate of stand mortality is applied against the larger standing biomass of older forests. Furthermore, fire pulses of wood are significantly greater in the 500-year fire cycle because of the greater standing biomass associated with longer growth cycles (Figure 15). Hence, longer fire cycles yield longer periods of higher recruitment rates and higher peak recruitment rates post fire. Post-fire toppling of trees in the 500-year cycle, however, accounts for only 15% of the total wood budget (in the absence of other wood recruitment processes). In contrast, drier forests with more frequent fires (e.g., 150-year cycle) have much longer periods of lower wood recruitment and lower maximum post-fire wood pulses (Figure 15). Because the average time between fires in the 150-year cycle is similar to the time when significant mortality occurs (100 yrs), the proportion of the total wood supply from post-fire toppling of trees is approximately 50%. Hence, stand-replacing fires in drier forests plays a much larger role in wood recruitment compared to fires in wetter forests. Although the range of variability of wood recruitment in the rainforest case is larger, the likelihood of encountering more significant contrasts (i.e., zero to a relatively high volume) is higher in drier forests.

Role of Bank Erosion

Bank erosion recruits trees at rates depending on erodibility of banks, flood frequency and magnitude, and stand density (Keller and Swanson, 1979; Murphy and Koski, 1989). During periodic flooding, bank erosion is typically greatest in lower, actively migrating portions of channel networks and least in upper networks where banks are comprised of bedrock or boulders and cobbles. Bank erosion also occurs when flow is diverted around debris jams and other obstructions, and can occur anywhere in a channel network. Hence, the importance of bank erosion should vary with position in a channel network and with flood frequency. Bank erosion has the potential to be an important recruitment agent since trees undercut by bank erosion tend to fall toward the channel (Murphy and Koski, 1989).

A simple model was devised that used the stand growth and random tree fall assumptions stated above in combination with bank erosion occurring on one side of the channel to compute the proportion of wood flux from bank erosion. At a low bank erosion rate (0.01 m/yr), wood loading is dominated by stand mortality and punctuated inputs from episodic fires (90%). In such environments, wood recruitment and storage may be relatively low in the absence of other disturbances, such as fires, landslides, or wind (Figure 16). In contrast, a higher bank erosion rate (0.5m yr^{-1}) dominates wood recruitment and yields an almost uniform distribution of storage, de-emphasizing effects of episodic disturbances, such as fires. Hence, the importance of stand mortality should decrease downstream in a network in direct proportion to the rate of increase in bank erosion.

Role of Mass Wasting

Shallow and deep-seated landslides and debris flows recruit large woody debris to channels and valley floors (Swanson and Lienkaemper, 1978; Keller and Swanson, 1979; McGarry, 1994). In a natural setting, concentrated landsliding and debris flows can occur under mature forests during large rainstorms (Benda et al., 1998) and following major fires that reduce rooting strength (Benda and Dunne, 1997). The importance of wood recruitment by mass wasting will depend on the type and size (area) of the landslide, the age (or size) of trees recruited, the number and area of landslide source areas intersecting a channel segment-t of a given length, and the temporal frequency of landsliding.

Based on parameter values in the literature for temporal frequency and spatial density of shallow landsliding (Swanson et al., 1982; Benda and Dunne, 1997a), mass wasting was predicted to be the single largest point source of wood to stream channels (Figure 17). However, the overall contribution to the long-term wood budget by debris flows was less than 15% because debris flows occurred every 3 to 6 centuries in conjunction with a annual decay rate of 3% (the mid point of field measurements). More frequently occurring landslides and debris flows in combination with a higher spatial density of sites should result in larger contributions from mass wasting. Wood recruitment from mass wasting has been estimated in field studies to range from 7% (Murphy and Koski, 1989) to 48% (McGarry, 1994).

CONCLUSIONS

It has proven difficult to scale up mechanistic descriptions of physical and biological processes at small scales to obtain an understanding of a system of such processes at larger scales (e.g., 10^4 km^2, 10^2 years). This is partly due to the inherent complexity and variability of ecosystems. Parameterizing landscape behavior, either in space or time, in the form of frequency or probability distributions allows characterizations of certain types of complexity and variability. As such, the general landscape theory is commensurable with recent advances in the study of complex systems (Kellert, 1993; Gell-Man, 1994; Bak, 1996; McIntrye, 1998).

Analyses at large scales indicate under what environmental conditions certain types of variability arise, such as sediment waves in fluvial environments or episodic sedimentation in estuarine and marine depositional records. Probability distributions also provide information on the most probable morphological state and variances around the mean state. Most probable states can be considered either at a single location over long time periods or across many locations over short time periods (e.g., the ergodic hypothesis).

The probability distribution of the flux and storage of mass from terrestrial through aquatic environments reflects the seemingly incongruous duality of landscape processes that destroy existing habitats when rejuvenating old or creating new riparian and aquatic habitats. The distribution parameter indicates how first-order environmental drivers govern the frequency and magnitude of habitat forming processes, whether they are moderate floods leading to wood recruitment or concentrated landsliding leading to large fluxes of sediment and wood. The role of extreme or low-probability events (i.e., disturbances) in maintaining ecosystems has become a central tenet in ecology (Pickett and White, 1985; Frissel et al., 1986; Swanson et al., 1988; Poff et al., 1997). Hence, there has been an increasing call for incorporating concepts of disturbance or dynamics into natural resource management, restoration, environmental assessments, and regulation (Botkin, 1990; Naiman et al., 1992; Reeves et al., 1995; Reid, 1998; Dunne, 1998b; Lackey, 1998; Benda et al., 1998). The general landscape theory offers a framework for incorporating such a perspective in watershed science, management, and policy.

The general theory of organized complexity also sets the stage for evaluating forms of knowledge and certainty. The theory, either in its general form or in its numerical applications, suggests that understanding of complex landscapes is conditioned by time and space scales. Knowledge at the level of distributions will be most applicable to larger scales. Detailed responses of systems at small spatial and temporal scales become uncertain due to limitations in scientific understanding and to the high degree of complexity and natural variability. At the scale of landscapes (including long time periods), evaluating environmental impacts may depend on whether certain landscape processes fall inside or outside the range of variability of process rates or environmental states, either in time or space. Because of uncertainties over a range of scales, science should not be considered the sole source of guidance on how society should respond to environmental effects of land use.

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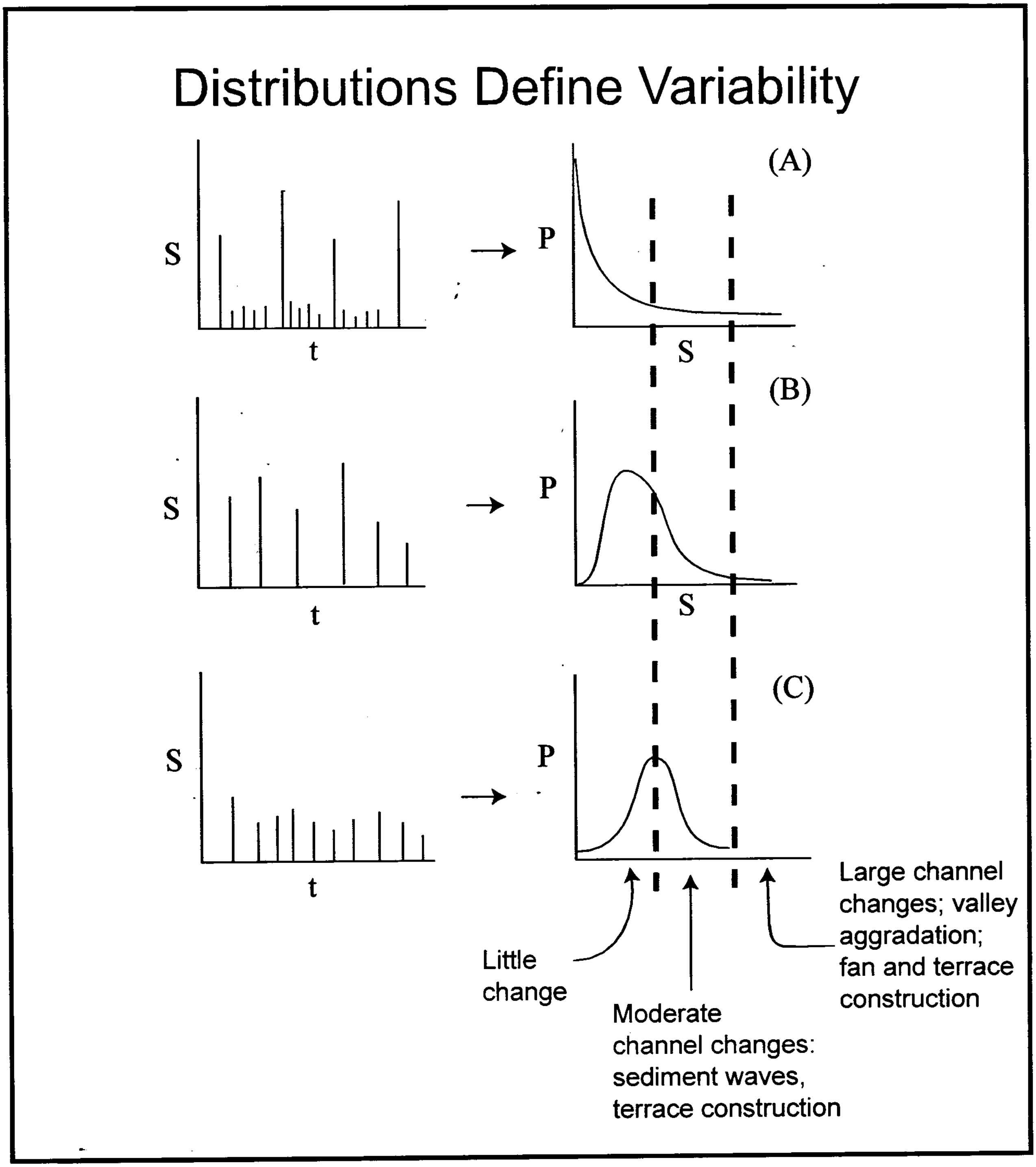

Figure 1. The study of landscapes requires landscape-scale parameters in the form of spatial and temporal probability distributions. Temporal distributions indicate the frequency and magnitude of process rates or environmental states. A positively-skewed or exponential distribution (A) indicates a dominance of high frequency, low magnitude conditions, infrequently punctuated by low frequency and high magnitude events. More symmetrical distributions (B & C) change the relationship between process frequency and magnitude with consequences to valley and channel morphology. Spatial distributions tabulated in any year partition the spatial ensemble of watershed attributes amongst the range of environmental conditions, often in the form of a frequency histogram.

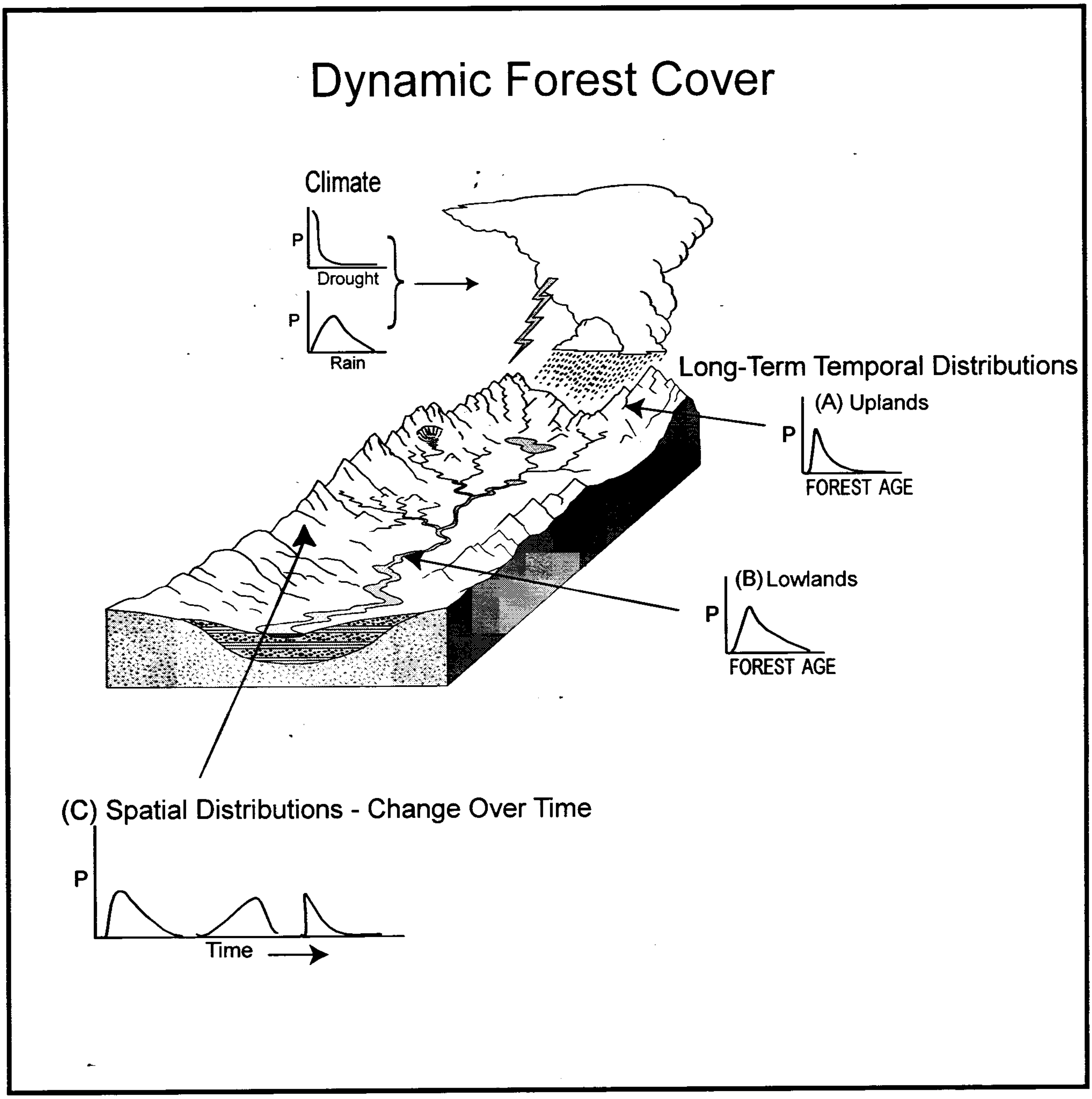

Figure 2. The probability distributions of climate interacting with distributions of topography and other physical and biological factors give rise to long-term temporal distributions of forest ages. Distributions are positively skewed but change with the frequency of stand-replacing disturbances and hence with topographic position (A & B). The spatial distribution of forest stand ages varies over time (C) due to a watershed-specific history of fires and other disturbances.

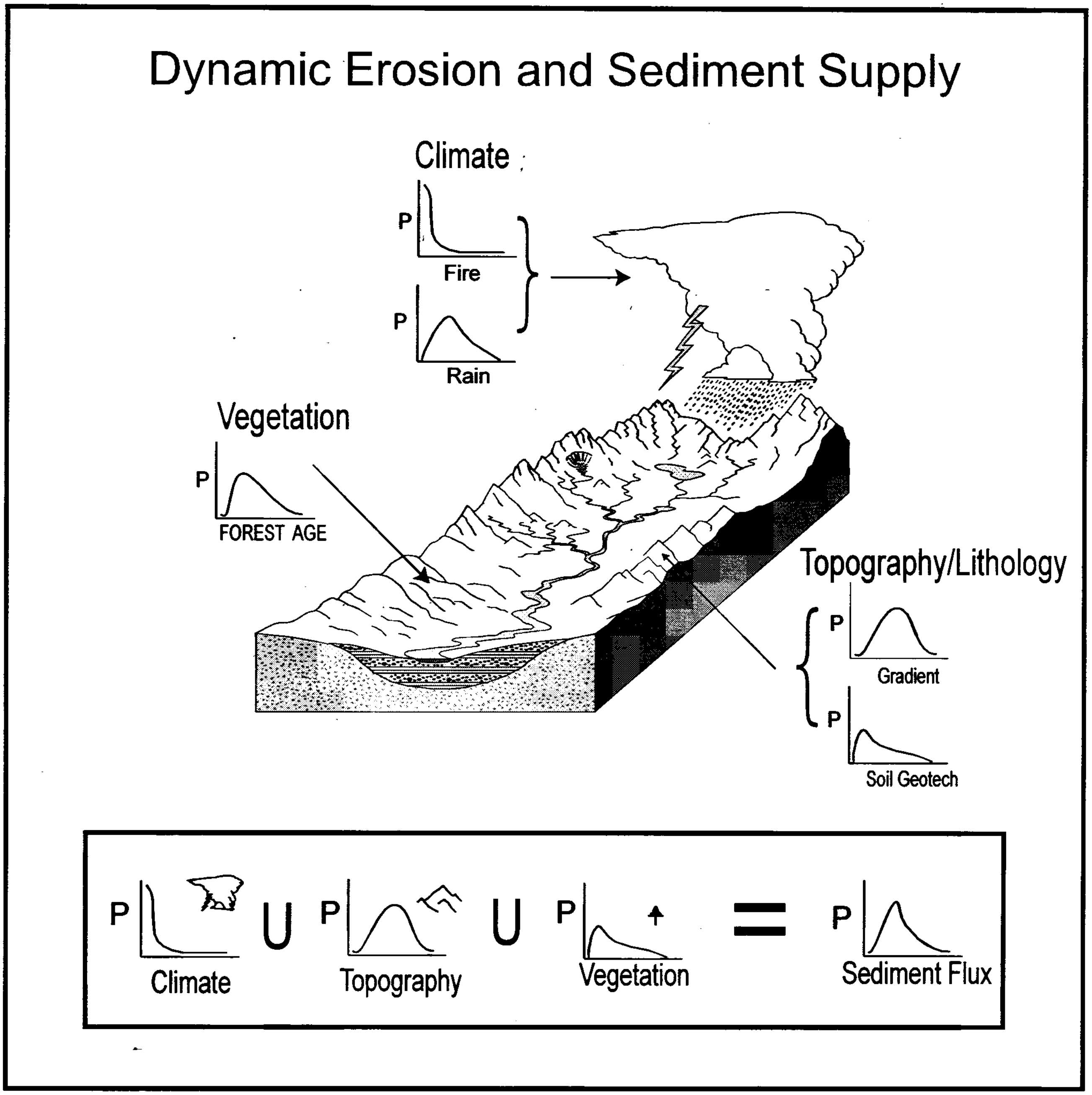

Figure 3. Time series of climatic events (for example fires and rain) can be represented by probability distributions. Climatic distributions interact with populations of erosion source areas (i.e., topographic attributes) and vegetation patches. Interactions yield a time series of erosion events or a probability distribution of sediment fluxes. Unique combinations of climate, topography (including lithology and soils), and vegetation will yield landscape-specific probability distributions of erosion and sediment flux.

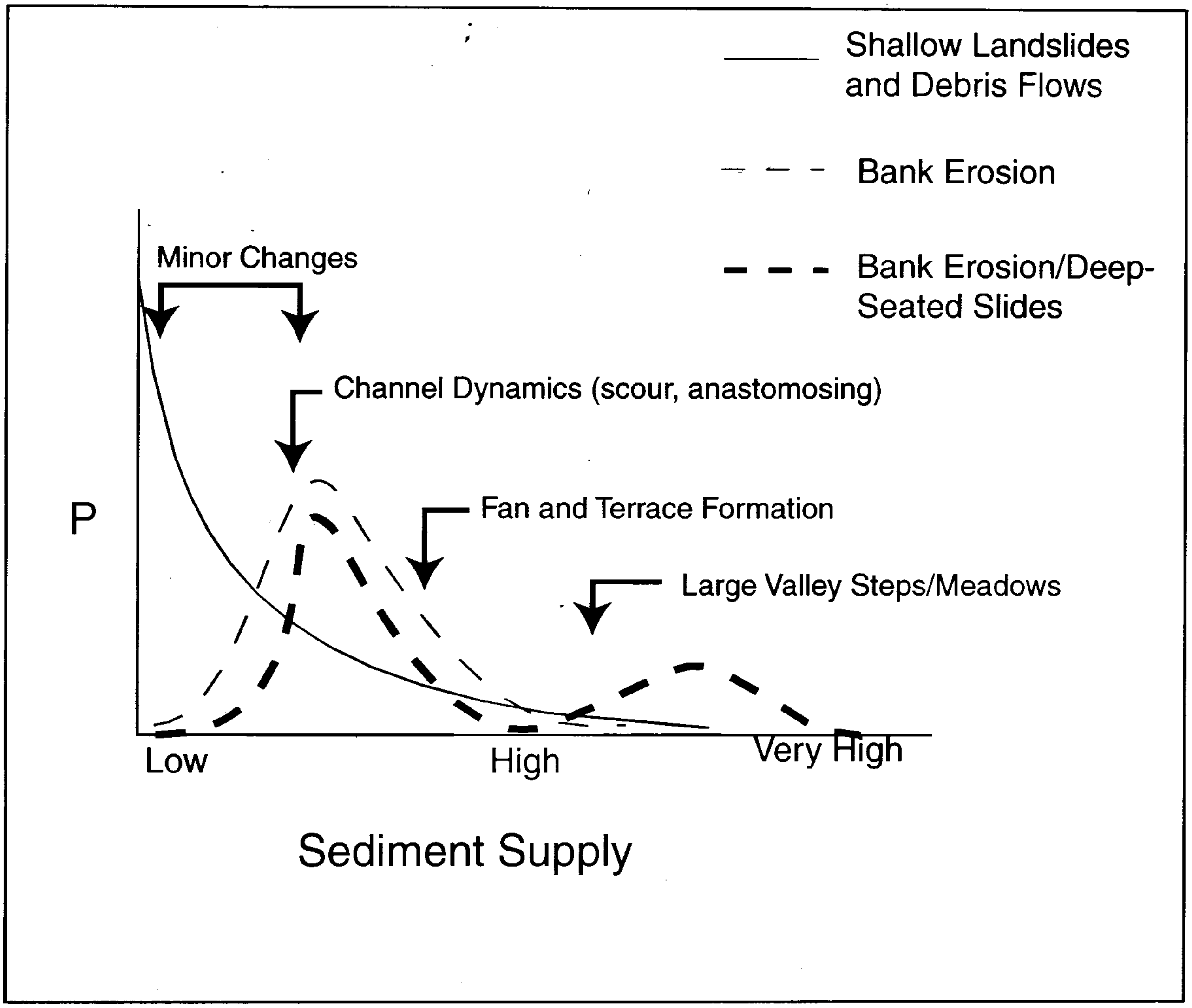

Figure 4. Three idealized distributions of erosion and sediment flux from different erosion processes. Threshold erosion processes, such as landsliding or sheet wash and gully erosion yield strongly right-skewed or even exponential distributions of sediment flux. In landscapes dominated by bank erosion, sediment flux may mimic flood flow distributions (more log normal). Very large but infrequent deep-seated landslides may result in polymodal distributions. In real landscapes, topographic heterogeneity will yield some mixture of the idealized distributions shown. Different distribution shapes have ramifications on channel and valley morphologies and habitats.

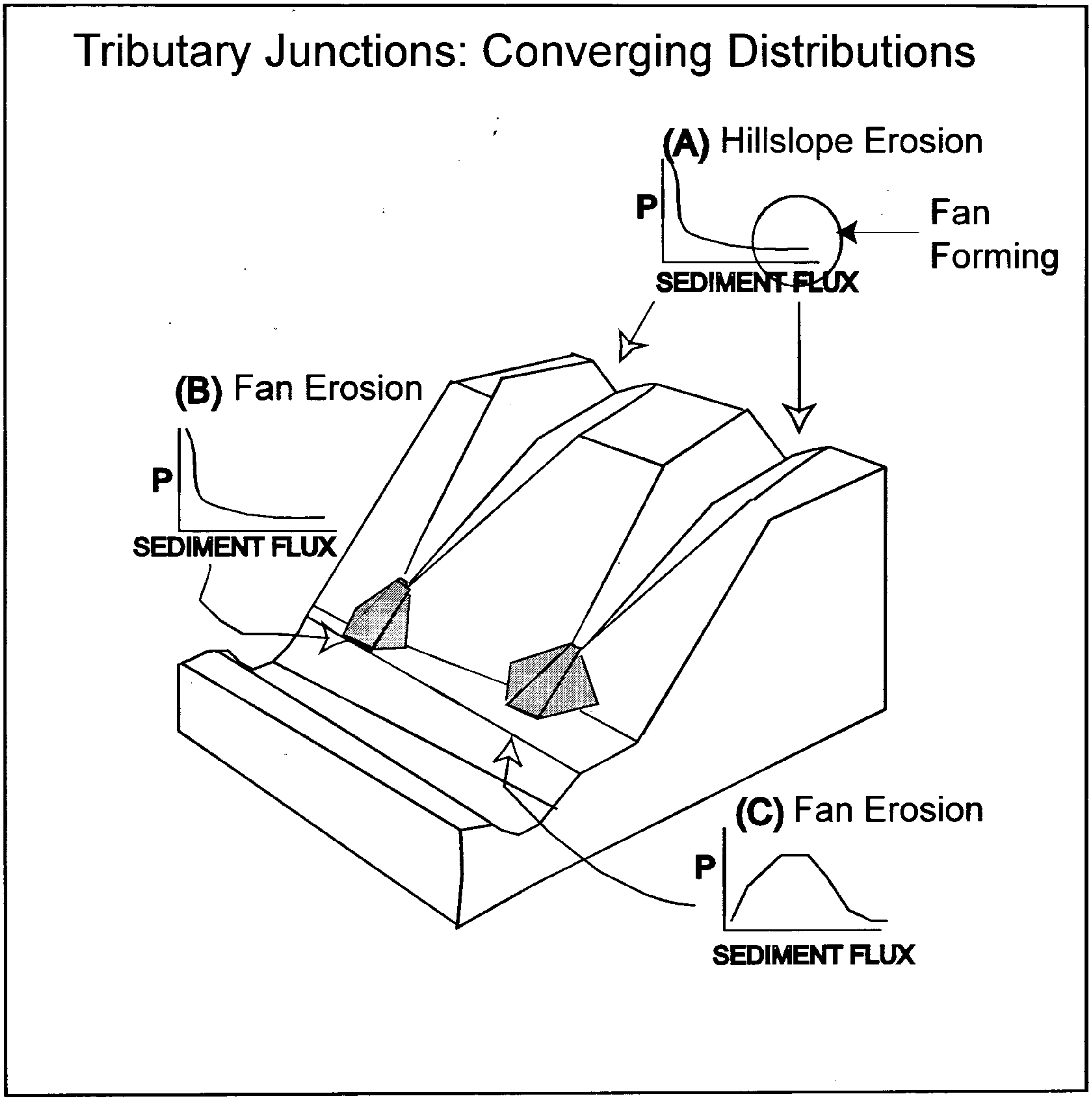

Figure 5. Tributary junctions represent abrupt mergers of different probability distributions of sediment flux. The right tail of erosion or flux distributions (A) strongly influences the size and texture of fans that can effect channel and valley morphologies. Narrow valley floors will cause sediment flux into the channel (B) to mimic the hillslope distribution of supply (A). Wider valley floors, in contrast, may absorb much of the delivered sediment thereby yielding a distribution of fluxes governed by bank erosion (C).

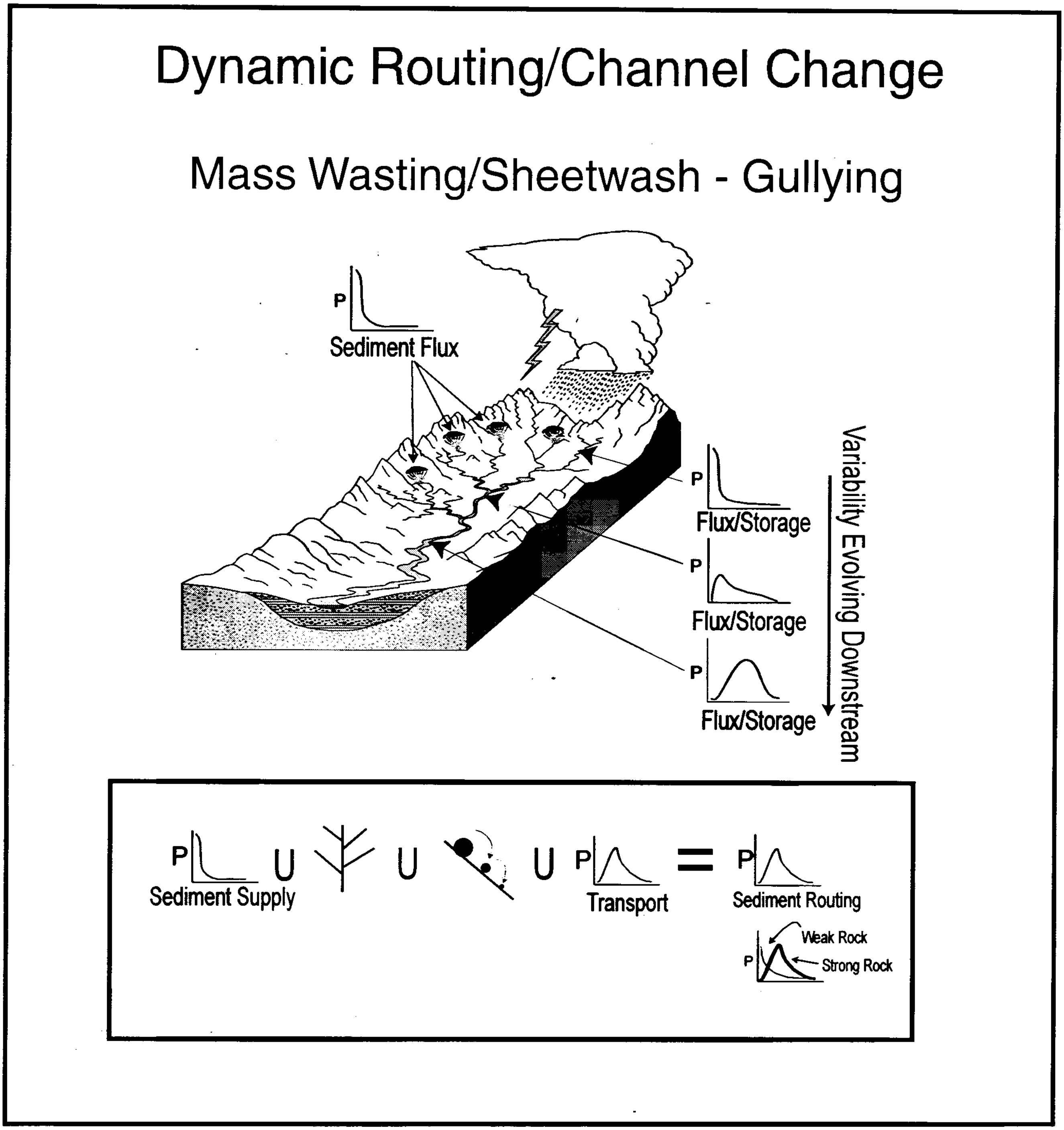

Figure 6. Sediment flux from hillslopes to stream channels can be correlated or uncorrelated in time. A channel network over long time periods obtains sediment from the probability distributions of sediment supply from individual hillslopes and tributary channels. Sampling from numerous independent distributions that increase in number downstream should yield a sum represented in more symmetrical distributions, a consequence of the central limit theorem. Other important factors govern the downstream evolution of sediment flux distributions, including particle attrition, transport capacities, and storage regimes (including obstructions).

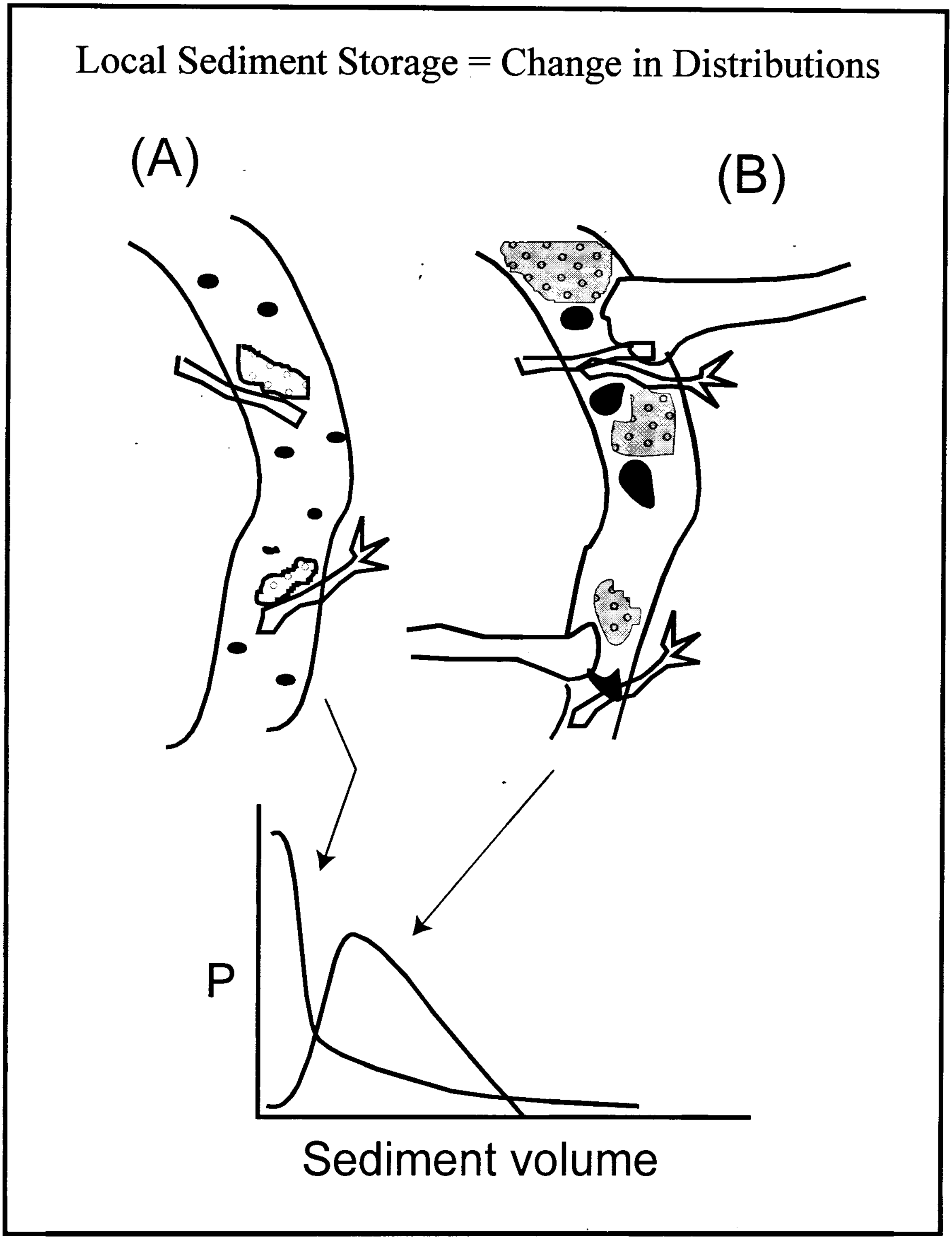

Figure 7. Obstructions, in the form of fans, boulders, and logjams can locally alter transport capacities and cause an increase in sediment storage. The number and location of such obstructions can vary deterministically based on network geometry. Supply of boulders, wood, and sediment can also vary stochastically over time. Different pattern of intersecting tributaries can lead to differences in in-channel sediment storage at the segment scale (10^3 m). Increasing roughness elements lead to increasing storage (B) and vice-a-versa (A).

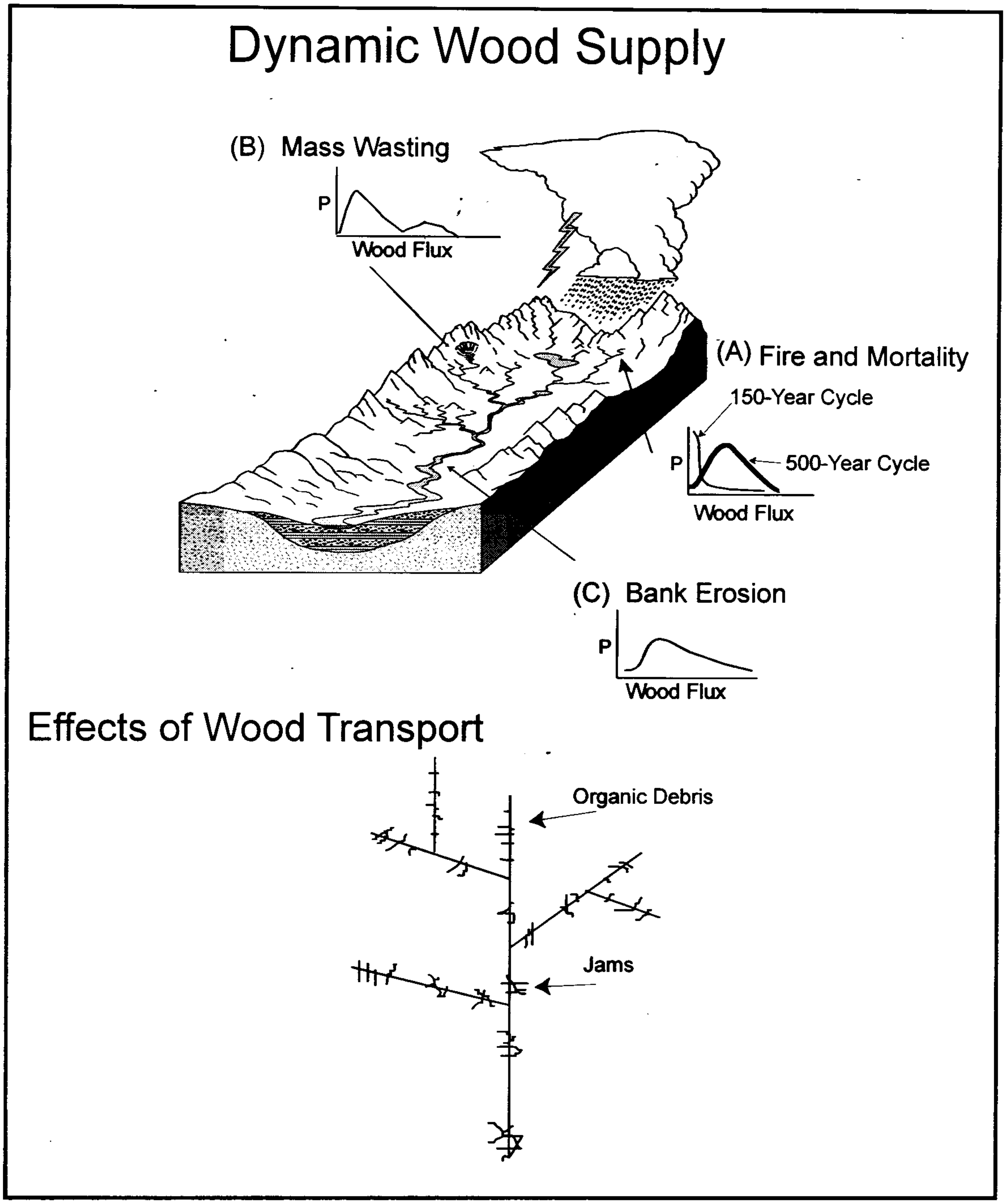

Figure 8. Recruitment and storage of large woody debris can be represented in the form of probability distributions. Universal processes that deliver wood to streams include fires, wind, mortality, bank erosion, and mass wasting. Fire cycles impose a strong influence on long-term wood supply by governing trajectories of forest growth and punctuated toppling of fire-killed trees. Hence, different fire regimes yield different distributions (A). Mass wasting is the largest single point source of wood, and it should affect the right tail of the distribution of wood loading (B). Since bank erosion increases downstream, the distribution of wood supply should evolve downstream with increasing supply of trees (C). Wood Transport: An increasing channel width downstream in conjunction with a constant piece size distribution will yield patterns of increasing inter-jam spacing and jam size downstream.

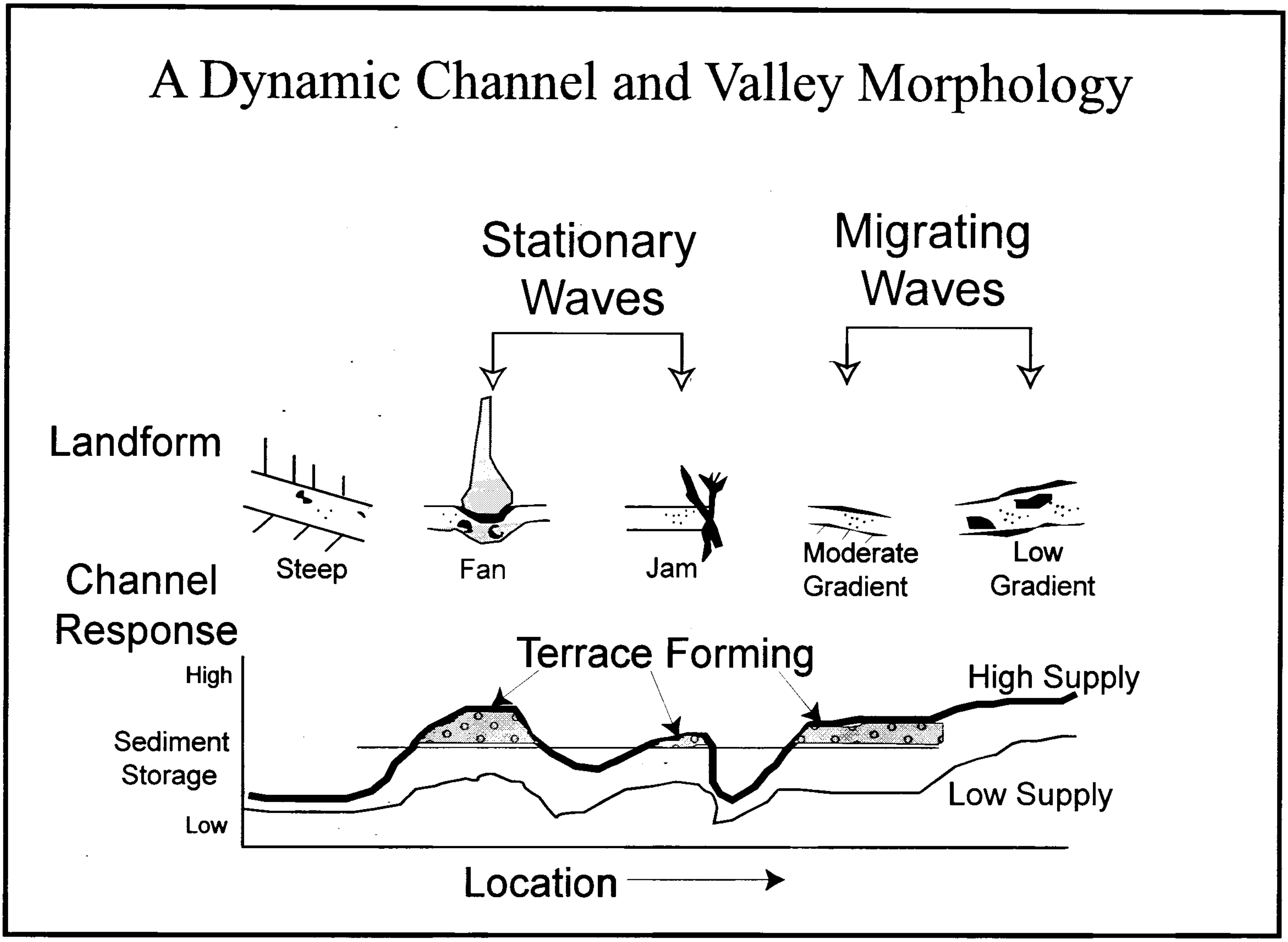

Figure 9. Channel and valley morphology have both stochastic and deterministic origins. Sediment storage generally increases deterministically downstream due to declining channel gradient (indicative of increasing sediment supply and decreasing transport capacities). Sediment also becomes stored upstream of obstructions. Stochastic effects include variation in sediment supply and in the number and location of obstructions. Migrating sediment waves increase storage mostly in moderate- to low-gradient portions of the channel network. Stationary waves form upstream of obstructions such as fans, boulders, and woody debris, extending and thickening existing sediment wedges. Cycles of aggradation and degradation lead to terrace formation.

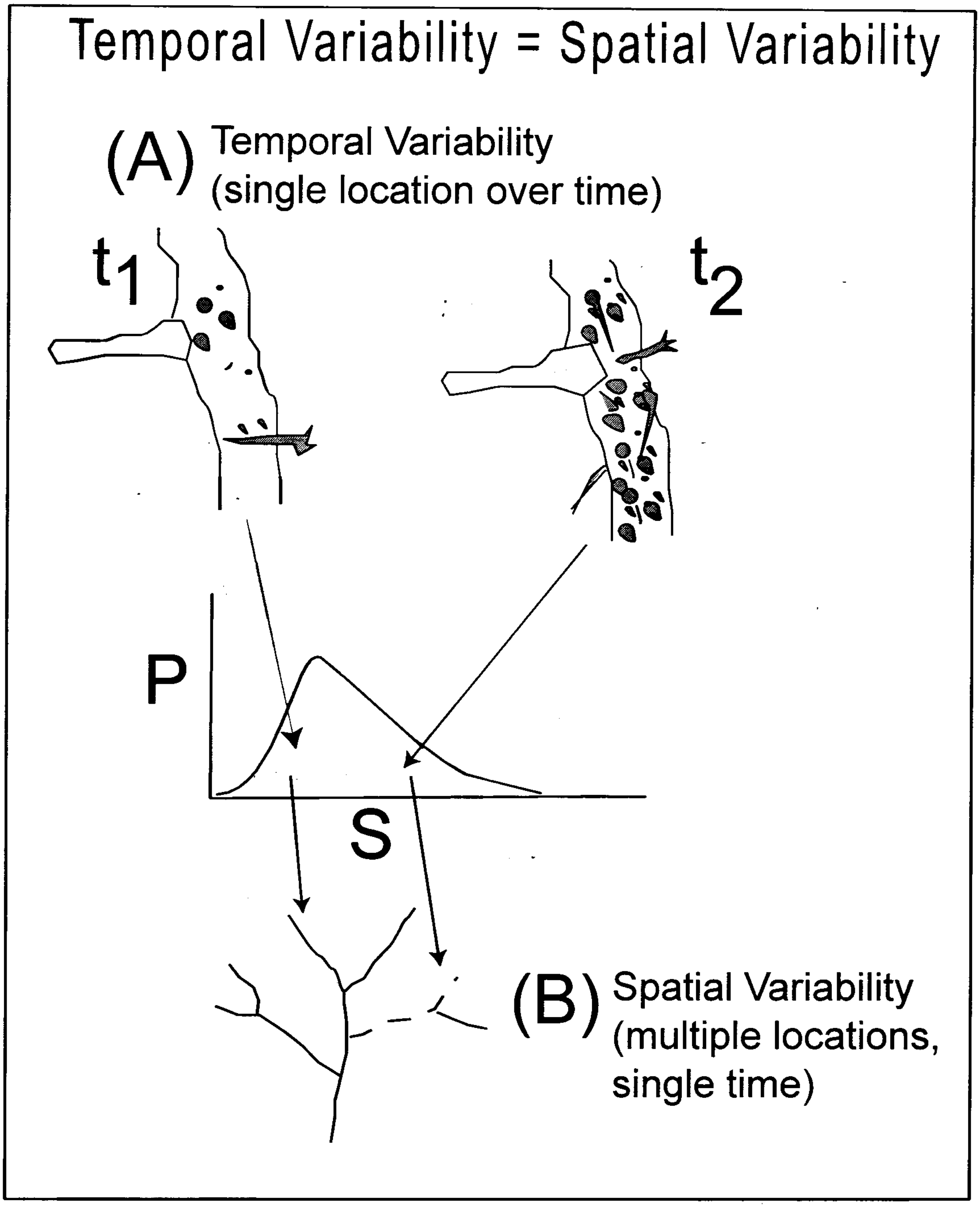

Figure 10. A stochastic supply of sediment and woody debris will yield a temporally-varying channel morphology, a condition parametrized by a probability distribution (A). Because disturbances are spatially variable across landscapes, temporal variability equals a spatial variability in channel form in any year (B). It may be feasible to estimate the temporal distribution based on spatial samples under the condition that the spatial ensemble of measurements is statistically equivalent to sampling over time at a single location (the ergodic theorem, Thornes and Brunsden, 1977).

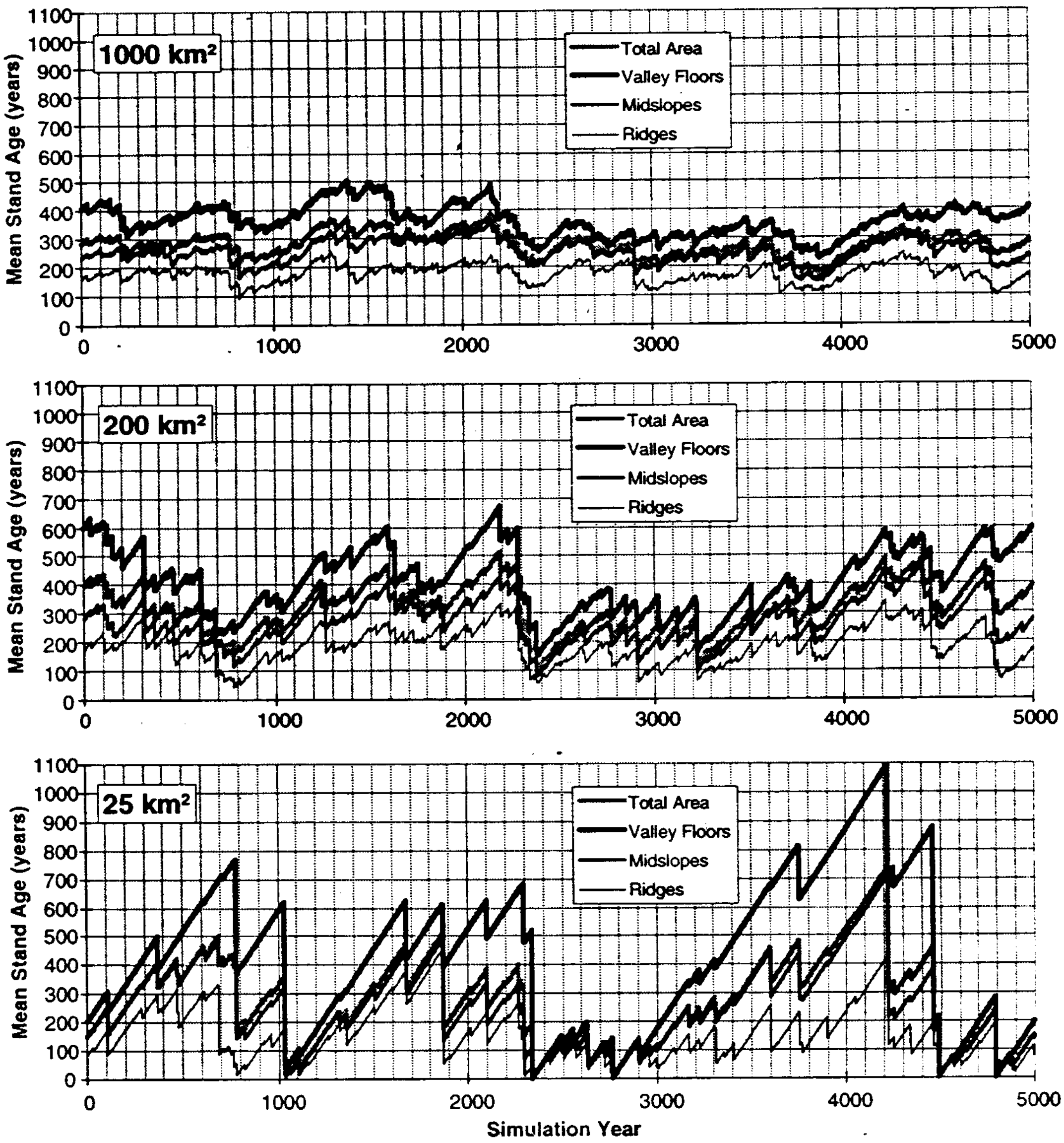

Figure 11. The stochastic nature of fire causes the forest age distribution to fluctuate over time. Mean stand age was calculated over three different basin areas and for three topographic locations. There is a systematic decrease in mean stand age moving from valley floors to ridgetops, indicating the field estimated gradient of fire susceptibility. There was also an increasing variability within smaller basins that is caused by mean fire size approaching basin size.

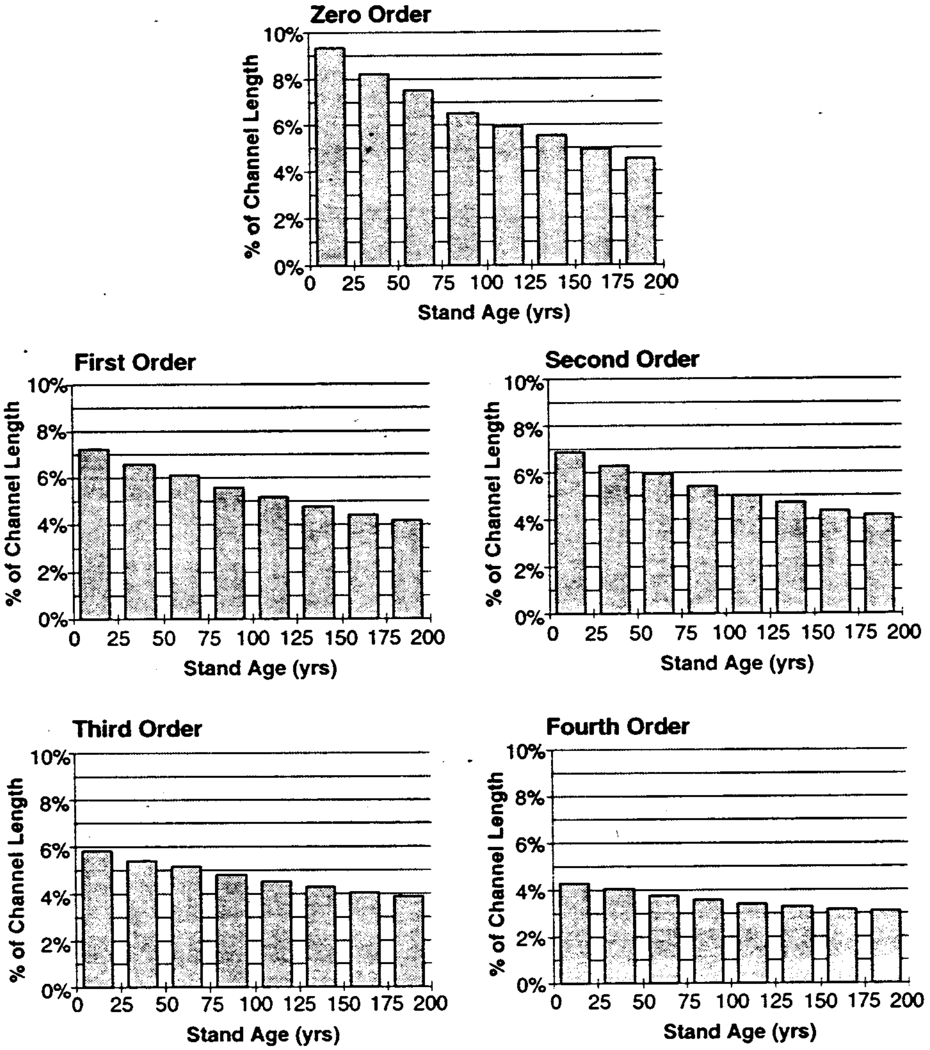

Figure 12. Probability distributions of riparian forest ages. The average proportion of channel length with forest stands of a particular age, using 25-year bins up to 200 years (i.e., forests greater than 200 years no shown) was tabulated for "zero-order" (i.e., shallow landslide sites) through fourth-order. These predicted histograms indicate, that on average, the proportion of the channel length containing trees less than 100 years old varied from 30% (zero-order), 24% (first-order), 24% (second-order), 21% (third-order), and 15% (fourth-order). The decreasing amount of young trees with increasing stream size is a consequence of the field-estimated susceptibility of fires. Fire frequency was the highest on ridges and low-order channels (~175 years) and the lowest (~400+ years) on lower gradient and wide valley floors.

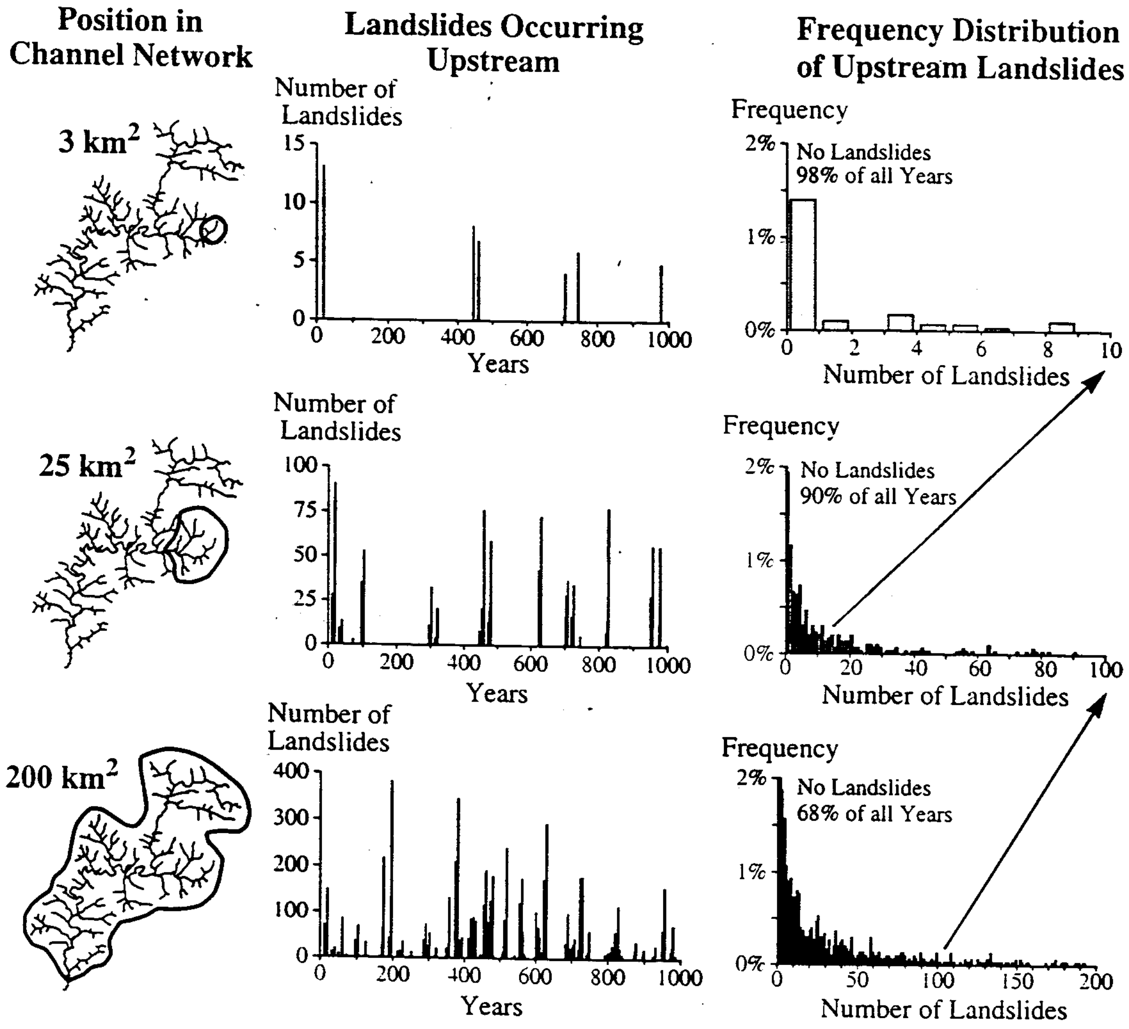

Figure 13. Model predictions of landsliding in the Oregon Coast Range over a simulated 1000 year period for three different drainage areas. Landslide rates are governed by the density of source areas, topographic attributes, soil geotechnical properties, soil production rates, frequency of tree death (fire), and frequency of large rainstorms. At 3 km^2, landsliding is rare occurring every few centuries. The number of landslides increases with increasing drainage area because the number of potential source areas and the frequency of fires increase. At 200 km^2, landslides occur somewhere in the basin every few years. At the site level, landslides are predicted to have an average frequency of about 2500 years. The probability distribution of erosion by landsliding approximates an exponential form. Adapted from Benda et al., 1998.

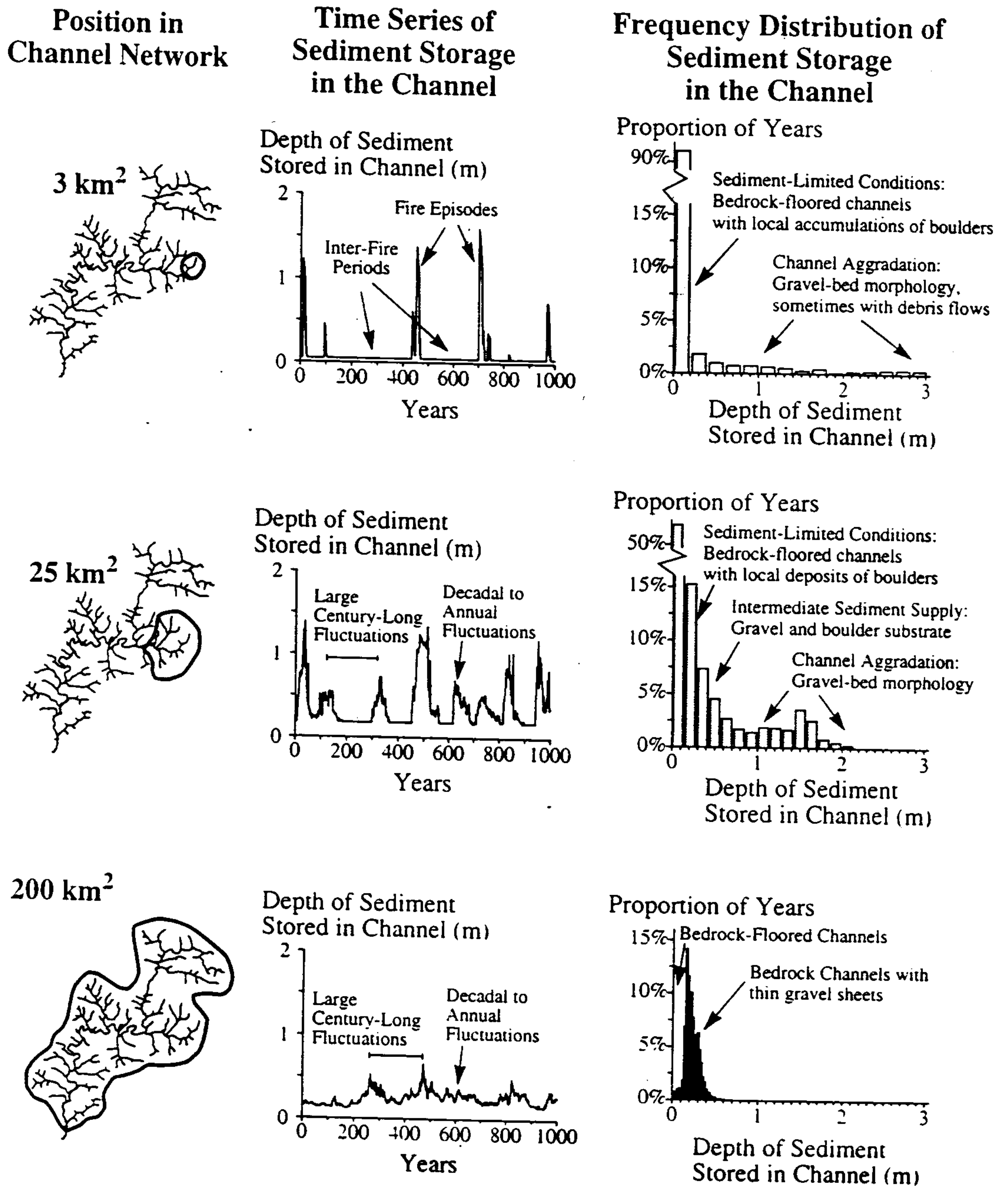

Figure 14. The exponential probability distribution of erosion (Figure 13) has consequences for the flux and storage of sediment throughout a 200 km^2 drainage basin in the Oregon Coast Range. The frequency of sediment perturbations is the lowest and the magnitude the highest at the smallest drainage areas. The distribution of flux and storage mimics the distribution of hillslope supply. With increasing drainage area, the probability distribution becomes more symmetrical because the channel is sampling from an increasing number of source distributions. At 200 km^2, the distribution is shifted left due to weak sandstone bedrock that has high attrition rates. Some consequences for channel morphology are shown. Adapted from Benda and Dunne (1997b).

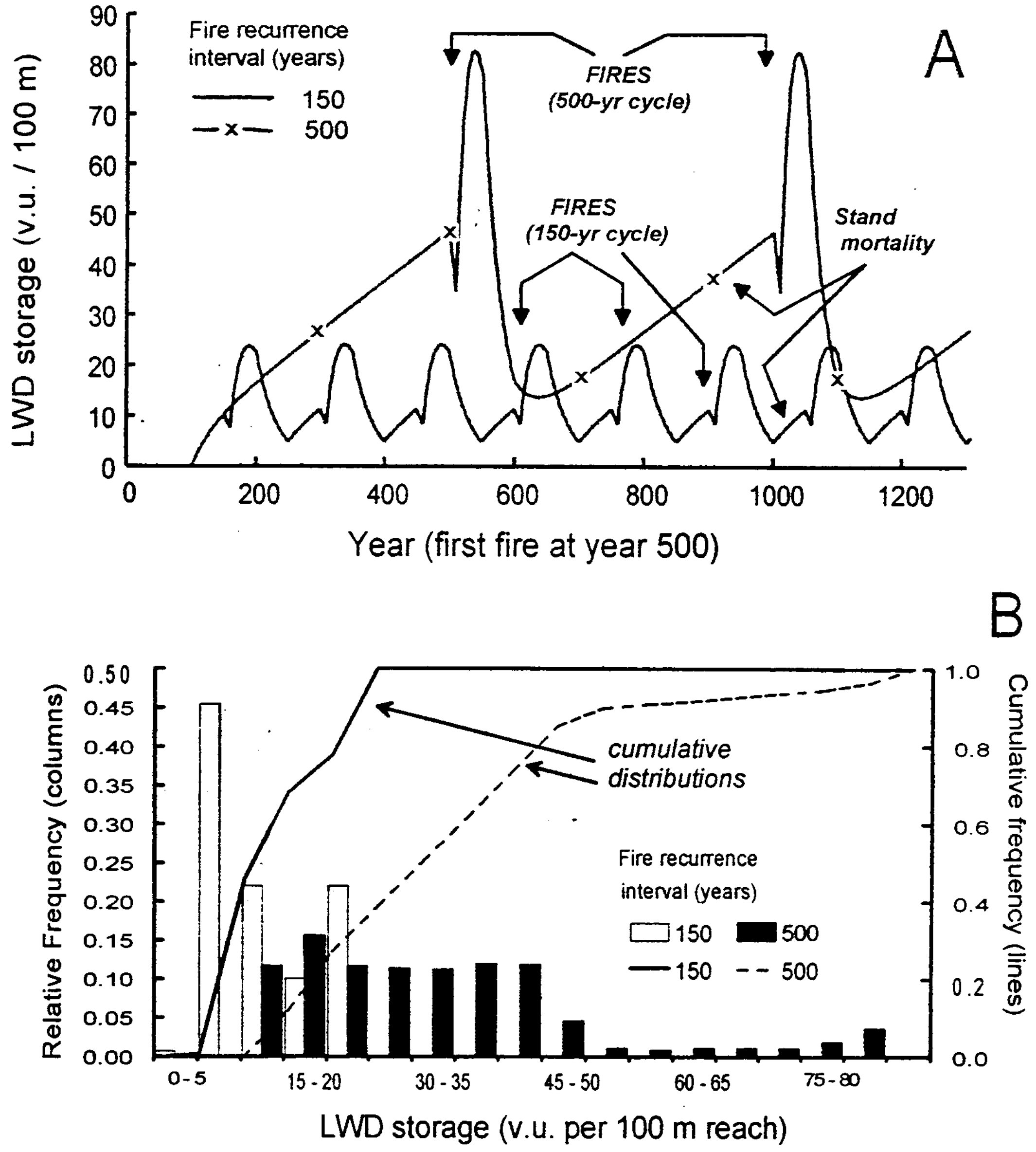

Figure 15. Using a simple set of first-order principles and parameter values (see text and Benda and Sias, 1998), the patterns of wood storage for two end member fire regimes are contrasted. The predicted time series and associated probability distributions are plotted. The 500-year fire cycle accumulates more wood since standing biomass increases linearly over time. Higher wood biomass also leads to larger punctuated fluxes due to toppling of dead trees post fire. The distributions indicate that there are theoretically large differences in wood loading between the two fire regimes. In wetter forests (i.e., Olympic Peninsula) large wood volumes persist over time. In contrast, in drier forests (i.e., east of the Cascade crest), very low wood volumes are predicted to occur a much larger proportion of time.

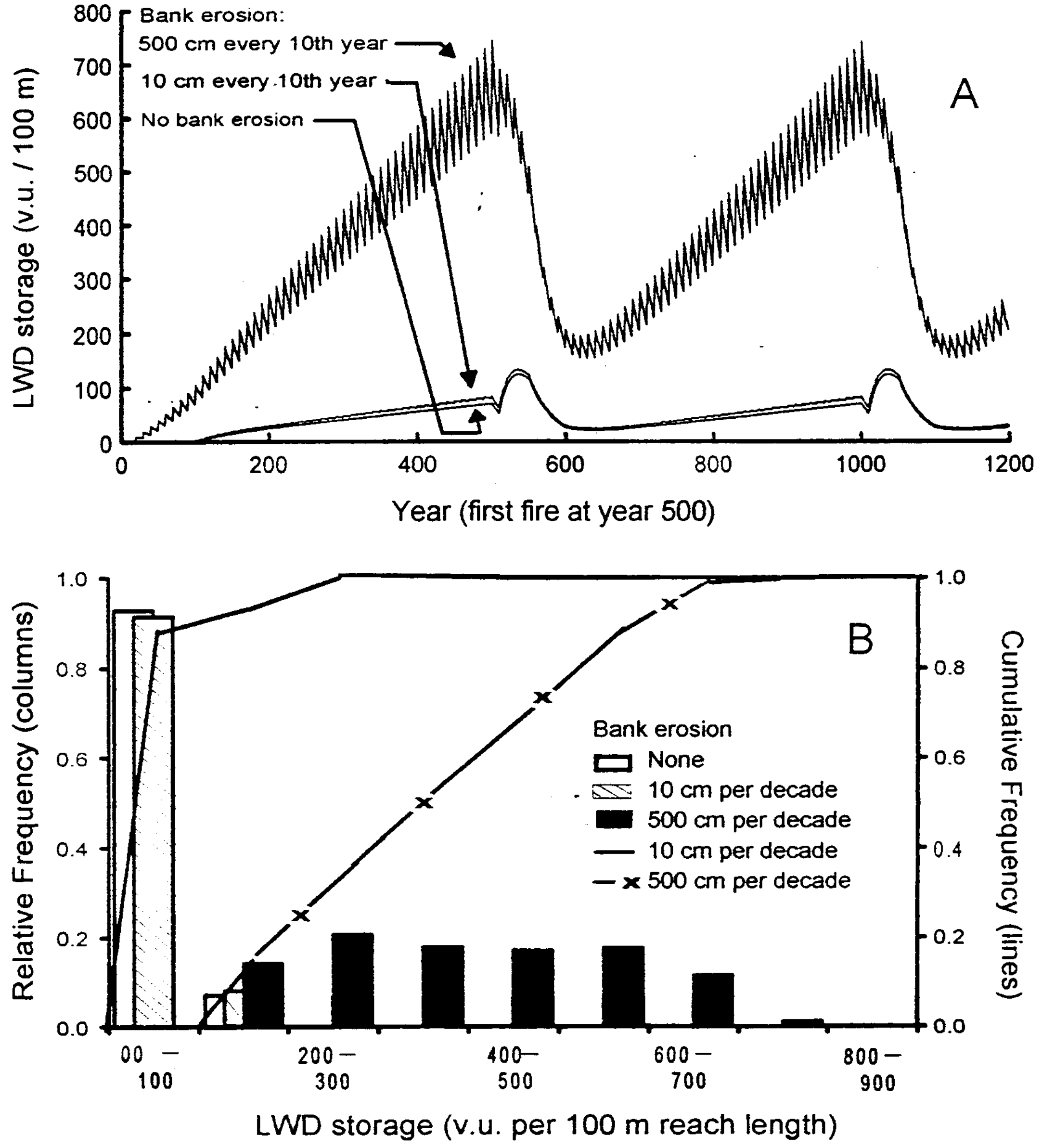

Figure 16. Bank erosion can be a very effective wood recruitment process since undercut trees tend to fall towards the channel. A simple set of rules and parameter values indicate the relative importance of wood recruitment compared to inputs from fires and mortality (using a 500 year fire cycle, see Figure 15). A 1 cm/yr bank erosion rate on one side of the channel contributes about 10% of the total wood flux. In contrast, a 50 cm/yr bank erosion rate, perhaps indicative of low-gradient and meandering channels, dominates wood recruitment (about 80%). It is predicted that bank erosion contributes approximately 50% of the total wood flux to streams when bank erosion approaches 8 cm/yr (on one side of the channel). Adapted from Benda and Sias (1998).

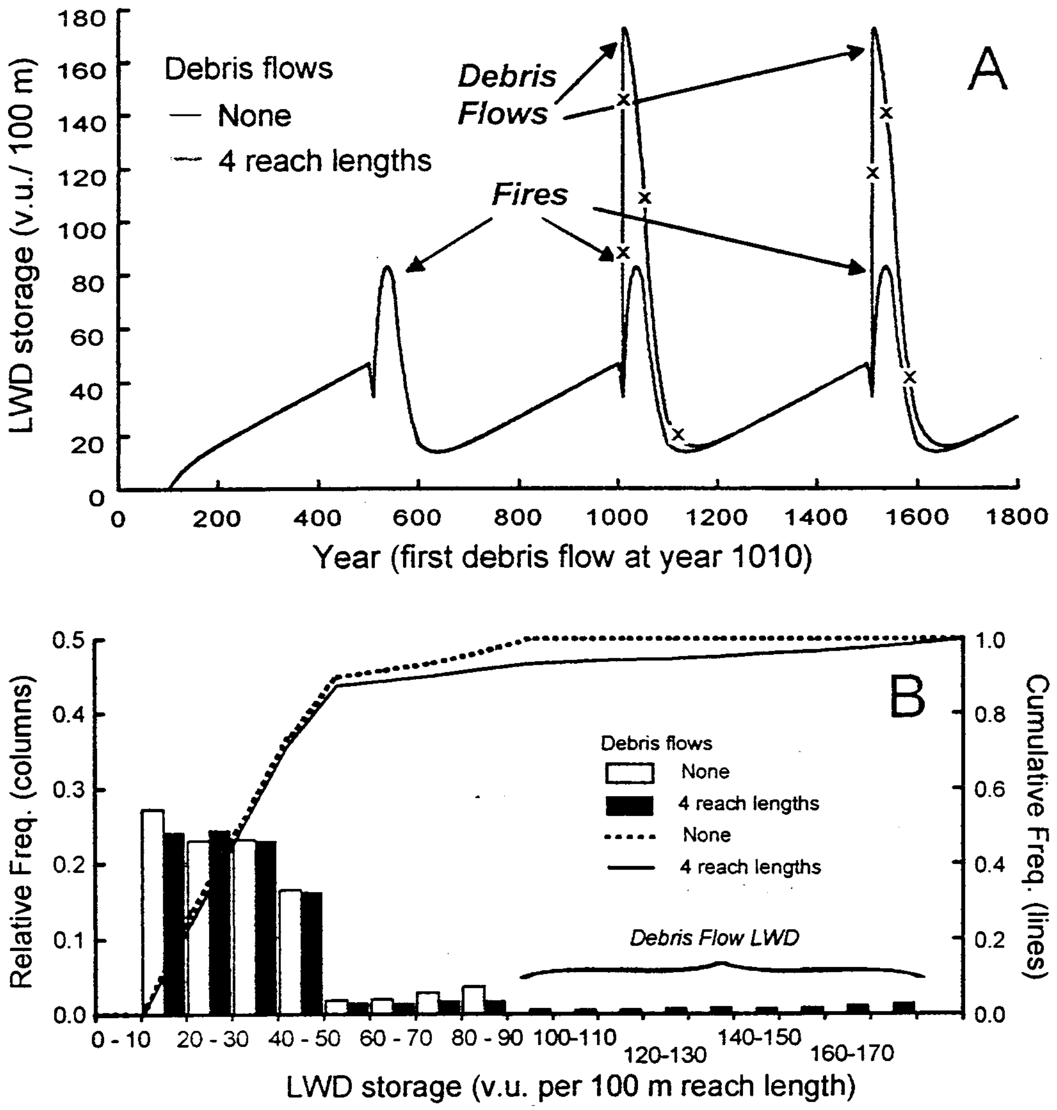

Figure 17. The role of debris flows in wood recruitment to streams in a 500-year fire cycle is shown. Debris flows occurring in first- and second-order streams account for the largest point loading of wood, even larger than post-fire toppling of dead trees. However, the predicted low frequency of debris flows (average 500 years) in conjunction with an annual decay rate of 3% limited the total amount of wood fluxed into the channel from mass wasting. The model predicted that debris flows accounted for less than 15% of the total wood recruitment in a forest with a 500-year fire cycle. However, the contribution from mass wasting will increase with increasing frequency of debris flows or a higher spatial density of landslide and debris flow source areas. Adapted from Benda and Sias (1998).