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The interactions between vegetation and erosion: new directions for research at the interface of ecology and geomorphology

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Earth Surface Processes and Landforms

ABSTRACT: Vegetation and processes of erosion and deposition are interactive. An objective of this paper is to review selected studies that emphasize the interdependencies. The reviews suggest new directions for research uniting ecology and geomorphology – the sub-discipline of biogeomorphology. The research, which recently has become vigorous, includes the sources, movement, and fates of fluvial loads of sediment, organic carbon, nutrients, contaminants, and woody debris to low-energy storage sites; the function of biota in causing soil evolution, stability, and sequestration of carbon; the development of new methods to characterize watersheds based on edaphic conditions; and the refinement of current empirical and conceptual models and dendrochronological techniques to measure landscape change. These well acknowledged topics and others less well anticipated ensure that biogeomorphology will remain vibrant. Published in 2011. This article is a US Government work and is in the publish domain in the USA.

KEYWORDS: vegetation; erosion; biogeomorphology; ecosystems and the services they provide; carbon sequestration

Introduction

Landforms are a control of vegetation, and vegetation is a regulator of landform evolution; to understand either requires the study of both (Martson *et al.*, 1995; Phillips, 1999; Corenblit *et al.*, 2007, 2010; Marston, 2010; Reinhardt *et al.*, 2010). Research into the interactions of biota, especially vegetation and a rapidly increasing global human population, with landscape form and function, particularly of bottomlands, has been energetic in the last few decades, and the dynamic nature of these studies has prompted numerous explorations into ancillary topics uniting physical, chemical, biological, and human-imposed watershed processes. The focus on these types of interdisciplinary studies is expected to continue, and a review of recent research thus provides insights of new directions, how further research might proceed. Studies of these interactions have been conducted by natural scientists for centuries, and described quantitatively at least since the late 1800s (Osterkamp and Hupp, 1996; Phillips, 1999; Marston, 2010; Reinhardt *et al.*, 2010; Hupp and Osterkamp, in press). Progress in studying the resulting ecosystems, however, has been sporadic because the understanding of ecosystems, and the services they provide (such as cleansing of water, soil genesis, and the curtailment of erosion), requires the blending of many interrelated variables. A result is an enormous but generally under-appreciated breadth and complexity of the sub-discipline of *biogeomorphology* (Viles, 1988; Thornes, 1990; Viles *et al.*, 2008), the focus of this paper.

Among the prominent foci leading up to modern biophysical studies (broadly, the effects and interactions that watershed characteristics exert on biota) have been (1) hydrologic controls, such as floods, on bottomland surfaces and vegetation, (2) formation and bioturbation of alluvial soils, (3) vegetation and hydrologic reconstructions, (4) flood-plain deposition and incision (Friedman *et al.*, 1996a), (5) sediment transport and vegetation (Friedman *et al.*, 1996b), (6) stream-corridor rehabilitation, and (7) bottomlands of regulated streams. These topics and others continue to warrant research attention, but it is clear that detailed, more narrowly considered, aspects of these lines of research must be investigated if biogeomorphology is to improve insights into how physical and biological processes combine to yield stable, equilibrated ecosystems. A case in point was discussed at the 2009 Binghamton Geomorphology Symposium, Blacksburg, Virginia. There it was noted that a large majority of investigations examining channel characteristics resulting from variable fluxes of water and sediment focus on simple, single-thread channels at the expense of complexities such as braided streams and channel islands.

Using selected studies as examples of the myriad of biophysical topics recently accented by watershed researchers, an objective of this paper is to identify areas of investigation needing and likely to receive research attention. Several research directions are proposed that, with focused attention, may improve our ability to comprehend watershed and landscape functions. Included are the interpretation of the changes in those functions as they occur (Catton, 1982; Murray, 2007), the ability to anticipate changes in function in reaction to alterations imposed on ecosystems (Costanza *et al.*, 1997), and the recognition of the ecosystem services [the production of renewable natural resources through processes yielding clean water, soil, vegetation, and wildlife (Osterkamp, 2008)] that are provided by watersheds. Much of this perspective is expressed as examples of specific research topics that have received minimal attention but may be essential to near-term progress in understanding both natural and human-stressed ecosystems. The examples are loosely lumped into three overlapping groups that emphasize (1) the movement and fate (change) of mixtures of sediment, organic material, nutrients, and contaminants to low-energy storage sites (Noe and Hupp, 2005, 2009; Hupp *et al.*, 2009), (2) the role of biota in furthering soil evolution and stability (Gabet *et al.*, 2003; Gyssels *et al.*, 2005), and (3) the application of advanced approaches to landscape modeling, to the effects of climatic change on watershed characteristics, and to techniques such as dendrochronology and the measurement of variable rates of mass movement (Alestalo, 1971; Kirkby, 1990; Arbellay *et al.*, 2010; Goodrich *et al.*, 2010). These well acknowledged emphases provide a means to understand where knowledge gaps are noteworthy and to anticipate which topics are likely to be most actively studied in the next decade or two.

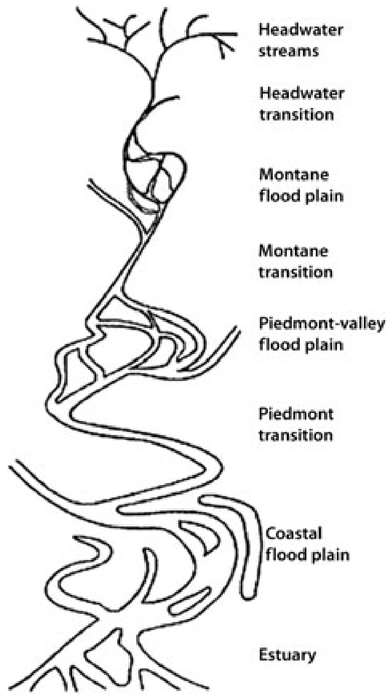

Figure 1. Depiction of the biophysical continuum, showing a representative downstream order of bottomland environments of a sub-continental scale drainage basin (from Stanford *et al.*, 1996).

Movement, Deposition, and Fate of Sediment and Related Loads

Many studies chronicling the movement of soil and sediment particles have been conducted, published, and applied to programs such as those of reservoir-deposition rates, sedimentation in irrigation canals, and damage to municipal water systems. Most, however, have treated the subject as physical loads of fluvial sediment or water-entrained mixtures of sediment and organic material. Often lacking has been consideration, and documentation, of (1) rates and volumes of sediment and plant material trapped upslope or upvalley from critical areas such as estuaries, and the role of vegetation in effecting the storage of the material, (2) on-site (autochthonous) versus external (allochthonous) sources of organic material, and (3) residence time of flood-plain deposits relative to erosion and the effects of vegetation. Closely related to the topic of sequestration of sediment and carbon in low-lying areas, such as the Coastal Plain of the south-eastern United States, is how much sediment and plant debris are stored annually in bottomlands at sub-continental areal scales. This topic has received very little research (Hilton *et al.*, 2008), but knowledge of these processes has application to other low-energy depositional environments as well as to fine-grained rock units of the stratigraphic record.

Much more realistic characterizations of natural drainage basins than Schumm's *Fluvial System* (1977) are conceptual models of the river or biophysical continuum (Vannotte *et al.*, 1980; Stanford *et al.*, 1996). Although an idealization as well, the biophysical-continuum model (Figure 1) acknowledges variable topography and energy conditions in any applicable large drainage basin. In like manner as the simplified representation of Schumm (1977), the biophysical continuum predicts the movement of sediment and organics from parts of a watershed of net erosion (i.e. headwater, montane-transition, and piedmont-transition areas) to sites of net storage on flood plains and in water bodies. Stream-gage records, especially those at which suspended-sediment transport is measured, have been invaluable indicators of the fluxes of water and sediment passing those sites, but they integrate all inputs from upslope and do not specify from where in a drainage basin the water and sediment originate or the times and proportions of the inputs that have been re-mobilized from the sites of storage.

Information of this sort can provide an ability to evaluate sources of sediment and plant material that may contribute to the filling of a reservoir, the clogging of an irrigation system, or the contamination of a public water supply (Walter and Merritts, 2008). Future investigations that quantify the average amount of fluvial sediment and plant debris stored annually on flood plains or in estuaries have the potential to refine estimates of where and how much carbon is sequestered terrestrially and in non-marine waters. Relative to agricultural productivity, human safety, and the health of biota in general, these studies can provide information vital to the understanding of ecosystem services and identify areas of storage for manufactured contaminants that present dangers of toxicity to all parts of the food network.

Examples of the types of investigations that may receive future attention are those that measure the flux rates and storage of fluvial sediment, plant material, organic load, and nutrients onto and from bottomland surfaces, those that identify the proportions of the imported versus locally derived loads of these fluxes and characterize the biochemical and hydrochemical processes that determine the manner and longevity of their storage, and those that measure the ability of vegetation and vegetative debris to effect the storage of plant debris during floods (Friedman and Lee, 2002). These three lines of fluvial inspection have distinctly different goals but the processes resulting in an ecosystem identity by each are difficult to separate.

The bottomland of a large, meandering river that maintains extensive alluvial surfaces of flood plain and low terraces (e.g. piedmont-valley or coastal flood plain of Figure 1) is represented diagrammatically in Figure 2. Overbank flow establishes hydrologic connectivity between the river and inundated surfaces during low-magnitude (normal) flooding and transports sediment (including organic material), nutrients, and contaminants onto the several alluvial surfaces, upon which they are

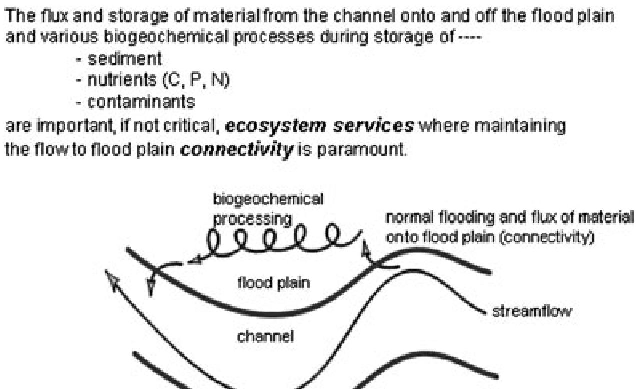

Figure 2. Diagram of the channel of a large river representing the flux and storage of sediment, nutrients, and contaminants onto and off of the flood plain and related bottomland surfaces during overbank flow (adapted from Hupp *et al*., 2009).

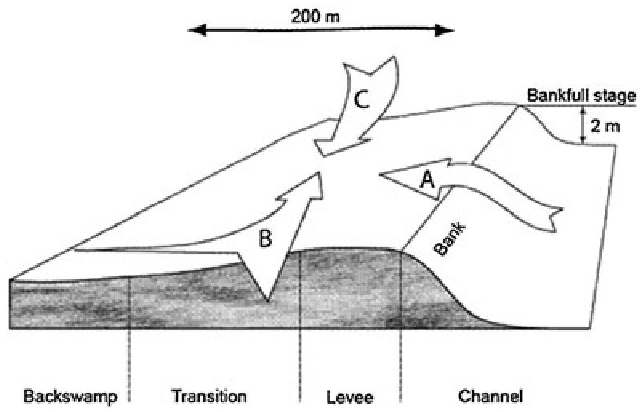

Figure 3. Diagram showing potential sources for deposition of fluvial sediment on a small area of coastal flood plain of the Atchafalaya River, Louisiana: (A) from an adjacent channel, (B) from an upstream slough, (C) from a downstream slough (Hupp *et al*., 2008).

deposited and stored for periods ranging from hours or days to millennia (Piégay, 1997; Hupp *et al*., 2009). If stored for millennia, the deposits may contain natural amounts of nutrients and organic materials, but if the storage time has been years to decades, much of the sediment and other flood deposits may be influenced physically and chemically by human activity.

While in storage, the flood deposits, including fine sediment, nutrients, and manufactured contaminants such as agrochemicals and industrial wastes, are subject to biophysical and chemical change. As long as a potential for connectivity, reentrainment, and transport of the material back to the fluvial system, persists, the changes that may occur in these materials can have highly significant effects on the ecosystem services that are provided through normal, or natural, biochemical processing. The degree to which these changes affect the entire biophysical system is nearly unknown, and research to understand these processes is of vital importance in the next few decades to understand how biota, specifically and in general, are affected.

The provenance, or origin, of sediment stored in a drainage basin or ecosystem with related plant-decay products, carbon compounds, and contaminants is a principal determinant of the biogeochemistry of the system and its ability to support a healthy plant cover and minimize erosion. Detailed data collection and analyses of subbasin contributions of fluvial loads and deposits are needed to gain the ability to identify sources of carbon available for storage and contaminants that may prove detrimental to the food network (Dunne and Black, 1970; Walter *et al*., 2000; Gburek *et al*., 2002). Increasing attention is also being focused on an ability to ascertain site-specific sources of contaminated sediment that may prove deleterious to the food network and food supplies (Gellis *et al*., 2009; Gellis and Walling, 2011).

Several studies have been conducted in recent years to identify the proportions of fluvial sediment derived from external versus on-site sources (e.g. Hupp *et al*., 2008; Gellis *et al*., 2009). The imported versus locally derived loads of these flows characterize the biochemical and hydrochemical processes that determine the manner and longevity of the storage, thereby defining the ecological conditions under which either native or agricultural vegetation will establish (Figure 3). Of at least equal importance, analyses of sediment contributed from tributary watersheds of a drainage basin can provide chemical signatures, 'fingerprints', of inputs from those tributary watersheds that lead to an understanding of active erosion/sediment-transport processes within the subbasins (Gellis and Walling, 2011). Knowledge of these processes provides insights into how applied management of bottomlands affects ecosystem health, long-term soil stability, crop production, and species richness of native vegetation. Considerable potential remains to increase the understanding of these processes and thereby to fill some of the knowledge gaps.

The storage of woody debris on bottomland surfaces and the quantification of its effect to induce either erosion or deposition during overbank discharges have received inadequate attention (Piégay, 1997; Lancaster *et al*., 2003; Webb and Erskine, 2003). The potential for investigations of this sort is widespread, with flood debris and deposits often remaining for decades on numerous alluvial surfaces of a large range of stream sizes (Figure 4). Advances in flood-hazard prediction, for example, seem feasible by calculations of the shear stresses caused by tree stems and stored woody debris at a range of flood stages. The calculations, possibly through two dimensional (2D) or three dimensional (3D) models, could yield insights into the magnitudes of vegetation-related scour and deposition during destructive flood events.

The distribution of the global carbon inventory is and will continue to be intensely studied by earth and atmospheric scientists, economists, and national leaders. A notable portion of the carbon budget is represented by carbon sequestered in fluvial and tidal-flat deposits (Li *et al*., 2010). The carbon stored in these deposits can be very significant along low-gradient coastal-plain streams and any other low-energy environment, where, if not fully sequestered, it becomes available for numerous biochemical processes.

A notable example of large-volume sediment and carbon storage is the Atchafalaya River Basin, which contains the only semi-natural riparian area along the mainstem Mississippi River downstream from its confluence with the Ohio River. The Atchafalaya River is formed from the Red River and diverted flow of the Mississippi River in the 'Old River Outflow Channel' (arrow from B to A, Figure 5), in eastern Louisiana at the south-western tip of Mississippi. The Atchafalaya River Basin (rectangular area, Figure 5) receives water and sediment from the Red River and the Mississippi River. Outflow from the Atchafalaya River Basin through Wax Lake Outlet (C, Figure 5) represents about 40% of the flow from the Atchafalaya River Basin to Atchafalaya Bay and the Gulf of Mexico, and the Lower Atchafalaya River (D, Figure 5), below a diversion to the Wax Lake Outlet, represents the remaining 60% of the outflow.

Recent estimates (Hupp *et al*., 2008) suggest that average annual sequestration in the basin is 4·3 billion kilograms of sediment, 435 million kilograms of organic material, and 175 million kilograms of total carbon (Figure 5). The loss of similar

Figure 4. Photographs of woody debris deposited against cottonwood trees during a high-magnitude flood of 1965, Plum Creek, central Colorado. (A) Stored debris, volume about 75 m^3, on a low terrace; (B) small accumulation of debris stored following toppling of one or more trees by the flood waters, resulting in an erosion pit and scour (photographs by W. R. Osterkamp, April 1983).

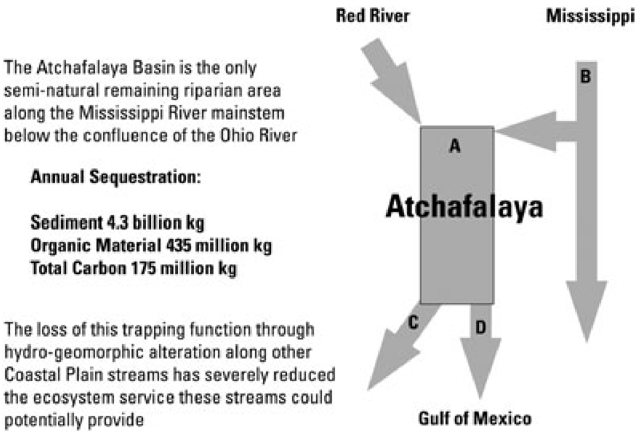

Figure 5. Schematic diagram showing inputs of sediment, organic material, and total carbon to the Atchafalaya Basin from the Red and Mississippi Rivers. (A) Headwaters of the Atchafalaya River; (B) Mississippi River upstream of diversion into the Atchafalaya Basin; (C) Wax Lake Outlet; (D) lower Atchafalaya River below diversion into the Wax Lake Outlet.

trapping function owing to alteration by hydroelectric plants (dams), levee construction, and channelization along other Coastal Plain streams has severely reduced the ecosystem service that these streams could otherwise provide by limiting streamflow connectivity with the flood plain. The significance to these estimates relative to analogous fluxes of sediment, organics, and carbon of other low-energy rivers worldwide is that disruption by human-imposed structures, particularly dams and reservoirs, may drastically reduce the inputs to areas of potential carbon, nutrient, and seed sequestration, thereby limiting ecosystem function (Johnson *et al*., 1976; Williams and Wolman, 1984; Johnson, 1994). Studies of the sediment and carbon fluxes of large rivers are imperative to achieve the goal of quantifying that portion of the global carbon distribution and its effect on possible global warming.

Although coastal plains and similar moist, low-gradient environments are important areas for carbon storage, other low- to moderate-energy landscapes receive and store sediment from upslope areas and may sequester significant amounts of carbon. Examples are stable montane and piedmont-valley flood-plain surfaces of medium- to large-sized rivers of continental interiors (such as lengthy reaches of the Missouri, Mississippi, Arkansas, and Snake Rivers, North America), natural grasslands and flood-plain areas of semi-arid and arid areas (de Steiguer, 2008), and areas of late-Pleistocene glaciation with numerous lakes and low-gradient streams of an immature drainage network (Figure 6). Relative to native grasslands, but no doubt other low-energy depositional environments as well, climate, hence future climate change, is the most important variable of soil-carbon dynamics, and increased understanding of those dynamics will depend on the integration of carbon-storage studies with effects of imposed management techniques (J. Brown, New Mexico State University, personal communication, 2010). An aspect of achieving a successful integration of carbon-storage knowledge with applied management is variable-source inputs to any sequestering system. Contributions per unit area of carbon from different tributary watersheds to a storage basin, for example, may vary substantially, thereby introducing complexity to the measurement and understanding of a system.

The Role of Biota in Furthering Soil Evolution and Stability

Vegetation and landforms of bottomland areas of watersheds are intimately linked with the uplands and through long-time periods they co-evolve by interacting processes and dynamic feedback mechanisms to yield stable landscapes (Marston, 2010). Two somewhat related interfluvial areas of geomorphic interest for which vegetation may play an important role are (1) the variable-source, or partial-area, concept in relation to recharge and runoff, and (2) the impact of tree uprooting (tree throw) on slopes. Regarding the former, not all areas in a catchment contribute equally to streamflow, particularly storm runoff (Hewlett and Hibbert, 1967; Dunne and Black, 1970; Bull *et al*., 1995; Walter *et al*., 2000). In consequence, sediment and related contaminants unique to a sub-watershed may be entrained and contribute to total loads of the catchment. Although the variable-source concept has been in use for at least four decades, its application has been, surprisingly, limited and increased, more sophisticated, use may prevail in the future.

Downslope movement of sediment may be greatly facilitated by tree throw (the uprooting of trees) (Denny and Goodlett, 1956; Mills 1984; Schaetzl *et al*., 1989; Norman *et al*., 1995; Gabet *et al*., 2003). In addition to geomorphic impacts, tree throw and the creation of canopy gaps may play a major role in forest ecology/community composition (e.g. Goodlett, 1954;

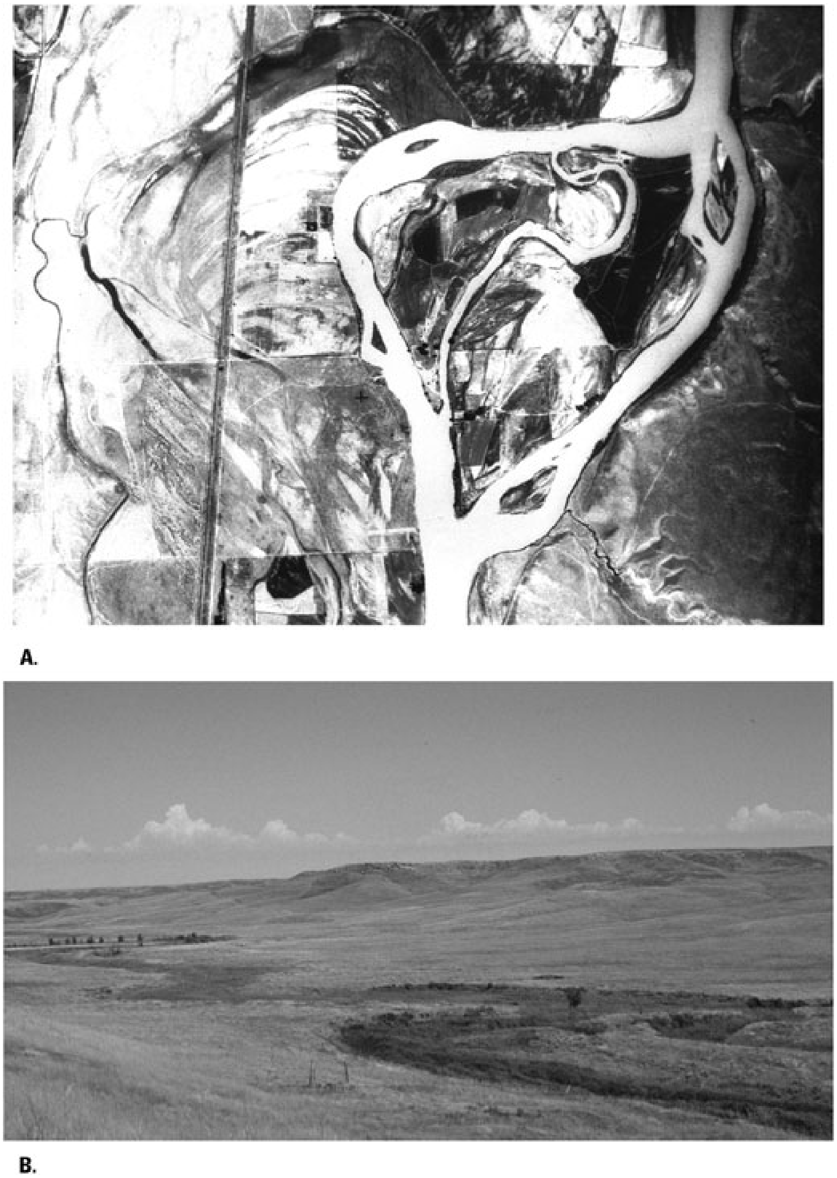

Figure 6. Photographs of bottomland areas of sediment and carbon storage. (A) Snake River, western Idaho, showing on-going flood-plain dynamics of both erosion and deposition; (B) the Foster Creek watershed, central South Dakota, where carbon is being stored on grassed upland surfaces as well as on moist bottomland surfaces.

White and Pickett, 1985). Soil disturbance by tree throw creates a pit-and-mound topography that can affect as much as 40% of the land surface in northern temperate forests (Denny and Goodlett, 1956). Because there are strong relations between mound volume and tree diameter (Gabet *et al.*, 2003) or trunk basal area (Lenart *et al.*, 2010), the species composition and tree ages and sizes within a forest may substantially affect sediment-flux rates. In regions with relatively high relief, tree throw may be among the most important agents of sediment transport (Norman *et al.*, 1995). Some studies have estimated rates of soil transport based on amount of tree throw per unit area (Mills, 1984; Osterkamp *et al.*, 2006: Lenart *et al.*, 2010). Gabet *et al.* (2003) produced an equation that predicts sediment flux averaged over space and time as functions of tree throw and hillslope properties (e.g. slope, direction of throw, soil density). Their equation predicts an average horizontal sediment flux of 8 m^3/ha/yr for a variety of forest types on a 10º slope and using data from Denny and Goodlett (1956) predicts a flux of 9·8 m^3/ha/yr in a northern hardwood forest. Thus, tree throw represents a substantial mechanism for slope denudation. Further, Osterkamp *et al.* (2006) have shown that tree throw may account for much of the fluvial sediment transported by high-gradient streams in semi-arid parts of western North America.

The effects of tree throw in forested uplands are exacerbated by other, often closely related, forms of bioturbation. Large trees on sloping surfaces provide a surcharge of weight, hence shear to upper soil horizons, that can promote soil creep and ultimately the toppling of trees and discharge of soil into streams. Near-surface soil bioturbation by root growth and decay, burrowing by mammals and other small vertebrates, particle mixing by invertebrates such as insects and worms, and chemical reduction of biological compounds within soils can combine to effect site-specific churning processes of upland soils. Integrated into larger spatial and temporal scales, these biophysical processes cause landscape disturbance and landform evolution of the types described so eloquently decades ago by investigators such as Cowles (1899), Clements (1916), Goodlett (1954), and Hack and Goodlett (1960).

Aspects of bioturbation that are widely recognized as basic processes of soil genesis but generally are overlooked as controls of erodibility and landscape evolution are the effects, hence health, of soil micro-organisms and organic compounds. Although very poorly understood, contamination of soils, resulting in soil toxicity, by a wide variety of manufactured organic compounds, particularly agricultural herbicides and fertilizers, may lessen the metabolic activity of soil organisms and in consequence reduce soil cohesiveness and resistance to erosion. Identification of the manner by which nutrients and contaminants (especially herbicides, pesticides, and pharmaceuticals) are transformed while they are in fluvial storage and the role of vegetation in causing the transformations have been and will continue to be research foci. Furthermore, the flux and storage of material from channels onto and off the flood plain, and various biogeochemical processes during the storage of sediment, nutrients (carbon, phosphorus, and nitrogen), and contaminants are important, perhaps critical, controls of ecosystem services and flood-plain connectivity (Noe and Hupp, 2005, 2009).

The potential, and therefore a need for research, of the toxic effects by unstable contaminants moved to streams and subsequently onto bottomland surfaces is illustrated by widely used agrochemicals. Classes of herbicides commonly applied to agricultural fields that may lead to water contamination are triazine, chloroacetanilide, and pleyurea. The fate, toxicity, half-lives, and degradation pathways of these chemicals and their metabolites are poorly known, but depend on interactions with vegetation. Triazine yields at least nine metabolites of concern, chloroacetanilide, six, and phenylurea six (Scribner *et al.*, 2000). Pathways for degradation of atrazine, which in soil degrades by both biotic and abiotic processes to a variety of metabolites, occur through a complex series of possible reactions (Figure 7). The longevity and toxicity of these metabolites are not well known. Until the degree of toxicity and mobility of the various herbicides and their metabolites are determined, the deleterious effects to biota in general, and to mammals specifically, can only be presumed.

Current Approaches to Landscape Modeling, Effects of Climatic Change, and Dendrochronology

Processes of sediment, carbon, and contaminant sequestration in altered fluvial and riparian-vegetation conditions remain

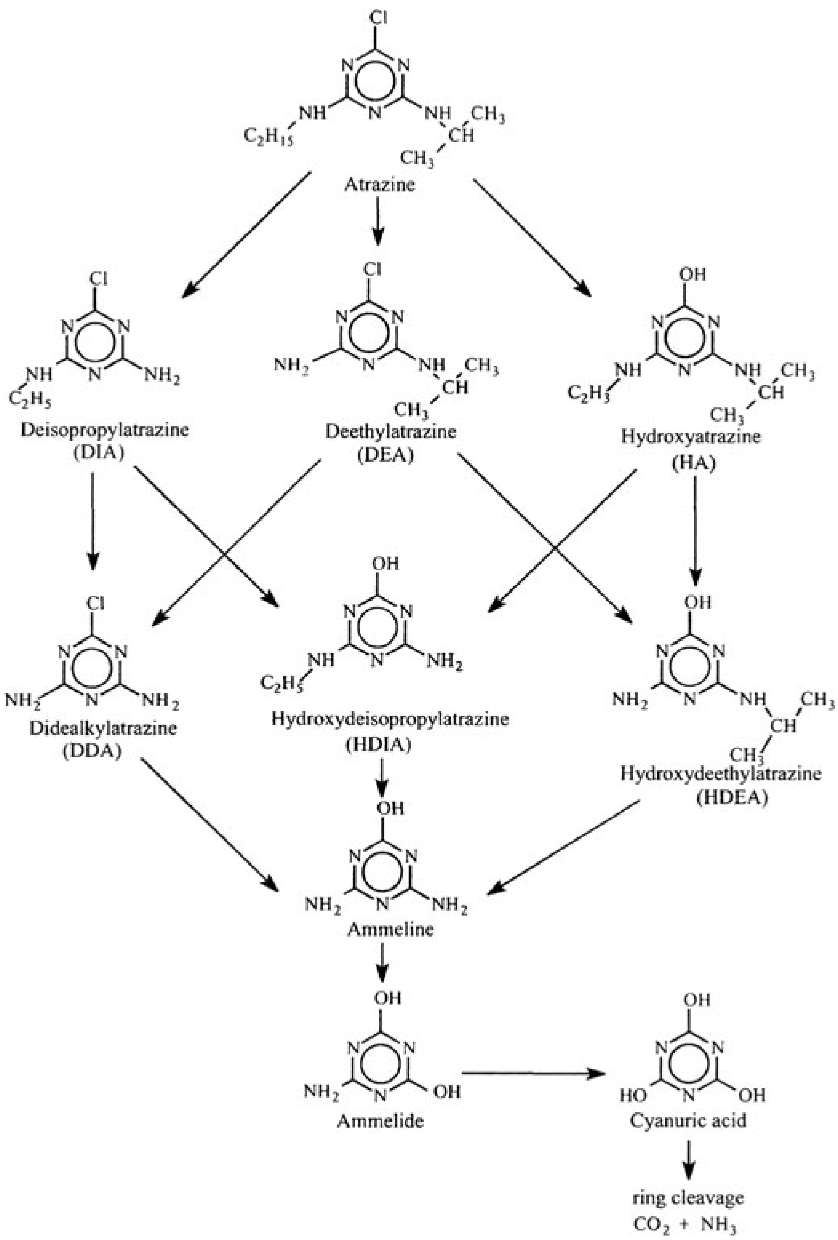

Figure 7. Flow chart showing pathways for degradation of atrazine by hydrolysis to ammeline, ammelide, and cyanuric acid (Scribner *et al.*, 2000), all of which are unstable at elevated temperatures but in soil may occur as salts of unknown persistence.

poorly studied. Among the most common and destructive forms of human-imposed stresses to biophysical systems are dams, reservoirs, channel alterations, and related accommodations to agriculture and urbanization. Agriculture of bottomlands often causes erosion and detrimental sediment deposition owing to containment by dikes and levees of flood flows. These structures affect the storage and movement of nutrients and other agrochemicals. Study of the influence of these processes on non-agricultural bottomland vegetation is needed to understand their effects. Some human-caused problems can be reduced or eliminated through modern practices of hydraulic and agricultural engineering, and many of the observed effects of imposed riverine change can be measured, both spatially and temporally, by the use of current methods of tree-ring analyses.

The development of empirical and conceptual models to describe interactions between erosion and vegetation has been a major means of addressing the research issues discussed earlier. In general, empirical models provide an ability to predict or estimate fluxes of water, sediment, and related fluvial loads, whereas conceptual models permit an interpretation of processes active in a given fluvial or landscape setting. Both provide valuable contributions and appear likely to be aggressively pursued in the near to intermediate future.

An ability to predict soil loss accurately and thereby enhance farm productivity has been a goal of agriculturalists and soil scientists for many decades (Wischmeier and Smith, 1965, 1978). Among early investigators, Cook (1936) recognized three major controls on soil loss by water: (1) susceptibility of soil to erosion, (2) potential erosivity of rainfall and runoff, and (3) soil protection afforded by plant cover. The first two controls are physical processes and could be studied empirically and quantitatively, leading to extensive research by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) and a series of empirical factor equations. The soil-loss prediction algorithms were designed mostly for hillslopes but are applicable also to bottomland agricultural areas (Marston, 2010). Included are the Universal Soil Loss Equation (USLE) (e.g. Wischmeier and Smith, 1965, 1978), versions of the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1997; Widman, 2004), and models of the Water Erosion Prediction Project (WEPP) (Flannagan and Nearing, 1995).

The third control, plant-cover protection, includes the reduction of erosion by rainsplash impact and resistance to erosion by vegetation roughness and soil cohesion due to roots. WEPP models in particular are concerned with the potential for gullying due to the concentration of runoff along natural drainageways of small watersheds, whereas a current version of RUSLE, RUSLE2 (Widman, 2004), is incorporating thousands of vegetation data bases, mostly for cropland, to permit correlations between soil loss and plant cover. Recent advances in model construction have included additions to consider (1) senescence dates for perennial plants, (2) canopy height in forested areas, (3) filter strips of native trees along streams to augment conservation and erosion-control methods, and (4) an algorithm to estimate root biomass (T.J. Toy, University of Denver, personal communication, 2010).

Progress on the ability to estimate the magnitude and collective effects of below-ground biomass, fungi, and microorganisms has been slow and may represent another near-term research emphasis. Most, if not all, erosion-prediction models contain algorithms for erodibility, an expression of the susceptibility of a soil surface to the erosion process. These algorithms concentrate on the ability of plants to cover and protect the soil from particle detachment and entrainment by moving water, but relative to micro-vegetation (microscopic in size) of soils, the algorithms, whether applied to cultivated fields of hillslopes or of lowlands, inadequately describe the ability of organic components of the soil to bind soil particles and inhibit erosion by surface runoff.

The combining of two or more empirical models to construct much more versatile, powerful predictive tools than would otherwise be feasible is certain to be performed routinely in coming years. For example, KINEROS2 (K2) (Goodrich *et al.*, 2006; Semmens *et al.*, 2008) is a broadly updated version of the KINEROS (Woolheiser *et al.*, 1990; Smith *et al.*, 1995) kinematic runoff and erosion model. KINEROS/K2 has traditionally been an event-based, physically-based model describing the processes of interception, infiltration, runoff generation, erosion, and sediment transport from small agricultural and urban watersheds for individual rainfall-runoff events. Recently the model has undergone a major restructuring. The recoding has enabled the addition of several major enhancements by incorporating sub-models of Opus2 (O2) (Diekkrűger *et al.*, 1991; Smith, 1992; Heatwole *et al.*, 1998) to form a continuous K2-O2 model. Among the enhancements permitted by O2 (Müller *et al.*, 2004) is the ability to determine estimates of soil–water dynamics and movement of agriculturally derived contaminants such as atrazine (Figure 7). The combined K2-O2 model will treat the major biogeochemistry cycles of carbon, phosphorus, and nitrogen, and will include a plant-growth sub-model treating changes in plant cover, soil–water conditions, and the soil and plant characteristics of a catchment or catchment portion (Goodrich *et al.*, 2006, 2010). Thus, it will accommodate changes in catchment management such as harvesting, planting, fertilizing, and tillage (D.C. Goodrich, USDA Agricultural Research Service, personal communication, 2010).

An example of current efforts to model the effects of vegetation on soil erosion is instructive. Although designed primarily for hillslopes, a recent model by Wang *et al.* (2008), which considers large plants, assesses the likely extent of soil erosion under three vegetation-influenced and often human-controlled conditions: (1) increasing plant cover and decreasing erosion, (2) decreasing plant cover and increasing erosion, and (3) transitional states between conditions 1 and 2. The model is intended for application in watersheds of high sediment yield owing either to deficient rainfall or stress resulting from poor plant cover due to human disturbance. Conceptual models and flume studies describing the reverse, the effect of hillslope or bottomland erosion and deposition on vegetation patterns are numerous (e.g. Graf, 1978; Johnson, 2000, 2002; Zong and Nepf, 2010), but attempts to develop digital models indicating how vegetation is affected by erosion or deposition have been sparse. Interactive changes in vegetation due to erosion, however, can be estimated by use of current versions of RUSLE (Widman, 2004) and WEPP (Flanagan and Nearing, 1995).

Closely related to factor equations to estimate erosion is modeling to anticipate carbon-sequestration potential relative to climate, vegetation cover, and management (Brown *et al.*, 2010). In a context of global climate change, carbon inventories and gradients of the stored carbon will receive increasing attention in the near term, both for the collection of basic data and the study of carbon migration into, through, and from soils of various climates and land-management practices. Results of such data collection and research will lead to abilities to predict changes in soil–carbon levels at the drainage-basin and landscape scales (Brown *et al.*, 2010).

The use of controlled conditions, flume experiments in particular, to understand biological and geomorphic interactions and develop empirical models has been employed extensively in recent decades and seems likely to continue to remain an important research tool. Past investigations, however, have mostly been of limited scope, designed to pursue questions of flow and sediment processes relative to channel change, and unequipped to consider effects of vegetation. The next generation of flume studies likely will explore interactions among fluxes of water and sediment, channel morphology, and vegetation. An example of how this line of investigation may proceed in the near term is given by a series of laboratory experiments conducted by Tal and Paola (2010).

The role of plant roots in channel dynamics, specifically bank stability, has received increasing attention during the past decade. Numerous studies have used the exposure of roots as a vehicle to estimate magnitude of bank erosion, but the ability of roots to prevent erosion remains poorly understood. Recent research, however, has shown that the roots of riparian vegetation may increase the geomechanical stability of stream banks dramatically (Pollen and Simon, 2005).

The influence on channel dynamics by vegetation in flume studies is generally difficult to evaluate, but the prudent use of proxies to simulate vegetative effects may provide data that bypass this difficulty. The study of Tal and Paola (2010) may be a harbinger of flume techniques that increasingly will be used as interactions between vegetation and small-scale channel dynamics are understood in greater detail. Alfalfa seeds, which sprouted and vegetated freshly deposited bars of a braided-channel system, progressively focused high flows of repeated cycles of alternating short-duration high flows and long-duration low flows into a single, dominant channel. Thus, the effects of the alfalfa plants prevented a reversion to a braided-channel condition, and conversion to a single-thread channel was irreversible on a short time scale. Whether applied to erosion-prediction technology, to channel-evolution models, or to conceptual models that will be used to understand the feedback mechanisms that vegetation imposes on channel processes, this sort of investigation inevitably seems likely to be conducted in laboratory experiments in the next decade or two.

The use of conceptual models to describe biogeomorphic processes has been an important tool within the natural sciences for at least half a century. In a classic paper on the relations between plant ecology and geomorphic form and process, Hack and Goodlett (1960) showed that forest types could be related to slope types where convex-upward slopes contributed mostly to runoff; concave slopes contributed mostly to ground-water recharge, and linear slopes were intermediate. They produced a map, a conceptual model, of vegetation types using key species that clearly delimited slope declivity and laid the groundwork for future studies. By present-day standards this sort of model to some may seem simplistic, but it yielded unrecognized insights at the time into interactions among topography, forest composition and stem density, and surface-water and ground-water hydrology. Although basic approaches of this sort to the understanding of ecosystems may be less favored now than those weighted with complexity and sophisticated algorithms, they remain a powerful and perhaps under-ultilized method by which landscape/vegetation interactions can be investigated.

The study area of Hack and Goodlett (1960) in central Appalachia was revisited and investigated 35 years later by Osterkamp *et al.* (1995), suggesting possibly that conceptual models continue to have relevance. They confirmed the key role that landform–water relations play in vegetation distribution across both fluvial and interfluvial surfaces. Vegetation mapping to delineate variable-source areas was explicitly advocated by Dunne and Black (1970), and was implemented in the UK, especially, where upland vegetation types have been successfully related to runoff in studies by Gurnell and Gregory (1987, 1995) and Thornes (1990).

The use of conceptual and numerical models to understand and predict landform response to human intervention of hydrologic and fluvial-geomorphic systems appears to be gaining increasing attention (Kirkby, 1990; Phillips, 1999; Corenblit *et al.*, 2007; Osterkamp and Hupp, 2010). A prime example of the application of a conceptual model to describe change due to human-imposed stress is the still-useful channel-evolution model of Simon and Hupp (1987). The model is a six-stage representation of progressive changes in channel form integrated with woody riparian vegetation following disturbance (Figure 8). Similar models that address other stresses, such as resistance to flow by vegetation (Klopstra *et al.*, 1997; Stephan and Gutknecht, 2002), volcanic activity, fire, or mass movement, and other time scales including those appropriate for addressing global climate change and vegetative reaction (e.g. Knox, 1972; Kirkby, 1990; Phillips, 1995), are bound to gain increased detail in coming years and decades.

The application of dendrochronological techniques to the study of landforms and fluvial processes has a long, highly productive record (e.g. McKenney *et al.*, 1995; Hupp and Bornette, 2003) and dendrogeomorphic analyses (Alestalo, 1971; Stoffel *et al.*, 2010) of erosion rates and processes promise to continue to yield invaluable research results. Erosion has visible and very direct impacts on vegetation, as does vegetation on erosion. The use of tree-ring variations, roots, and bole damage and inconsistencies, however, remains an incompletely tapped source of information on frequency and magnitude of floods, ages of bottomland surfaces, times of fire and forest disease, periods of disturbance such as drought, mass movement, and volcanic activity, and the understanding of erosional and depositional processes.

An understanding of basic processes of alluvial-bottomland erosion and deposition are easily broadened by the consideration of standard tree-ring data, but surprisingly this approach is often disregarded. It appears likely that techniques including dendrochronological observations will be applied routinely in future field investigations. Long-recognized but infrequently applied dendrochronological techniques to determine rates of channel migration and a time-series of channel incision and establishment of inset terraces are given by examples from the coal district of southwestern Virginia and Mount Shasta, northern California. The first (Figure 9) illustrates movement of a stream channel affected by surface mining as documented by 25-year alders on the flood plain and a later growth of sycamore trees on a depositional bar. The second example (Figure 10), from a glacial-meltwater stream incising volcanic rocks of Mount Shasta, shows how dates of cohorts of pine trees were used to determine when seven separate inset terraces of Ash Creek originated and became preserved. Similar examples are from the Swiss Alps, where damage in old trees and germination times of in-channel vegetation were used to date paleochannel activity (Bollschweiler *et al.*, 2008; Arbellay *et al.*, 2010), spatio-temporal dynamics of source-to-sink (Lugon and Stoffel, 2010), and deposition processes (Stoffel *et al.*, 2008) on alpine debris-flow cones.

LaMarche (1966, 1968) was among the first to analyze changes in roots to document erosion. His quantification of long-term *degradational rates* was based on changes in growth concentricity, kill dates of roots, and vertical distance between the root axis and the underlying ground surface. Similar approaches have been used to assess medium-term slope retreat (Hupp and Carey, 1990) and gully erosion (Vandekerckhove *et al.*, 2001). Rather than using changes to the root axis, Carrara and Carroll (1979) examined microscopic growth in roots, such as compression wood or the initial cambium dieback ('scar' formation), to calendar-date exposure of roots affected by hillslope erosion.

Abrupt suppression of growth as well as tangential rows of traumatic resin ducts are now being used to recognize

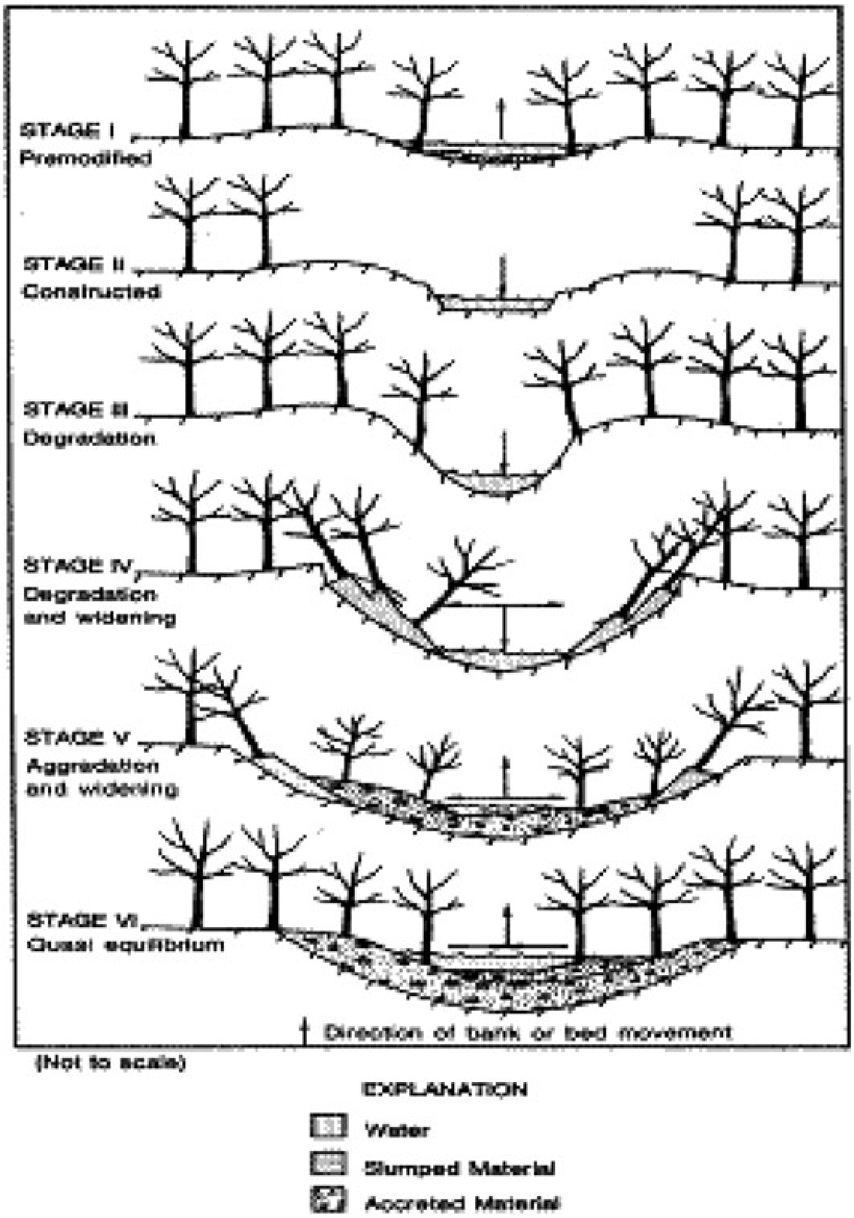

Figure 8. Diagram of a conceptual channel-evolution model that recognizes five stages of adjustment following a pre-modified condition (stage I) and progressing through channel responses to re-establish an adjusted condition (stage VI) (adapted from Hupp, 1992).

anomalies that reflect erosion in the root zone. As a further result of the loss of edaphic cover, that is, the uppermost soil horizons, roots produce earlywood tracheid cells and vessels with lumina of significantly reduced width (Gärtner *et al.*, 2001; Bodoque *et al.*, 2005; Hitz *et al.*, 2008). Corona *et al.* (2011a) recently demonstrated that the reduction of cell lumina starts to occur before the root is exposed and as soon as the soil mantle covering the uppermost segment of the root is reduced to about 30 mm. Provided that a correction is added to account for vertical uplift of the root axis due to growth after root exposure, denudation rates obtained with dendrogeomorphology has proved to be as accurate as rates obtained through continuous monitoring of sediment yield in traps at the outlets of basins (Corona *et al.*, 2011b; Lopez *et al.*, 2011).

Where affected by surface lowering, root exposure normally results in decreased plant stability. Erosion processes are also likely to hamper water and nutrient uptake in plants and may thus reduce their vitality. Reduction in vitality is caused by cambium dieback on the upper root surface following exposure (Carrara and Carroll, 1979) and as roots are only functional as long as the meristematic zone and root cap remain within the soil (Waisel *et al.*, 2002). However, roots directly affect erosion. Gyssels *et al.* (2005) state in a review paper that the decrease in water-erosion rates with increasing root mass is exponential, and that roots (Pollen and Simon, 2005; Pollen-Bankhead and Simon, 2010) are at least as important as vegetation cover for erosion processes in rills and ephemeral gullies.

Plants affected by slope degradation and retreat have been used repeatedly to analyze and quantify spatial and temporal erosion modes and rates. Reduced vitality of plants and sudden reduction of growth rates in stems have been used to decipher shore (Bégin *et al.*, 1991a, 1991b; Fantucci, 2007) or hillslope erosion histories (McAuliffe *et al.*, 2006; Scuderi *et al.*, 2008; Casalí *et al.*, 2009).

The technology of stream-channel, stream-corridor, and watershed rehabilitation has been of practical concern and intense interest in the recent past, and methods to reverse undesired changes caused by channel modifications and stream impoundments are being sought actively for both urban and

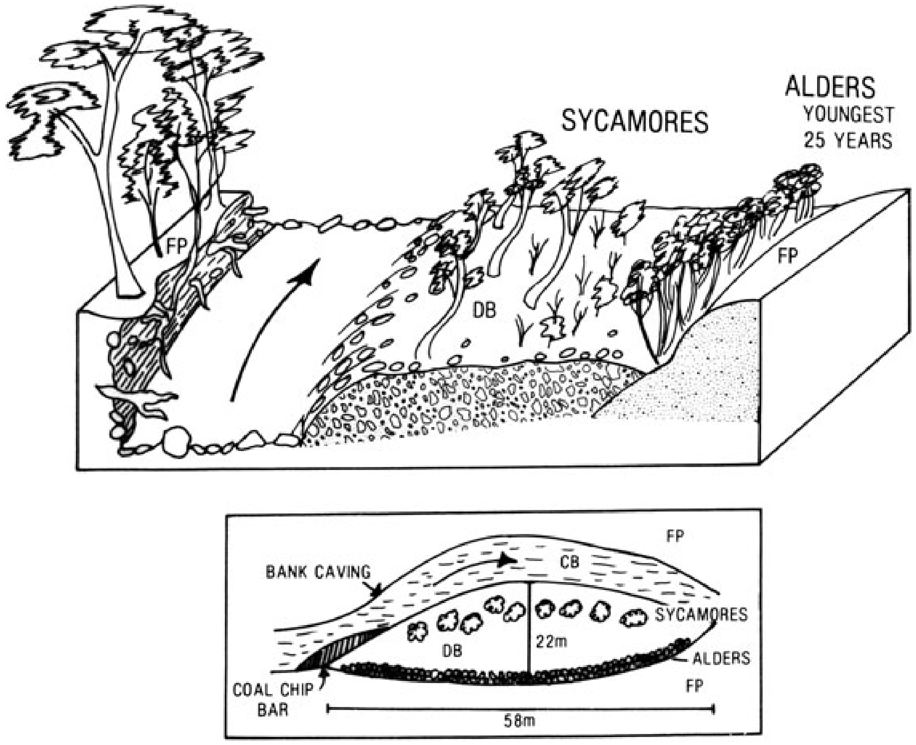

Figure 9. Block- and plan-view diagrams showing how observations of cohorts of alder and sycamore saplings provide evidence of channel migration. DB is depositional bar and FP is flood plain.

agricultural environments of diverse climate (e.g. Briggs, 1996; Briggs and Cornelius, 1998; Federal Interagency Stream Restoration Working Group, 1998; Marston *et al*., 2003; Marston and Furin, 2004; Jacobson and Galat, 2006). Much effort and money have been expended inefficiently and ineffectively to rectify previous modifications (generally abuses) that have altered stream systems throughout the developed world. Traditional technologies of river engineering, such as energy dissipaters, alteration of channel conveyance, rip-rap, vegetative bank stabilization, and channelization, have been used widely but generally have lacked a scientific basis for their application. A common consequence has been unexpected and unintended effects of the treatments, particularly to stream corridors of perennial streams.

A reaction, which may accelerate as more urban and agricultural projects are funded, has been development of procedures and models to address rehabilitation goals. Among them is the channel-evolution model of Simon and Hupp (1987) (Figure 8), which has direct application to counter the effects of previous channel straightening imposed in large areas of western Tennessee (Figure 11), and a channel classification to evaluate potential for cottonwood re-establishment (Jacobson *et al*., 2010). Many of the treatments suggested by Briggs (1996) for arid-lands streams are applied but are based on knowledge of fluvial dynamics.

Summary

Research activity of the recent past has been productive, but a continuing and vibrant research agenda is essential if the discipline of biogeomorphology is to provide insightful contributions to studies of fluvial processes, the management of watersheds and their ecosystem services, and biophysical responses to global climate change. An energetic research program must be much more than progress toward achieving an understanding of landscape processes, but must embrace a means to direct attention to the research venues that appear most likely to be productive in near-term and intermediate time periods. Among these recent emphases are: (1) hydrologic controls on bottomland surfaces and vegetation, (2) formation and bioturbation of alluvial soils, (3) vegetation and hydrologic reconstructions, (4) flood-plain deposition and incision, (5) sediment transport and vegetation, (6) stream-corridor rehabilitation, and (7) bottomlands of regulated streams. These indicators of future research suggest the following as possibilities:

(a) The documentation of rates and volumes of trapped material upslope or upvalley from critical areas such as estuaries and the role of vegetation in effecting the storage of the material are on-going research topics for which much progress remains to be made. It has long been acknowledged that bottomlands, especially flood plains, are areas of sediment storage. Significant advances have been achieved in quantifying the amounts of sediment stored under various hydrologic conditions. Less recognized has been the importance of carbon storage, largely as vegetative debris, in lowlands. Qualitative, mostly observational, studies have yielded the recognition that bottomlands are both areas where carbon is stored and vegetation is a principal variable in regulating the magnitude of the storage.

(b) Fresh plant material and contaminants stored on flood plains are subject to chemical alteration, particularly by oxidation, but partially decomposed vegetative debris is further reduced by hydrolysis and biochemical processes into organic compounds with the release of nutrients and other organic compounds. The identification of the biochemical reactions by which nutrients and contaminants are reduced while in fluvial storage and the role of vegetation in causing the transformations may continue to be topics of both scientific and economic interest.

(c) The determination of the autochthonous and allochthonous sources of organic material (on-site vegetation inputs

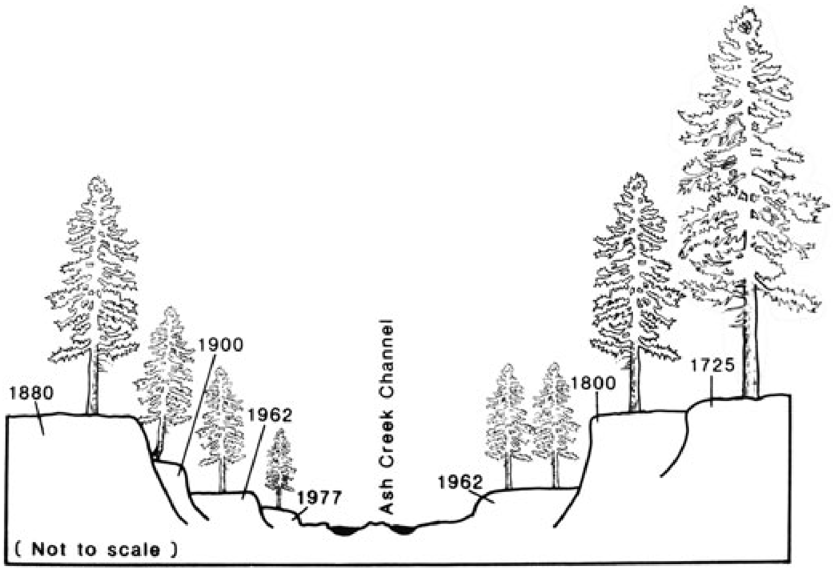

Figure 10. Cross-section diagram of Ash Creek gorge, Mount Shasta, California, showing ages of alluvial-terrace surfaces as indicated by cohorts of pine trees; dates given for each surface are those indicated by tree-ring ages of the oldest cohort of trees on that surface (from Hupp *et al.*, 1987).

Figure 11. Photograph of the straightened channel of Obion River, western Tennessee. The channel straightening caused increased energy conditions and erosion despite abundant riparian-zone vegetation (photograph by W.R. Osterkamp, 1987). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

versus vegetation transported into the system) and the identification of variable-source inputs of carbon to the hydrologic system will permit larger-scale investigations.

(d) The quantification of carbon sequestration in fluvial and tidal-flat/estuarine deposits, which can be very important along low-gradient coastal-plain streams and any other low-energy environment, will be fundamental in attaining precision in global carbon inventories. Easily observed interrelations between geomorphic process and vegetation, such as the facility of plants to resist the erosive effects of floods, have been closely investigated, but biochemical reduction of soil plant material and the consequent effects on soil stability in large part have been disregarded.

Fundamental models of Darwinian evolution and equilibrium, upon which much of this discussion is based, have required generalized views of erosion/vegetation interactions (Osterkamp and Hupp, 1996; Corenblit *et al.*, 2007). We no longer have the luxury to view our concerns in a simplistic manner. Our discipline needs to do more than merely measure morphology and inventory plants on hillslopes or in bottomlands. Rather, a consensus seems to be emerging that the now unexplainable, complicated situations observed in the field must be studied carefully and thoroughly if we want our discipline to advance.

Many of our current research problems cannot be constrained by the standardly accepted boundaries or disciplines as generally defined, and cooperative efforts are needed to continue to yield significant results. Changes in population impacts, including climatic characteristics and patterns, and the amount of carbon dioxide available to plants, may represent the most challenging issues that we must consider in the next century. Our society tends to sidestep the threats that population increase has on global health, and thus it is a concern that we as natural scientists need to be able to address.

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