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Fluvial processes and vegetation — Glimpses of the past, the present, and perhaps the future

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A B S T R A C T

Most research before 1960 into interactions among fluvial processes, resulting landforms, and vegetation was descriptive. Since then, however, research has become more detailed and quantitative permitting numerical modeling and applications including agricultural-erosion abatement and rehabilitation of altered bottomlands. Although progress was largely observational, the empiricism increasingly yielded to objective recognition of how vegetation interacts with and influences geomorphic process. A review of advances relating fluvial processes and vegetation during the last 50 years centers on hydrologic reconstructions from tree rings, plant indicators of flow- and flood-frequency parameters, hydrologic controls on plant species, regulation of sediment movement by vegetation, vegetative controls on mass movement, and relations between plant cover and sediment movement.

Extension of present studies of vegetation as a regulator of bottomland hydrologic and geomorphic processes may become markedly more sophisticated and widespread than at present. Research emphases that are likely to continue include vegetative considerations for erosion modeling, response of riparian-zone forests to disturbance such as dams and water diversion, the effect of vegetation on channel and bottomland dynamics, and rehabilitation of stream corridors. Research topics that presently are receiving attention are the effect of woody vegetation on the roughness of stream corridors and, hence, processes of flood conveyance and flood-plain sedimentation, the development of a theoretical basis for rehabilitation projects as opposed to fully empirical approaches, the effect of invasive plant species on the dynamics of bottomland vegetation, the quantification of below-surface biomass and related soil-stability factors for use in erosion-prediction models, and the effect of impoundments on downstream narrowing of channels and accompanying encroachment of vegetation.

Bottomland vegetation partially controls and is controlled by fluvial-geomorphic processes. The purposes of this paper are to identify and review investigations that have related vegetation to bottomland features and processes, to distinguish the present status of these investigations, and to anticipate future research into how hydrologic and fluvial-geomorphic processes of bottomlands interact with vegetation.

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1. Introduction

The study of geomorphic processes is dependent on those variables that control the processes, and vegetation is among the controlling variables. This paper mostly identifies and reviews some of the numerous investigations that have considered vegetation to gain an increased understanding of bottomland fluvial-geomorphic processes. Recognizing that in earlier decades a gulf generally separated the substantive study of physical and biological systems, we try to distinguish a *state-of-the-art* for selected topics for what has been termed by Viles (1988) as biogeomorphology — the study of relations between biota and geomorphic form and process. The intent is to anticipate how rewarding research into interactions between hydrologic and fluvial-geomorphic processes of bottomlands and the vegetation that helps control them may progress.

Streamflow magnitude and variability, alluvial landforms, and bottomland vegetation are intimately interrelated and, thus, are fundamental components of riverine biophysical systems. Prior to about 1960, the complexities caused by interacting variables generally caused scientific investigations to focus on a specific part of these systems, and to simplify studies, the controls that vegetation exerts on and receives from fluvial processes were typically disregarded. Exceptions to this generalization included papers relating (1) vegetation to fluvial processes (Hefley, 1937; Ware and Penfound, 1949), (2) vegetation patterns to bottomland surfaces or elevation above a stream channel (Shelford, 1954; Smith, 1957), and (3) vegetation to frequency and duration of flooding (Hall and Smith, 1955; Wistendahl, 1958). An explosion of research into fluvial-geomorphic processes in the 1950s

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and 1960s provided the necessary foundations for the effects of vegetation to be considered (Bennett and Simon, 2004), and since then, significant advances in biogeomorphology have been achieved.

Plant ecology developed as a discipline in the second half of the 19th century, but until about 1900 was largely restricted to plant classifications or the compilation of species lists (Joyce, 1993; Osterkamp and Hupp, 1996). Plant communities were considered static functions of climate, and interpretation or recognition of the effects of fluvial process was not considered. The period of emphasis only on data collection ended when botany and plant ecology became influenced by Darwinian thought, and later by equilibrium theory (Osterkamp and Hupp, 1996). Field ecologists and geomorphologists continue, of course, to emphasize data collection, but now the integration of data into a research plan is better executed.

Darwinists Henry Cowles (1899, 1911) and Frederick Clements (1909, 1916) revolutionized concepts of interactions between Earth-surface processes and vegetation by introducing the model of plant succession, the hypothesis that plant communities are explained in terms of orderly change within the communities, not as functions of environment. An alternative explanation was offered by equilibrist H. A. Gleason (1925, 1926), who stressed that for plants to survive in space and time they must be adapted to local and current environmental requirements. Robert McIntosh (1958, 1960) and other integrationists proposed approaches to plant ecology that found common ground between the opposing schools of Darwinism and equilibrium.

The tradition of data compilation that was established by botanists over a century ago remains basic to the practice of plant ecology and how vegetation affects and is controlled by fluvial-geomorphic processes. Vegetation mapping, which must always be an underlying tool for exploring plant/surface interactions, originally was based on transect and quadrat data but now relies also on aerial photography and related remotely-sensed imagery. Whether applied to vegetation studies or to geomorphic investigations, the use of transects and quadrats documents the presence or absence of species, height or trunk diameter of trees, surface area covered by plants, the characteristics of particular assemblages of species, or the size of sediment particles.

2. Hydrologic controls on bottomland surfaces and vegetation

Detailed investigations on fluvial-geomorphic processes in the 1950s (e.g. Leopold and Maddock, 1953; Wolman, 1955; Hack, 1957; Wolman and Leopold, 1957; Trask, 1959; Schumm, 1960; Wolman and Miller, 1960) provided the foundation necessary to incorporate issues of vegetation into the understanding of fluvial processes, especially floods. A major breakthrough was the publication of USGS Professional Papers 424-C (Sigafoos, 1961) and 485-A (Sigafoos, 1964). In the 1961 paper, Sigafoos reported distinctive vegetation bands along the Potomac River near Washington, D. C. He related the bands to inundation frequency and suggested that disturbance from floods of differing magnitudes and frequencies were a plausible explanation for the banding. A similar study by Everitt (1968) related the regeneration patterns of cottonwoods (*Populus* spp.) to bottomland flood dynamics.

Two decades later detailed investigations along three streams of northern Virginia, including the Potomac River, demonstrated that alluvial bottomland surfaces along the streams support characteristic assemblages of tree and shrub species and that each geomorphic surface, with its specific plant community, also can be identified uniquely in terms of flow and flood frequencies (Osterkamp and Hupp, 1984; Hupp and Osterkamp, 1985). Depositional bars (DB, Fig. 1) are in-channel features that typically are inundated by discharges exceeding 40% flow duration and in northern Virginia may have occasional seedlings of *Salix nigra* (black willow), *Platanus occidentalis* (American sycamore), *Populus deltoides* (eastern cottonwood), or *Alnus serrulata* (smooth alder). The active-channel shelf of perennial streams (AS, Fig. 1) typically corresponds to the stage of mean discharge, usually 5 to 20% flow duration, and in northern Virginia supports a riparian-zone forest that includes *A. serrulata*, *Cornus amomum* (silky dogwood), *Viburnum dentum* (southern arrowwood), and *Physocarpus opulifolius* (common ninebark). Flood-plain levels (FP, Fig. 1) of perennial streams often correspond to the stage of the mean-annual flood, a return period of about one to three years; in northern Virginia the flood-plain is often distinguished by tree stands that include *Juglans nigra* (black walnut), *Liriodendron tulipifera* (tulip poplar), *Viburnum acerifolium* (mapleleaf viburnum), and *Carya cordiformis* (bitternut hickory). Alluvial terraces (T_l and T_u, Fig. 1) can occur through a range of elevations above stream level, are inundated by discharges greater than the mean-annual flood, and in northern Virginia support flood-intolerant species such as *Carya tomentosa* (mockernut hickory) and *C. glabra* (pignut hickory), *Sassafras albidum* (sassafras), and *Quercus prinus* (chestnut oak) (Osterkamp and Hupp, 1984; Hupp and Osterkamp, 1985).

Complementing the Virginia investigations, studies in North America, Europe, New Zealand, and Japan also have related distributions of characteristic plant species to specific fluvial landforms and

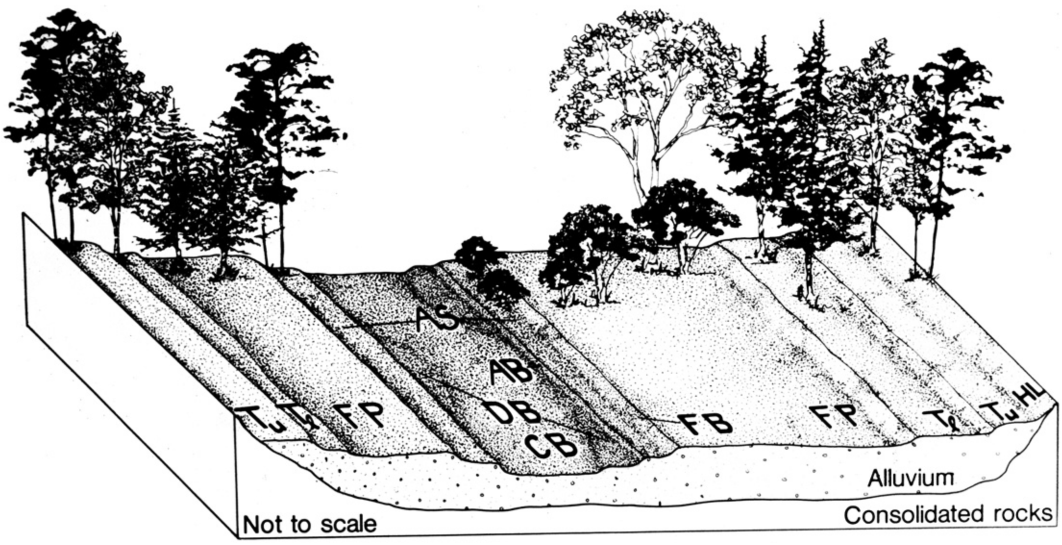

Fig. 1. Block diagram showing alluvial surfaces of perennial streams of northern Virginia; from the lowest, the surfaces are CB, channel bed; DB, depositional bar; AB, active-channel bank; AS, active-channel shelf; FB, flood-plain bank; FP, flood-plain; T_l, lower terrace; and T_u, upper terrace (from Osterkamp and Hupp, 1984).

processes (Johnson et al., 1976; Décamps et al., 1988; Tabacchi et al., 1990; 1998; Gregory, 1992; Naiman et al., 1993; Pautou and Arens, 1994; Marston et al., 1995; Bravard et al., 1997; Davies-Colley, 1997; Hughes, 1997; Bendix and Hupp, 2000; Nakamura and Shin, 2001; Gurnell and Petts, 2003). Although the various investigators acknowledged that bottomland vegetation patterns are not solely dependent on hydrologic processes, the relations can be used to infer flow conditions where gauging-station or other hydrologic information is lacking.

Vegetation–landform relations are useful also to determine the stage of riparian-zone recovery following disturbance, such as channelization or gravel extraction (Hupp, 1992; Hupp and Rinaldi, 2007). "Pioneer" plant communities may establish on recently formed fluvial surfaces resulting from human-induced disturbance. These surfaces then may support subsequent communities that reflect the increasing stability and dominant geomorphic trends (channel evolution); the sequential communities may be indicative of the stage of recovery. Specific indicator communities were described by Hupp (1992) for channelized streams in Tennessee and by Hupp and Rinaldi (2007) for gravel-mine induced channel incision in Tuscany, Italy.

Substantial progress has been made in the interpretation of channel evolution through the use of conceptual models (Schumm et al., 1984; Simon and Hupp, 1992; Surian and Rinaldi, 2003). These models imply that a resiliancy exists in fluvial systems that may return the system to dynamic equilibrium after alteration, human or otherwise. The Simon and Hupp (1992) model includes general changes in the riparian vegetation that are associated with channel evolution toward increased stability after channelization. Research by Rinaldi (2003) supports the generality of return to equilibrium, but shows that models developed for fine-grained, low-gradient channels, such as that of Simon and Hupp, may not be transferable among physically distinct regions with differing long-term alteration histories.

2.1. Floods

Botanical evidence of floods includes (1) tree age, (2) corrasion scars, (3) adventitious sprouts, and (4) ring anomalies. Many other disturbances can yield these forms of evidence, and careful examination and replication are required to limit spurious interpretations. Formative floods, ranging from long-duration flows along large, low-gradient streams to flashy, high-magnitude discharges of high-gradient streams, may be the most important extrinsic controls of natural bottomland ecosystems. Thus, knowledge of flood magnitudes and frequency is of great utility to the study of fluvial geomorphology. Times of past floods may be determined by tree-ring analyses of woody vegetation on fluvial landforms, from scars and sprouts of damaged stems (Sigafoos, 1964; Hupp, 1988), and from differences in properties of wood anatomy related to flooding (Yanosky, 1982).

Because bottomlands are shifting mosaics of landforms adjacent to stream channels (Bravard et al., 1986; Swanson et al., 1988) or relatively predictable, largely linear arrays of landforms (Osterkamp and Hupp, 1984; Hupp and Osterkamp, 1996), considerable variation in hydrogeomorphic processes can occur over short distances and even across a single surface such as a flood-plain. This complexity of physical form and process leads to considerable diversity within the plant communities occupying the bottomlands (Nilsson et al., 1989; Naiman et al., 1993). Frequent disturbance by flows that may flood, scour, or aggrade lowlands may be the principal fluvial-geomorphic process causing high biodiversity in riparian ecosystems (Vannote et al., 1980; Hupp and Osterkamp, 1985; 1996; Nilsson et al., 1989; Gregory, 1992; Sharitz and Mitsch, 1993; Bornette et al., 1998; 2008; Gurnell and Gregory, 1995; Hupp, 2000).

Inundation frequency and length (hydroperiod) produce discrete vegetation patterns, the identification of which can aid in hydrologic reconstruction (Osterkamp and Hupp, 1984). Variations in hydroperiod, sedimentation and erosion, and plant-adaptive strategies largely explain observations of complex patterns of riparian-zone distributions (Wharton et al., 1982; Leitman et al., 1984; Mitsch and Gosselink, 1993, Sharitz and Mitsch, 1993). Specific patterns of woody-species distribution and quantitative relations with water level and sediment dynamics, however, remain incompletely understood. For example, streamflow of varying magnitude and duration and changes in sediment dynamics create new areas for plant establishment such as point bars, ridge-and-swale features, and sediment-size gradients across the flooded surfaces. These fluvial processes are insufficiently understood to permit accurate prediction at a site, but even less understood is the role of riparian vegetation in affecting fluvial processes (Hupp and Osterkamp, 1996).

2.2. Vegetative response to floods

Biogeomorphic research of the last three decades also has demonstrated that vegetation is a control of fluvial processes. Osterkamp and Costa (1987) and Friedman et al. (1996a, 1996b) related the establishment of riparian-zone plants [especially willows (*Salix* spp.) and cottonwoods (*Populus* spp.)] following a catastrophic flood along Plum Creek, a sand-bed stream south of Denver, Colorado, to the stabilization of the depositional features. As the islands and bars evolved toward flood-plain level, vegetation caused channel narrowing, reduction in channel gradient, replenishment of flood-winnowed fine-grained sediment, increased channel roughness, and reduced in-channel conveyance capacity. Similarly, Johnson (2000) found that seedling mortality of willow and cottonwood along the Platte River in south-central Nebraska is dominated by pulses of streamflow following summer thunderstorms and by winter river-bed changes caused by movement of ice. At Plum Creek and the Platte River, vegetation, especially willows and cottonwoods, was essential in establishing or helping to cause biophysical adjustment to the variable hydrologic and geomorphic processes that defined and determined its ecological setting.

Disturbances, such as periodic flooding, play major roles in the development of many vegetation patterns in alluvial bottomlands (Johnson et al., 1985; Day et al., 1988; Kirkman and Sharitz, 1994) and control some plant communities that persist in dynamic equilibrium (e.g. Hack and Goodlett, 1960; Pickett, 1980; Osterkamp et al., 1995) with no temporal loss of species compositional integrity. For wetland forests along low-gradient streams, the tight relation between type of vegetation and hydroperiod is well documented (Wharton et al., 1982; Sharitz and Mitsch, 1993). Bottomland surfaces of moderate-gradient streams of eastern North America, as indicated by the hydrogeomorphic analyses of Osterkamp and Hupp (1984), Hupp and Osterkamp (1985), and Bendix and Hupp (2000), typically develop consistent and persistent linear fluvial landforms that are maintained by predictable variation in discharge. Similar but sometimes less extensively developed fluvial-landform patterns are common also in other hydroclimatic environments (Hupp and Osterkamp, 1996; Bendix and Hupp, 2000). Furthermore, these analyses suggest that the overriding influence on the distributional patterns of species is the frequency of inundation and the susceptibility of plants to destructive flooding. Thus, the hydrogeomorphic processes operating on the different landforms affect the plant patterns but not the landforms themselves.

2.3. Moisture availability and depth to groundwater

Centuries of observations confirm correlation between phreatophytic vegetation and near-surface groundwater or perennial underflow beneath a channel bed, particularly in water-deficient areas, but detailed data relating the level of groundwater saturation to vegetation abundance are meager. Meinzer (1927), for example, noted that mesquites (*Prosopis* spp.) can tap groundwater as deep as

15 m. In-depth investigations into the control on phreatophytes by groundwater levels were conducted by Culler (1970) for *Tamarix pentandra* (saltcedar) and other pheatophytes, by McQueen and Miller (1972) for saltcedar, willows, cottonwoods, and mesquites, and also for saltcedar by Van Hylckama (1974). Results of these studies showed that roots of *T. pentandra* can extend as deep as 10 m to saturated groundwater (Van Hylckama, 1974), and that stands of phreatophytes, particularly *T. pentandra*, can be quite dense in lowlands, thereby slowing the velocity of flood flows, reducing conveyance, increasing flood duration, and promoting sediment deposition (Culler, 1970). Later, Harner and Stanford (2003) related growth rates of bottomland cottonwood groves to interactions between shallow groundwater and surface water.

In most humid areas such as eastern North America, the availability of excess moisture and depth to groundwater help control hyporheic-habitat diversity (Poole et al., 2006), but do not appear to determine the position of bottomland trees. The investigation by Osterkamp and Hupp (1984) in Virginia showed that *J. nigra*, for example, is largely restricted to flood-plain surfaces, regardless of the depth to groundwater. An extension of that study, however, suggested that in the arid southwestern United States, depth to the level of groundwater saturation strongly controls the occurrences of woody phreatophytes (Hupp and Osterkamp, 1996).

As in areas of arid climate, moisture availability appears to be a limiting factor for the distributions of riparian-zone plant species in semiarid areas such as the Great Plains of North America (Friedman and Lee, 2002). Phreatophytes, including species such as cottonwoods, are sensitive to even small sustained declines in the level of saturated groundwater (Scott et al., 1999). Moisture availability and depth to saturation also may affect riparian-species distributions in Mediterranean climates (e.g. Italy), where channel incision or rapid narrowing has caused drainage of saturated alluvium and thus lowered groundwater levels (Hupp and Rinaldi, 2007).

3. Formation and bioturbation of alluvial soils

An alluvial soil is a layered mixture of mineral and rock fragments and particles that generally includes organic matter and weathering products depending on soil age; it reflects the natural and human-imposed hydrologic and geomorphic processes that have resulted in its formation (Osterkamp, 2008). The fundamental importance of vegetation to pedogenesis and soil-geomorphic research has been recognized at least since the early 1940s (Jenny, 1941) but more recently by Birkeland (1999) and by the USDA Agricultural Research Service as components of its soil-loss models RUSLE2 (Widman, 2004) and of the Water Erosion Prediction Project (WEPP). Where the decomposition of fallen tree boles on alluvial surfaces, particularly terraces, is rapid (e.g. Torres, 1994; Brown et al., 1998; Osterkamp et al., 2006), addition of organic matter and the sequestration of carbon in the uppermost soil horizons may be significant, thereby promoting plant cover, pedogenesis, and protection from erosion during floods.

Root throw, a type of bioturbation, commonly occurs when bottomland trees are toppled during flooding or by strong wind in any part of a watershed, resulting in a disturbance by which a volume of soil in the root ball of the previously standing tree is elevated to or above the surface (Osterkamp, 2008). Although root throw is an important pedogenic process, it also is a major determinant of small-scale features of alluvial bottomlands and of the regeneration of plants. Among these features are (1) pits where soil has been moved upward by root throw and a new seed bank may collect (Beatty, 1984; Beatty and Stone, 1986), (2) corresponding mounds of sediment that ultimately falls from the elevated root ball (Schaetzl et al., 1989; Osterkamp et al., 2006; Gallaway et al., 2009), and (3) stacking of large woody debris (LWD) against fallen trees during floods. Especially at the time a tree is toppled by a flood, a pit becomes vulnerable to intense erosion by the flood waters, thereby contributing to the micro-topography of bottomland surfaces. Similarly, where large piles of LWD become stored behind toppled trees, or those that remain standing, the resistance to flow may cause the deposition of sand splays down flow from the obstructions (Osterkamp and Costa, 1987; Gabet et al., 2003).

In channels of streams draining forested areas, meandering, avulsion, braiding, sediment deposition, and changes in morphology may be affected by LWD (Keller and Swanson, 1979; Bilby and Ward, 1989; Robison and Beschta, 1990; Nakamura and Swanson, 1993; Wood-Smith and Swanson, 1997; Piégay, 2003; Montgomery and Piégay, 2003; Montgomery et al., 2003). Accumulations of LWD in channels are related to disturbance history, forest type, successional stage, decomposition rate, and channel size (Gurnell and Petts, 2003; Montgomery et al., 2003; Moulin and Piégay, 2004) and may armour a channel locally but promote scour elsewhere. Thus, sediment may be deposited at a site but a nearby pool may be eroded (Wood-Smith and Swanson, 1997; Wallerstein, 2003; Wallerstein and Thorne, 2004). Riparian-zone deforestation in the eastern United States has been related to channel narrowing and reduction of ecosystem services (Sweeney et al., 2004), whereas Trimble (1997) found that forested stream banks of southwestern Wisconsin are less stable and less effective at controlling bank erosion than are grass-covered banks.

Theoretical models of LWD loading have been developed for several types of streams (Gregory et al., 1993; Braudrick and Grant, 2001) or for conceptual budgeting (Sobota et al., 2006). Although the impact of LWD in many low-gradient systems is minor (Golladay et al., 2007), the character and delivery of LWD may be an important determinant of riparian-zone processes.

Riparian trees combined with beaver activity may effect potentially profound fluvial-geomorphic alterations. Beaver damming to create aquatic habitat also creates sediment-storage sites; studies in Montana, Quebec, Virginia, and North Carolina indicate that individual ponds may store thousands of cubic meters of sediment (Naiman et al., 1986; Butler and Malanson, 1994; D.E. Kroes, pers. com.). Where ponds can develop fully, they may overlap, resulting in a meadow complex where sediment and woody material from older dams are buried by deposition of newly constructed dams (Ives, 1942). If wood of old dams is buried, it forms barriers to future erosion and channel migration (Ives, 1942; Bilby, 1984; D.E. Kroes, pers. com.).

Like LWD, the presence of woody vegetation may affect fluvial processes and the development of alluvial soils. Stems and roots may impede the flow of water and increase resistance to erosion. Protruding tree abutments, root crowns, and temporarily stabilized subtending banks are common along eroding streams. These abutments are testament to the erosion-resistant effects of streamside trees and the effect on channel processes (Rutherford and Grove, 2004). Tree roots strengthen riparian surfaces and reinforce shallow soils because of tensile strength (Thorne, 1990). The weight surcharge on banks from woody plants, however, under some conditions may adversely affect bank stability (Simon and Collison, 2002). Vegetation, as whole plants, influences multithread channels by reducing flow in small channels through increased roughness and by armoring banks and exposed channel and point bars (Tal et al., 2004). The effects of this type of channel control have been quantified (Gray and Barker, 2004) and modeled, permitting prediction of channel-change vulnerability (Smith, 2004). Plantings on banks are now a common stabilization practice, although some studies suggest that increased bank strength by roots has been overestimated (Pollen et al., 2004).

4. Vegetation and hydrologic reconstructions

Tree-ring dating to interpret geomorphic processes is a common technique owing to several important papers including those of Sigafoos (1964), Everitt (1968), Alestalo (1971), Helley and LaMarch (1973), and Schweingruber (1988). An extensive review of tree-ring dating is in Jacoby and Hornbeck (1987). Dendrogeomorphology

(Shroder, 1978) has been used in a range of applications including floods (Sigafoos, 1964; Yanosky, 1982; Hupp, 1988), flood-plain deposition (Sigafoos, 1964; Hupp, 1988; Hupp and Bazemore, 1993), and channel dynamics (Hupp, 1992; Friedman et al., 1996a; Scott et al., 1997; Auble and Scott, 1998). Standard dendrochronological techniques that incorporate the measurement of ring width to interpret geomorphic processes may be quite useful, especially if ancillary information is lacking.

Despite an inability to quantify relations among hydrology, geomorphology, and vegetation, the striking presence of vegetation zones across lowlands has tempted researchers to develop classifications of vegetation patterns (Kellison et al., 1998). Small differences in elevation may lead to pronounced differences in hydroperiod and to community composition (Mitsch and Gosselink, 1993). Thus, most classifications infer that hydroperiod is the most influential factor in controlling species patterns, most probably from anaerobic conditions related to flooding (Wharton et al., 1982). Anaerobic respiration within the roots of plants leads to toxic byproducts and limits water and nutrient uptake (Hupp, 1992). Flood-tolerant plants have developed physical and/or metabolic adaptations to withstand inundation and anoxia (Wharton et al., 1982). The degree to which individual species have adapted to anoxia-related stresses presumably controls the striking changes in vegetation composition across very short distances on many flood plains in lowland areas (Huffman and Forsythe, 1981).

5. Flood-plain deposition and incision

Scour and clast sorting are limiting factors for vegetation establishment on bottomland substrates. Erosion and channel cutoffs may lead to long-term pools that support aquatic vegetation whereas terrestrial vegetation may be restricted to narrow ranges of sediment-size. Because most woody plants must maintain actively absorbing roots in the upper 15 cm of soil (Kramer and Kozlowski, 1979), only species capable of rapid root growth along newly buried stems (e.g. species of *Salix* and *Populus*) may occupy bottomlands affected by frequent or thick sediment deposition or by rapid channel migration along point bars (Hupp, 1988). If erosion removes all or part of the soil in the root zone, trees will be killed or severely damaged.

5.1. Flood-plain deposition

Vertical accretion, the “slow” accumulation of overbank sediment without appreciable later channel migration, is the primary process by which most lowland flood plains develop within the Coastal Plain (Nanson and Croke, 1992; Middlekoop, 2002; Walling and He, 1998). Discharges that occur less than 10% of the time may be responsible for 50 to 90% of suspended-sediment transport in alluvial-river systems (Meade, 1982). The flood plains may be inundated multiple times a year, often for extended periods during winter and spring. With minimal erosion caused by lateral migration and little remobilization and export of flood-plain sediment, particulate storage in the Coastal Plain can be decades or longer (Meade, 1982; Raymond and Bauer, 2001). Coastal Plain riverbanks are typically low and inundation often extends across the entire flood-plain, significantly limiting flow competence. Natural levees, typically sand, may form adjacent to the channel by deposition of coarse suspended-load sediment (Pizzuto, 1987; Hupp, 2000). Elevations typically vary no more than a few meters within the flood plain, so small changes in flood stage or groundwater level can greatly affect inundation frequency and hydroperiod across large areas.

Aggradation along streams, natural or modified, provides new sites for plants to colonize and may initiate a series of vegetation stages indicative of progressive changes in hydrogeomorphic conditions. Dominance by pioneer species is explained by life-history characteristics including a large seed crop, seeds that are effectively dispersed by wind or water to suitable sites, rapid germination, and rapid shoot and root development to withstand flooding or desiccation. Vegetation establishment increases hydraulic roughness, which facilitates further sedimentation and ultimately changes initially unstable surfaces into relatively stable sites, suitable for the later recruitment of stable-site species (Hupp, 1992; Johnson, 1994; Friedman et al., 1996a, 1996b). Along sand-bed streams, particularly braided channels subject to winter freezing, redistribution of sediment by flow variation and the effects of moving ice may have profound effects on the mortality and regeneration of tree seedlings (Johnson, 1994) (Fig. 2).

Along streams dominated by aggradation, extensive depositional areas may be generated during each flood. Such flood plains are common along streams of the southeastern U.S., where upstream agricultural practices and channelization generate large amounts of fine sediment (Bazemore et al., 1991; Hupp, 1992). Where channel degradation (incision) occurs, large eroded zones may be generated and the stream becomes decreasingly connected to its flood plain. Such conditions are common along streams with regulated flow.

5.2. Incision, response to channel alteration, and modeling

Channel incision increases stream power, which actuates bed and bank erosion and sediment transport (Schumm et al., 1984; Bravard et al., 1997). In the upper parts of an incised-channel system, bank failure and high rates of sediment transport typically occur, whereas in lower reaches sediment may accumulate because of decreased gradient, obstructions such as debris jams, and slow stream velocity. LWD is often very effective at forming stable channel features that may control stream hydraulics and the riparian-forest development for decades to centuries (Abbe and Montgomery, 1996).

Aggradation in the lower reaches of a stream can cause simultaneous filling and widening of the channel, which is the characteristic recovery process following channelization (Schumm et al., 1984; Simon and Hupp, 1987). Increases in the rate of deposition in these lower reaches, however, can also disrupt functional processes of wetland systems (Happ et al., 1940; Brierley and Murn, 1997). Examples of flood-plain alterations as a result of channelization include: disturbed-surface and sub-surface hydrologic connectivity (Shankman and Pugh, 1992; Tucci and Hileman, 1992), altered rates of sedimentation (Happ et al., 1940; Pierce and King, 2008), reduced

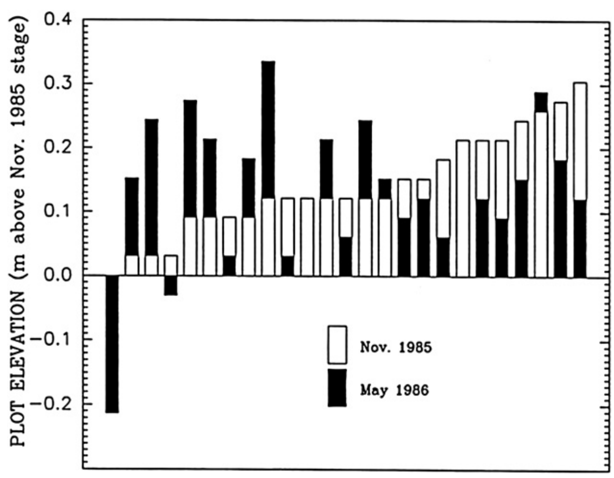

Fig. 2. Bar graph showing changes in elevation of vegetation plots on sand bars of the Platte River, November, 1985 through May, 1986. River-bed restructuring was caused in large part by ice moving in the river that resulted in nearly complete mortality (98%) of a population of cottonwood and willow seedlings. The pre-winter plot elevations are the heights of the white bars and the post-winter elevations are the heights of the black bars; the difference between bar (i.e. the amount of black in a bar) is a measure of the amount of sediment redistribution (Johnson, 1994).

lateral channel migration that creates sloughs and oxbow lakes (Shankman, 1993), loss of aquatic habitat (Hohensinner et al., 2004), reduced growth and premature mortality of flood-plain tree species (USDA, 1986), loss of plant-species diversity (Miller, 1990), and changes in plant-species composition (Oswalt and King, 2005; Pierce and King, 2007).

Channelization is a common procedure designed to control flooding and drain wetlands. The practice affects nearly all hydrogeomorphic forms and processes within, upstream, and downstream of the channelized reach and has led to degradation and erosion on the channel bed and banks until a new quasi-equilibrium is attained and channel-bed aggradation begins (Simon and Hupp, 1992). The riparian environment is likewise severely affected, particularly on the channel banks but also on the adjacent flood-plain (Hupp, 1992). Many streams in the Central Plains and the southeastern Coastal Plain of the U. S. are channelized, which has severely affected fluvial-geomorphic processes at multiple spatial and temporal scales upstream and downstream of the reaches and along tributaries (Simon and Hupp, 1987; Shankman, 1993).

A cycle, of erosion, accretion, and return to equilibrium, that is based largely on observations of modified stream channels in west Tennessee and incorporates vegetation is described in a six-stage model (Fig. 3) of geomorphic processes. The erosional phase of the cycle often removes all woody vegetation. Late in this phase refugia occur in protected areas, usually downstream of slump blocks from mass movement on the banks (Hupp, 1992). These refugia offer enough stability for ruderal riparian vegetation to establish (Fig. 3), but upland species especially tolerant of erosive conditions (*Rhus glabra* (staghorn sumac), *Ulmus alata* (winged elm), *Gleditsia tricanthos* (honey locust), and *Robinia pseudoacacia* (black locust)) may occur high on the banks. During the highly aggradational phase of the cycle, species found in refugia of the late erosional phase (*S. nigra*, *Betula nigra* (river birch), *Acer saccharinum* (silver maple), *Acer negundo* (boxelder), *P. deltoids*, and *P. occidentalis*) are tolerant of high rates of sediment accretion and become dominant. A two-fold increase in percent occurrence has been observed for most species and a nearly four-fold decrease occurs in un-vegetated sites in the aggradational phase (Fig. 3); excepting a small percent of *R. glabra*, the erosional indicator species are lacking (Simon and Hupp, 1987, 1992; Hupp, 1992).

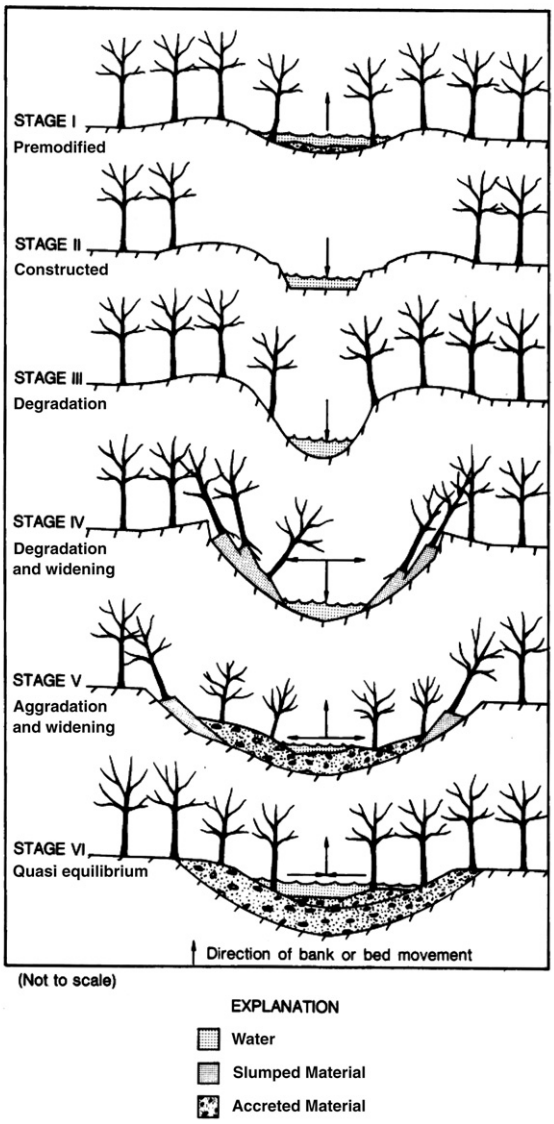

Fig. 3. Diagram of six-stage channel evolution model of Simon and Hupp (1987). Degradation, channel incision begins in stage 3 and continues in stage 4 with associated channel widening; widening continues in stage 5 but the channel bottom aggrades. Stream initially reacts through vertical processes (arrows) after channelization, then vertical and lateral processes operate ending with a shift to lateral process domination and mild aggradation (adapted from Hupp, 1992).

6. Sediment transport and vegetation

Flood plains and other riparian-zone features contain important locations for the storage of fluvial sediment, and knowledge of the channel processes that move and store sediment in bottomlands is basic to understanding watershed function (Phillips, 1989; Steiger et al., 2005; Hupp et al., 2008). Although the literature contains many references to buffering (the trapping of sediment and nutrients from upland flow by riparian zones), few papers have addressed the trapping and retention of sediment from flood flows by bottomlands (Noe and Hupp, 2009). Many Coastal Plain riparian areas are the last fresh-water sites for significant storage of riverine sediment (Hupp, 2000), although a study by Walter and Merritts (2008) suggests that prior to European settlement little sediment, but much organic carbon, was stored on wetlands bordering many of these streams. Along with mineral sediment, substantial amounts of nutrients (P, N) and organic material (C) now may be stored (Noe and Hupp, 2009). Worldwide, bottomlands of large rivers may be important areas for carbon sequestration (Raymond and Bauer, 2001).

6.1. Channel change and bottomland dynamics and functions

Many investigators, too numerous to cite, during the last century and before have reported results of studies examining rates of lateral channel movement, meander migration, an accompanying change in channel gradient, cut banks, and point-bar development. In recent decades many of the studies, also too numerous to warrant detailed review here, have described changes in riparian-zone vegetation from processes such as meander movement and avulsion. Conversely, a smaller number of studies (e.g. Gran and Paola, 2001; McBride et al., 2007) have addressed the question of how riparian-zone vegetation influences channel processes. In part because of the economic importance of irrigated bottomlands as an agricultural resource, investigations of the last 30 years or more into tillage practices and the use of fertilizers and herbicides have focused on the long-term effects of agricultural practices on soil chemistry, soil structure, infiltration characteristics, runoff, soil erodibility, and the crops and native vegetation supported by the soils.

Similar research has been minimal for naturally vegetated bottomlands, whether in temperate climatic zones or in the tropics, which have roughly half of the global forested area (UNESCO, 1978). An exception, however, is the work of Frangi and Lugo (1985), who made detailed measurements of the carbon, phosphorus, and water cycles, and related ecosystem characteristics of a subtropical flood-plain forest in northeastern Puerto Rico. Results indicated that frequent flooding (partly from hurricanes), poor soil aeration, consistent and abundant rainfall, and typically high humidity largely controlled hydrologic processes of the palm-dominated flood-plain forest. Abundant data on above-ground and below-ground biomass demonstrated that rapid rates of plant growth and leaf and stem decay have pronounced effects on soil and water chemistry of the flood-plain and of the runoff entering the drainage network.

6.2. Vegetation and water erosion

The use of vegetation to minimize erosion and soil loss has been a goal of soil scientists for many decades. Among the controls of soil loss, natural and applied, are plant (leaf) cover, which reduces erosion potential by rainsplash impact, and vegetation roughness and soil cohesion because of roots, which help protect soil surfaces from erosion by runoff (Cook, 1936).

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 models require an estimate of erodibility, an expression of the susceptibility of a soil surface to the erosion process. These models are constructed to evaluate the ability of macro-plants to cover and protect the soil from particle detachment and entrainment by moving water, but they inadequately describe the ability of micro-vegetation and organic components of the soil to bind soil particles and inhibit erosion by surface runoff.

7. Stream-corridor rehabilitation

Many stream corridors, especially in populated settings, have been altered in manners now considered controversial, and much effort and money have been expended with limited success to reverse the previously applied modifications to landforms and riparian-zone vegetation. Guidelines suggesting considerations, procedures, and precautions to rehabilitate altered bottomlands are summarized by Briggs (1996). Emphasis is on the acquisition of detailed, data-based knowledge of those fluvial-geomorphic processes that determine alluvial surfaces and vegetation patterns on those surfaces as a pre-requisite to a rational project design. Fundamental to the development of a well constructed project design is the recognition that interactive hydrologic and vegetative processes determine fluvial landforms; the landforms are not determinants of process. An objective, therefore, is to understand how observations of altered watershed dynamics, considered in a context of geomorphic adjustment, complex response, thresholds, and equifinality (Osterkamp, 2008), can lead to a credible rehabilitation project.

Important knowledge accumulated from many attempts to achieve riparian-zone recovery centers on current habitat conditions, the extent of decline, and the causes for ecosystem degradation (Van Haveren and Jackson, 1986; Briggs et al., 1994). Recent activity in stream-corridor rehabilitation has focused on evaluating site conditions as a means to understand why ecological decline has occurred, but information on drainage-basin processes is essential if success is to be likely (Briggs and Osterkamp, 2003).

Suggested components of implementing a rehabilitation project include the development of an understanding of how and why changes have occurred, the development of a plan with broadly based backing, and construction of a well defined technical program (Briggs, 1996). Guidelines for such a program, for example, were offered by Scatena (1990) for riparian-zone forests of the Luquillo Mountains of Puerto Rico. Much of the program, both for application and post-rehabilitation phases, can be designed in response to inquiries of how a watershed has changed, what processes have caused the changes, and what the desired effects of a rehabilitation program should be. A well constructed rehabilitation plan may require the recognition that an observed set of channel characteristics can occur through a variety of basin processes, and thus site-specific conditions do not specify the processes that yield them.

8. Bottomlands of regulated streams

Most major U.S. rivers have become regulated by the construction of large dams and reservoirs and the bottomland forests of those rivers are especially affected by the alterations to flow regime. The changes in flow regime and reduction of peak discharges caused by regulation have resulted in changes in channel and bottomland dynamics and alteration of riparian-zone vegetation (Stanford et al., 1996; Stanford and Ward, 2001; Hauer and Lorand, 2004). Detailed analyses of vegetation changes that have occurred as functions of time and distance downstream from a dam have been reported, among others, by Johnson (1994) for the Platte River in central Nebraska, by Richter et al. (1996) for the lower Roanoke River in North Carolina, by Scott et al. (1997) for the Missouri River in Montana, by Marston et al. (2005) for the Snake River in Grand Teton National Park, and regionally for the Great Plains by Friedman et al. (1998). The complexity of riparian-forest response to river regulation was demonstrated regionally for the Great Plains by Friedman et al. (1998), who related stream regulation and consequent channel narrowing along braided streams to increased rates of pioneer-tree establishment along formerly meandering channels in the southern Great Plains. Conversely, rates of reproduction of woody riparian pioneer species declined owing to reduced rates of channel migration along formerly meandering channels in the northern Great Plains. Channel incision downstream from dams is common along some alluvial streams, which can lead to extensive bank erosion and nearly complete removal of bank vegetation; large amounts of suspended-sediment also may be generated and deposited on down-valley flood plains (Hupp et al., 2009).

Precipitous declines in the regeneration of pioneer cottonwood and willow forests downstream from dams along the upper Missouri River were forecast by Johnson et al. (1976) because of a major reduction in the rate of river meandering. The altered hydrology also was cited as affecting the growth rates and population structure of later successional bottomland trees including *A. negundo*, *Ulmus americana*, and *Fraxinus pennsylvanica*. In a later study, however, Johnson (2000) reported increases in cottonwood forests on flood-plain areas of Colorado and Nebraska following dam construction. These two studies show that geomorphological differences can lead to opposite responses of riparian-zone vegetation to river regulation.

The middle Snake River, southwestern Idaho, is a stream of low discharge variability that is reduced also by pronounced regulation. Transect data and GIS mapping were used to demonstrate that vegetation growing on channel islands and on alluvial surfaces along the river is well adapted to the stable discharges. Systematic changes in species composition are evident as vertical, horizontal, and longitudinal gradients along and normal to the river channel (Johnson et al., 1995; Osterkamp et al., 2001). Fig. 4, adapted from Johnson et al. (1995), illustrates the differences in vegetation zones observed on channel islands of upstream reaches (A–C) of the middle Snake River, which has unusually stable discharge owing to the combined effects of low natural variability and flow regulation, and on lower reaches of the middle Snake River (C–E), which has higher flow variability largely because of tributary inflows. Presumably because flows exceeding mean discharge along the lower reaches attain stages up to about a meter higher than do discharges of comparable flow frequency in the upper reaches, the vegetation zones on island sides also exhibit a meter of offset (Fig. 4).

In recent years digital channel-dynamics models have been developed to describe geomorphic effects and vegetation response to altered hydrologic regimen. These models (i.e. Larsen and Greco, 2002; Larsen et al., 2007) are designed to permit stream-corridor specialists to

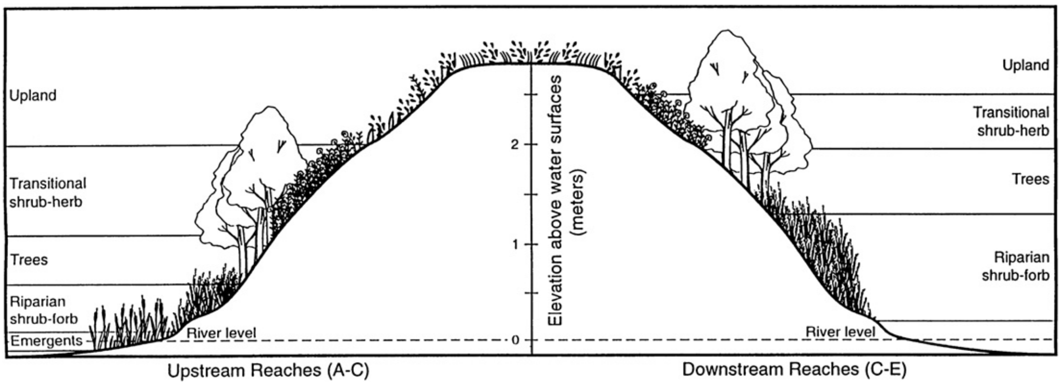

Fig. 4. Diagram of middle Snake River island banks comparing vegetation zones above river level for upstream reaches A–C and downstream reaches C–E (Osterkamp et al., 2001; modified from Johnson et al., 1995).

restore hydrologic function to dammed rivers. The work of Larsen and his colleagues is designed particularly for planning habitat recovery and conservation of degraded bottomlands of large, meandering rivers without causing conflict with imposed infrastructure.

9. Glimpses of the future

Future research to relate fluvial processes and vegetation cannot be confidently predicted, but it can be anticipated. Among the topics that seem likely to warrant attention in the near-term are the interactive effects that vegetation and soil genesis exert on each other, the influence of flow regime on bottomland biota, the effects of invasive exotic plant species on native plant communities, and the effects of possible climate change.

9.1. Future research

Rich potential appears to exist for innovative research for variable spatial and temporal scales at the interface between soil-geomorphic processes and plant ecology. The composite role of fine roots, fungi, microorganisms, mineral secretions of plants (phytoliths), and decomposing plant material to affect soil genesis is well established, but quantification of the process relative to different ecological conditions is poorly understood, especially for the time required. At a micro-scale, these inputs to pedogenesis, soil chemistry and composition, and soil erodibility by different plant species are largely unknown and not considered by erosion models. Sparse data, regardless of climate, watershed position, or land use, until recently have precluded an ability to evaluate rates of erosion. Affecting the erosion are the growth and decay of root material and the extents to which variable densities of root biomass expedite infiltration of precipitation or promote bioturbation. In consequence of sparse data, particle detachment and sediment discharge also have been inadequately explored (Osterkamp and Friedman, 1997).

Nearly half of the controls of infiltration dynamics, probably mostly plant related, on bottomland surfaces are not included in present conceptual or numerical models. Thus, an agenda to develop models to estimate the rates and effects of pedogenesis seems very likely in the near-term. With a similar objective but for a larger areal scale, the potential for rainfall simulation to investigate the effects of individual plant species on runoff following rainfall and flooding in lowlands appears significant. The development of improved field methods to quantify the effect of below-surface vegetation and vegetation byproducts may be essential to meet this objective.

Research leading to an improved understanding of relations between flow regime and habitat for lotic and riparian-zone organisms may require integrated studies of ecology and sediment transport. Many native fish, such as salmon, in western rivers of North America need a narrow range of particle sizes for spawning (Stanford et al., 2006), and specific bottomland features such as open back-channels for rearing of young fish (Milhous, 1996; Van Steeter and Pitlick, 1998; Osmundson et al., 2002). Many riparian-zone plants reproduce only on moist, recently deposited sediment, but these species are also subject to removal by flows that mobilize sediment of underlying surfaces (Scott et al., 1996). Predicting effects of flow alteration on aquatic and riparian communities, therefore, requires integration of models of ecology and sediment transport at scales ranging from a gravel bar to an entire river. High flows, for example, are essential for maintaining bottomland features such as sand bars as well as populations of many native lotic and riparian-zone species (Scott et al., 1996). Prescription of high flows for a managed river, however, requires a broad understanding of the effects of varying the seasonal timing, duration, magnitude, and frequency of the flows (Stanford et al., 1996; Stanford and Ward, 2001). Similarly, understanding the biological effects of contaminated sediment introduced to rivers by mining or other land use activities will require detailed information on sediment transport and the patterns of abundance and sensitivity to toxicity of the affected organisms.

Exotic shrubs, especially saltcedar (*Tamarix* spp.) and Russian olive (*Elaegnus augustifloia*), are altering riparian habitat, sediment transport, and bottomland geometry of many streams in semiarid areas of North America (Burkham, 1972; Graf, 1978). Although abundances of these exotics vary greatly from one bottomland to another, the factors controlling susceptibility to colonization are poorly known. Nevertheless, it is apparent that the spread of these exotic species has been favored by factors related to water development including increased salinity, decreased flood magnitudes, and changes in flood timing. Detailed knowledge of these factors may allow water mangers to control populations of these species by adjusting the flow regime.

A wide variety of modeling development is sure to have a large impact on biogeomorphic research. As examples, new breakthroughs describing the effect of vegetation on soil loss seem assured, and the technology of stream-corridor rehabilitation almost certainly will profit by the development of new models describing channel dynamics of regulated streams (Larsen and Greco, 2002; Larsen et al., 2007). The study, design, and implementation of engineered habitats, whether in channels or other parts of bottomlands, are likely to be important applied activities in coming years and decades (Johnson, 2002).

These potentials for future directions of research in biogeomorphology are examples of numerous possibilities, and the extent to which productive research might be accomplished cannot be fathomed without scientists exploring together what those possibilities may be. Many of the current research problems cannot be constrained by the standardly accepted boundaries of disciplines as generally defined, and cooperative efforts may be needed to continue to yield significant results.

9.2. Effects of climate change

Owing to the complexity of interactions between ecosystems and climatic fluctuations, responses to recent climatic disturbances of alluvial landforms and the vegetation that they support have received little study. Even for short time scales, changes in near-surface soil horizons resulting from the combined effects of drought and high-magnitude storms can be noteworthy (Beard et al., 2005). For longer time scales, the effects may be more integrated but likely will be of greater magnitude.

Flood plains in lowland areas may sequester substantial amounts of organic material from autochthonous and allochthonous sources. Recent studies have shown that coastal lowlands may be important sinks for carbon (Ludwig, 2001; Raymond and Bauer, 2001) and associated nutrients (Noe and Hupp, 2005). Hupp et al. (2008) found that the central Atchafalaya River Basin, with the largest contiguously forested flood-plain in North America, conservatively may trap 5 million Mg of sediment annually, of which over 500,000 Mg are organic material. Investigation of lowland fluvial systems, such as the Atchafalaya River Basin, may be critical for our understanding of global cycling, which in turn has direct implications for nutrient processing, marine “dead zones”, and global climate change.

Recent models predicting decadal-scale climate change suggest a trend of slight warming and increased winter precipitation in most parts of North America, with the greatest changes or impacts in the water-deficient Southwest (Kerr, 2008). The impact may be least along more moist coastal areas of the mid-Atlantic U.S. In the southwestern U.S. and northwestern Mexico, where the greatest changes in effective precipitation seem likely, large change in fluvial-geomorphic processes and related vegetation can be anticipated. Several recent studies in the southwestern U.S. already have documented severe mortality of conifers, such as *Pinus edulis*, in response to drought and consequent insect infestations (Allen and Breshears, 1998; Breshears et al., 2005), and the likely increases in hillslope erosion caused by the die-offs in turn will strongly affect fluxes of runoff and sediment to alluvial bottomlands. Several monitoring programs, such as a National Phenology Network (Betancourt et al., 2007), have been established to identify and evaluate these possible changes and it seems highly likely that as the effects of climate change become more apparent to governmental leaders and the general public, funding for research will increase.

10. Summary and conclusions

Riparian-vegetation patterns and fluvial landforms and processes are closely integrated along most perennial streams. In temperate fluvial systems, water, either through streamflow conditions or groundwater availability, is the most proximal control of distributional patterns of perennial riparian plants. Riparian-zone vegetation also may affect strongly rates of erosion and of sediment deposition, and may be integral in the stability of fluvial surfaces. This is particularly evident in streams disturbed by human alteration, which can lead to channel incision and narrowing. Our analyses show that the riparian-vegetation patterns, even along highly altered streams, identify present and ongoing fluvial forms and processes and simultaneously reflect stages of channel evolution following alteration.

The community organization and dynamics of vegetation in bottomlands are strongly governed by fluvial-geomorphic processes and landforms created and maintained by variable fluxes of water and sediment. Similarly, bottomland vegetation affects fluvial-geomorphic processes and landforms. The likelihood of a species vigorously growing on an alluvial surface depends on (1) the suitability of the surface for germination and establishment (ecesis), and (2) the ambient environmental site conditions that permit persistence at least until reproductive age (e.g. Grubb, 1977; Zimmermann and Thom, 1982; Hupp and Osterkamp, 1996; Hupp and Bornette, 2003; Pike and Scatena, 2008). Thus, plants as indicators of landforms provide considerable information about hydrogeomorphic conditions because the distributional patterns reflect specific disturbance regimes and therefore tolerance for biotic interactions under prevailing stress levels.

Separating factors that simultaneously influence vegetation patterns and geomorphic processes is difficult because most are interdependent, and consistent definitions of landform and process often are lacking within geomorphology and particularly between the geomorphic and plant-ecological sciences. Where conformity occurs between sciences it is usually in the common belief that hydrologic processes control most aspects of fluvial-bottomland ecosystems. Indeed, only hydrologic characteristics provide independent parameters consistent on all perennial streams.

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