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Floods, Flood Control, and Bottomland Vegetation

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Bottomland plant communities are typically dominated by the effects of floods. Floods create the surfaces on which plants become established, transport seeds and nutrients, and remove established plants. Floods provide a moisture subsidy that allows development of bottomland forests in arid regions and produce anoxic soils, which can control bottomland plant distribution in humid regions. Repeated flooding produces a mosaic of patches of different age, sediment texture, and inundation duration; this mosaic fosters high species richness. Because of the many influences of floods on bottomland plant communities, the effects of flood control are pervasive. The response of channel geometry and bottomland vegetation to flood control are conditioned by local fluvial processes, which are determined by the geologic and climatic factors that govern flow variability and sediment load. Construction of upstream reservoirs, bank stabilization, and levee construction generally decrease flow variability and isolate a river from its floodplain. This decreases the physical disturbance on the bottomland and stabilizes water levels, thereby decreasing habitat complexity. Over the long term, pioneer species typically decline and shade-tolerant species increase; however, in the decades after imposition of flood control, adjustments of channel form such as narrowing may cause a transient pulse of establishment of pioneers. Although floods are commonly regarded as a hazard to human communities, they are usually necessary to maintain biotic diversity in bottomlands. By changing the magnitude, frequency, or duration of floods, flood control often constitutes a hazard to riparian vegetation.

Introduction

Bottomland plant communities are diverse, productive, and subject to intense pressure from economic development (Brinson et al., 1981; Gregory et al., 1991). As a result the effects on bottomland vegetation are increasingly included in assessments of proposed flood-control projects. Bottomland vegetation reflects the history of flood timing, frequency, magnitude, and duration. Therefore, altering the flooding regime will affect the vegetation. However, a general prediction of these effects is difficult because of the multiple influences of flooding on bottomland ecosystems.

In this chapter we start by reviewing the principal mechanisms by which floods influence bottomland vegetation. Floods function as transport vectors, distributing plant propagules and importing and exporting sediment and nutrients. Floods affect the moisture regime of bottomland sites in ways that can be either positive or negative for plant growth and survival. In dry landscapes, floods can provide a beneficial moisture subsidy. In other environments, flooding can lead to waterlogged and anoxic soils that produce severe stress for terrestrial plants. The physical disturbance of flooding can damage and remove plants. The character of the vegetation, in turn, is an important component of resistance to flow and thus influences flood hydraulics. The flooding disturbance and channel change that remove some plants also create the bare, moist sites necessary for seedling establishment of many plant species.

Prediction of how flood control will change a particular bottomland community requires quantifying and integrating these multiple influences of flooding on vegetation for a specific location. Nonetheless, general

patterns can be identified along several dimensions. We discuss flood-related strategies of bottomland herbs and trees, regional patterns in bottomland forests, and relations between flood disturbance and reproduction of pioneer trees. Finally, we summarize some of the well-documented cases of vegetation response to flood control. Although the scope of the presentation is international and includes the entire plant community, the emphasis reflects our experience working with trees in bottomlands of the western United States.

For the purposes of this chapter, a bottomland is the area receiving surface or subsurface water from a stream for at least part of the time. The rest of the landscape is the upland. All vegetation influenced by surface water or alluvial groundwater from a stream occurs on its bottomland. The term riparian zone, not used in this chapter, is sometimes synonymous with bottomland and sometimes refers more restrictively to that portion of the bottomland immediately adjacent to the stream. The bottomland includes the flood plain, loosely defined here as the alluvial surfaces subject to frequent inundation.

Floods as Transport Vectors

Floods disperse seeds of many bottomland species (Kalliola et al., 1991). For example, along streams in central Amazonia, most species that occupy sites subject to flooding disperse seeds via water (Kubitzki and Ziburski, 1994). Many species, including the willow family (Salicaceae), use both wind and water transport (Johnson, 1994; Kalliola et al., 1991). Some species disperse by means of floating vegetative propagules such as rhizomes or branch fragments (Johansson and Nilsson, 1993; Shafroth et al., 1994). Water dispersal enhances dispersal range, and long distance dispersal may contribute to the high species richness of many bottomland communities (Nilsson et al., 1994). Many bottomland plants time their release of seed to coincide with or to follow flood peaks (White, 1979; Hupp, 1992; Johnson, 1994), which prepare a seedbed and disperse seeds high enough along the bank to avoid future disturbances such as ice scour (Auble and Scott, 1998). Patterns of adult plants in a bottomland are influenced by processes that control deposition of plant propagules (Schneider and Sharitz, 1988; Nilsson et al., 1991; Johansson and Nilsson, 1993; Rood and Kalischuk, 1998).

Flooding promotes exchange of solutes and both organic and inorganic sediments between river and floodplain (Finley, Chapter 7, this volume). Because of nutrients supplied by the river, floodplains typically have high primary productivity (Frangi and Lugo, 1985; Mitsch and Gosselink, 1986). However, the nutrient subsidy depends on both the quantity of nutrients transported by the river and the frequency of flooding. Storage of materials on floodplains is temporary; therefore, during a given flood, the floodplain may act as a source or sink of sediment, nutrients, and contaminants (Mitsch et al., 1979; Sanchez-Perez et al., 1991).

Floodplain plants take up inorganic nutrients and return partially decomposed leaves and stems to the river. Therefore, floodplains can be net importers of inorganic forms of nutrients and net exporters of organic forms (Elder, 1985). Organic matter from floodplains may be important for stream productivity, especially where shade or high-sediment load limits growth

of plants and algae in the stream (Vannote et al., 1980). Large woody debris from floodplain trees strongly influences channel geometry and patterns of discharge and provides an important habitat for fish and other aquatic organisms (Harmon et al., 1986). Floodplain bacteria can increase nitrogen in a riverine ecosystem through nitrogen fixation (Walker and Chapin, 1986). On the other hand, periodic wetting and drying of soils releases nitrogen to the atmosphere through denitrification (Mitsch and Gosselink, 1986). Floods may flush away contaminants such as salts that otherwise would accumulate through evaporation on the floodplain surface (Ohmart et al., 1988).

Flooding and Anoxia

Flooding may increase or decrease growth of plants (Stockton and Fritts, 1973; Mitsch et al., 1979). Mortality or reduced growth from prolonged inundation is typically associated with exhaustion of energy reserves or oxygen depletion in the root zone (Stockton and Fritts, 1973). Depletion of oxygen leads to reducing conditions and development of toxic concentrations of metals and organic compounds. Therefore, many species in flood-prone environments have air spaces in roots and stems for transport of oxygen down to the root zone or chemical mechanisms for tolerance or alteration of toxic compounds. The duration of flooding a bottomland plant can survive is influenced by the species and size of the plant; the depth, temperature, and clarity of the water; and the timing of inundation relative to the growing season (Gill, 1970; Whitlow and Harris, 1979; Stevens and Waring, 1985; Friedman and Auble, 1999). Adult trees of North American swamps such as bald cypress (*Taxodium distichum*) or water tupelo (*Nyssa aquatica*) typically survive deep inundation for more than one growing season, whereas shagbark hickory (*Carya ovata*) and white oak (*Quercus alba*) do not survive inundation for more than a few days (Whitlow and Harris, 1979). Within a given species larger plants are usually more tolerant of flooding because of their greater energy reserves and because shallow flooding may not completely submerge the plant (Gill, 1970). Plants are less tolerant of flooding during the growing season and at high temperatures, when relatively rapid metabolism exhausts reserves and depletes soil oxygen (Gill, 1970).

Moisture Subsidy

In a dry environment streams provide a moisture subsidy that allows survival of plants that otherwise could not occur (Hughes, 1990). For example, in much of the Great Plains and Great Basin of North America, forest is mostly restricted to bottomlands. In some situations the moisture subsidy is unrelated to flooding. For example, plants may derive water from sideslope drainage or from an alluvial aquifer controlled largely by base flow. On the other hand, on surfaces high above the channel, survival and growth of plants may depend on a moisture subsidy due to flooding (Reily and Johnson, 1982; Rood et al., 1995). If moisture enters floodplain soils as downward percolation after overbank flooding, then moisture may be provided even by floods of short duration. If moisture enters by lateral infiltration of the bank without overbank flooding, then sustained high flows

may be necessary to provide sufficient water. Many bottomland plants in arid climates are sensitive to changes in depth of the alluvial water table (Scott et al., 1999). Floods may cause mortality of bottomland plants by changing the bed level, thereby altering the water-table depth (Cooke and Reeves, 1976).

Physical Disturbance

High flows can physically damage or remove bottomland plants (Ellery et al., 1990; Menges, 1990). Flood debris and floating ice abrade tree bark and provide a point of entry for disease organisms (Sigafoos, 1964; Yanosky, 1982). Debris trapped on the upstream side of a plant magnifies the fluid drag exerted by water against the stem and may cause the plant to be uprooted or the stem to be broken or bent (Osterkamp and Costa, 1987; Oplatka and Sutherland, 1995); many bottomland species resprout from roots or broken or bent stems (Sigafoos, 1964; Hupp, 1988; Krasny et al., 1988; Rood et al., 1994). The plant can be washed away if flood shear stresses are sufficient to mobilize the sediment in which it is rooted (Stevens and Waring, 1985; Osterkamp and Costa, 1987; Friedman and Auble, 1999). A plant may also be injured by deposition of sediment transported by floods (Hupp, 1988). Finally, plants growing on top of a bank can be removed by bank failure after fluvial erosion of sediment at the base of the bank (Thorne, 1990; Hupp, 1992; Mertes, Chapter 5, this volume).

Whereas physical damage resulting from flooding is usually related to the peak discharge, damage from oxygen depletion or exhaustion of energy reserves is more strongly related to flood duration. Because the effects of these two processes differ depending on the species and the position in the bottomland, the influence of controlled floods can be managed by adjusting the flood magnitude and duration (Stevens and Waring, 1985; Friedman and Auble, 1999).

Influence of Vegetation on Flooding

Although the focus of this chapter is the influence of floods on vegetation, living and dead plants in turn can have an important influence on flooding. Vegetation is an important roughness element in channels. The taller, more rigid, and more closely packed the stems, the greater the resistance to flow (Arcement and Schneider, 1989). The reduction in velocity caused by vegetation decreases shear stress on the bank, but it also raises the elevation inundated at a given discharge. Thus vegetation can attenuate flood flows by slowing velocities and causing water to spread higher on the floodplain.

Woody debris in channels can greatly increase channel roughness. However, once this debris has been mobilized by a flood, it can become an agent of erosion (Burkham, 1972; Harmon et al., 1986). Most changes in channel pattern along the Squamish River in British Columbia involve channel abandonment and flow diversion associated with logjams (Hickin, 1984). Removal of woody debris to improve navigability can transform channel geometry even in large rivers (Sedell and Froggatt, 1984; Thorne, 1990).

Reduced velocity around vegetation or woody debris leads to deposition of the fine sediment that is essential for bank cohesion (Nanson

and Beach, 1977; Osterkamp and Costa, 1987; McCarthy et al., 1992). Roots bind sediment particles, increasing the critical shear stress necessary to induce erosion. Smith (1976) found that the rate of erosion of a silt bank increased by four orders of magnitude when the mat of willow and graminoid roots was removed and concluded that vegetation was largely responsible for the slow rate of lateral migration in anabranches of an Alberta stream. In New Zealand, willows have been planted to reduce the width of braided channels (Nevins, 1969). In Australia and the western United States, reduction in grass cover by grazing may have helped bring about the development of incised channels by reducing the critical shear stress for sediment transport (Cooke and Reeves, 1976; Prosser et al., 1995).

The influence of plant growth form on channel geometry is scale dependent. Reaches of small streams in grassland are narrower than reaches of the same streams under forest (Zimmerman et al., 1967), possibly because root density of grass sod is higher than that of forest floor and because living and dead wood increase turbulence. On the other hand, woody plants generally have deeper and larger roots than grasses, which give wooded banks along large streams better protection against undercutting (Thorne, 1990). Hey and Thorne (1986) found that rivers with grassy banks were on average 1.8 times as wide as rivers with forested banks. As the forces of the river become large relative to the ability of plants to resist them, the influence of the vegetation on channel pattern should be diminished (Zimmerman et al., 1967; Hickin, 1984). However, vegetation and woody debris can influence the geometry even of large rivers (Sedell and Froggatt, 1984; Harmon et al., 1986).

Flood Disturbance and Bottomland Plant Communities

Damage to some plants provides opportunities for the establishment and growth of others. Thus floods maintain populations of plant species that would decline because of competition in the absence of disturbance (Menges, 1990; Friedman et al., 1996). The character of flood disturbance varies both parallel and perpendicular to the channel. Perpendicular to the channel, from the thalweg to the valley edge, are gradients of decreasing frequency, intensity, and duration of flood disturbance. These disturbance gradients are strongly correlated with vegetation patterns (Bedinger, 1971; Furness and Breen, 1980; Wharton et al., 1982; Bravard et al., 1986; Day et al., 1988; Glavac et al., 1992; Auble et al., 1994, 1997), but their effects are often difficult to distinguish from those of other strongly correlated gradients, including light, nutrients, moisture availability, anoxia, and sediment particle size (Illichevsky, 1933; Robertson et al., 1978; Menges and Waller, 1983; Friedman et al., 1996). Interactions among disturbance, sediment transport, and vegetation growth often lead to development of distinct fluvial surfaces occupied by distinct plant communities (Hupp and Osterkamp, 1985; Harris, 1987). Parallel to the stream, the character of flood disturbance varies in response to changes in sediment supply, lateral constraint, stream gradient, and tributary influence (Hupp, 1988; Nilsson, 1987).

When a flood disturbs part of a bottomland, the resulting new patches of moist, bare ground are colonized by vegetation. As the river moves

and sediment is deposited or eroded from these patches, the local flood disturbance regime changes (Wohl, Chapter 6, this volume). Vegetation on such patches develops over time in response to the changing disturbance regime, the changing substrate, and biotic interactions. Although the new area made available by flooding may be small in any given year, the processes of vegetation change begun on such patches continue for decades or centuries, and movement of the channel can result in a complex mosaic of patches with different disturbance histories and vegetation (White, 1979; Pickett and White, 1985; Hupp, 1992; Baker and Walford, 1995; Friedman et al., 1996). This flood-generated mosaic may occupy a large proportion of the land surface, increasing both landscape and species diversity. For example, in a 0.5×10^6 km^2 area of the Peruvian Amazon Basin, 12% of the total land area is occupied by river floodplains and an additional 14.6% is occupied by older fluvial terraces (Salo et al., 1986).

Flood-Related Strategies of Bottomland Herbs

Floods affect bottomland vegetation directly by controlling the frequency, intensity, and duration of physical disturbance and indirectly by influencing sediment particle size, seed availability, and availability of light, moisture, and nutrients. These factors vary greatly in a bottomland in space and time, resulting in a variety of environments, many of which are unique to bottomlands. This variety is responsible for the high species richness typical of bottomlands (Gregory et al., 1991; Pollock et al., 1998).

The influences of flooding lead to a predictable sequence of herbaceous species along a bottomland cross section. Immediately adjacent to the channel, flood frequency, intensity, and duration are too great for long-term plant survival, and the dominant herbs are ruderal species such as smartweed (*Polygonum punctatum*) that are capable of carrying out their life cycle between floods, usually in a single growing season (Grime, 1977; Menges and Waller, 1983). They allocate a large proportion of their resources to producing seeds that are dispersed to other disturbed sites. The rapid growth employed in the ruderal strategy requires abundant nutrients. In some bottomlands of Ontario there is no ruderal community adjacent to the channel, apparently because nutrient scarcity prevents plants from completing their life cycle between floods (Day et al., 1988).

At moderate heights above the channel are plants that can tolerate physical disturbance and anoxia, such as the sedges (*Carex* spp.). These plants survive flood disturbance because of their small size, thin flexible leaves, and placement of rapidly dividing cells close to the ground. To survive the anoxia associated with prolonged inundation, these plants often have hollow stems for transport of oxygen to roots and chemical pathways for detoxification of the products of anaerobic respiration (Gill, 1970).

At greater heights, physical disturbance and anoxia are less important, moisture is abundant, and nutrients have time to accumulate in the soil. Here the dominant herbs are fast-growing and tall and can often spread laterally by root sprouts or runners, characteristics that enable them to monopolize available resources in the absence of physical disturbance (Menges and Waller, 1983; Wilson and Keddy, 1986). Typical species include nettle (*Urtica dioica*) and sunflower (*Helianthus* spp.) (Menges

and Waller, 1983). Because trees may be important in this zone, many of the herbs are tolerant of shade.

At still greater heights moisture or nutrient subsidies from the stream may be reduced. In an arid or semiarid climate such surfaces may be prone to drought stress. For example, in the plains of eastern Colorado, the dominant herbs on these surfaces, such as sand dropseed (*Sporobolus cryptandrus*), have adaptations for drought avoidance and water and nutrient conservation including taproots and involute leaves (Friedman et al., 1996).

Regional Patterns in Bottomland Tree Communities

The success of any particular plant strategy with respect to floods depends on the frequency, intensity, and duration of flooding, which are controlled by geology, climate, and position in the bottomland. For example, strategies for tolerating anoxia are useful only where flood intensity is low enough to allow plant survival, and flood duration is high enough to produce anoxia.

Regional patterns in flood intensity, flood duration, and drought stress can help to explain regional differences among bottomland forests. In humid regions trees can survive without moisture provided by a stream; therefore, forest occupies almost all the bottomland, an area that is typically much larger than the zone disturbed by the stream in any year (Figure 8.1). Forests in the zone of intense riverine disturbance are dominated by pioneer species: trees and shrubs that release abundant wind- or water-dispersed seeds early every growing season near the time of peak flows. These species grow rapidly, are able to resprout after breakage or burial by floods, and tolerate a moderate amount of anoxia (Sigafoos, 1964; Yanosky, 1982), but they require abundant water and light (White, 1979; Salo et al., 1986). Examples of pioneers in North America include *Acer saccharinum, Betula nigra, Populus deltoides*, and *Salix nigra* (Hupp, 1992). Examples in the western Amazon Basin include *Tessaria integrifolia* and *Gynerium sagittatum* (Kalliola et al., 1991). Away from the zone of heavy disturbance are shade-tolerant trees, often with larger animal-dispersed seeds. In North America these include *Quercus laurifolia* and *Magnolia grandiflora*. These species are slower at colonizing new sites but are able to become established under existing trees in the shade. Where gradients are low and bottomlands wide – for example along rivers in the Coastal Plain of the southeastern United States – there may be a broad area that is not subject to physical disturbance from the stream but that is subject to extended inundation and anoxia. This zone is dominated by trees able to tolerate the stress of anoxia, such as *Taxodium distichum* and *Nyssa aquatica*. In this situation tolerance of anoxia is often considered the most important characteristic affecting bottomland plant distribution (Bedinger, 1971; Wharton et al., 1982). Pioneer tree species occupy a small proportion of

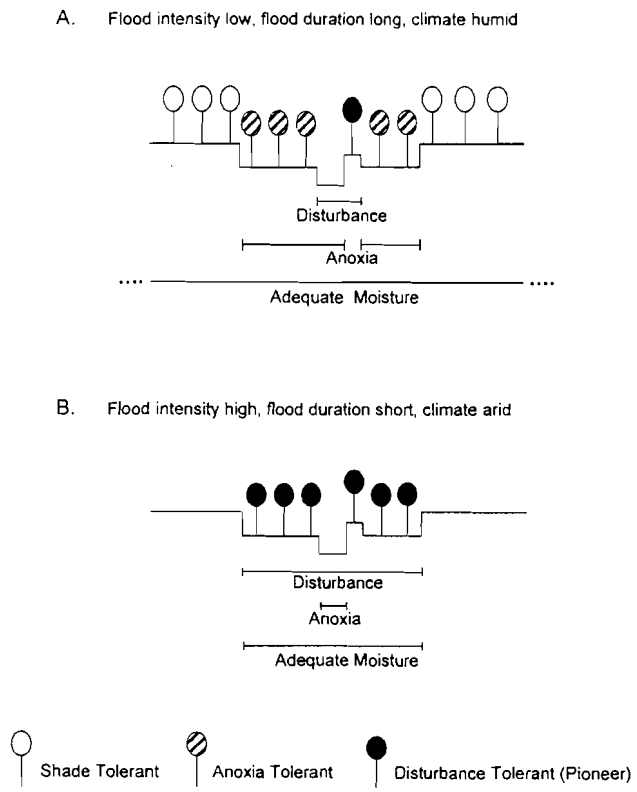

Figure 8.1. Influence of environmental stresses on the distribution of bottomland trees with different strategies. Bars under cross sections show the extent of physical disturbance, anoxia, and adequate moisture for survival of trees. Although the three tree strategies are presented as distinct, many species combine strategies. The term shade tolerant refers to trees that are able to reproduce in the shade of other trees in the absence of physical disturbance. (A) Cross section typical of bottomlands in low-gradient streams in the Coastal Plain of the southeastern United States (Bedinger, 1971). (B) Cross section typical of bottomlands in the western Great Plains (Friedman et al., 1997).

the bottomland (Figure 8.1), and many tree species become established in light gaps provided by disturbances other than riverine deposition and erosion, including fire, wind, and extended inundation.

In arid and semiarid regions bottomland forests are narrower because the area capable of supporting trees is limited to a zone adjacent to and receiving moisture from the river (Hughes, 1994). Relatively high flow variability results in a wider zone of riverine disturbance and a narrower zone wet enough throughout the growing season to support trees. In this situation, much or all of the forested zone may be within the area that is frequently disturbed by the river. As a result pioneers such as cottonwood (*Populus* spp.) and willow (*Salix* spp.) can be the dominant and are sometimes the only trees present (Figure 8.1) (Friedman et al., 1997). Plant stress from anoxia occurs in bottomlands of dry regions (Friedman and Auble, 1999) but is often limited in extent (Auble et al., 1994) because flood peaks are of relatively short duration (Baker, 1977; Wolman and Gerson, 1978). Although flow variability in arid watersheds is usually high, many of the large dryland rivers receive much of their flow from relatively humid mountains. The resulting stable flow regime reduces the importance of physical disturbance and increases the importance of shade-tolerant species not requiring disturbance (Hughes, 1990; Friedman et al., 1998).

Figure 8.1 illustrates only two examples of the influence of climate and specific levels of flood intensity and duration on the abundance of tree species with different strategies. Other important combinations occur. For example, many low-energy rivers in humid regions have forest communities like that shown in Figure 8.1A. However, where rivers are higher in energy the zone of disturbance is wider, and pioneer species occupy a larger proportion of the cross section. This combination of high flood intensity, long flood duration, and humid climate is exemplified by the lower Mississippi River before flow regulation and the whitewater rivers of the western Amazon Basin (Kalliola et al., 1991).

Floods and Reproduction of Bottomland Pioneer Trees

Over the past 30 years there have been many studies relating flood disturbance history to the pattern of different-aged trees across a bottomland (Everitt, 1968; Johnson et al., 1976; Bradley and Smith, 1986; Scott et al., 1997). Much of this work has occurred in semiarid interior western North America, where floodplains are dominated by a small number of disturbance-dependent species with distinct annual rings (but see Nanson and Beach, 1977; Gottesfeld and Gottesfeld, 1990; Hupp, 1992; Nanson et al., 1995). This approach is more difficult to apply where floodplain trees reproduce in the absence of flood disturbance or where annual rings are difficult to discern (Hughes, 1990).

Although floods can remove trees, they also promote establishment of pioneer species by providing the necessary bare, moist patches of sediment (White, 1979; Friedman et al., 1997). In nonflood years such patches are formed in locations susceptible to future scouring by ice or water, and long-term survival is therefore low (Figure 8.2) (Auble et al., 1997). Flooding can lead to more long-term survival by forming bare, moist patches in

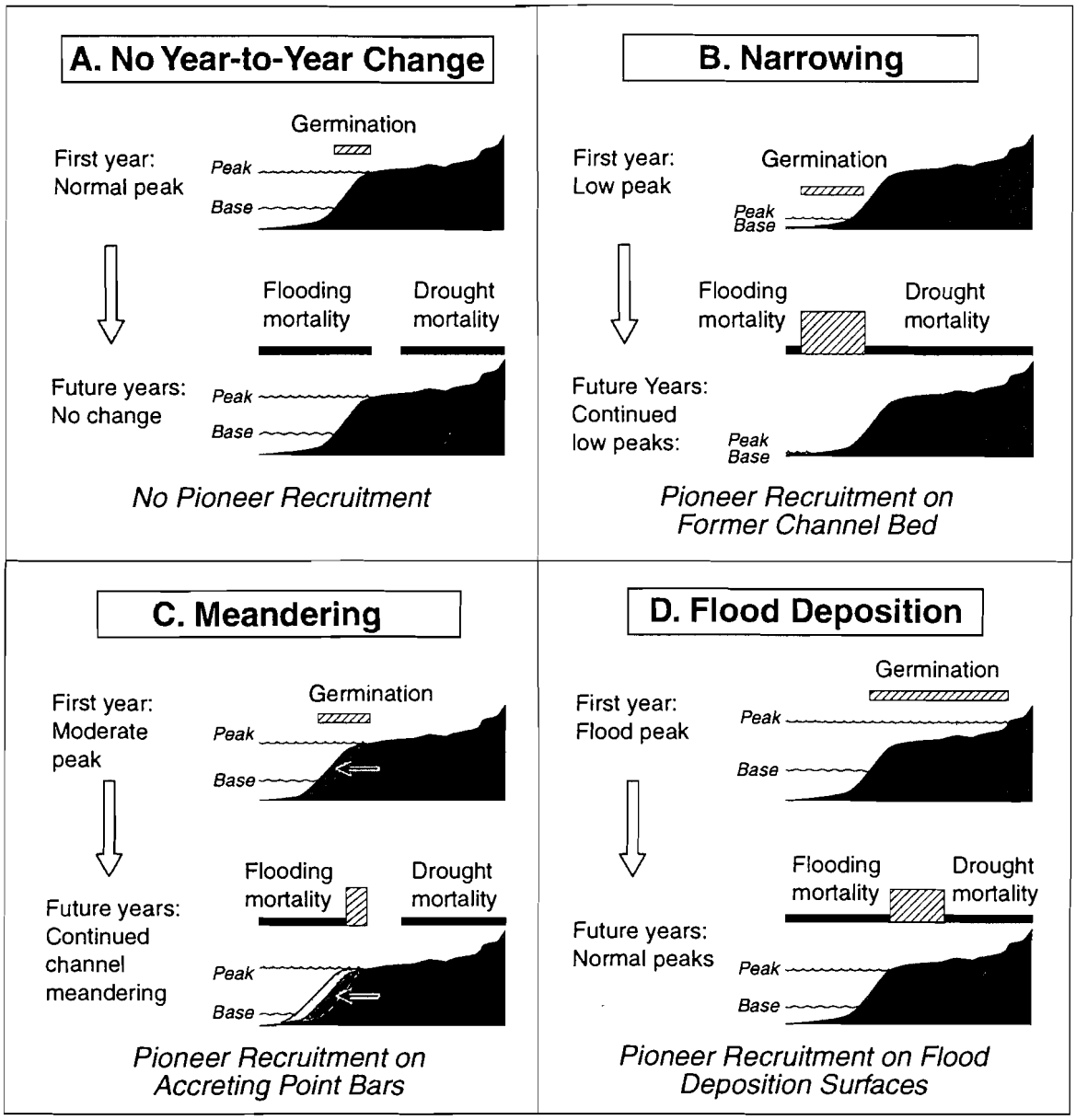

Figure 8.2. Hydrogeomorphic control of recruitment of woody riparian pioneer species. Seed germination, early seedling mortality, and tree recruitment are shown in relation to annual high and low flow lines along a bottomland elevational gradient. Four idealized situations are depicted with a single bottomland cross section. (A) Little or no tree recruitment in the absence of interannual flow variability and channel movement; (B) channel narrowing with recruitment on the former channel bed; (C) recruitment on point bars of a meandering river; and (D) tree recruitment at high elevations associated with infrequent floods and no channel movement. In each of the four situations the cross-hatched area in the upper part indicates the zone of seedling establishment, and the cross-hatched area in the lower part indicates the zone of long-term survival (redrawn from Auble and Scott, 1998).

positions that are relatively safe from future disturbance. Scott et al. (1996) described three examples of flood-related processes that can lead to tree establishment: flood deposition, postflood channel narrowing, and channel meandering (Figure 8.2). These processes are not mutually exclusive and the list is not exhaustive. The purpose of this approach is to emphasize how fluvial processes condition the relation between flow and tree establishment.

Flood Deposition

Because they deposit and erode sediment high above the channel, floods often produce the bare, moist, safe sites suitable for tree establishment (Figure 8.2). This phenomenon occurs on a wide range of streams, but it is especially important where a narrow valley prevents channel movement and the associated creation of relatively low sites safe from future disturbance. In this situation, forests occur as narrow bands, and reproduction occurs only after the largest floods. Along a constrained portion of the Missouri River in central Montana, Scott et al. (1997) excavated and aged plains cottonwood trees, and found that most adult trees were established more than 1.2 m above the lower limit of perennial vegetation and 0–2 years after a flood with a recurrence interval of 9 years or greater. In nonflood years seedlings germinate lower on the bank and are removed by subsequent winter ice and spring floods (Auble and Scott, 1998). The authors argued that maintenance of the frequency and magnitude of extreme floods is essential for reproduction of cottonwoods along this portion of the Missouri River.

Postflood Channel Narrowing

Flood erosion often widens channels. Subsequently, channel narrowing occurs as vegetation, including trees, becomes established on portions of the former channel bed. In this case, vegetation establishment occurs at low positions during periods of relatively low flow (Figure 8.2) (Scott et al., 1996). Postflood narrowing may continue for decades before a narrower equilibrium width is approached (Schumm and Lichty, 1963; Burkham, 1972; Johnson, 1994; Friedman et al., 1996). Thus tree establishment is related to low flows in the short term but is also an indirect result of flood-related widening (Friedman et al., 1996; Stromberg et al., 1997). Postflood channel narrowing is most important along streams subject to large variation in width. Variable width is promoted by a suite of factors that result in low bank strength and high shear stress, especially high flow variability, high channel gradient, high bed sediment load, and a low ratio of valley width to channel width. These characteristics are demonstrated by the braided channels of the High Plains in the southcentral United States (Osterkamp, 1978; Friedman et al., 1998) and by many ephemeral channels in arid regions. Although the focus in this section is on channel narrowing after flood-related widening, narrowing is often caused by other factors including flood control and flow diversion (Petts, 1979; Williams and Wolman, 1984; Friedman et al., 1998), climate change (Schumm, 1969; Nanson et al., 1995), and intrinsic processes of channel change (Nanson, 1986).

Channel Meandering

Where flood shear stresses are low relative to bank strength, channel width is small and stable and postflood channel narrowing is relatively unimportant. This situation is favored by low flow variability, low channel gradient, high suspended sediment load, and a high ratio of valley width to channel width, which decreases flood shear stress by spreading overbank flows over a wide area (Osterkamp, 1978). In these streams channel change occurs less by changes in channel width and more by changes in channel location. A common process in such streams is channel meandering, in which stream bends move progressively outward and downstream while sediment is deposited on the inside of bends on arcuate point bars. Point bars are suitable sites for establishment of bottomland pioneer trees because they are bare and moist, and because progressive channel movement and sediment deposition reduce subsequent local flood disturbance (Figure 8.2) (Bradley and Smith, 1986; Hughes, 1990). Forests consist of parallel arc-shaped bands increasing in age away from the channel (Nanson and Beach, 1977; Bradley and Smith, 1986). Bands of trees are numerous and most are small, reflecting the fact that most channel migration is accomplished by relatively frequent high flows.

Many rivers produce little of the bare, moist habitat suitable for pioneer tree establishment and therefore support only small areas of pioneer forest. For example, some rivers of the coastal plain of the southeastern United States are so low in energy that channel migration is slow, and the rate of formation of bare, moist surfaces is also slow. As a result, pioneer species occupy less area than species that can reproduce in the absence of physical flood disturbance (Bedinger, 1971).

Relative Importance of Floods with Different Recurrence Intervals

Although floods strongly influence the vegetation of most bottomlands, the relative importance of frequent moderate floods and infrequent extreme floods varies with climate and landscape position (Baker, 1977; Wolman and Gerson, 1978). Along large, low-gradient streams in humid climates flow variability tends to be low, and most channel change and pioneer tree establishment occurs during frequent floods. Because any one of these events alters only a small portion of the bottomland (Wolman and Miller, 1960), channel width, forested area, and forest age structure may approach a steady state. When extreme events do occur, channel change is modest because dense vegetation promotes bank strength, and recovery is rapid because flows between extreme events are high enough to readjust the channel (Costa, 1974; Wolman and Gerson, 1978). Meandering channels are typical of streams whose geometry is controlled by frequent, moderate floods (Wolman and Miller, 1960; Hughes, 1994).

Along small or steep streams or in arid climates flow variability is usually higher, and extreme floods tend to have greater and more lasting effects. More channel change and establishment of bottomland forest occurs as a result of infrequent extreme floods that disturb a large portion of the bottomland (Hack and Goodlett, 1960; Burkham, 1972; Wolman and Gerson, 1978; Ish-Shalom-Gordon and Gutterman, 1991). Along these

streams, channel width, forested area, and forest age structure are all a function of the magnitude of and time since recent floods (Hughes, 1994; Friedman et al., 1996, 1997). For example, in the late 19th century, the Cimarron River in southwestern Kansas was a 15-m-wide stream with few bottomland trees. A major flood in 1914 widened the channel and destabilized the floodplain, resulting in further widening during subsequent lesser floods. By 1942 the channel was 370 m wide. During the next 12 years, the channel narrowed by half and a large forest of bottomland pioneers was established (Schumm and Lichty, 1963).

Effects of Flood Control on Bottomland Vegetation

Seventy-seven percent of the total discharge of the 139 largest river systems in the northern third of the world is moderately to strongly affected by reservoirs (Dynesius and Nilsson, 1994). Reservoir construction results in immediate and severe impacts on the inundated area upstream and more subtle impacts downstream. In the United States, 5% of the length of major streams has been inundated by large reservoirs (Brinson et al., 1981). Along some extensively regulated rivers, such as the Columbia in Washington, USA, the Missouri in South Dakota and North Dakota, USA (Hitt, 1984), and most large rivers in Sweden (Nilsson, 1984), the river has been transformed into a staircase of reservoirs along which almost all the preexisting bottomland is inundated. Permanent inundation eliminates the bottomland vegetation, replacing it with an aquatic ecosystem (Monosowski, 1986). The new reservoir shoreline includes some bottomland species, but their total area is small because bank slopes are steep. In addition, species richness and cover are typically very low because water-level fluctuations are greater in magnitude than, and different in timing from, those of unregulated rivers (Nilsson, 1984). In sediment-rich systems, long-term reservoir operation produces deltaic deposits that could be managed to promote development of bottomland ecosystems. However, this would require moderation of fluctuations in water levels, which could compromise use of the reservoir for power generation or downstream flood control.

Downstream of reservoirs, the bottomland ecosystem is not immediately eliminated, but it may be altered in many ways. Reservoirs may interfere with plant dispersal by trapping seeds or reducing the high flows that deposit seeds high on the bank in positions suitable for germination and survival (Johansson and Nilsson, 1993). Flood control may alter the timing of peak flows, uncoupling the temporal relation between the period of seed release and the formation of sites suitable for seedling establishment (Fenner et al., 1985; Everitt, 1995). By reducing the exchange between river and floodplain, dam or levee construction may alter temperature, increase salinity, and decrease availability of moisture and nutrients in floodplain soils (Gill, 1973; Ohmart et al., 1988). Reduction of plant growth and decreased habitat quality for animals commonly result (Attwell, 1970; Gill, 1973; Reily and Johnson, 1982; Stromberg and Patten, 1992; Rood et al., 1995).

Dikes and upstream flood-control dams reduce physical disturbance adjacent to a channel, decreasing populations of disturbance-dependent plants (Reich, 1994; Gill, 1973), increasing populations of shade-tolerant

species (Johnson et al., 1976; Bravard et al., 1986; Shafroth et al., 1995a) and allowing encroachment of vegetation toward the channel (Turner and Karpiscak, 1980; Nilsson, 1984; Johnson, 1994; Sherrard and Erskine, 1991; Friedman et al., 1997). By reducing flood magnitude and increasing flood duration, flood control may increase the importance of plant stress from anoxia relative to that from physical disturbance (Friedman and Auble, 1999). Decreases in flow variability reduce the spatial and temporal variability of the bottomland environment, resulting in reduced area and diversity of the bottomland plant community (Nilsson, 1984; Auble et al., 1994). Elimination of native species and creation of novel conditions may promote spread of exotic species in bottomlands (Nilsson, 1984).

Channel widening or downcutting may be caused by any flood-control activity that increases the sediment transport capacity of the stream or decreases the sediment load. Such activities include construction of dikes, which increases flow depth; channel straightening, which increases channel gradient; and dam construction, which reduces sediment load. The resulting increase in channel conveyance further isolates the river from its floodplain (Petts, 1979; Williams and Wolman, 1984; Hupp, 1992; Reich, 1994; Marston et al., 1995). In some cases a new floodplain may eventually develop. For example, in the southeastern United States many channels have been straightened, in part to increase flood conveyance. Streams responded by downcutting. Collapse of vertical banks led to channel widening and a new inset floodplain was developed after several decades. The vegetation changes associated with this fluvial process are described by Hupp (1992).

The different effects of flood control may act in combination. For example, along the lower Colorado River and other streams in the dry interior of the western United States, flood control has been associated with the spread of the exotic pioneer shrub saltcedar (*Tamarix* spp.). Like its native counterparts, cottonwood and willow, saltcedar produces abundant wind- and water-dispersed seeds capable of becoming established immediately on bare, moist substrates. Compared with cottonwood and willow, adult saltcedar is more tolerant of high salinity, fire, and drought (Busch and Smith, 1995; Shafroth et al., 1995b) but less tolerant of flood disturbance (Stromberg et al., 1993). Whereas viable seeds of cottonwood and willow are present for only 1–2 months in early summer, saltcedar releases seeds throughout the summer (Warren and Turner, 1975). Flood control and river diversion have fostered increases in saltcedar and decreases in cottonwood and willow by reducing the moisture subsidy and allowing accumulation of salts on the floodplain (Ohmart et al., 1988), decreasing physical disturbance, allowing the accumulation of flammable leaf litter (Ohmart et al., 1988), and delaying peak flows beyond the cottonwood seed viability period (Everitt, 1995). By 1994, saltcedar occupied about 500,000 ha of bottomlands in the United States (Brock, 1994).

Because the influence of floods on bottomlands is mediated by physiographic and climatic factors, the effects of flood control on processes of channel change vary within and among regions. For example, the principal response of wide, shallow braided channels to flood control is channel narrowing (Williams and Wolman, 1984; Johnson, 1994; Church, 1995; Ligon et al., 1995), and the principal response of relatively narrow and deep

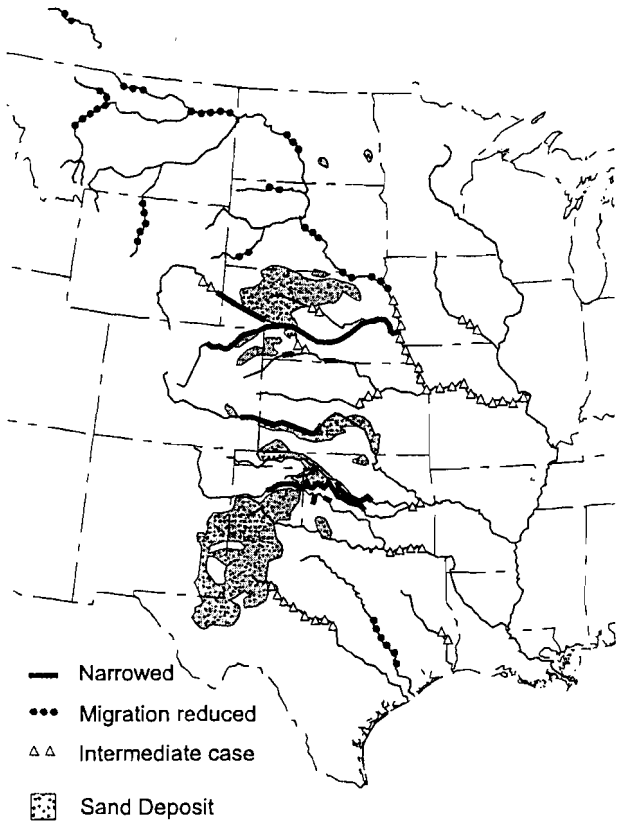

Figure 8.3. Downstream effects of dams on channel width and migration rate in central United States. Location of sand deposits is from Hunt (1979). (Redrawn after Friedman et al., 1998)

meandering channels is a reduction in the channel migration rate (Johnson et al., 1976; Bradley and Smith, 1986; Hughes, 1990). There is a regional pattern in the response of rivers and bottomland forests to flood control in the central United States (Figure 8.3) (Friedman et al., 1998). Before water management, braided channels were most common in the southwestern Plains, where flow variability was high, sand was abundant, and clay and cobbles were relatively scarce; meandering channels were more common to the east and north, where flow variability was low, and clay and cobbles were more abundant. As a result, the principal response to flood control has been channel narrowing in the southwest and reduction in migration rate in the east and north (Figure 8.3) (Friedman et al., 1998).

Channel narrowing is associated with a burst of establishment of native and exotic woody bottomland pioneer species on the former channel bed (Johnson, 1994). Reduction in channel migration rate is associated with a decrease in reproduction of woody bottomland pioneers (Bradley and Smith, 1986). Therefore, bottomland pioneer forests in the southwestern Great Plains have temporarily increased in area after dam construction, while such forests in the northern and eastern plains are declining (Friedman et al., 1998; Johnson, 1998). These regional changes in forest abundance have strongly affected animal communities. For example, almost 90% of the 82 breeding bird species predictably present each spring on the steppe of eastern Colorado were not present in 1900 (Knopf, 1986). The new species use forests that developed during channel narrowing along rivers such as the South Platte as well as trees planted in shelterbelts. At the same time, channel narrowing along the Platte River in Nebraska has degraded the habitat for birds such as the whooping crane (*Grus americana*) and the least tern (*Sterna albifrons*) that use wide braided channels (U.S. Fish and Wildlife Service, 1981).

The current regional contrast in forest development in the central United States is a transient effect of vegetation establishment during the period of channel narrowing along formerly braided streams (Petts, 1979; Church, 1995). The long-term response throughout the Great Plains is a decrease in pioneer species and an increase in shade-tolerant trees, shrubs, and herbs that can reproduce in the absence of physical disturbance (Bravard et al., 1986; Johnson, 1998).

Conclusions

Because of the pervasive influence of floods on bottomland plant communities, the effects of flood control are strong and complex. The response of channel geometry and bottomland vegetation to flood control are conditioned by local fluvial processes, which are determined by the

geologic and climatic factors that govern flow variability and sediment load. Construction of upstream reservoirs, bank stabilization, and levee construction decrease flow variability and isolate a river from its floodplain. This decreases the physical disturbance on the bottomland and stabilizes water availability, thereby decreasing habitat complexity on the bottomland. Over the long term, disturbance-dependent forest species typically decline and shade-tolerant species increase; however, in the decades after imposition of flood control, adjustments of channel form such as narrowing may cause a transient pulse of the establishment of species that require bare ground for establishment.

Although the occurrence of floods is commonly regarded as a hazard to human communities, floods are usually necessary for maintenance of biotic diversity on bottomlands. By changing the magnitude, frequency, or duration of floods, flood control often constitutes a hazard to riparian vegetation.

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