

EXTREME FLOODS, CHANNEL CHANGE, AND RIPARIAN FORESTS ALONG EPHEMERAL STREAMS

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Abstract. The geomorphic effectiveness of extreme floods increases with aridity and decreasing watershed size. Therefore, in small dry watersheds extreme floods should control the age structure and spatial distribution of populations of disturbance-dependent riparian trees. We examined the influence of extreme floods on the bottomland morphology and forest of ephemeral streams in a semiarid region. Along six stream reaches on the Colorado Piedmont we examined channel changes by analyzing a rectified sequence of aerial photographs spanning 56 yr, and we investigated the spatial distribution of different-aged patches of forest by aging 189 randomly sampled cottonwood trees. Channel change in these ephemeral sand-bed streams is dominated by widening, which occurs over a span of hours during infrequent floods, and postflood narrowing, which occurs over decades between floods. Narrowing is accelerated where reliable moisture increases the density and growth rate of vegetation on the former bed. Reproduction of cottonwood trees has occurred mostly in former channel bed during periods of channel narrowing beginning after floods in 1935 and 1965 and continuing for as long as two decades. Thus cottonwood establishment is related to low flows at the time scale of a year, but to high flows at the time scale of decades. At sites that have not experienced major floods in the last 80 yr, little channel change has occurred, cottonwood reproduction has been limited, tree density has declined, and succession to grassland is occurring. Because channel change and tree reproduction in this region are driven by infrequent local events, channel width and tree age distributions vary greatly over time and among sites. For the same reason, riparian forests along these ephemeral streams can be as wide as forests along perennial rivers with much higher mean discharge.

Key words: *bottomland forest; channel narrowing; Colorado, eastern; cottonwood, plains; disturbance, fluvial; flood; High Plains; succession.*

INTRODUCTION

The geomorphic effects of floods persist longer in rivers with high flow variability (Baker 1977). Because flow variability tends to increase with increasing aridity and decreasing watershed size, floods often have a persistent effect on bottomland morphology and vegetation in dry regions (Schumm and Lichty 1963, Burkham 1972, Stromberg et al. 1991, Friedman et al. 1996a) and in small watersheds (Hack and Goodlett 1960, Wolman and Gerson 1978). The influence of floods is especially persistent in small, dry watersheds (Schick 1974).

In dry regions of interior western North America bottomland ecosystems are often the principal forest in the landscape. These forests are typically dominated by pioneer trees, especially cottonwood (*Populus* spp.), whose seedlings become established on bare, moist surfaces protected from subsequent fluvial disturbance (Mahoney and Rood 1998). The relation between streamflow and formation of such surfaces is conditioned by local fluvial processes. For example, during channel narrowing, bare, moist sites safe from distur-

bance occur on portions of the bed abandoned by the stream, and tree establishment is associated with a period of relatively low peak flows lasting one to several years (Johnson 1994, Scott et al. 1996). In contrast, during channel meandering, establishment occurs on point bars following moderate or higher peak flows (Everitt 1968, Bradley and Smith 1986). The relative importance of these and other processes of establishment varies with the geologic and climatic setting (Scott et al. 1996, Friedman et al. 1998).

The best documented cases of channel narrowing and its effects on riparian vegetation are large regulated sand-bed rivers such as the South Platte and Arkansas rivers of the western Great Plains (Williams and Wolman 1984, Johnson 1994, Friedman et al. 1998). Water management reduced peak flows, especially the sustained snowmelt peaks in June, and raised floodplain groundwater levels. This allowed proliferation of riparian vegetation on the bed and narrowing of formerly wide, braided river channels by as much as an order of magnitude (Parshall 1922, Nadler and Schumm 1981, Johnson 1994). Development of riparian forest in areas where trees were formerly scarce is partly responsible for increases in forest animal species in areas of the western Plains. For example, nearly 90% of the 82 breeding bird species reliably present each spring

Manuscript received 2 January 2001; revised 11 July 2001; accepted 14 August 2001.

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on the steppe of eastern Colorado were not present in 1900 (Knopf 1986).

While recent channel and vegetation changes in the few perennial rivers of the western Great Plains are fairly well understood, the ephemeral tributaries have received less attention, even though their forest width often approaches that of the large rivers and their aggregate length is far greater. Tributary streams with sandy channel boundaries and high loads of bed sediment are susceptible to large fluctuations in channel width (Osterkamp and Hedman 1982); therefore, channel narrowing can be expected to be an important process of channel change promoting tree reproduction along tributary streams.

Extreme floods should have more lasting effects in the Plains tributary streams than in the major rivers such as the South Platte and Arkansas. The major rivers are dominated by montane snow melt, which produces annual high flows of large volume, moderate peak, and long duration, with relatively little difference among years. The Plains tributaries are dominated by local rainfall, which produces flows low in volume and short in duration, but occasionally very large in magnitude (Follansbee and Sawyer 1948). Although mean annual discharges are far less in the tributaries, peak instantaneous discharges in these tributaries approach the highest discharges ever recorded on the South Platte and Arkansas rivers (Follansbee and Sawyer 1948, Matthai 1969, Jarrett 1990). Channel recovery following floods should be slower along Plains tributary streams because the relatively small flows between floods do little work (Wolman and Gerson 1978).

The goal of this study was to determine the influence of extreme floods and postflood channel narrowing on the bottomland morphology and forests of ephemeral streams in a semiarid region. We documented channel and forest changes at six sites by overlaying sequences of aerial photographs spanning 56 yr. At the same sites, we used tree rings to investigate the spatial distribution of different-aged patches of forest. We tested the hypothesis that cottonwood establishment is limited to surfaces made available during the process of postflood channel narrowing.

METHODS

Study area

This study focuses on streams draining Palmer Divide, just east of the Rocky Mountains in the Colorado Piedmont section of the Great Plains (Madole 1991) in eastern Colorado (Fig. 1). Palmer Divide (elevation 2560 m) is an eastward extension of the foothills of the Rocky Mountains separating the headwaters of the South Platte and Arkansas rivers. In this semiarid area floods occur between mid-May and late September and result from local, intense thunderstorms that can produce as much as the mean annual precipitation (36 cm [Hansen et al. 1978]) in a few hours (Matthai 1969,

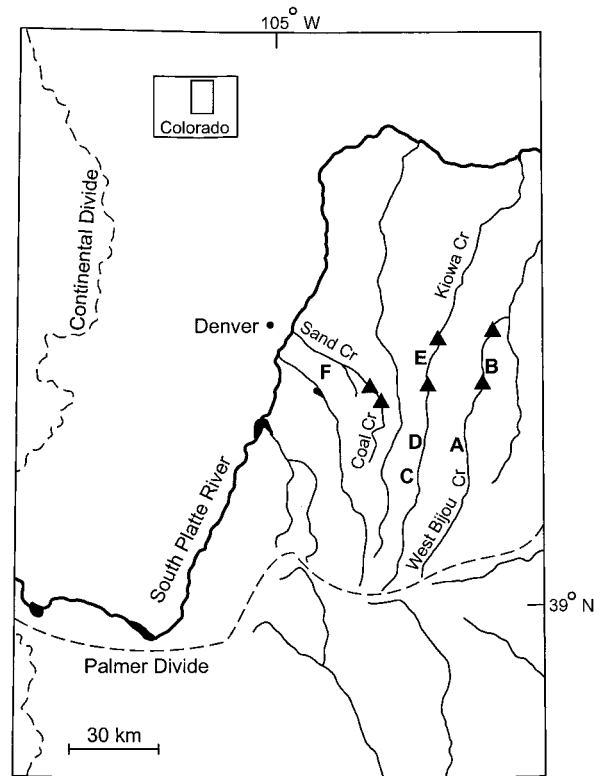


FIG. 1. Location of study sites and flood measurements in eastern Colorado, USA. Triangles indicate the six study sites. Letters A–F indicate the locations of flood measurements near the study sites described in Table 2.

Osterkamp and Costa 1987). Although the storms are often grouped within mesoscale convective complexes, areas of extreme precipitation from individual storms are generally smaller than 300 km² (Hansen et al. 1978). This situation contrasts with that in some semiarid parts of the southwestern USA, where floods may occur in any month, and may result either from local summer thunderstorms or from more extensive events such as synoptic-scale frontal systems occurring over tens of thousands of square kilometers over many days (Hirschboeck et al. 2000). Intense precipitation is most likely in the study area when southeasterly surface winds carry warm moist air from the Gulf of Mexico up the High Plains and Palmer Divide and into a cold front. Extreme local rainfall occurs when unusually weak high-level winds allow intense storms to move slowly enough to deliver large amounts of rain in a small area (Matthai 1969, Maddox et al. 1980). Most of the larger streams draining the Palmer Divide have experienced floods exceeding 1500 m³/s in this century (Matthai 1969, Snipes et al. 1974, Capesius 1996, Friedman et al. 1996a). Flooding was especially widespread on 30–31 May 1935, and on 14–17 June 1965. These floods have caused major changes in channel width and alignment (Fig. 2; McKee et al. 1967, Matthai 1969, Osterkamp and Costa 1987).

TABLE 1. Basic description of study sites in six drainage basins in eastern Colorado.

| Sites | Latitude | Longitude | Elevation (m) | Drainage area (km ²) | Channel gradient (1994) |
|------------------------|----------|-----------|---------------|----------------------------------|-------------------------|
| Upper West Bijou Creek | 39°39' N | 104°13' W | 1606 | 742 | 0.0036 |
| Lower West Bijou Creek | 39°50' N | 104°11' W | 1493 | 949 | 0.0030 |
| Upper Kiowa Creek | 39°39' N | 104°26' W | 1709 | 603 | 0.0048 |
| Lower Kiowa Creek | 39°48' N | 104°24' W | 1621 | 667 | 0.0037 |
| Upper Coal Creek | 39°36' N | 104°38' W | 1783 | 110 | 0.0061 |
| Lower Coal Creek | 39°39' N | 104°39' W | 1737 | 174 | 0.0055 |

We examined six accessible forested reaches of West Bijou, Kiowa, and Coal creeks, sand-bed streams flowing north from the Palmer Divide into the South Platte River near Denver (Fig. 1). Elevation of these sites ranges from 1493 to 1783 m, drainage area ranges from 110 to 949 km², gradient ranges from 0.0030 to 0.0061 (Table 1), and study-reach length varies from 5.0 to 7.6 km. Lithology is dominated by sandstone, most prominently the Dawson Arkose (Tweto 1979). The study reaches occupy valleys >0.5 km wide consisting of eolian deposits, rarely inundated Quaternary alluvial terraces, and frequently inundated alluvial deposits. Bedrock is exposed locally in banks at both Coal Creek sites and at upper Kiowa Creek. The upper West Bijou Creek site flows intermittently in the spring; the other five sites are ephemeral streams with surface flow only during and immediately after rainfall. Subsurface flow in the sandy alluvium sustains the bottomland forests.

Major floods were reported along West Bijou or Kiowa Creek in 1935, 1951, 1954, and 1965 (Table 2). The largest known flood at Kiowa Creek occurred in 1935; the largest known flood at West Bijou Creek occurred in 1965. These floods were not exceptional for the region in terms of discharge or unit discharge (Matthai 1969, Friedman et al. 1996a). Minor high flows, but no major floods, have been reported along Coal Creek (Table 2). In most years the peak instantaneous discharges on these creeks are far below the flood discharges reported in Table 2. A short-lived stream gaging station near the mouth of Bijou Creek at Wiggins (U.S. Geological Survey gage 06759000, drainage area 3403 km²) from 1950 to 1956 had a median peak instantaneous annual discharge of 161 m³/s

(range 22–1419 m³/s). A similar gaging station along Kiowa Creek at Kiowa from 1956 to 1965 (gage 06758200, drainage area 287 km²) reported a median peak instantaneous annual discharge of 24 m³/s (range 1–558 m³/s). Response of these channels to flooding appears to be typical of sand-bed channels in semiarid to arid regions. Channel widening and migration during floods are typically followed by decades of narrowing (Fig. 2). Because the sandy floodplain sediments form noncohesive easily eroded banks, fluctuations in channel width are large compared to fluctuations in bed elevation (Schumm and Lichty 1963, Friedman et al. 1996b).

The riparian forests along these streams are dominated by plains cottonwood (*Populus deltoides* Marshall ssp. *monilifera* (Aiton) Eckenwalder) but also include peachleaf willow (*Salix amygdaloides* Andersson), and lanceleaf cottonwood (*P. × acuminata* Rydberg), a hybrid between plains cottonwood and the montane species narrowleaf cottonwood (*P. angustifolia* James). All of these trees are riparian pioneers whose seedlings require bare, moist substrate for establishment (Mahoney and Rood 1998). Riparian areas on the Colorado Piedmont have been used for livestock grazing since the mid-19th century. Prior to settlement, these areas were grazed by bison (Hartnett et al. 1997). In the year of sampling, all of our study sites were grazed by cattle.

Bottomland change

In this region, aerial photographs at image scales from 1:20 000 to 1:40 000 have been taken once or twice per decade beginning in 1937. We selected years

TABLE 2. Instantaneous discharge and drainage area for floods on West Bijou Creek, Kiowa Creek, and Sand Creek, Colorado.

| Site label | Site | Drainage area (km ²) | Discharge (m ³ /s) | | | |
|------------|-------------------------------------|----------------------------------|-------------------------------|------|------|------|
| | | | 1935 | 1951 | 1954 | 1965 |
| A | West Bijou Creek south of Strasburg | 484 | 1257 | | | |
| B | West Bijou Creek at Byers | 717 | † | 1161 | | 2138 |
| C | Kiowa Creek at Kiowa | 287 | | | 431 | 558 |
| D | Kiowa Creek north of Kiowa | 492 | 3115 | | | |
| E | Kiowa Creek at Bennett | 611 | 2133 | | | 705 |
| F | Sand Creek near Aurora | 293 | | | | 379 |

Notes: Sand Creek receives flow from Coal Creek (Fig. 1). All known flows from the study area with unit discharge >1 m³ · s⁻¹ · km⁻² are shown. The locations of these floods are indicated by site label in Fig. 1. Data are from Matthai (1969), Capesius (1996), and unpublished files of the U.S. Geological Survey (R. Jarrett, unpublished data).

† A reported value of 4664 m³/s has been determined by Follansbee and Sawyer (1948) to be a gross overestimate.



FIG. 2. Aerial photographs showing change in bottomland morphology and vegetation between 1969 and 1993 at upper West Bijou Creek, Colorado, USA.

of photography to isolate the effects of the major floods in 1935 and 1965. Dates and scales of the selected aerial photographs were 17–20 July 1937, 1:21 000; 26–27 June 1963, 1:19 000; 7–15 August 1969, 1:20 000; and 23–26 June 1993, 1:22 000. All photos were black-and-white paper prints, and all were contact prints except for the 1993 set, which were 2× enlarge-

ments. Overlapping photos were acquired and a stereo viewer was used for photointerpretation. Mapped reaches ranged in length from 5.0 to 7.6 km.

For each photograph we used a mylar overlay to map the bottomland as a mosaic of three cover types: channel, forest, and open. The channel, dry in the photos, was defined as the unvegetated area on the lowest flu-

vial surface in the bottomland as seen using the stereo viewer. The channel exhibited fresh alluvial deposits and was usually separated from higher fluvial surfaces by a topographic break of 0.5 m or more. Higher surfaces, always vegetated, were characterized as either forest or open (treeless). The area mapped at a site was identical for all four photo dates and included all of the bottomland up to and including the highest naturally established forest patch. This mapped area was typically bounded by a higher, unforested Quaternary terrace (Scott 1963, Jordan 1997).

We digitized the overlays using a CALCOMP 9100 digitizing tablet and rectified them to U.S. Geological Survey 7.5-min topographic maps (1:24 000 scale) using a projective transformation algorithm in ARC/INFO Version 7.1.1, Environmental Systems Research Institute, Redlands, California, USA. Projective transformation allows for correction of feature placement due to scaling, location, rotation and obliqueness of the source aerial photograph by minimization of the root mean square error between actual tic position and transformed tic position. Residual root mean square error values were <10 m, with typical values 4–8 m. We calculated temporal changes in the total area occupied by the three land cover types as well as transition probabilities among cover types from one photo year to the next. To normalize polygon area measurements we divided them by the valley length of the mapped reach; the resulting values had units of meters and were interpreted as mean widths. This usage of the term “width” is different from a typical usage in geomorphology where channel width is equal to channel area divided by channel (not valley) length. We used a paired *t* test to determine whether channel is more likely than open area to be transformed into forest. For each photo interval at each site ($n = 3$ intervals \times 6 sites = 18 interval–site combinations) we compared the proportion of channel that became forest to the proportion of open area that became forest. The null hypothesis was that these two proportions were the same. Proportions were log-transformed to produce a normal distribution. Statistical calculations were carried out using SAS, Release 7.00, SAS Institute, Cary, North Carolina, USA.

Forest age structure

We used a combination of stand mapping and coring of randomly selected trees to investigate the age structure of forest populations in 1-km subreaches at the six sites. All sites were strongly dominated by plains cottonwood, but lanceleaf cottonwood and peachleaf willow were sometimes also present. The riparian forest was a mosaic of apparently even-aged stands. At each site we recognized two to four age classes of cottonwoods based primarily on the depth of bark furrows (Hickin and Nanson 1975, Merigliano 1996) and secondarily on stem diameter. These age classes were visually distinct and rarely overlapped spatially. We

mapped their distribution in the subreaches using mylar overlays on 1:10 000-scale enlargements of black-and-white aerial photographs taken 23–26 June 1993. Willow trees were not mapped, but never constituted >5% of the stems in the forest. Using these maps and a dot grid we measured the total area occupied by each age class and randomly selected 10 locations within each age class at each site. Between 10 June and 27 October 1994, we located the randomly selected points in the field, and determined the age of the closest cottonwood stem: stems smaller than 5 cm were sectioned at ground level, and larger stems were cored using an increment borer 30 cm above the ground surface. We measured stem diameter (1.5 m above the ground surface) of the ten cottonwoods closest to the randomly selected point. We estimated stem density (D) in the vicinity of each randomly selected point using a plotless method (Engeman et al. 1994) based on measurement of the area containing the nearest 10 trees:

$$D = 10/\pi r^2$$

where r is the mean of the distances from the randomly selected point to the tenth and eleventh closest cottonwood stems.

Stem sections and cores were sanded with progressively finer sandpapers to a median particle size of 15 μm (600 grit; Phipps 1985). Ring number and width were recorded using a University Model incremental measuring machine (obtained from Curt Zahn, formerly of Fred C. Henson Company) and the TRIMS (Version 1.2) software system from Madera Software. Each core was interpreted by two readers following Scott et al. (1997).

To calculate the bottomland widths occupied by cottonwoods of different ages at each site we weighted the number of trees established in a given year by the mean width of the age class the trees represented as measured on the subreach map. Therefore, the width, w , occupied by trees established in a given year at a site was

$$w = \sum_{i=1}^n P_i W_i$$

where n is the number of mapped age classes, P_i is the proportion of randomly selected trees in age class i that were established in the year of interest, and W_i is the mean width occupied by age class i .

RESULTS

Bottomland change

The observed channels widened during floods and narrowed between floods. The larger the flood, the greater the increase in width. At all sites along W. Bijou and Kiowa creeks the channel was widest in 1937 and 1969, following the two largest floods in 1935 and 1965 (Tables 2 and 3). At the West Bijou Creek sites, the 1969 width was similar to or larger than the 1937 width,

TABLE 3. Mean width (m) of cover types through time measured from sequential aerial photographs of bottomlands on the Colorado Piedmont.

| Watercourse | Cover type | 1937 | 1963 | 1969 | 1993 |
|------------------------|------------|------|------|------|------|
| Upper West Bijou Creek | channel | 175 | 112 | 200 | 35 |
| | forest | 153 | 215 | 186 | 381 |
| | open | 183 | 184 | 124 | 93 |
| Lower West Bijou Creek | channel | 142 | 116 | 141 | 92 |
| | forest | 27 | 43 | 51 | 84 |
| | open | 215 | 225 | 192 | 209 |
| Upper Kiowa Creek | channel | 78 | 60 | 70 | 33 |
| | forest | 50 | 82 | 81 | 102 |
| | open | 94 | 80 | 71 | 87 |
| Lower Kiowa Creek | channel | 158 | 86 | 97 | 47 |
| | forest | 169 | 240 | 238 | 286 |
| | open | 106 | 108 | 99 | 100 |
| Upper Coal Creek | channel | 66 | 52 | 51 | 45 |
| | forest | 87 | 93 | 93 | 93 |
| | open | 50 | 58 | 59 | 64 |
| Lower Coal Creek | channel | 57 | 46 | 38 | 29 |
| | forest | 113 | 116 | 121 | 123 |
| | open | 31 | 38 | 41 | 49 |

reflecting the greater magnitude of the 1965 flood (Tables 2 and 3). In contrast, at Kiowa Creek, where the 1965 flood was smaller than the 1935 flood, the 1969 widths were less than those of 1937.

The rate of postflood narrowing decreased with time. The two Coal Creek sites, which were the only sites not to experience a major flood in 1935, were much narrower than all other sites in 1937 (Table 3). Between 1937 and 1993, in the absence of major floods, the Coal Creek sites both underwent gradual narrowing. The sites at Kiowa and Bijou Creek narrowed more rapidly following flood-related widening. By 1993, 28 yr after the last flood on Kiowa and West Bijou creeks, widths

at Coal Creek were similar to those of the other sites (Table 3).

Channel narrowing was accompanied by an increase in forest width of similar magnitude (Table 3). At Kiowa and West Bijou Creeks, where postflood narrowing was pronounced, there was a marked contemporaneous increase in forest. At Coal Creek, both the decreases in channel and the increases in forest were less pronounced because of the absence of large floods in the period of record. These trends are consistent with the hypothesis that tree establishment occurs in former portions of the channel bed.

Channels can move without changing in width.

TABLE 4. Selected cover-type transitions measured from sequential aerial photographs of bottomlands on the Colorado Piedmont.

| Stream | Cover type | Photo interval | | |
|------------------------|-------------|----------------|-----------|-----------|
| | | 1937–1963 | 1963–1969 | 1969–1993 |
| Upper West Bijou Creek | new channel | 54 | 99 | 6 |
| | new forest | 113 | 34 | 215 |
| | new open | 70 | 14 | 30 |
| Lower West Bijou Creek | new channel | 26 | 29 | 5 |
| | new forest | 18 | 12 | 37 |
| | new open | 39 | 3 | 33 |
| Upper Kiowa Creek | new channel | 10 | 14 | 2 |
| | new forest | 41 | 11 | 32 |
| | new open | 16 | 7 | 23 |
| Lower Kiowa Creek | new channel | 18 | 23 | 9 |
| | new forest | 89 | 23 | 65 |
| | new open | 35 | 13 | 17 |
| Upper Coal Creek | new channel | 11 | 10 | 11 |
| | new forest | 18 | 11 | 12 |
| | new open | 19 | 12 | 19 |
| Lower Coal Creek | new channel | 11 | 6 | 9 |
| | new forest | 17 | 13 | 13 |
| | new open | 15 | 11 | 16 |

Note: The value of "new channel" for an interval is the mean width of channel (m) on the end date of the interval that was not channel on the beginning date.

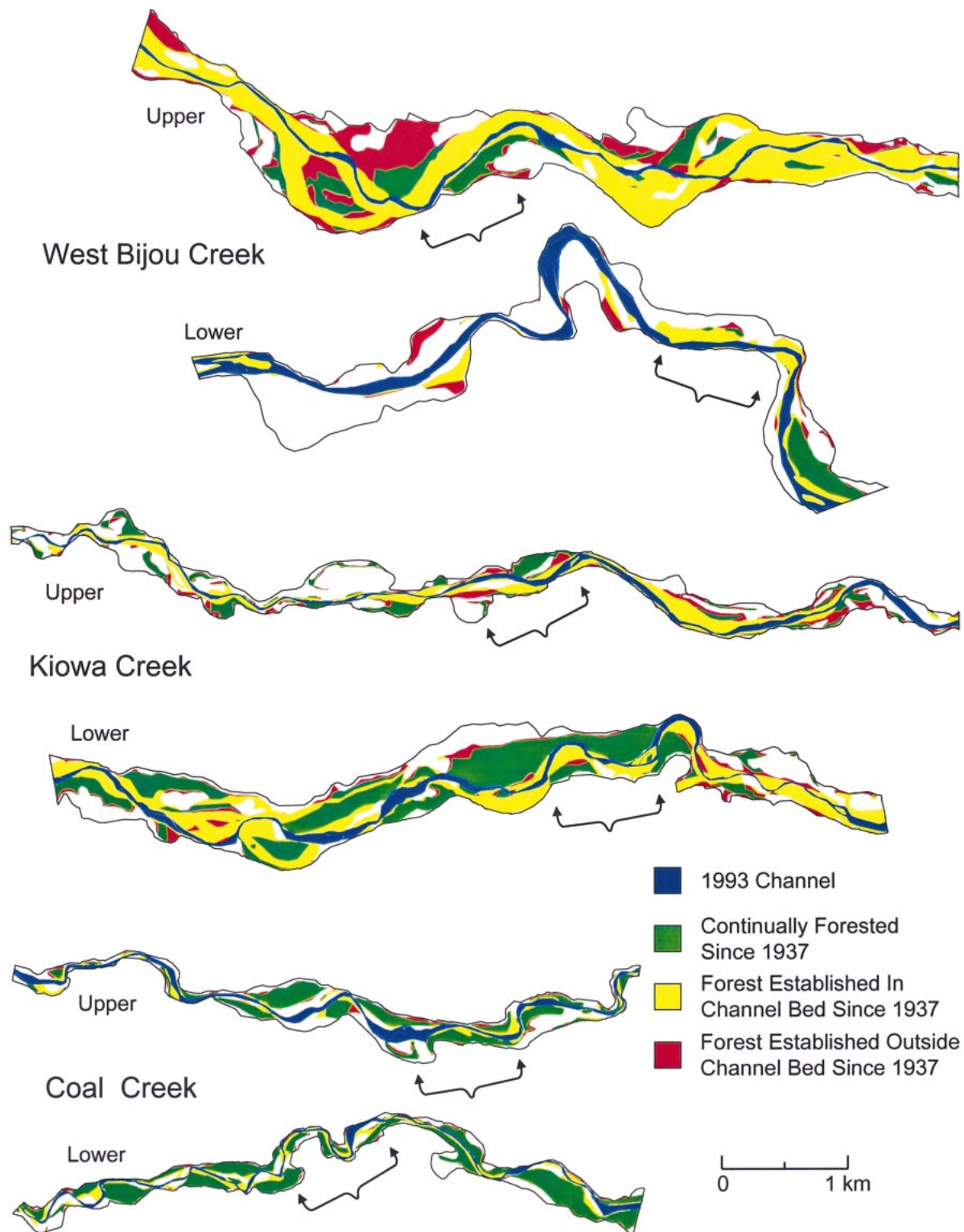


FIG. 3. Origin of forest stands along six streams in the Colorado Piedmont as indicated by aerial photography. Brackets indicate subreaches where tree diameter and age were sampled. Flow is to the right.

Therefore, the width of new channel formed during an interval can be a more complete measurement of the channel-forming work done by the stream than is the net change in channel width. Formation of new channel can be measured only when aerial photographs from different years have been registered to the same coordinate system, as in this study. At all sites along West Bijou and Kiowa creeks, the width of new channel formed was greatest in the interval 1963–1969, moderate in the interval 1937–1963, and least in the interval 1969–1993 (Table 4). This is consistent with the occurrence along these two creeks of a large flood in 1965, moderate floods in the early 1950s (Table 2), and no floods since 1969. At Coal Creek the amount of new channel was small and was similar for all three photo intervals, reflecting the absence of flooding during the photo record (Tables 2 and 4).

Most new forest was established in portions of former channel bed abandoned during the process of channel narrowing (Fig. 3). The width of 1993 forest established in former channel bed was $1.7\text{--}4.3 \times$ the width of forest established in formerly open nonchannel locations (mean = $2.69 \times$, $n = 6$ sites, Fig. 3). This preference for channel was not simply a reflection of a greater abundance of channel (Table 3). In the eighteen transitions (six sites \times three photo intervals) the proportion of channel that became forest (mean = 0.24) was higher than the proportion of open locations that became forest (mean = 0.14). This difference was significant according to a paired t test ($n = 18$ tests, $P = 0.0287$). Aerial photographs indicated that most of the forest originating outside of the channel bed consisted of stands established on historical flood deposits on the flood plain. Therefore, almost all forest establishment was flood related. The width of forest established along the flood-prone West Bijou and Kiowa Creeks was far greater than that established along Coal Creek in the absence of recent historical flooding (Fig. 3).

Floods remove some patches of forest while promoting establishment of others. At these sites, however, flood-related establishment exceeded flood-related removal, resulting in a net increase in forest width following floods. Forty-three and 83% of 1937 forest survived to 1993 at upper and lower West Bijou Creek, 67% and 83% survived at upper and lower Kiowa Creek, and 77% and 82% survived at upper and lower Coal Creek. Thus, the loss of forest to floods and other factors at lower West Bijou Creek and lower Kiowa Creek was small and similar to the loss at Coal Creek in the absence of major floods. Destruction of forest, apparently by flooding, was greatest at upper West Bijou Creek. However, this also was the site with the greatest net increase in forest (mostly from postflood channel narrowing, Table 3, Fig. 3). In the absence of recent major floods, the Coal Creek sites have experienced little growth in forest width (Table 3), and the

forest is now strongly dominated by older trees. Following major floods, the Kiowa and West Bijou creek sites have experienced large increases in forest width (Table 3) and now have substantial patches of younger trees.

Forest age structure

We aged 189 cottonwoods and measured the diameter of 1860. Of the individuals whose diameter was measured, 96% were plains cottonwood and the remainder were the hybrid lanceleaf cottonwood. Because our cores were collected above ground, the ages we report are minimum ages. A cottonwood growing under favorable conditions can reach coring height (30 cm) in its first year. However, damage from animals, floods, drought, sediment deposition, or ice can delay growth or cause dieback. Many stems were part of multiple-stemmed individuals that apparently resprouted after a tree was broken or toppled by a flood, especially the flood of 1965. Excavation of several of these individuals suggested that they were derived from stems that had been knocked down parallel to the direction of flow. Some small stems appeared to be hedged by livestock; beaver cutting of stems was uncommon, and we saw little evidence of fire. Because the channels are dry most of the winter, ice damage was infrequent. Therefore, the reported ages provide a minimum estimate of the number of years since germination or since the most recent time a tree was cut or toppled.

Cottonwood ages and diameters demonstrated that the apparent age classes mapped in the field were distinct, but not even aged (Figs. 4 and 5). Trees ranged in age from 1 to 146 yr and in diameter up to 1.89 m. The relation between age and stem diameter exhibited the wide scatter typical of cottonwood (triangles in Fig. 5), supporting our use of bark characteristics as the principal indicator of stem age. Randomly sampled trees from a single apparent age class never all dated to the same year, but the age distributions of the classes mapped at a site were distinct in almost all cases (Fig. 4). Furthermore, stems older than 25 yr rarely had neighbors with diameters < 10 cm (Fig. 5). The exceptions to this rule were root sprouts, especially from lanceleaf cottonwood (e.g., individuals with 0 diameter at age 51, 99, and 135 yr in Fig. 5). These results indicate that there is little reproduction of plains cottonwood within mature stands.

The cottonwood age distributions (Fig. 6) show widespread establishment of forest since 1935 in the four sites at West Bijou and Kiowa creeks that experienced major recent floods (Table 2). The percentage of forest established since 1935 was 77% and 100% at upper and lower West Bijou Creek and 88% and 34% at upper and lower Kiowa Creek (Fig. 6). In contrast, the two sites along Coal Creek that did not experience such floods had only a small percentage of forest established since 1935: 22% at upper Coal Creek, and 18% at lower Coal Creek. At West Bijou Creek, where

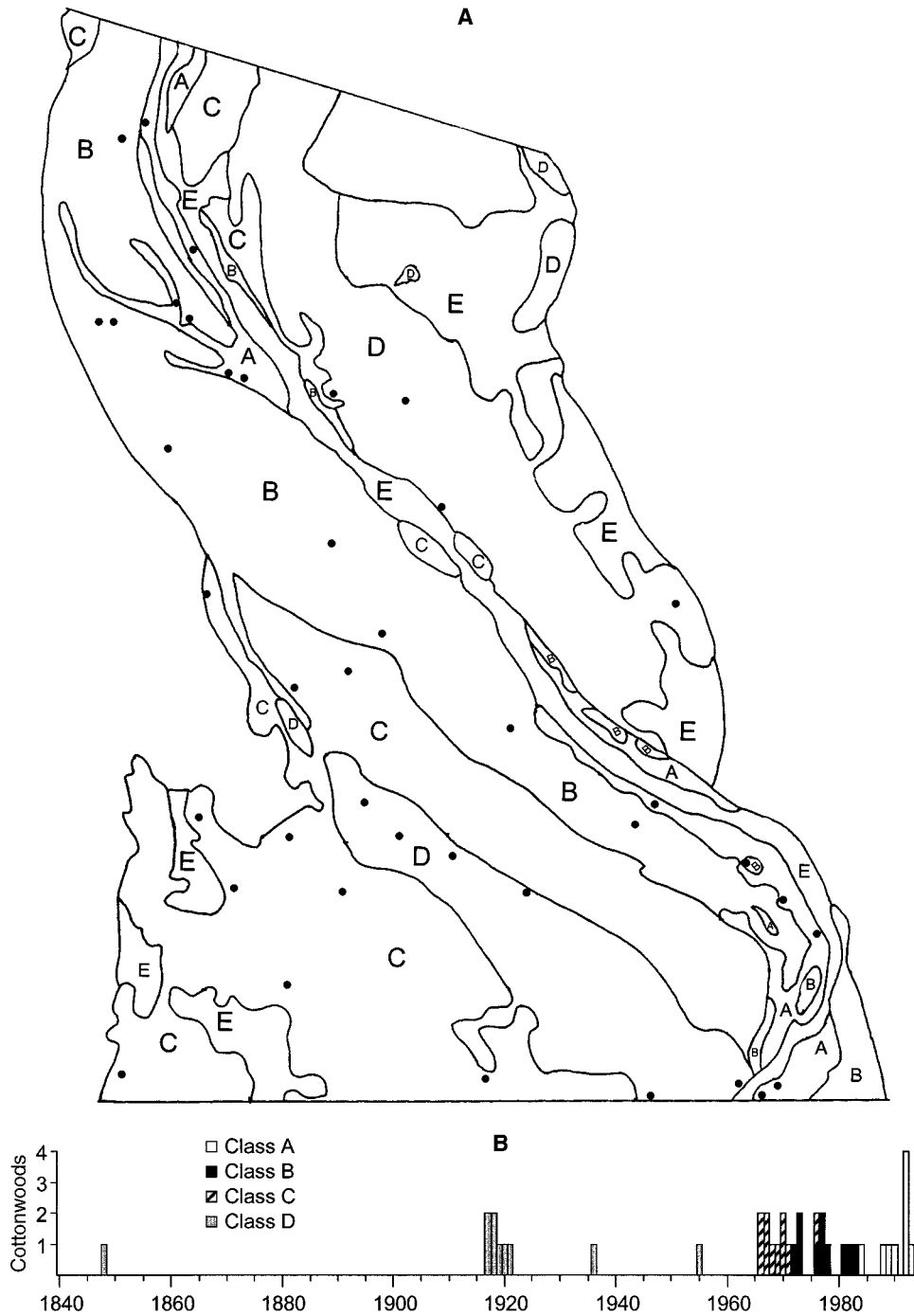


FIG. 4. Example of data used to determine the spatial and temporal distribution of cottonwood establishment along streams in the Colorado Piedmont. Data are from the upper West Bijou Creek site. (A) Field map showing spatial distribution of apparent cottonwood age classes (area types A–D) and treeless areas (area type E). The two unlabeled areas have been disturbed by human activity. Dots are randomly selected sampling locations. (B) Age and apparent age class of the cottonwoods closest to the sampling locations.

the flood of 1965 was greater than that of 1935, the width of forest established following 1965 was greater than that established following 1935 (Fig. 6). The reverse is true for Kiowa Creek, where the flood of 1935

was larger than that of 1965. Because the reach in which trees were cored was a subset of the reach examined using aerial photography (Fig. 3), forest properties determined by the two methods were not iden-

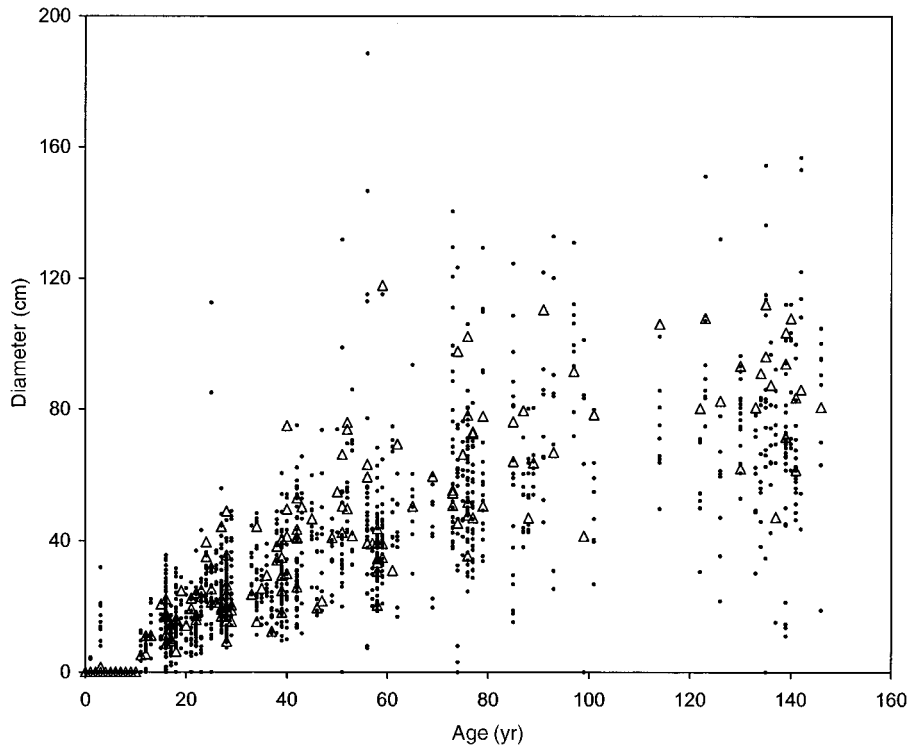


FIG. 5. Stem diameter (1.2 m aboveground) as a function of stem age for cottonwoods along streams on the Colorado Piedmont. Triangles are diameters of cored stems, and circles are diameters of neighboring trees that were not cored.

tical. This was most apparent at lower West Bijou Creek, where almost all of the existing trees established before 1937 were in a patch outside of the reach in which trees were cored (Fig. 3).

There were not large widths of forest dating precisely to flood years (Fig. 6). However, there generally were large widths of forest dating to periods beginning in a flood year and continuing for as long as two decades (Fig. 6). The duration of these periods varied across sites. For example, most of the forest at lower West Bijou Creek dated to the short periods 1935–1936 and 1965–1967. In contrast, at upper West Bijou Creek most of the forest dated to the two decades following 1965. At both Kiowa Creek sites, large widths of forest became established in the two-decade periods following the floods of 1935 and 1965, but there were apparent lags between the floods and tree establishment; for example, at both sites a greater width of trees was established between 1950 and 1959 than in the period 1935–1949.

Clusters of establishment years for older trees indicate periods of establishment prior to the record of flooding for these creeks. For example, many trees were established at upper Kiowa Creek in the years following 1903, at lower Kiowa and Coal Creeks in the years following 1853, at upper Coal Creek in the years following 1893 and 1915, and at upper West Bijou Creek in the years following 1917 (Fig. 6). Stands of trees

dating to the 1850s and 1860s were especially extensive in spite of mortality that must have occurred since their establishment. Considering all six sites together, a larger width of forest dated to the period 1853–1872 than to any other 20-yr period except 1965–1984 (Fig. 6).

Maximum cottonwood stem density at randomly selected points decreased approximately exponentially with increasing stand age (Fig. 7). Young cottonwood stands had a wide range of densities, but older stands had only low densities. After 140–150 yr mean stand densities were typically only 30 stems/ha. At this density there were large unshaded grass-dominated areas between trees. As stands of trees mature, stem density decreases and basal area increases. Thus the ratio between density and basal area was lowest where trees were oldest (i.e., at Coal Creek, Table 5).

Between-site variation in cottonwood stem density, basal area, and forested width was positively related to water availability. On 27 October 1994, the water table on the channel bed was within 2 m of the thalweg at all sites except lower West Bijou Creek, where a well 7.3 m below the thalweg failed to reach the water table. Apparently as a result of drought stress, lower West Bijou Creek had the lowest basal area of all sites and a much smaller forested width and stem density than the upper West Bijou Creek site (Tables 3 and 5). In contrast upper West Bijou Creek, the only site with

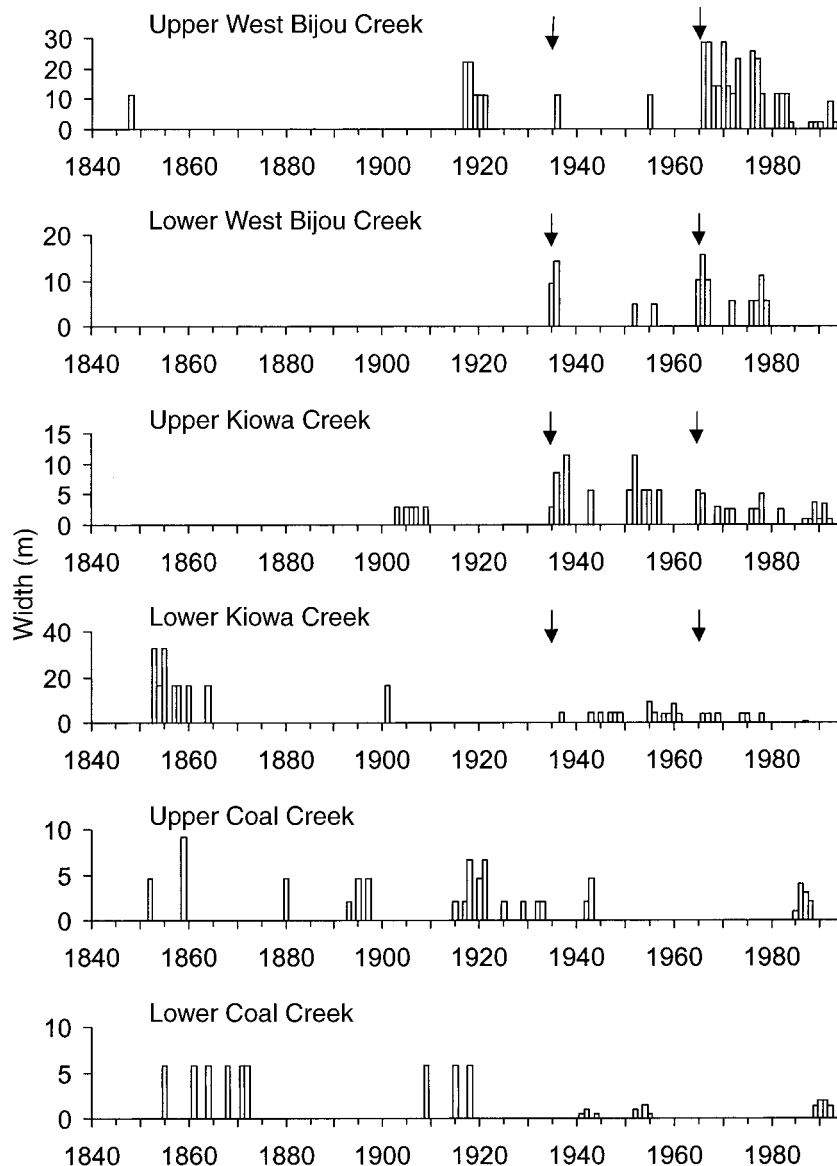


FIG. 6. Mean bottomland width occupied by cottonwoods of different age classes along streams in the Colorado Piedmont. Arrows indicate years of known major floods.

sustained flows in the spring, had the highest stem density and forested width of all sites (Tables 3 and 5).

DISCUSSION

Extreme floods and cottonwood establishment

Reproduction of cottonwood trees along these ephemeral sand-bed streams occurs mostly in former channel bed during periods of channel narrowing following major floods. At West Bijou and Kiowa creeks most cottonwood establishment in the last 80 yr has occurred during periods of channel narrowing beginning after the floods of 1935 and 1965 and continuing as long as about two decades. Although floods have

removed some trees, the long-term influence of floods has been to increase the total width and density of forest and to maintain the abundance of young trees. At both Coal Creek sites, channel change in the absence of major floods has been minor, and little cottonwood establishment has occurred in the last 80 yr. As a result the forest along Coal Creek has aged (Fig. 6), and tree density has decreased (Table 5).

Establishment of cottonwood 1–3 yr following a flood has been reported elsewhere (Bradley and Smith 1986, Baker 1990, Stromberg et al. 1991, Scott et al. 1997). The present study, however, shows that floods can promote forest regeneration for decades by initi-

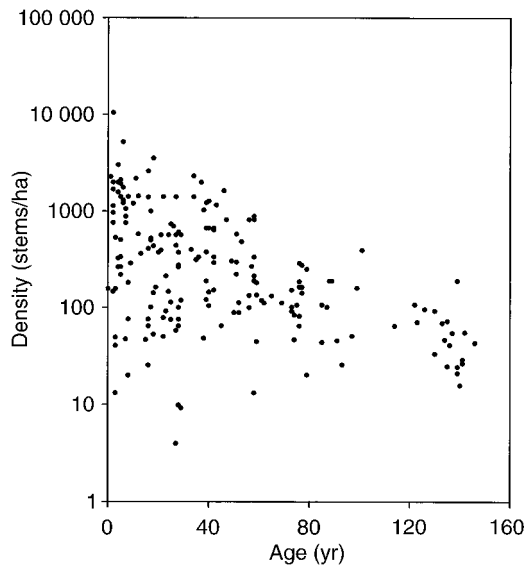


FIG. 7. Cottonwood stem density at randomly selected points as a function of the age of the nearest stem for bottomlands on the Colorado Piedmont.

ating a long-term process of channel change. Most trees were established on the channel bed during years of low flow as part of the process of postflood channel narrowing. Thus cottonwood establishment was related to low flows at the time scale of a year, but to high flows at the time scale of decades. This result underscores the role of fluvial processes in mediating the relation between flow and riparian vegetation (Scott et al. 1996, Friedman et al. 1997, Auble and Scott 1998).

Channel narrowing has been documented elsewhere as a response to flood-induced widening (Schumm and Lichty 1963, Osterkamp and Costa 1987, Friedman et al. 1996a), climate change (Schumm 1969), construction of upstream dams (Williams and Wolman 1984, Johnson 1994), and introduction of exotic bottomland plant species (Graf 1978), or as part of a cyclic, autogenic process (Patton and Schumm 1981). The immediate cause of narrowing is one to many years of flow lower than that necessary to rework the entire channel bed (Scott et al. 1996). This relatively low flow allows establishment of vegetation on the bed. The newly established vegetation promotes deposition of fine sediment (Osterkamp and Costa 1987) and increases resistance to erosion (Smith 1976), thus stabilizing the channel at a narrower width. Narrowing can be facilitated by flow-related fluctuations in channel bed elevation (Schick 1974, Friedman et al. 1996b).

Although postflood channel narrowing is the principal mechanism promoting reproduction of riparian pioneer trees along intermittent and ephemeral streams in eastern Colorado, this process is dominant only where large fluctuations in channel width or flood-related avulsion are common. Factors promoting large fluctuations in channel

width include high flow variability, high gradient, easily eroded banks dominated by noncohesive sand, a heavy load of sediment transported as bedload, and lack of lateral constraint. These factors are most common along laterally unconstrained alluvial channels in arid and semi-arid regions (Osterkamp and Hedman 1982, Friedman et al. 1998; Shafroth et al. 2002). In other situations, channel width can be more stable, and other processes may be more important for tree reproduction. For example, along some perennial streams with shallow gradient, less variable flow, and cohesive silt-clay banks, most channel change is accomplished by the process of meandering, and most pioneer tree establishment occurs every few years in arcuate bands on point bars (Bradley and Smith 1986).

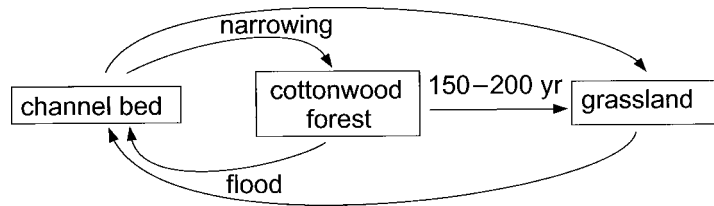
Along our Great-Plains streams, old and young trees rarely occur together (Figs. 4 and 5), and stem density declines with stand age (Fig. 7). These results confirm the observation of Everitt (1968) and Johnson et al. (1976) that young plains cottonwoods rarely become established within existing mature stands. Experimental studies in Colorado and Utah have demonstrated that moisture scarcity and shade limit *P. deltoides* seedling establishment within existing vegetation (Cooper et al. 1999, Katz et al. 2001). Even where seedlings cannot become established, vegetative reproduction (root and stem sprouts) may still occur. In these forests of plains cottonwood, vegetative reproduction is uncommon in older stands; however, vegetative reproduction is more frequent in other cottonwood species, especially narrowleaf cottonwood and balsam poplar (*Populus balsamifera* [Gom and Rood 1999]). Stands of these other species may, therefore, have a wider range of ages than the stands of plains cottonwood observed here.

Absence of reproduction within mature stands of plains cottonwood should result in succession to grassland after 150–200 yr without fluvial disturbance (Fig. 8; Lindauer 1983, Cordes et al. 1997). Forest patches as old as ~140 yr were common at the study sites. Most of these were grasslands with widely spaced trees (Fig. 7). This successional trajectory (Fig. 8) contrasts with old-field succession in the more humid eastern United States, where grassland typically reverts to forest in the absence of disturbance (Drury and Nisbet 1973). Trajectories longer than 146 yr are not shown

TABLE 5. Density and basal area of cottonwood in bottomlands on the Colorado Piedmont.

| Stream | Density (stems/ha) | Basal area (m ² /ha) |
|------------------------|--------------------|---------------------------------|
| Upper West Bijou Creek | 597 | 14 |
| Lower West Bijou Creek | 76 | 4 |
| Upper Kiowa Creek | 414 | 32 |
| Lower Kiowa Creek | 165 | 17 |
| Upper Coal Creek | 68 | 11 |
| Lower Coal Creek | 103 | 13 |

FIG. 8. Bottomland forest dynamics on the Colorado Piedmont (modified from Friedman et al. [1997]).



in Fig. 7 because patches were aged using existing trees. Scarcity of older trees may be partly explained by tree cutting, especially during early settlement (Johnson and Boettcher 2000).

Identification of the relation between flooding and cottonwood establishment along ephemeral streams makes it possible to date floods for which there are no historical records. For example, 20% of the forest width at Upper West Bijou Creek dates to the period 1917–1921 (Fig. 6). This suggests a flood in 1916 or 1917 followed by 5 yr of narrowing. Published flood records for this period are sparse and include no information about a flood along West Bijou Creek. However, a database of extreme precipitation events in Colorado (Colorado Climate Center, *unpublished data*) documents an accumulation of 13.5 cm of rain in 5 h on 29–31 July 1916 in Hoyt, which is 40 km from the Upper West Bijou Creek site. Use of trees to date otherwise unrecorded floods should be more precise along intermittent streams like Upper West Bijou Creek than along ephemeral streams like Kiowa Creek, where narrowing and tree establishment may be delayed for many years because of inadequate moisture (Fig. 6). The large width of forest dating to the 1850s and 1860s at lower Kiowa Creek and both Coal Creek sites suggests that floods may have occurred around 1850. Because this is prior to settlement of the region, historical records are scarce; however widespread flooding is known to have occurred in the South Platte River basin in 1844 (Follansbee and Sawyer 1948).

Age-class maps and stratified random sampling enabled us to characterize efficiently the area-weighted age distribution of 1-km stream reaches containing 1400–28 000 cottonwoods. This approach avoids the spatial autocorrelation and limited area of sampling that occur with traditional transects. However, in our sampling scheme a tree that is far from its nearest neighbor is more likely to be sampled than a tree of the same age class that is close to its nearest neighbor. This is appropriate where the goal is to relate forest area to age, as in this study (Fig. 6). However, because different individuals have a different probability of being chosen, the sampled set of trees is not a representative sample of the population.

Extreme floods and the absence of steady state

Infrequent cottonwood establishment events covering large proportions of the flood plain lead to tree age distributions that vary greatly over time and between

sites (Fig. 6). These variable age distributions along ephemeral sand-bed channels contrast with the stable distributions observed along perennial meandering streams (Hughes 1994). Along meandering channels most cottonwood establishment is associated with the formation of point bars (Wolman and Miller 1960, Everitt 1968, Nanson and Beach 1977, Auble and Scott 1998), an incremental process dominated by moderate high flows occurring every few years. Frequent establishment of small stands combined with a process of stand removal that is independent of age leads to a population in which the proportion of the flood plain occupied decreases exponentially with increasing age (Everitt 1968). In the absence of climate change or flow regulation (Bradley and Smith 1986) such exponential age distributions along meandering channels should show relatively small variation over time or between sites. These stable age distributions can often be interpreted as a steady-state phenomenon (Everitt 1968, Nanson and Beach 1977). In contrast, age distributions along the ephemeral streams examined in this study are a non-steady-state reflection of the history of extreme floods (Fig. 6).

Along these ephemeral sand-bed streams, channel width is unstable over time, and widening and narrowing are brought about by flows of different magnitudes operating over different time scales. Most widening occurs during infrequent summer floods over periods of hours. Most narrowing occurs at low flows over the decades between floods. Perennial channels can often be characterized as fluctuating around a steady-state morphology determined by a single channel-forming discharge (Wolman and Miller 1960). Along these ephemeral streams, channel dimensions are strongly influenced by both extreme high flows and low flows, and a single steady-state morphology is rarely approached (Wolman and Gerson 1978). A similar, though less extreme, situation has been reported for the perennial Powder River, Montana (Pizzuto 1994, Moody et al. 1999).

Factors influencing the narrowing rate

Plant stems promote sediment deposition by decreasing flow velocity. Plant roots promote sediment stability by increasing bank resistance to failure (Thorne 1990) and the shear stress necessary to mobilize sediment (Smith 1976). Both effects should promote channel narrowing (Andrews 1984, Wolman and Gerson 1978). Although this study has focused on trees, other

species may also be of importance at various stages of narrowing. If vegetation plays a role in channel narrowing, factors that influence the vigor of vegetation, like water availability and livestock grazing, should influence the narrowing rate. Establishment and growth of riparian vegetation along a sand-bed channel are influenced both by surface flows and availability of groundwater. The relationship between flow and narrowing is nonlinear in that narrowing is most strongly promoted by moderate base flows (defined here as the flows that occur over the extended time between floods). Low or zero base flows can slow narrowing by preventing vegetation establishment through drought stress (Schumm and Lichty 1963). Higher base flows can prevent vegetation establishment by covering the potential seedbed throughout the time of seed germination (Johnson 1994).

At our sites in eastern Colorado base flows never appear to be high enough to slow narrowing, but drought stress in dry years may slow narrowing and may explain differences in rate of narrowing between sites. In this study, the lower West Bijou Creek site had a far greater depth to water table than the other sites. The importance of drought stress at this site was indicated by the low basal area and density of forest (Table 5), the small forested width (Table 3), the scarcity of young individuals (Fig. 6), and the tight clustering of establishment around flood years (Fig. 6). Lower West Bijou Creek was the only site where we found no cottonwoods less than ten years old. The limitation of plant establishment by drought stress at this site is reflected in the slow rate of channel narrowing, 35% between 1937 and 1993, which is less than the rate of narrowing at the other three sites along West Bijou and Kiowa creeks (Table 3).

The wettest of the study sites was upper West Bijou Creek, the only site with sustained flow during the spring. This site had the highest overall cottonwood stem density (Table 5) and individuals were established in all but nine of the years since 1965 (Fig. 6). Narrowing was greatest at this site (Table 3) and tree ages indicate there was no delay in postflood narrowing as observed at the two Kiowa Creek sites. Baker (1977) and Wolman and Gerson (1978) argued that channel recovery from extreme floods is slower in arid than in humid regions, in part because recovery of vegetation can be slower in arid regions. However, as this study demonstrates, the limitation on vegetation density and channel recovery rate imposed by regional aridity can be locally relaxed by a water subsidy to the plants from streamflow or alluvial groundwater (Zimmerman 1969; Shafroth et al. 2002).

Another factor that should affect vegetation density and rate of channel narrowing is livestock grazing. Long-term heavy grazing decreases the density of vegetation, which could slow channel narrowing after a flood. We have no information on long-term patterns of grazing at our study sites. Upper West Bijou Creek

and upper Kiowa Creek were less heavily grazed than the other four sites in 1994. These two sites also had the greatest cottonwood stem densities (Table 5), suggesting that current grazing patterns may have persisted long enough to affect the forest. However, our data provide no strong evidence of the influence of grazing on channel narrowing at these sites (Table 3).

Lower Bijou Creek is the most drought-prone site examined in this study. However, even greater depths to water table are common along these streams downstream of the study areas. Many such reaches are devoid of trees or support only stunted, widely scattered cottonwoods. Groundwater pumping has lowered water tables by many meters along Bijou and Kiowa creeks downstream of the study areas (VanSlyke 1994), and these water-table declines appear to be causing cottonwood mortality. Mortality of plains cottonwood in Colorado can be caused by rapid declines in alluvial water tables of as little as 1 m (Scott et al. 1999).

None of the streams examined here have large main-stem dams. However, they all have numerous small tributary dams, especially Kiowa Creek. By June 1961, 60% of the watershed of Kiowa Creek above Kiowa was upstream of small dams, mostly constructed between 1955 and 1961 (U.S. Department of Agriculture 1967). Although many were overtopped by the flood of 1965, these structures decreased its magnitude by ~38% at Kiowa (U.S. Department of Agriculture 1967). Such dams are even more effective at reducing the discharge of smaller floods (Mundorff 1964, Schoof et al. 1980, Livingston and Minges 1987). Small dams probably contributed to the channel narrowing observed in this study since 1965, at least on Kiowa Creek. Similar narrowing downstream from small dams has been observed elsewhere (Bergman and Sullivan 1963, Schoof et al. 1980).

Watershed size and the effectiveness of extreme floods

The influence of extreme floods on bottomland morphology increases with increasing flow variability (Baker 1977). As flow variability increases with decreasing watershed size, the influence of extreme events should also increase (Wolman and Gerson 1978). This appears to be the case for the South Platte River and its Plains tributaries (Fig. 1). Because the largest floods in the region result from localized thunderstorms, peak discharges along the South Platte have been similar to those along the Plains tributaries (Follansbee and Sawyer 1948, Matthai 1969). Furthermore, because the South Platte River has a shallower gradient than its Plains tributaries, stream power during extreme floods is larger in the tributaries. In contrast, because of the contribution of montane snowmelt, discharges between floods are higher along the South Platte River than along its Plains tributaries. As a result, extreme floods of a given recurrence interval accomplish more channel change along the Plains tributaries than along

the South Platte River, and channel recovery between floods is slower along the tributaries. This study has shown that tree establishment along Plains tributaries occurs in decades of channel narrowing following widening caused by extreme floods. Along the South Platte River, tree establishment also occurs during decades of channel narrowing (Sedgwick and Knopf 1989, Currier 1982), but this process is not strongly related to the occurrence of extreme floods (Johnson 1994).

Because channel change and forest regeneration along the study channels are driven by infrequent extreme flows, these streams can produce a broad forest in relation to their mean discharge. Cottonwood forest widths along these streams (Table 3) are similar to those of the two principal rivers of eastern Colorado; the South Platte River has a mean cottonwood forest width of 352 m and an additional shrubland width of 83 m, and the Arkansas River has a mean cottonwood forest width of 127 m and an additional shrubland width of 294 m (Snyder and Miller 1991). Shrublands along the study streams are limited in extent. This similarity in forest width between the large rivers and the study streams occurs in spite of the fact that mean discharges on the South Platte and Arkansas rivers are far greater than those of the study streams. In an analysis of alluvial streams in the Verde River watershed, Arizona, Stromberg (1993) found that riparian forest width increased with mean discharge over a range in mean discharge from 0.2 to 12 m³/s. Her contrasting result may reflect the importance in the Verde River watershed of winter frontal storms, which produce rainfall over broad areas (Hirschboeck 2000), allowing flood discharges of the Verde River to be greater than those of its tributaries.

Water management led to dramatic channel narrowing and forest expansion along the formerly braided South Platte and Arkansas rivers in eastern Colorado in the early to mid 1900s. This increase in riparian forest along the major rivers and tree planting near settlements are thought to have led to increases in forest-dependent animals in the Colorado Plains (Knopf 1986). The present study, however, has shown that there has been a concurrent increase in forest along smaller streams as a result of postflood channel narrowing following floods in 1935 and 1965. The flooding along the study creeks was not exceptional for the region (Matthai 1969, Friedman et al. 1996a). Similar forest regeneration occurred following 1935 storms along the Arikaree and South Fork Republican rivers (Katz 2001), and following 1965 storms along Plum Creek (Friedman et al. 1996a) and Jimmy Camp Creek (J. Friedman, *personal observations*). Therefore, the increase in forest and forest-dependent animal species in eastern Colorado in this century is only partly a result of human activity (Friedman et al. 1997). Because tree reproduction along smaller streams of eastern Colorado is controlled by infrequent floods, the age and width of forest can be expected to vary greatly

from one decade or century to the next even in the absence of water management, tree planting, or climate change.

ACKNOWLEDGMENTS

We thank N. Atwater, L. Blair, T. Bradbury, D. Cuypers, and the State of Colorado for generously allowing this work on their land. G. Auble, M. Scott, and P. Shafroth made extensive contributions in the field and to the conceptual basis of the research. E. Eggleston and A. Fitzpatrick assisted ably in the field and laboratory. K. Vincent, G. Auble, and two anonymous referees provided constructive reviews of the manuscript.

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