Recent Fluvial History and Environmental Change of Some Ephemeral Streams in the Little Missouri Badlands of Southwestern North Dakota

by
Mark A. Gonzalez

Report of Investigation No. 101
NORTH DAKOTA GEOLOGICAL SURVEY
John P. Bluemle, State Geologist
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On the cover: The ephemeral streams of the Little Missouri Badlands contain a complex record of fluvial adjustments to environmental changes during the Holocene Epoch. This view of the middle reach of Paddock Creek illustrates a sequence of several fill terraces separated from each other by periods of incision that have gradually lowered the elevation of the stream channel. The highest and oldest fill terrace is eight to ten meters above the modern floodplain. This photograph was taken viewing east southeast from a vantage in the NW ¼ of the SW ¼ of Section 22 in Township 140N and Range 101W in the fall of 1986.

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ABSTRACT

An interdisciplinary examination of the recent fluvial history and riparian ecology of seven ephemeral streams in the Little Missouri Badlands of southwestern North Dakota provides a record of environmental change immediately before, during, and since European settlement of the region. The objectives are: (i) to determine the timing and cause(s) of the most recent episodes of fluvial incision, (ii) to develop a process-response model that illustrates the formation and evolution of arroyos in this region, and (iii) to determine the geomorphic processes and other local factors that affect establishment of cottonwood trees along ephemeral channels.

Dendrochronologic and dendrogeomorphic analyses of riparian cottonwood trees provide an inexpensive, high-resolution dating method to constrain the time of fluvial adjustments, thereby permitting determination of the cause(s) of fluvial incision by evaluating environmental conditions prior to and at the onset of the fluvial adjustments. An examination of seven small (10 to 100 km^2) drainage basins revealed that ephemeral streams have undergone a four-stage cycle of change within the past 200 years, comprising: (i) an initial period of relative geomorphic stability with pedogenesis on the flood plain and low rates of lateral channel migration, (ii) a period of channel incision with subsequent widening of the flood plain through lateral corrasion along middle and upstream reaches, (iii) a concomitant period of aggradation along downstream reaches, and finally (iv) a period of downstream incision.

Dendrochronologic data and dendrogeomorphic relations indicate there have been three distinct periods of fluvial incision in the past 200 years. The first period of incision began in the 1860s and 1870s before European settlement in the area. This period of incision occurred along the middle reaches of all seven of the streams examined and coincided with a severe, protracted drought, suggesting an allogenic cause. The second period of incision occurred during the end of the 19th Century and into the 20th Century along the upstream reaches of streams. This period of incision was mentioned in some written accounts of early settlers and coincided with the introduction of cattle and historical overgrazing of the region. However, overgrazing may not have caused the incision of this period, but instead exacerbated or accelerated the upstream migration of incision knickpoints formed earlier along middle reaches. A third period of incision has occurred since the 1950s along the lower reach of Jones Creek and since 1979 along the lower reaches of Dantz Creek and Toms Wash. This incision was possibly initiated by road construction or caused by the process of meander cutoff, an autogenic process that decreases sinuosity and increases channel slope, stream power, and the potential to incise along adjacent stream reaches.

Episodes of geomorphic instability last for two or more decades and have a recurrence interval of one hundred to a few hundred years. The highest rate of establishment of cottonwood trees coincides with periods and places of geomorphic instability. The decline in cottonwood population in the study region during historical time coincides with an interval of geomorphic stability and cannot be attributed to human activities, as is the case in much of the western United States.

Keywords: Ephemeral streams, Fluvial features, Arroyos, Incision, Aggradation, Riparian ecology, Cottonwood, Tree rings, Great Plains, North Dakota

INTRODUCTION

Widespread records of fluvial instability during the latter half of the 19th Century throughout the western United States suggest this was an unusual period and streams had to adjust to either climate change, land-use change related to European settlement of the region, or a combination of the two. The landforms and deposits of rivers serve as integrators of environmental conditions, because much of the eroded sediment and surface water within a watershed passes through stream channels. These fluvial features provide an archive of information on present and past environmental conditions throughout the watershed. Ephemeral streams in particular can record subtle changes in the environment because these streams generally occur in smaller watersheds where contributing areas are correspondingly small, the residence time of surface and ground water is short, and the linkages between conditions on hillslopes and processes in channels are close in space and time, thereby creating great sensitivity to individual hydrometeorological events (*e.g.*, Gonzalez, 1987a, b; Wells, 1988; Balling and Wells, 1990). The hydrologic response is more attenuated in larger watersheds as the local effects of small, intense thunderstorms are diluted down valley. Consequently, larger watersheds are generally more complacent and far less affected by short-term, spatially limited, hydroclimatic events.

Ephemeral streams are common in the western United States. The dynamic nature of ephemeral streams makes them a sensitive indicator of environmental conditions. Small changes in land use, vegetation cover, or climate may result in large changes in the sediment budget and surface runoff of the watershed, which manifest as substantial and readily apparent changes in the geomorphic behavior of ephemeral streams. The sensitivity of ephemeral streams makes them ideal for the analysis of landscape responses to recent environmental changes of land use and climatic fluctuations. Herein I examine two interrelated problems. First, I examine the geomorphic response of several ephemeral streams to recent environmental changes in the Little Missouri Badlands of southwestern North Dakota. Second, I examine the effect that recent geomorphic processes have had on the population of cottonwood trees along ephemeral streams.

An accurate dating method is essential in the reconstruction of the environmental history of a basin. Riparian cottonwood trees provide a high-resolution (annual) dating method of recent fluvial deposits and landforms because the cottonwood's life history is closely related to and dependent upon fluvial processes. It is this close relation between cottonwood ecology and stream processes that makes possible a reconstruction of the recent history of environmental change. Furthermore, because the Little Missouri Badlands was among the last places settled in the contiguous 48 states, the environmental changes that have occurred immediately before, during, and since European settlement of the area are within the life span of the riparian cottonwood trees.

Geomorphic response of ephemeral streams to recent environmental changes

One of the typical responses of an ephemeral stream to environmental changes is the formation of an arroyo, a deeply incised channel with vertical banks cut through a thick accumulation of alluvium. Development of arroyos has been widespread in the western United States during historical times. The processes by which arroyos form and the causes of fluvial incision have been extensively studied, widely debated, and repeatedly reviewed (Schumm, 1973; Cooke and Reeves, 1976; Knox, 1983, 1984; Hereford, 1984; Graf, 1988; Bull, 1997; Elliott *et al.*, 1999; among others). Most investigators concluded that fluvial incision is triggered by climate change (Huntington, 1914; Bryan, 1928; Antevs, 1952; Knox, 1983; Hereford, 1984; Hereford and Webb, 1989; Balling and Wells, 1990; Hall, 1990), changes in land-use (Dodge, 1902; Rich, 1911; Duce, 1918; Gifford and Hawkins, 1978), changes in base-level (Bull, 1977), and/or episodic adjustments related to intrinsic factors (Schumm and Hadley, 1957; Schumm, 1973, 1977; Humphrey and Heller, 1995). Whereas examples of each process listed above can be found, in many other cases the cause of stream incision is difficult to ascertain, especially when temporal constraints are poor.

The ephemeral streams in the Little Missouri Badlands of North Dakota contain multiple fill terraces (Fig. 1) underlain by Holocene alluvium (Hamilton, 1967a,b; Gonzalez, 1987a, b; Kuehn, 1995). My objectives are to determine the timing and cause(s) of the most recent episodes of fluvial incision, and to develop a process-response model that illustrates the formation and evolution of arroyos in this region. The purpose is to distinguish natural from anthropogenic (human induced) changes to the landscape and to discriminate allogenic (i.e., produced by an extrinsic factor, such as climate) from autogenic (i.e., produced by an intrinsic factor, such as stream slope) causes of incision, thereby gaining a greater sense of how steep, relatively small, ephemeral streams evolve.

Geomorphic processes and the establishment of riparian cottonwood trees

Many native plant communities throughout North America have been undergoing dramatic changes since European settlement. For example, many investigators have noted historical changes in the ecological structure of riparian communities of Great Plains and Southwest streams. Dominant native trees, such as cottonwood (*Populus* spp.), are in rapid decline along many streams or have exhibited a short-lived increase in numbers followed by a subsequent decline. Declines have been attributed to alteration of the flow regime by dam construction and regulation of streamflow (*e.g.*, Johnson *et al.*, 1976; Brown *et al.*, 1977; Crouch, 1979a; Reily and Johnson, 1982; Bradley and Smith, 1986; Akashi, 1988; Rood and Heinze-Milne, 1989; Rood and Mahoney, 1990; Johnson, 1994; Shafroth *et al.*, 1998), alteration of flood-disturbance regimes (*e.g.*, Behan, 1981; Fenner *et*

Fig. 1. Multiple fill terraces underlain by Holocene alluvium are common along ephemeral streams of the Little Missouri Badlands. (View is to the east from a vantage in the SW ¼ of Section 31 in Township 138 N/Range 101 W; photograph was taken on 11 August 1996.)

al., 1985) or by withdrawal of streamflow for irrigation and other consumptive purposes (*e.g.*, Rood and Heinze-Milne, 1989). In other cases, declines are attributed to intense use of riparian zones by cattle (*e.g.*, Brown *et al.*, 1977; Crouch, 1979b; Behan, 1981); to herbivory by beavers (*e.g.*, Bradley and Smith, 1986; Baker, 1990); to alteration of natural disturbance regimes through the elimination of high-magnitude streamflows (*e.g.*, Johnson *et al.*, 1976; Bradley and Smith, 1986; Rood and Mahoney, 1990; Scott *et al.*, 1997); to groundwater withdrawals that lower the water table of shallow alluvial aquifers, inhibit new cottonwood trees from establishing, and cause early mortality of established cottonwood trees (*e.g.*, Segelquist *et al.*, 1993; Stromberg *et al.*, 1996; Scott *et al.*, 1999); and to loss of habitat attributed to land clearing and timbering (Akashi, 1988; Rood and Mahoney, 1990). In contrast, some other studies provide examples where cottonwood populations have experienced a short-lived local increase due to channel narrowing following dam construction and modifications of streamflow (*e.g.*, Johnson, 1994), and channel narrowing following catastrophic floods that rework extensive flood-plain areas (*e.g.*, Friedman, 1993; Friedman *et al.*, 1996a, b).

Most previous investigators have examined factors affecting cottonwood establishment along perennial streams with regulated streamflow, in contrast to this study, in which I have reconstructed the history and pattern of cottonwood establishment along small ephemeral streams in a relatively pristine setting. My objectives are two-fold: (i) to identify the factors that affect establishment of cottonwood trees along small ephemeral streams, and to contrast these factors with factors operating along large perennial streams; and (ii) to determine the role of natural geomorphic processes on the establishment and mortality of cottonwood trees along streams in environments free of anthropogenic factors, such as flow regulation, water withdrawal, habitat destruction, and intensive grazing. This study of cottonwood trees along small ephemeral streams is meant to supplement the existing knowledge garnered about cottonwood trees along large perennial streams.

STUDY AREA

I conducted fieldwork in the Little Missouri Badlands of southwestern North Dakota in seven small basins, ranging from 10 to <100 km^2 in area (Fig. 2). Four basins (Jones Creek, Jules Creek, Paddock Creek, and Talkington Draw (informal name)) are within the South Unit of the Theodore Roosevelt National Park (Fig. 2). The other basins (Dantz Creek, Bear Creek, and Toms Wash) are

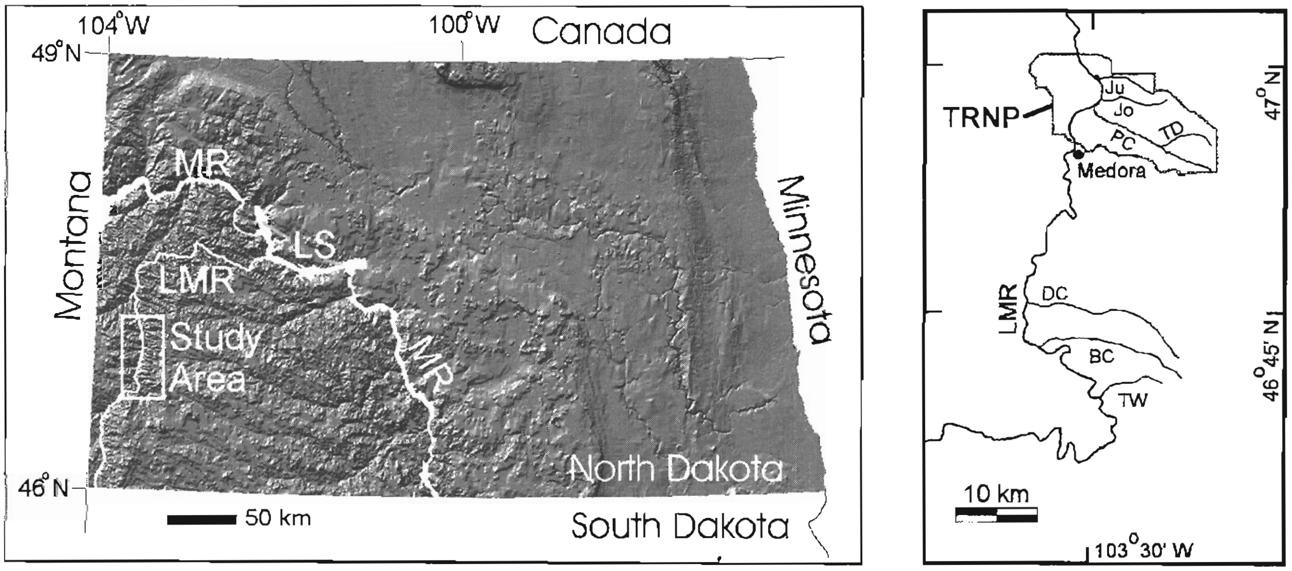

Fig. 2. Location map indicates study sites within the Little Missouri Badlands and principal drainages of western North Dakota. Abbreviations are as follows: MR Missouri River; LMR Little Missouri River; LS Lake Sakakawea; TRNP South Unit of Theodore Roosevelt National Park; Ju Jules Creek; Jo Jones Creek; PC Paddock Creek; TD Talkington Draw; DC Dantz Creek; BC Bear Creek; and TW Toms Wash.

several kilometers south of Theodore Roosevelt National Park within the Little Missouri National Grasslands (Fig. 2). I chose these basins because they have similar physiography, climate, vegetation, and geology; are drained by ephemeral streams; and are readily accessible as public lands or through permission of the resident ranchers.

Settlement history and land use in the Little Missouri Badlands

The Little Missouri Badlands was among the last places settled, primarily because this was the last frontier in the contiguous United States reached by railroad. The early and mid-19th Century was a time of great change in the Northern Great Plains. The trade in beaver pelts in the region began in modest-scale in 1807 with the use of keelboats (Robinson, 1966, pp. 49-50), although the use of steamboats on the upper Missouri River beginning in 1830 (Robinson, 1966, pp. 90 and 94) dramatically escalated the harvest of beavers. Also, the population of Native American Indians in the region was greatly reduced by catastrophic smallpox epidemics, especially those in 1782, 1837, and 1866 (Robinson, 1966, pp. 32 and 97-98). In addition, trade in buffalo hides occurred during much of the century, but the large-scale decimation of buffalo herds in the Little Missouri Badlands occurred in 1881 and 1882 (Robinson, 1966, pp. 185-186; Manning, 1995, p. 87). In the period immediately preceding European settlement, the establishment and survival of cottonwood trees along ephemeral streams of the Little Missouri Badlands may have been affected by the reduction in beaver, buffalo, and Native American populations in the region.

Ranching activities and homesteading began in the early 1880s when the Northern Pacific Railroad extended its track westward to Medora, North Dakota (Robinson, 1966, p. 184, 188-190), a small historic cattle town on the east bank of the Little Missouri River (Fig. 2). The cattle boom in the Little Missouri Badlands was short-lived. A drought, grasshopper infestation, and widespread fire in the summer of 1886, combined with a severe protracted winter in 1886-1887, led to the loss of an estimated 75% of the cattle in the region (Roosevelt, 1888; Robinson, 1966). By 1889 Medora was deserted (Robinson, 1966, p. 190).

The region was grazed severely in places during the mid-1880s. The four basins (Jones Creek, Jules Creek, Paddock Creek, and Talkington Draw) within the Theodore Roosevelt National Park were grazed by livestock during a 50-year interval from the 1880s to the 1930s; however, livestock grazing has been generally excluded from the South Unit of the park in the past 60 years. The Theodore Roosevelt National Park is now managed, in part, as a game preserve for bison, deer, feral horses, bighorn sheep, and elk. Bison and feral-horse populations are controlled by episodic roundups with surplus animals culled from the herd. The land in the other study sites (Dantz Creek, Bear Creek, and Toms Wash basins) was purchased by the federal government under provisions of the Bankhead-Jones Farm Tenant Act of 1937 and is now part of the Little Missouri National Grasslands, administered by the U.S. Forest Service. These federal lands are interspersed with private ranch holdings. Personnel from the U.S. Forest Service and the Medora Livestock Association make annual inspections of federal grazing leases in the area to adjust grazing levels. In addition to cattle grazing, the Little Missouri National Grasslands are used for oil production, hunting, hiking, and recreation, activities that are relatively minor with respect to geomorphic processes and establishment or mortality of cottonwood trees although construction of roads for the oil industry may have local effects on fluvial processes.

Physiography, geology, climate, and vegetation

The Little Missouri Badlands is a highly dissected terrain with high drainage density, sparsely vegetated hillslopes, and high local relief (as much as 200 m/km^2)(Fig. 3). The bedrock geology comprises the Paleocene age Bullion Creek and Sentinel Butte formations (ascending order) of the

Fig. 3. View of the headwater region of the Paddock Creek basin illustrates the typical topography, vegetation cover, and relief in much of the Little Missouri Badlands.

Fort Union Group (Bluemle *et al.,* 1986). These formations consist of intercalated beds of sandstone, siltstone, mudstone, shale, lignite, and clinker (also known locally as scoria). The mudstone and shale strata are sparsely covered by vegetation and erode readily to form a colorful badlands terrain. Alluvial deposits along the riparian corridors consist of material derived from the Bullion Creek and Sentinel Butte formations.

Southwestern North Dakota is a semiarid region averaging about 400 mm of precipitation per year (Table 1), although annual totals vary considerably. Nearly three-quarters of the annual precipitation occurs from April through September (Table 1). Summer thunderstorms provide the primary source of runoff in the ephemeral streams of the Little Missouri Badlands. Annual temperatures generally range from -40° to 40°C (National Climatic Data Center records for North Dakota Climate Division 7 (Southwest)).

Vegetation reflects the semiarid continental climate and varies with respect to geology and microclimatic conditions on hillslopes. Uplands comprise a mixed-grass prairie, dominated by grama grass (*Bouteloua gracilis* Marsh.), green needle-and-thread grass (*Stipa comata* Trin. & Rupr.), and little bluestem (*Andropogon scoparius* Michx.); north-facing slopes support Rocky Mountain juniper (*Juniperus scopulorum* Sargent) and creeping juniper (*Juniperus horizontalis* Moench); coulees, hillslope depressions, and flood-plain margins contain buffalo berry (*Shepherdia argentea* Nutt.); clayey soils of badlands slopes contain greasewood (*Sarcobatus vermiculatus* (Hook.) Torr.), colluvium and alluvium contain silver sage (*Artemisia cana* Pursh.) and some big sagebrush (*Artemisia tridentata* Nutt.); and riparian corridors contain plains cottonwood (*Populus deltoides* Marsh.) (Rydberg, 1932; Stevens, 1950).

Table 1. Summary of average monthly and annual climate data for southwestern North Dakota[a]

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Ave. temperature (°C)	-10.7	-8.2	-2.5	5.5	11.7	16.9	20.6	19.5	13.5	6.9	-1.9	-7.8	5.3
Precipitation (mm)	11.87	10.24	17.99	36.54	59.22	90.53	54.79	42.04	34.26	23.29	13.63	9.03	403.43

[a] National Climatic Data Center records for North Dakota Climate Division 7 (Southwest) from 1895 through 1999

METHODS

The types of fluvial processes and the history of recent stream adjustments were reconstructed through dendrochronologic and dendrogeomorphic techniques and by constructing maps that summarize time-space relations of features along ephemeral streams. Dendrochronology of riparian cottonwood trees provides an inexpensive, high-resolution dating method to constrain the time(s) of recent stream adjustments. Only when the times are well constrained is it possible to relate periods of channel adjustments to specific climatic factors, anthropogenic activities, and/or episodic, autogenic processes of sediment movement.

Plains cottonwood (*Populus deltoides* Marsh.) is ubiquitous along streams of the Little Missouri Badlands (Stevens, 1950). Numerous geomorphologists and riparian ecologists (Everitt, 1968; Friedman, 1993; Friedman *et al.,* 1996a; Scott *et al.,* 1996) have found that the establishment of cottonwood trees is directly linked to fluvial processes. For example, Everitt (1968), Nanson and Beach (1977), and Scott *et al.* (1996) among others have found that cottonwood seeds do not compete well on vegetated sites. Instead, the seeds prefer to germinate on moist, bare sediment found on recently accreted point bars (Fig. 4), channels, and flood plains. Friedman (1993) and Friedman *et al.* (1996) found that channels typically narrow from deposition following catastrophic floods that temporarily enlarge the channel. Channel narrowing by deposition provides a short-lived opportunity for a new cohort of cottonwood trees to establish. Johnson *et al.* (1976) noted that cottonwood seedlings require light; therefore, they do not establish on vegetated surfaces where overstory reduces light. Consequently, germination occurs on newly constructed surfaces that are free of competition (Fig. 4).

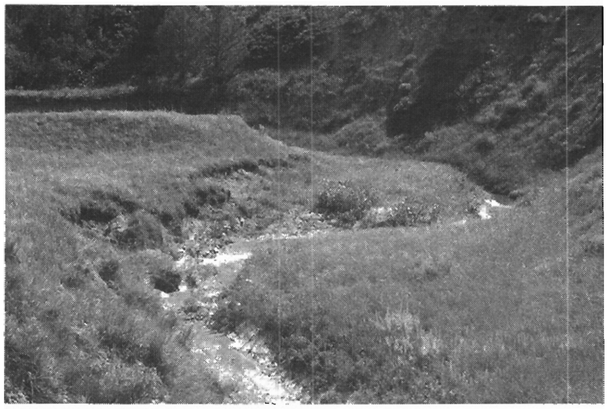

Fig. 4. Cottonwood trees typically germinate on newly constructed fluvial surfaces, such as point bars (as shown), channel bars, or flood plains that are free of competition from existing vegetation. (View is to the south from a vantage along Jones Creek in the SW ¼ of Section 4 in T 140 N/R 101 W; photograph was taken on 7 August 1996.)

Collection and preparation of tree cores

I extracted cores from cottonwood trees with various increment borers (40 to 70 cm long, 5.15-mm bore) to determine the ages of the trees and their dates of establishment. Generally, only one core was extracted from a tree; multiple samples were collected if the initial core was badly twisted or had rotten wood that complicated analysis of tree rings. The cores were dried, glued to a mounting cradle (strip of lath that had a semi-circular groove carved into it with a 6-mm-diameter, cove-shaped, router bit), and sanded with progressively finer grades of sandpaper (80-120-200-400 grits) following conventions described by Fritts (1976), Maeglin (1979), and Phipps (1985). Twisted cores were cut on a diagonal across the growth rings, rotated, and glued to mounting cradles so that a transverse view of the growth rings could be obtained through the twisted increments. No stain was required to study growth rings, which were readily distinguished using a low-magnification (5X to 45X) zoom stereoscope and low-angle incidental light. Episodes of drought created marker years and permitted cross dating of annual growth rings in many cores across fragmented, twisted, and rotten intervals. The tree-ring pattern in some cores could not be cross dated because they exhibited complacency (insensitivity to climatic fluctuations), even during known droughts. Most likely complacent trees could extract water from shallow alluvial aquifers, thereby moderating any effects of climatic fluctuations. The date of establishment and the age of a tree can be determined by counting the number of annual growth rings from the cambium to the pith. Errors in dating can arise from several factors, particularly tree rot, eccentric growth, and collection of cores far above the original root collar.

Generally, cores were collected as close to the original root crown as possible to determine the date of establishment. Where channel migration or cutbank erosion exposed the base of the tree, cores were extracted directly above the root crown so that the precise year of establishment could be determined. Cores from most other trees were collected from 20 to 35 cm above ground surface, a height dictated by the length of the handles on the increment borers. The remaining cores were collected as much as 140 cm above ground surface where dense ground cover inhibited extraction any closer to the ground. Above-ground sampling can lead to underestimation of tree age, particularly if there has been extensive burial of the root crown. The estimated germination date was adjusted, depending upon the height at which the sample was collected, to compensate for the time required for trees to grow to various heights. For example, Wilson (1970) collected all his increment cores at mean breast height, and then added four years to the number of annual growth rings counted to determine the age of the tree. Akashi (1988, pp. 23-24) examined seedlings and determined that they reached 30 cm height during the first growing season, 50 cm by the second, and 70 cm by the third year. Consequently, he adjusted the age of the tree by adding 1, 2, or 3 year(s) for samples collected from 1-40, 41-71 cm, or >70 cm above ground, respectively. My approach was similar, but differed in two respects. First, because the growth ring at the pith represents the earliest growth year, I did not add a year for samples collected < 30 cm above the root crown. Consequently, my age adjustments were 1, 2, or 3 years for samples collected from >30 to 50, >50 to 100, and >100 cm above the root crown, respectively. Second, I also compensated for whether the root crown was visible at the ground surface. I assumed that at least 10 cm of alluvium is required to bury completely a mature root crown. Therefore, if no part of the root crown was visible, I adjusted the age of the tree by 1, 2, or 3 years for samples collected from >20 to 40, >40 to 90, and >90 cm above the ground surface, respectively.

In no case did I adjust the age of the tree by more than three years, even though some samples were collected far more than 100 cm above the root crown. The rate of growth of cottonwood trees is too variable to justify age adjustments beyond three years. Cutbank exposures revealed that the root crowns of some of the oldest trees have been buried (Fig. 5) by as much as 3 m of alluvium. In cases where the root crown is deeply buried, the calculated date is one to several years later than the actual date of establishment.

Excavation of buried trees to core at the root collar was impractical in this study for several reasons. First, above-ground coring has much less environmental impact and poses less harm to trees than does excavation. The permits to collect samples in federal lands (Theodore Roosevelt National Park and the Little Missouri National Grasslands) included stipulations to minimize impact to trees and surroundings and prohibited felling or excavation of trees. Second, as Scott *et al.* (1997) noted, excavation is a time-intensive process, typically requiring two to 16 person-hours per tree. Excavation reduces sample collection by an order of magnitude as compared to above-ground coring. In the time available for fieldwork, excavation methods would have limited core collection to a few tens of trees in one or two basins, in comparison to above-

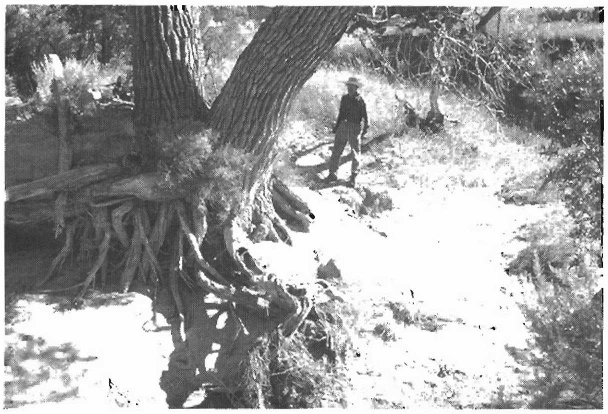

Fig. 5. Many root crowns of older trees are buried by alluvium. The cottonwood tree (Sample # 823Q), shown in this photograph, established around 1840. The root crown has been buried by slightly more than one meter of overbank deposits, and recent fluvial incision since 1979 has re-exhumed the root crown and much of the root system. (Photograph was taken on 23 August 1996 of a tree found along Dantz Creek in the NE ¼ of Section 20 in Township 138 N/Range 102 W.)

ground coring that permitted detailed study of a few hundred trees throughout seven basins. Because many ephemeral streams undergo autogenic cycles of cutting and filling that result from intrinsic changes within a basin (Patton and Schumm, 1981), it is imperative to conduct detailed investigations in several neighboring basins to identify and distinguish between random autogenic and simultaneous allogenic stream processes. Third, the questions pursued here do not require annual-level precision, but can be addressed adequately with decadal-level precision, provided a large data set is obtained. In studies where cottonwood establishment is related directly to specific, low-frequency hydrologic events (*e.g.,* Baker, 1990; Stromberg *et al.,* 1991, 1993; Scott *et al.,* 1996), excavation is probably advisable. In this study, cottonwood establishment is related to geomorphic processes of meander migration, knickpoint migration, channel incision and valley aggradation. These are time-transgressive processes for which decadal-level precision is sufficient.

Some samples were collected from trunks where annual growth rings were eccentric, making it difficult to locate the pith of the tree with an increment borer. In these cases, the ages of the trees were estimated in part with a pith locator. Pith locators can reduce dating errors associated with eccentric growth by providing an estimate of the number of annual growth rings missing between the inside ring of an increment core and the missed pith (Fig. 6).

In other cases, heart rot, a common affliction in cottonwood trees, prevented accurate determination of the ages of some samples. Cores with extensive rot were not analyzed. In some cases the increment borer was deliberately aimed off center so that the curvature of rings seen in the increment core could be used in conjunction with a pith locator (*see* Fig. 6) to estimate the number of tree rings missing due to heart rot.

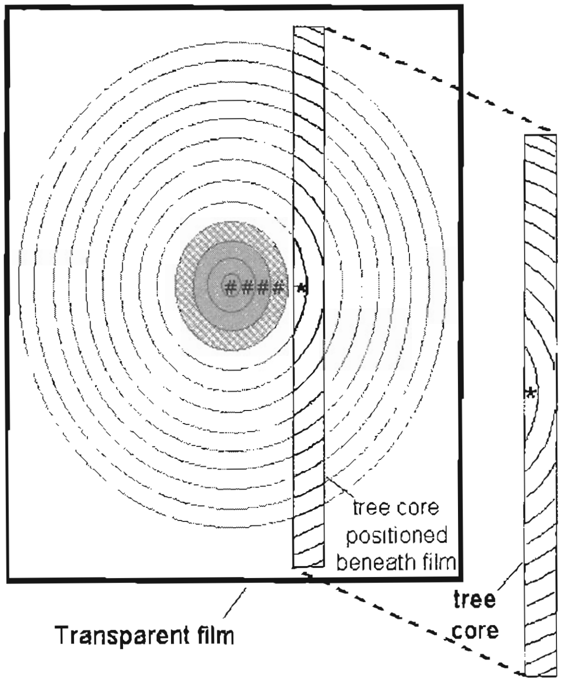

Fig. 6. Pith locators are made by transcribing concentric circles on a sheet of transparent film or plastic. The increment core is placed beneath the transparent pith locator and its position is adjusted until the arc of the inner growth rings is aligned with the concentric circles of the pith locator. The number of missing rings (#) between the inside ring (*) on the core and the pith of the tree can be estimated from the pith locator, assuming that annual growth rings are of uniform width in the first few years of life. Numerous pith locators are made that vary by the interval between concentric rings to approximate different rates of growth of various trees.

Principles of dendrogeomorphology

The age of a tree provides a minimum age for the sediment at and beneath the root crown of the tree and a maximum age for sediment that overlies the root crown (Figs. 5, 7A and 7B). The age of the tree also helps to date landforms and constrains the period when stream adjustments occurred. For example, the time of channel incision within a reach is constrained by the establishment dates of the youngest trees on the elevated fluvial surface *(i.e.,* the terrace) and the oldest trees on the inset fluvial surface (*i.e.,* the flood plain) (Figs. 8A and 8B). Also, an average rate of aggradation can be calculated conservatively by dividing the thickness of sediment that has accumulated above a root crown by the age of the tree (Figs. 7A and 7B).

Mapping of temporal-spatial relations and geomorphic positions

Along Jones Creek, Jules Creek, Paddock Creek, and Toms Wash, the number of cottonwood trees was sufficiently low that it was possible to core every living cottonwood larger than a sapling (sapling has diameter <10 cm, as defined by

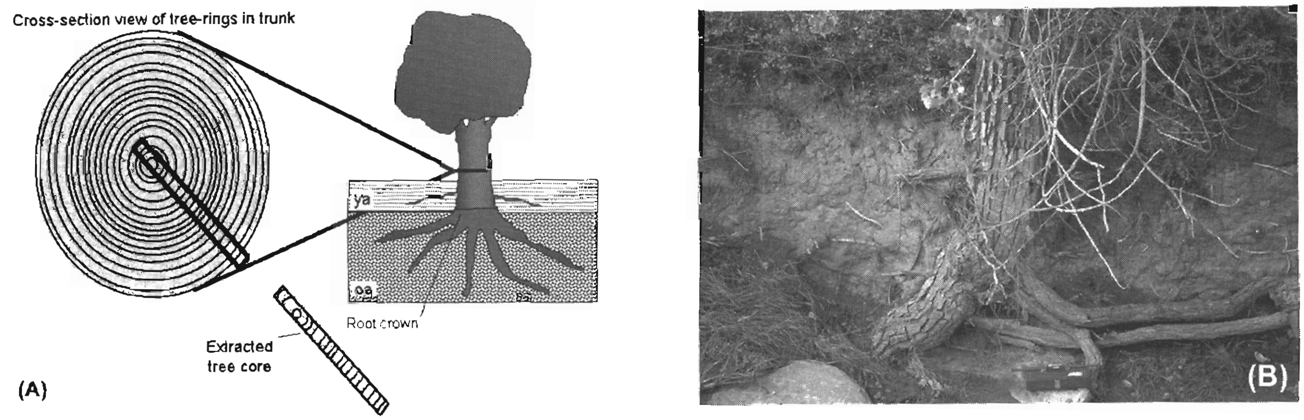

Fig. 7. Schematic (A) and field (B) views illustrate the relation between root crowns and age of alluvium. Tree ages provide minimum age constraints on older alluvium (oa) that lies at or beneath the root crown and maximum age constraints on younger alluvium (ya) that lies above and buries the root crown. In addition, an average rate of aggradation can be calculated conservatively by dividing the thickness of younger alluvium (ya) by the tree age. (Toolbox for scale in bottom center of (B) is 40 cm long.)

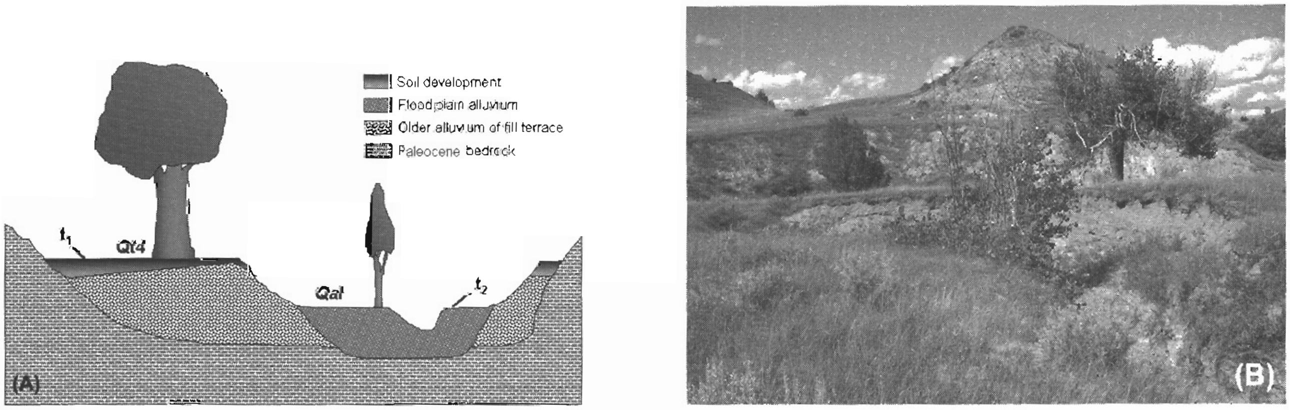

Fig. 8. Schematic (A) and field (B) views of cottonwood trees on two different fluvial surfaces, Qt4—a low terrace, and Qal—the modern floodplain. Tree ages permit dating of the fluvial surfaces. The time of stream incision within a given reach is constrained by the age of the youngest cottonwood tree on the abandoned surface (i.e., Qt4 terrace) and the oldest tree on the inset active flood plain (Qal). The schematic cross-section (A) portrays valley cross-section relations along the middle and upper reaches of the streams studied (*see* cross-section y-y' in Fig. 10B for relative position within basins). Along middle reaches, incision commenced in the 1860s and 1870s. Incision lagged by one or more decades along upper reaches and commenced in the 1880s and 1890s or later. Some headwater reaches incised as late as the 1930s and 1950s.

Johnson *et al.*, 1976). Along Dantz Creek, Bear Creek, and Talkington Draw, the number of cottonwood trees is much greater. Many meander bends contained arcuate-shaped stands of presumably even-aged trees, based on similarities in stem diameter, limb thickness, and crown height. Only one or two trees from each even-aged arcuate stand were cored to determine the establishment history along the reach and to acquire a representative collection of cores throughout the seven study basins. Additional sampling along the few more-heavily forested reaches would have been redundant.

The location, geomorphic position (e.g., inset flood plain, aggrading floodplain, point bar, channel bar, low terrace, etc.), and age of each analyzed tree were plotted on 1:24,000-scale topographic base maps to create time-space relations of fluvial adjustments within each basin. Geomorphic, botanic, and sedimentary features were used to determine if the stream reach around each tree had aggraded and/or incised since germination. For example, burial of a root crown, formation of adventitious roots, and accumulation of overbank sediment or woody flood debris around the trunk of the tree provide evidence of channel aggradation; whereas formation of a lower, inset, fluvial surface indicates channel incision.

RESULTS

Approximately 350 riparian cottonwood trees were cored in the seven study basins. Heart rot or grossly missed piths reduced the number of useable cores to 275. These cores were analyzed to determine the age of trees, their date of establishment, their geographic distribution within each basin, and their dendrogeomorphic relations (Table 2). A histogram, portraying the decade in which each tree established, reveals: (1) cottonwood trees as old as 225 years occur along the ephemeral streams of the Little Missouri Badlands (Fig. 9); (2) cottonwood trees are on two fluvial surfaces, a terrace, Qt4, elevated 1 to 3 m above the modern flood plain, Qal [Note: In places, the modern flood plain, Qal, has been incised since 1950, and the elevated pre-incision flood plain is labeled Qoal (older alluvium) and the inset, post incision flood plain is labeled Qyal (younger alluvium)(*see* Fig. 10C).]; (3) nearly two-thirds (65%) of the trees established from the 1860s through the 1890s, and half (51%) established in the 1860s and 1870s (Fig. 9). Decrease in the number of trees established before 1860s is related in part to senescence (aging) and the expected rate of mortality of cottonwood trees more than 140-years old. The decrease in the number of cottonwood trees established since the 1870s suggests that

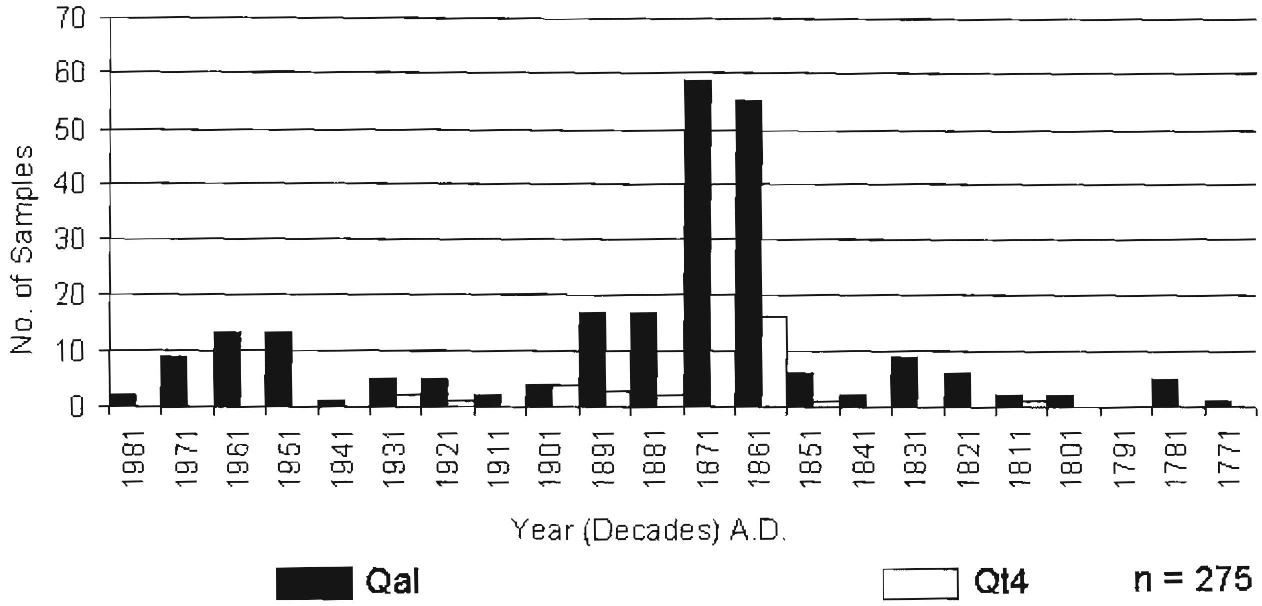

Fig. 9. Histogram showing the decade of establishment of 275 sampled trees and the surface (Qal or Qt4) on which the trees are found. [Decades are treated as beginning in year 1 (*e.g.*, 1841) and ending in year 10 (*e.g.*, 1850) of the decade.]

Table 2. Summary of dendrochronology from seven study basins

	Jules Creek		Jones Creek			Talkington Dr.		Paddock Cr.		Bear Creek		Dantz Creek			Toms Wash			Total	Total	Total
Decade	Qt4[a]	Qal[b]	Qt4	Qyal[c]	Qal	Qt4	Qal	Qt4	Qal	Qt4	Qal	Qt4	Qoal[d]	Qal	Qt4	Qoal	Qal	Qt4	Qal	Qoal
1751	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1761	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1771	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0
1781	0	0	0	0	0	0	0	0	0	0	4	0	1	0	0	0	0	0	4	1
1791	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1801	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	2	0
1811	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	1	1	1
1821	0	0	0	0	0	0	0	0	1	0	3	0	2	0	0	0	0	0	4	2
1831	0	0	0	0	0	0	0	0	1	0	4	0	0	3	0	1	0	0	8	1
1841	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	2	0
1851	0	0	0	0	0	0	0	1	1	0	3	0	2	0	0	0	0	1	4	2
1861	0	0	5	0	0	3	0	0	3	0	18	8	1	27	0	5	1	16	49	6
1871	2	1	1	0	2	4	0	0	11	1	9	2	8	23	0	3	2	10	48	11
1881	0	0	0	0	1	0	0	0	3	1	4	0	1	7	1	1	0	2	15	2
1891	0	0	1	0	0	2	3	0	4	0	2	0	0	1	0	0	7	3	17	0
1901	0	0	2	0	0	2	0	0	0	0	1	0	0	3	0	0	0	4	4	0
1911	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0
1921	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	3	1	5	0
1931	0	0	0	0	0	1	2	0	0	0	0	1	0	1	0	0	2	2	5	0
1941	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
1951	0	0	0	7	0	0	4	0	0	0	1	0	0	0	0	0	1	0	13	0
1961	0	0	0	5	2	0	5	0	0	0	0	0	0	1	0	0	0	0	13	0
1971	0	0	0	3	0	0	4	0	0	0	0	0	0	1	0	0	1	0	9	0
1981	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0
Total:	2	1	9	15	5	13	20	1	24	3	53	11	16	72	1	10	19	40	209	26

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[a] Qt4 is the youngest and lowest terrace identified along the ephemeral streams. It is no longer inundated by floods under the current hydrologic regime.

[b] Qal is the modern flood plain and is inundated once every year to few years.

[c] Qyal is the inset channel alluvium that has been deposited since the 1950s along the lower reach of Jones Creek. [Note: Trees found on the Qyal surface are lumped with those on the Qal surface in Fig. 9.]

[d] Qoal is a terrace that has formed since 1979 along a few reaches when local incision occurred as a result of the cutoff of meander necks. [Note: Trees found on the Qoal surface are lumped with those on the Qal surface in Fig. 9.]

environmental factors in the past 120 years have not been as conducive for the successful establishment and survival of cottonwood trees as they were in the 1860s and 1870s. Generally, the cottonwood trees are oldest and most abundant in the downstream reaches and are sparse or absent in the headwater reaches. Following, I present dendrochronologic, dendrogeomorphic, spatial, and temporal data from the seven study basins to constrain the times of fluvial incision or aggradation, to illustrate the evolution of arroyos, and to illustrate the relations between establishment of cottonwood trees and geomorphic processes in the ephemeral stream channels of the Little Missouri Badlands.

Jones and Jules creeks

Jones and Jules creeks are the two smallest basins studied with drainage areas of 12.2 and 10.6 km^2, respectively. Both basins are in the South Unit of Theodore Roosevelt National Park (Fig. 2). Most cottonwood trees in these basins were dead, and analysis was limited to cores from 32 living trees (Fig. 10A). No cottonwood trees were found along the uppermost 2 km of Jones Creek or in the uppermost 3 km of Jules Creek, where the gradients of the valley axis are steep (> 1.5%) and the streams flow in bedrock channels with low sinuosity (1.16) (Fig. 11; Tables 3A and 3B). The straight, steep headwater reaches store little sediment; consequently, there are few point bars where cottonwood trees could establish.

Of the 32 trees studied, 16 established along the lower reaches of these creeks. Fifteen of these established from 1952 through 1978 in the

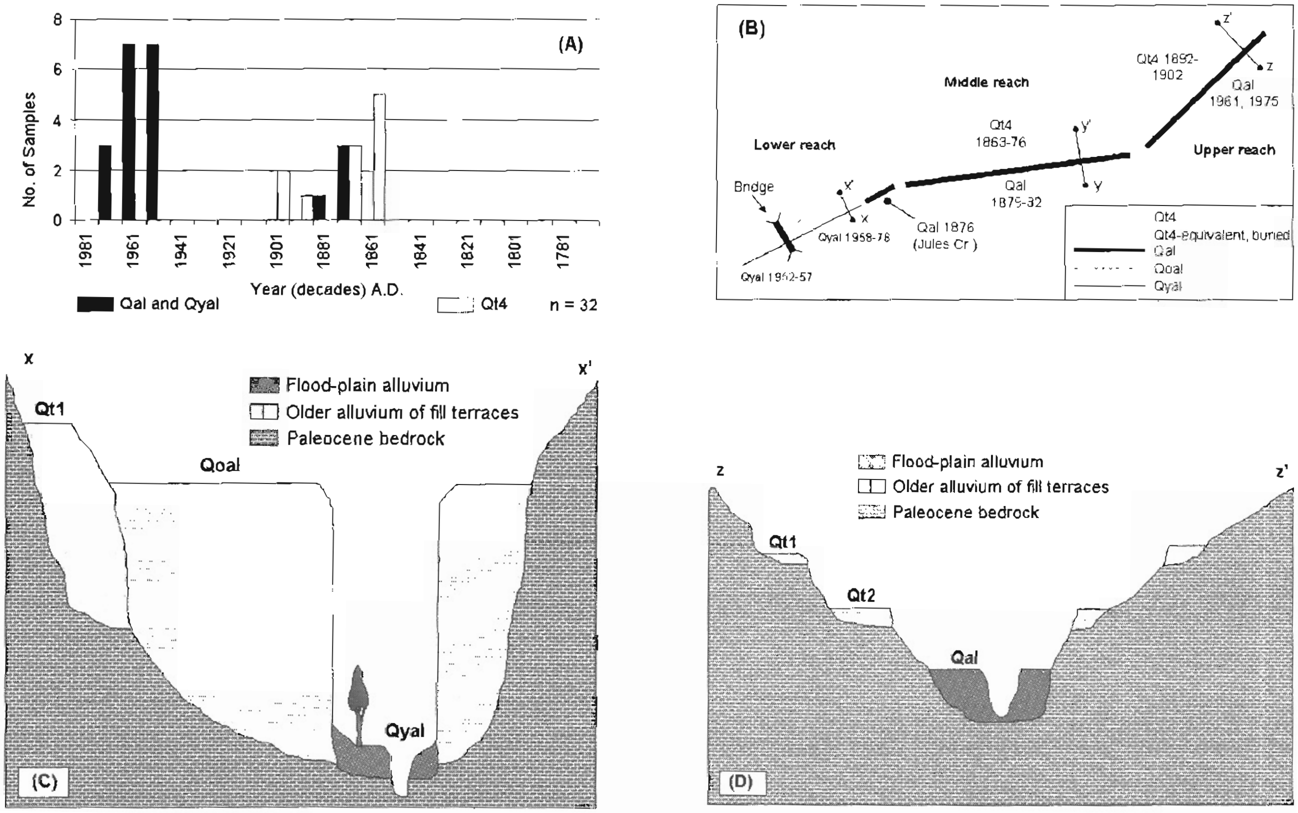

Fig. 10. (A) Histogram of establishment dates of cottonwood trees on Qal and Qt4 surfaces along Jones and Jules creeks. (B) Dendrogeomorphic relations along Jones and Jules creeks. (C) Schematic valley cross-sectional profile (x-x'; *see* Fig. 10B for location) across the lower reach of Jones Creek illustrating the deep, inset channel and narrow inset flood plain (Qyal) beneath the Qt2 surface. No remnants of a Qt4 surface have been found in this reach. (D) Schematic valley cross-sectional profile (z-z'; *see* Fig. 10B for location) across the upper reach of Jones Creek. The terraces are primarily straths (*i.e.*, erosional surfaces cut on bedrock) cut on Paleocene bedrock with thin veneers of alluvium overlying the straths. Little sediment is stored along the upper reaches of the streams studied. The fluvial landforms illustrated along the upper reach of Jones Creek are similar to those observed in the upper reaches of all the other streams in this study.

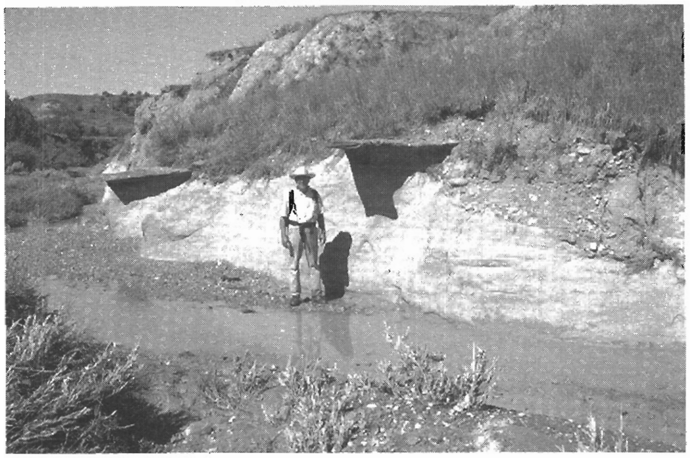

Fig. 11. Bedrock reaches are straight, steep reaches that generally do not have point bars or channel bars. (View is toward the west northwest in the SW ¼ of Section 19, T 138 N/R 101 W along Dantz Creek.)

Table 3A. Average slope (%) in reaches of each stream

Stream basin (drainage area, km^2)	Reach: Alluvial Lower	Alluvial Middle	Alluvial Upper	Bedrock Lower	Bedrock Upper[a]
Jules Creek (11)	0.66	0.62	0.73	2.13	N.A.
Jones Creek (12)	0.98	0.64	0.87	2.93	N.A.
Paddock Creek (70)	0.24	0.29	0.59	1.36	11.46
Talkington Draw (20)	0.22	0.28	0.59	1.92	12.61
Dantz Creek (65)	0.32	0.41	0.83	3.01	N.A.
Bear Creek (50)	0.36	0.36	0.53	0.85	3.49
Toms Wash (17)	0.66	0.52	1.13	3.08	10.62

Table 3B. Average sinuosity[b] in reaches of each stream

Stream basin (drainage area, km^2)	Reach: Alluvial Lower	Alluvial Middle	Alluvial Upper	Bedrock Lower	Bedrock Upper[a]
Jules Creek (11)	1.47	1.50	1.43	1.05	N.A.
Jones Creek (12)	1.08	1.48	1.44	1.13	N.A.
Paddock Creek (70)	2.31	2.66	1.56	1.04	1.05
Talkington Draw (20)	2.31	2.48	1.56	1.04	1.05
Dantz Creek (65)	2.33	1.43	1.45	1.06	N.A.
Bear Creek (50)	1.85	2.08	1.14	1.06	1.06
Toms Wash (17)	1.92	1.53	1.07	1.04	1.05

[a] Average slope and sinuosity are calculated from 7.5-minute topographic maps. The mapped trace of some ephemeral channels does not extend up some steep bedrock canyons. The slope in these reaches has not been calculated and is indicated as N.A., not applicable.

[b] Sinuosity is a dimensionless value derived from the ratio of channel to valley length.

inset flood-plain alluvium (Qyal) along Jones Creek; and, one of these established around 1876 and was deeply buried in flood-plain alluvium of Jules Creek (Fig. 10B; Table 4). The modern flood plain along the lower reach of Jones Creek is narrow and deeply inset beneath the Qoal terrace surface (Fig. 10C). Remnants of the Qt4 surface have not been found along this reach.

The establishment of trees on the Qyal alluvium from 1952 through 1978 coincides with a period of stream incision that is documented, in part, by stereographic aerial photographs (1:20,000-scale), taken on 2 August 1957 by the U.S. Department of Agriculture. These photographs show where Jones Creek passed through a culvert under the East River Road. The channel was not incised at or upstream of the culvert; however, the channel was incised 5-6 m immediately downstream of the culvert and remained incised along the 0.3-km-long reach of Jones Creek from the East River Road to its confluence with the Little Missouri River. Today (2001), the same road has a bridge across Jones Creek and the channel is incised 6 m along its lower 2 km. The reach of Jones Creek downstream of the bridge has three trees which established on the Qyal surface from 1952 through 1957. The reach upstream of the bridge has trees established on the Qyal surface from 1958 through 1978 (Fig. 10B).

The middle reaches had 12 living cottonwood trees—nine established on the Qt4 surface from 1863 through 1876 and three established on the Qal surface from 1879 through 1882 (Fig. 10B; Table 4). The dendrogeomorphic relations indicate that the Qt4 surface remained an active fluvial surface until at least 1876 and incision occurred by at least 1879 in the middle reaches (*see* Fig. 8A).

The upper reaches had only five living cottonwood trees—three established on the Qt4 surface from 1892 through 1902 and two established on the Qal surface in 1961 and 1975 (Fig. 10B; Table 4). Whereas the dates of establishment document mid-reach incision during a tightly constrained period prior to European settlement, the data from the upstream reaches indicate the incision of upstream reaches lagged behind incision of middle reaches until some poorly constrained time in the 20th Century, after settlement and introduction of domesticated cattle in the region.

A schematic map of Jones and Jules creeks illustrates a time-transgressive trend in the dates of establishment of cottonwood trees and formation of geomorphic surfaces (Fig. 10B). The lower reaches of both creeks have channels cut into bedrock and narrow flood plains (Qal in Jules Creek and Qyal in Jones Creek),but do not have a low terrace (Qt4). The oldest cottonwood trees were found in the flood-plain deposits along the lower reaches. Farther upstream, along the middle reaches of the streams, the treads of a terrace (Qt4 surfaces) emerge from the flood plains and rise higher above the Qal surfaces with increasing distance upstream. Along the middle reach of Jones Creek, the Qt4 surface contained old cottonwood trees with establishment dates in the 1860s and 1870s. Along the middle reach of Jules Creek, all (eight) of the trees on the Qt4 surface were dead. Stereographic aerial photographs (scale 1:20,000), taken on 1 August 1957 show that all of these trees were alive in 1957. These trees most likely died sometime during a recent severe drought, such as the one occurring from 1988 through 1992, the most severe drought in the area since the 1950s.

The dates of cottonwood establishment indicate when different reaches and fluvial surfaces were active. As long as a fluvial surface is episodically disturbed by floods and/or sedimentation, then conditions for establishment of cottonwood trees exist. When a fluvial surface is abandoned, *i.e.*, no longer flooded, establishment of cottonwood trees will cease due to the lack of moisture, the lack of bare mineral surfaces for germination of cottonwood seeds, and the inability of cottonwood seedlings to compete with other vegetation on the surface (*e.g.*, Johnson *et al.*, 1976; Friedman *et al.*, 1996b; Scott *et al.*, 1996). The pattern of cottonwood establishment indicates that prior to and through the 1870s, the Qt4 surface was the then-active flood plain along the middle

Table 4. Dendrochronology of Jones and Jules Creeks

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom. Surface	Root Crown[4]	Flood debris[5]	Comments
Upper reaches								
807-R	1908	5	50 gs	1901	Qt4	b	a, wos	
807-Q	1913	8	90 gs	1902	Qt4	b	a, wos	
807-P	1979	2	50 gs	1975	Qal	b	a, w	
807-O1	1897	3	70 gs	1892	Qt4	b	a, w	
807-O2	rot	N.D.	70 gs	N.D.	Qt4	b	a, w	
807-N1	1970	8	20 gs	1961	Qal	b	a, wr	Flood-tipped tree
807-N2	1973	10	20 gs	N.D.	Qal	b	a, wr	Flood-tipped tree
Middle reaches								
806-A	1888	7	50 gs	1879	Qal	b		
806-B	1885	4	70 rc	1879	Qal	v	wo	Qal surface 1.5 m below Qt4 surface
806-C	1877	8	100 rc	1867	Qt4	v	wo	Many dead trees on Qt4
806-D	1876	7	70 rc	1867	Qt4	v	wo	Many dead trees on Qt4
806-E1	1893	(rot)	100 gs	N.D.	Qal	b	a, wo&r	
806-E2	1895	10	100 gs	1882	Qal	b	a, wo&r	Many saplings (<10 y old?) on Qal
806-F	1868	2	80 gs	1864	Qt4	b	a	
806-G	1876	4	80 gs	1870	Qt4	b	a	
806-H	1868	3	70 gs	1863	Qt4	b	a	
806-I	1885	6	100 rc	1876	Qt4	v		
806-J	1899	20?	50 gs	N.D.	Qt4	b	a, wo	
808-A	1881	6	100 gs	1872	Qt4	b	a, wos	
808-B	1883	8	100 gs	1872	Qt4	b	a, wr&o	
Lower reaches								
808-C	1886	7	100 gs	1876	Qal	b	a, wo	Many saplings (<10 y old?) on Qal
806-K1	1980	3	20 rc	N.D.	Qyal	v		
806-K2	1979	5	20 rc	1974	Qyal	v		
806-L1	1968	1	20 rc	N.D.	Qyal	v		
806-L2	1966	0	20 rc	1966	Qyal	v		
807-A	1968	8	70 gs; 100 rc	1958	Qyal	c (30)	p	
807-B1	1987	8	30 rc	N.D.	Qyal	v	w	
807-B2	1982	3	30 rc	1978	Qyal	v	w	
807-C	1972	8	40 gs	1963	Qyal	b	a, w	
807-D	1968	3	50 gs	1963	Qyal	b	a	
807-E	1964	4	30 gs	1959	Qyal	b	a, w	
807-F	1971	3	40 gs	1967	Qyal	b	p, w	
807-G	1974	2	50 gs	1970	Qyal	b	a, w	
807-H	1975	4	120 gs	1968	Qyal	b	w	
807-I	1960	0	70 gs	1958	Qyal	b	a, w	
807-J	1962	2	70 gs	1958	Qyal	b	a, w	
807-K	1961	4	70 gs	1955	Qyal	b	a, w	
807-L	1958	3	100 gs	1952	Qyal	b	a, w	
807-M	1961	1	100 gs	1957	Qyal	b	a, w	

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[1] 39 cores collected from 32 trees; 7 cores not analyzed due to rot, widely missed piths, or damaged cores

[2] Coring height affects age determination. Adjust age of trees 1 y for cores collected 30-50 cm above **rc,** root crown; 2 y 51-100 cm; and 3 y > 100 cm above the root crown. When root crown is not visible add a minimum of 10 cm of alluvium to determine age adjustment when core is collected above **gs**, ground surface.

[3] **N.D.** No data—establishment date uncertain; sample not dated due to rot, widely missed pith, or damaged to core

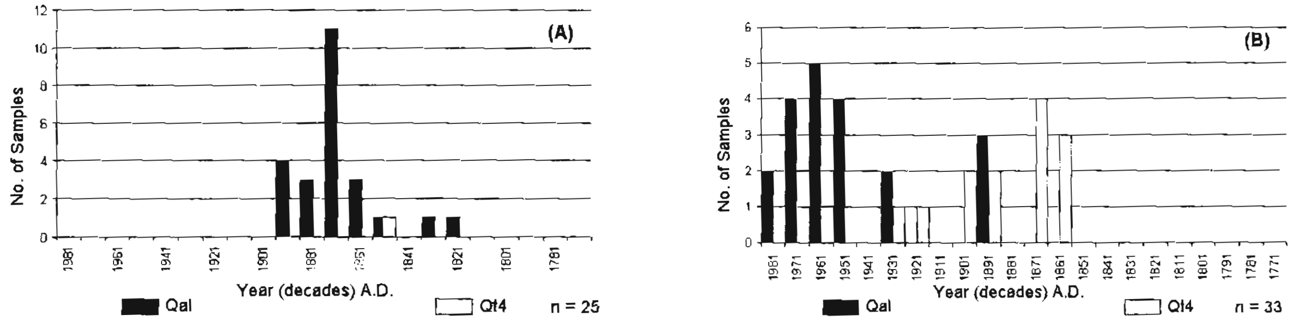
[4] Nature of root crown: **b** buried; **c (40)** exposed in cut bank (40 cm beneath ground surface); **v** visible at ground surface

[5] Nature of flood debris if present around trunk: **a** overbank alluvium; **c** channel deposits; **d** desiccation cracks; **o** old, weathered; **p** point-bar deposits; **r** recent; **s** interstitial spaces of woody flood debris filled with sediment; **v** vegetation growing through debris pile; **w** woody flood debris on upstream side of trunk

reaches of these two streams. Channel entrenchment, beginning in the 1870s along the middle reaches, led to the progressive abandonment of the Qt4 surface and concomitant formation of the inset Qal surface (Fig. 8A). Channel entrenchment precluded cottonwood germination on the elevated, vegetated, flood- and disturbance-free Qt4 surface. In addition, the Qt4 surface is several meters above the water table of shallow alluvial aquifers. In general, cottonwood seedlings on a terrace are unable to develop roots that reach the alluvial aquifers without an extremely unusual period of extended heavy precipitation that maintains adequate soil moisture throughout the vadose zone while the embryonic root systems are developing (*see* Segelquist *et al.*, 1993).

Paddock Creek and Talkington Draw

Paddock Creek is 16 km long and drains an area of 73 km^2. Talkington Draw (informal name derived from the surname of one of the families to



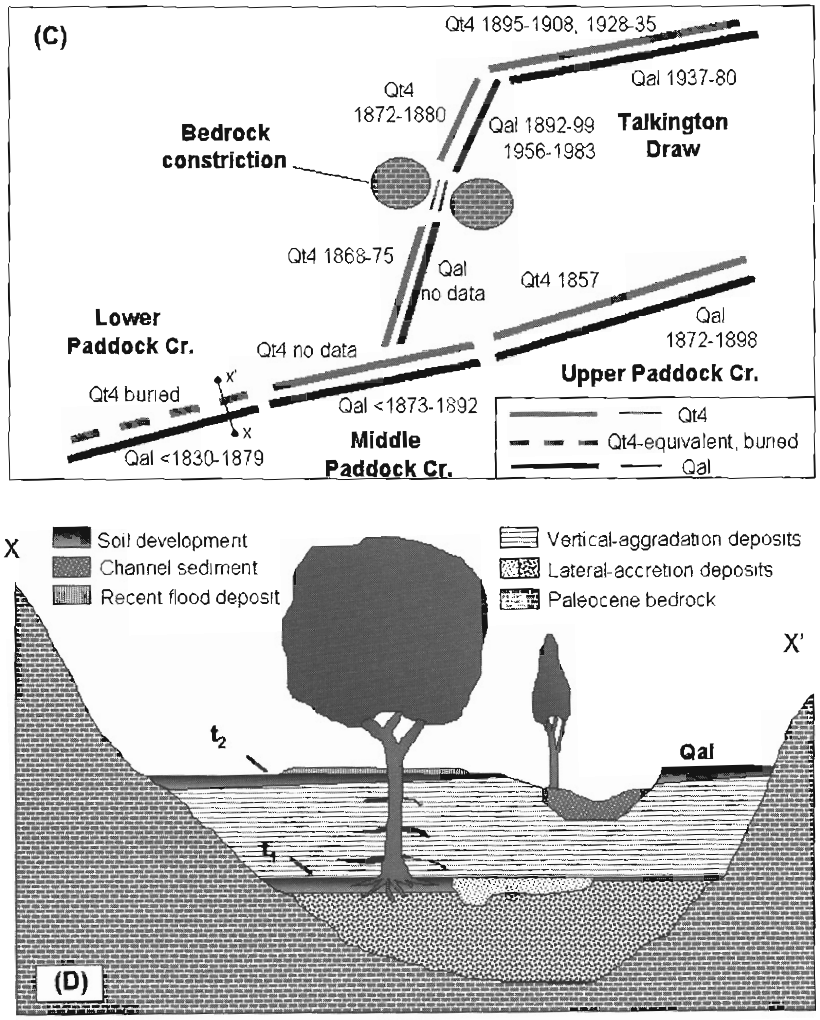


Fig. 12. (A) Histogram of establishment dates of cottonwood trees on Qal and Qt4 surfaces along Paddock Creek. (B) Histogram of establishment dates of cottonwood trees on Qal and Qt4 surfaces along Talkington Draw. (C) Dendrogeomorphic relations along Paddock Creek and Talkington Draw. (D) Schematic valley cross-section profile (x-x', *see* Fig. 12C for location) across the lower reach of Paddock Creek. The fluvial surface that is time equivalent to the Qt4 surface along middle and upper reaches is deeply buried by vertical-accretion deposits. Consequently, no Qt4 surface is exposed along the lower reach. Instead the Qal surface has been vertically aggrading for more than 100 years. Similar fluvial landforms occur along the lower reaches of Jules and Bear creeks.

Table 5. Dendrochronology of Paddock Creek

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom. Surface	Root Crown[4]	Flood debris[5]	Comments
Upper reach								
C-7	1901	5	140 gs	1893	Qal			
C-8	1881	5	140 gs	1873	Qal			
C-9	1906	5	140 gs	1898	Qal			
C-10	1909	9	140 gs	1897	Qal			
C-11A	1863	3	140 gs	1857	Qt4	v		
C-11B	1866	rot	140 gs	N.D.	Qt4			
C-12	N.D.	rot	140 gs	N.D.	Qal			
C-13	1892	8	140 gs	1881	Qal			
C-14	twisted	5	140 gs	N.D.	Qal			
C-15	1897	9	140 gs	1885	Qal			
C-16	1877	2	140 gs	1872	Qal			
Middle reach								
C-6	1902	7	140 gs	1892	Qal	b		
C-5	1898	8	140 gs	1886	Qal	b		
C-4	N.D.	rot	140 gs	N.D.	Qal	b		
C-3	1876	rot	140 gs	<1873	Qal	b		
C-2	1887	8	140 gs	1876	Qal	b		
Lower reach								
C-1	1872	3	140 gs	1866	Qal	b		
C-17A	1884	rot	140 gs	N.D.	Qal	b		
C-17B	1885	3	140 gs	1879	Qal			
C-18	1874	rot	140 gs	<1871	Qal	b		
C-19	1872	rot	140 gs	<1869	Qal	b		
C-20	1882	rot	140 gs	<1879	Qal	b		
C-21	1881	4	140 gs	1874	Qal	b		
C-22	1884	6	140 gs	1875	Qal	b		
C-23	1859	rot	140 gs	<1856	Qal	b		
C-24	1833	rot	140 gs	<1830	Qal	b		
C-25	1838	4	140 gs	1831	Qal	b		
C-26	1872	4	140 gs	1865	Qal	b		
C-27	1874	rot	140 gs	<1871	Qal	b		
C-28	1886	3	140 gs	1877	Qal	b		

[1] 30 samples from 28 trees; 5 cores not dated due to rot, missed piths, or broken or twisted cores

[2] Coring height affects age determination. Adjust age of trees 1 y for cores collected 30-50 cm above **rc,** root crown; 2 y 51-100 cm; and 3 y > 100 cm above the root crown. When root crown is not visible add a minimum of 10 cm of alluvium to determine age adjustment when core is collected above **gs**, ground surface.

[3] **N.D.** establishment date uncertain; sample not dated

[4] Nature of root crown: **b** buried; **v** visible at ground surface

[5] Nature of flood debris if present around trunk: **a** overbank alluvium; **c** channel deposits; **d** desiccation cracks; **o** old, weathered; **p** point-bar deposits; **r** recent; **s** interstitial spaces of woody flood debris filled with sediment; **v** vegetation growing through debris pile; **w** woody flood debris on upstream side of trunk

first homestead in this area, and also from the Talkington trail, which parallels much of the creek) is the largest tributary of Paddock Creek , is 8 km long, and drains an area of 20 km^2. The Paddock Creek basin is in the South Unit of Theodore Roosevelt National Park (Fig. 2). Many of the trees along Paddock Creek are dead, particularly along the upstream reaches. No cottonwood trees were found along the uppermost 4 km of Paddock Creek, a steep (>1.7%), low sinuosity (<1.2) bedrock reach (Fig. 11; Tables 3A and 3B). I analyzed 58 tree cores in the basin: 25 along Paddock Creek and 33 along Talkington Draw (Figs. 12A and 12B; Tables 5 and 6). Many trees along Paddock Creek

Table 6. Dendrochronology of Talkington Draw

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
Upper reach								
813-A	1970	3	30 gs	1966	Qal	b	w	Flood-tipped tree
813-C1	1972	5	20 rc	1967	Qal	v	wr	
813-C2	1976	5	20 rc	N.D.	Qal	v	wr	
813-C3	1972	4	20 rc	N.D.	Qal	v	wr	
813-D1	1946	broken	50 gs	N.D.	Qal	b	p	Rooted on active point bar
813-D2	1947	8	50 gs	1937	Qal	b	p	Rooted on active point bar
813-E	1946	4	40 gs	1940	Qal	b	p, wr	Rooted on active point bar
813-F	1966	4	40 gs	1961	Qal	b	p, wr	Rooted on active point bar
813-G1	1940	9	50 gs	N.D.	Qt4	b	a, wo	
813-G2	1932	2	50 gs	1928	Qt4	b	a, wo	
813-H	1913	7	30 gs	1905	Qt4	b	wo	Numerous dead trees on Qt4
813-I1	N.D.		30 rc	N.D.	Qt4	c (300)	a, wo	Buried 3 m in alluvium
813-I2	1911	3	30 rc	1908	Qt4	c (300)	a, wo	Buried 3 m in alluvium
813-J	1980	3	30 rc	1977	Qal	v	p, wr	Flood-tipped tree
813-K	1982	2	30 rc	1980	Qal	v	p, wr	Flood-tipped tree
813-L1	1909	8	70 gs	N.D.	Qt4	b	a	Adventitious roots visible in alluvium
813-L2	1908	7	70 gs	1899	Qt4	b	a	Adventitious roots visible in alluvium
813-M	1940	3	40 gs	1935	Qt4	b	wo	
813-N	1960	2	50 gs	1956	Qal	b	wr	
813-O	1976	2	20 gs	1973	Qal	b	p, wr	Rooted on active point bar
816-F1	1905	8	50 gs	1895	Qt4	b	a, wos	
816-F2	1912	8	50 gs	N.D.	Qt4	b	a, wos	
Middle reach								
816-E1	1985	1	20 gs	1983	Qal	b	p, wr	Rooted on active point bar
816-E2	1985	broken	20 gs	N.D.	Qal	b	p, wr	Rooted on active point bar
816-D1	1987	2	20 gs	N.D.	Qal	v	p	Rooted on active point bar
816-D2	1987	4	20 gs	1983	Qal	v	p	Rooted on active point bar
816-C1	1904	4	50 gs	N.D.	Qal	b	w, r & o	
816-C2	1910	10	50 gs	N.D.	Qal	b	w, r & o	
816-C3	1903	4	50 gs	1897	Qal	b	w, r & o	
816-B1	1901	0	50 gs	1899	Qal	b	w, r & o	
816-B2	1903	rot	50 gs	N.D.	Qal	b	w, r & o	
816-A1	1900	rot	50 gs	N.D.	Qal	b	wr	
816-A2	1901	7	50 gs	1892	Qal	b	wr	
814-M	1889	7	40 rc	1880	Qt4	v	wo	
814-L	1980	8	40 gs	1970	Qal	b	wr	
814-K	1965	7	40 gs	1956	Qal	b	wr	
814-J	1962	4	20 gs	1957	Qal	b	wr	
814-I	1874?	0	70 gs	1872	Qt4	b	wo	
814-H	1975	3	40 rc	1971	Qal	v	wo	
814-G	1964	0	40 gs	1962	Qal	b		Qal inset beneath Qt4; channel cut on bedrock
814-F1	1961	0	60 gs	1959	Qal	b		Qal inset beneath Qt4; channel cut on bedrock
814-F2	1962	1	60 gs	N.D.	Qal	b		Qal inset beneath Qt4; channel cut on bedrock
Lower Reach								
814-E	1875	2	70 gs	1871	Qt4	b		Trunk chewed by beaver
814-D1	1892	rot	50 gs	N.D.	Qt4	b	a, wo	
814-D2	1881	4	50 gs	1875	Qt4	b	a, wo	
814-C	1872	2	40 gs	1868	Qt4	b		

Table 6. Dendrochronology of Talkington Draw, continued

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
814-B	1872	2	40 gs	1868	Qt4	b	wo	
814-A	1876	4	100 gs	1869	Qt4	b	a, wo	Trunk chewed by beaver

[1] 48 cores collected from 33 trees; 15 cores not analyzed due to rot, widely missed piths, or damage to cores

[2] Coring height affects age determination. Adjust age of trees 1 y for cores collected 30-50 cm above **rc,** root crown; 2 y 51-100 cm; and 3 y > 100 cm above the root crown. When root crown is not visible add a minimum of 10 cm of alluvium to determine age adjustment when core is collected above **gs**, ground surface.

[3] **N.D.** No data—establishment date uncertain; sample not dated due to rot, widely missed pith, or damaged to core

[4] Nature of root crown: **b** buried; **c (300)** exposed in cut bank (300 cm beneath ground surface); **v** visible at ground surface

[5] Nature of flood debris if present around trunk: **a** overbank alluvium; **c** channel deposits; **d** desiccation cracks; **o** old, weathered; **p** point-bar deposits; **r** recent; **s** interstitial spaces of woody flood debris filled with sediment; **v** vegetation growing through debris pile; **w** woody flood debris on upstream side of trunk

were dead, similar to Jones and Jules creeks. Extensive heart rot prevented collection of increment cores from many of the largest and oldest appearing trees. Standing dead trees were most prevalent along the middle reach of Paddock Creek.

The lower reach of Paddock Creek had 13 living cottonwood trees. These trees established before 1880, and all are located within the flood plain (Fig. 12C; Table 5). The Qt4 surface is not visible along this reach. The middle reach of Paddock Creek had four living cottonwood trees on the Qal surface; these established before 1873 through 1892 (Table 5). Remnants of the Qt4 surface are well preserved in this reach, but there were no living cottonwood trees on this surface. The upper reach had eight living cottonwood trees. One of these established in 1857 on the Qt4 surface; the rest established from 1872 through 1898 on the Qal surface (Fig. 12C; Table 5).

The oldest cottonwood trees are located along the lower reaches of Paddock Creek, and all of them are partially buried by overbank deposits. No incision has occurred along the lower reach since at least 1832 (Fig. 12D). Incision of the Qt4 surface and development of an inset flood plain is confined to the upper and middle reaches of Paddock Creek. Incision occurred after 1857 and prior to 1872 (*see* Fig. 8A).

Living cottonwood trees occurred on the Qt4 and Qal surfaces of Talkington Draw in three discreet stands (Fig. 12C). A bedrock constriction separates the two stands farthest downstream (Fig. 12C). All the cottonwood trees on the Qt4 surface established from 1868 through 1875 downstream of the bedrock constriction, during the 1870s immediately upstream of the constriction, and from 1895 through 1935 along the headwater reach of Talkington Draw (Fig. 12C; Table 6). Cottonwood trees on the Qal surface established from 1892 through 1899 and from 1956 through 1983 immediately upstream of the bedrock constriction and from 1937 through 1980 along the headwater reach of Talkington Draw (Fig. 12C; Table 6). No cottonwood trees occur along the uppermost 4 km of Talkington Draw, a steep (>1.5%) low sinuosity (<1.18) bedrock reach (Tables 3A and 3B).

Below and immediately upstream of the bedrock constriction, the Qt4 surface was the active fluvial surface until at least the 1870s. Immediately upstream of the bedrock constriction, incision began by at least the mid-1890s. Incision of the Qt4 surface continued until at least the 1930s along the upper reach (Fig. 12C).

Bear Creek

Bear Creek is 17 km long and drains an area of 50 km^2. All of the sampled trees were located

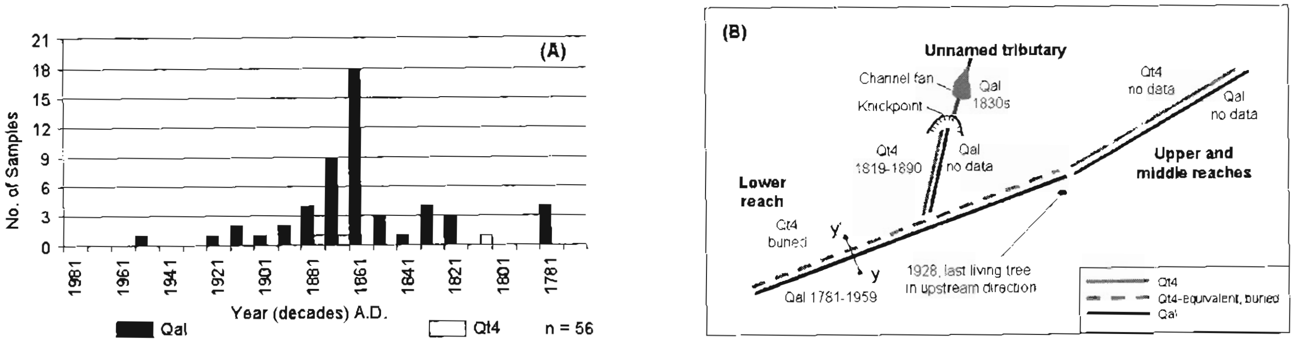


Fig. 13. (A) Histogram of establishment dates of cottonwood trees on Qal and Qt4 surfaces along Bear Creek. (B) Dendrogeomorphic relations along Bear Creek.

Table 7. Dendrochronology of Bear Creek

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
Lower reach								
811-C1	1938	9	40 rc	1928	Qal	v	w	
811-C2	rot	N.D.	40 rc	N.D.	Qal	v	w	
830-A1	rot	N.D.	60 gs	N.D.	Qal	b	ard	
830-A2	1898	6	60 gs	1890	Qal	b	ard	
830-B1	rot	N.D.	80 gs	N.D.	Qal	b	ard	
830-B2	1900	0	80 gs	1898	Qal	b	ard	
830-C1	rot	N.D.	140 gs	N.D.	Qal	b	ard	
830-C2	1886	7	50 gs	1877	Qal	b	ard	
830-D	1876	1	60 gs	1873	Qal	b	ard	
830-H	1964	3	60 gs	1959	Qal	b	ar	Located on natural levee
830-I	1907	7	70 gs	1898	Qal	b	ar	
830-J	1868	0	60 gs	1866	Qal	b	ard	
830-K	1888	10	70 gs	1876	Qal	b	ard, wr	3 large dead trees nearby
830-L	1833	5	70 gs	1826	Qal	b	ard	
829-S	1877	5	100 gs	1869	Qal	b	ard, wos	
829-R	1867	3	70 gs	1862	Qal	b	ard, wos	
829-Q1	1930	rot	140 gs	N.D.	Qal	b	ard	
829-Q2	rot	N.D.	140 gs	N.D.	Qal	b	ard	
829-P	1866	1	80 gs	1863	Qal	b	ard, wos	
829-O	1886	3	120 gs	1880	Qal	b	ar, wr	
829-N1	1877	5	70 gs	1870	Qal	b	ard, wr	
829-N2	rot	N.D.	70 gs	N.D.	Qal	b	ard, wr	
829-N3	rot	N.D.	70 gs	N.D.	Qal	b	ard, wr	
829-M	1874	2	70 gs	1870	Qal	b	ard, wr	
829-L	1871	3	80 gs	1866	Qal	b	ard, wos	
829-K	1878	2	60 gs	1874	Qal	b	ard, wos	
829-J	1875	3	80 gs	1870	Qal	b	ard, wos	
829-I	1873	2	80 gs	1869	Qal	b	ard, wo	
829-H	1874	4	100 gs	1867	Qal	b	ard, wo	
829-G	1843	2	120 gs	1838	Qal	b	ard	
829-F	1854	3	50 gs	1849	Qal	b	ard, wr&o	
829-E	1872	9	120 gs	1860	Qal	b	ard, wr	
829-D	1918	0	40 gs	1916	Qal	b	ard, wr	
829-C	1919	0	40 gs	1917	Qal	b	ard, wr	
829-B	1784	0	50 gs	1782	Qal	b	ard	
829-A	1881	3	50 gs	1876	Qal	b	a, wr&o	

Table 7. Dendrochronology of Bear Creek, continued

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
822-X1	1851	rot	100s	N.D.	Qal	b	ard	
822-X2	1788	0	100 gs	1785	Qal	b	ard	
822-W	1886	7	100 gs	1878	Qal	b	ard	
822-V	1888	6	100 gs	1879	Qal	b	ard	
822-U	1905	rot	N.D.	N.D.	Qal	b	ard	
822-T	1899	8	50 rc	1889	Qal	c (150)	wr	
822-S	1880	2	60 gs	1876	Qal	b	a, wr&o	
822-R	1911	5	60 gs	1904	Qal	b	ar, wos	
822-Q	1868	5	100 gs	1860	Qal	b	ar, wos	
822-A	1840	5	70 gs	1833	Qal	b	ard	
822-B	1872	2	70 gs	1868	Qal	b	ard, wo	
822-C	1868	1	60 gs	1865	Qal	b	ard, wo	
822-D	1869	4	60 gs	1863	Qal	b	ard, wos	
822-E	1893	9	70 gs	1882	Qal	b	a	
822-F	1872	3	70 gs	1867	Qal	b	a, wr	
822-G	1870	0	100 gs	1867	Qal	b	a, wo	
822-H	1878	5	100 gs	1870	Qal	b	a, wr	Larger, dead trees nearby
822-I	1873	4	100 gs	1866	Qal	b	a, wr	
822-J	1792	3	90 gs	1786	Qal	b	a, wos	
822-K	1834	5	100 gs	1826	Qal	b		
822-L	1865	6	30 gs	1858	Qal	b	wr	
822-M	1789	3	100 gs	1783	Qal	b	wo	
822-N	1840	7	100 gs	1830	Qal	b		
822-O	1878	7	80 gs	1869	Qal	b	a, wr	Chewed by beaver
822-P	1887	4	50 gs	1881	Qal	b	a, wo	Chewed by beaver
Tributary reach								
830-E	1832	11	90 rc	1819	Qt4	v		Mouth of tributary
830-F	1895	3	90 rc	1890	Qt4	v		Mouth of tributary
830-G	1883	4	70 rc	1877	Qt4	v		Mouth of tributary
830-M	1845	5	70 rc	1838	Qal	v		
830-N	1846	5	50 rc	1839	Qal	v		

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[1] 66 cores from 56 trees; 10 cores not dated due to rot, missed piths, or broken or twisted cores

[2] Coring height affects age determination. Adjust age of trees 1 y for cores collected 30-50 cm above **rc,** root crown; 2 y 51-100 cm; and 3 y > 100 cm above the root crown. When root crown is not visible add a minimum of 10 cm of alluvium to determine age adjustment when core is collected above **gs**, ground surface.

[3] **N.D.** establishment date uncertain; sample not dated

[4] Nature of root crown: **b** buried; **c (150)** exposed in cut bank (150 cm beneath ground surface); **v** visible at ground surface

[5] Nature of flood debris if present around trunk: **a** overbank alluvium; **c** channel deposits; **d** desiccation cracks; **o** old, weathered; **p** point-bar deposits; **r** recent; **s** interstitial spaces of woody flood debris filled with sediment; **v** vegetation growing through debris pile; **w** woody flood debris on upstream side of trunk

along the lower 3 km of the Bear Creek valley. Although there were some dead trees, no living cottonwood trees were found along the upper 14 km of the Bear Creek valley. I collected and analyzed cores from 56 trees, of which 52 were located within the flood plain and only 3 were located on the Qt4 surface (Figs. 13A and 13B; Table 7).

The dendrochronologic data and dendrogeomorphic relations indicate that the lower reach of Bear Creek has experienced extensive vertical aggradation (Fig. 14A) in the past 70 or more years. All the trees established before the

Fig. 14. Aggrading reaches are recognized by: (A) burial, flooding, and deposition of woody debris and sediment on the flood plain (view to the west across the section line between Sections 34 and 35 in T 138 N/R 102 W along Bear Creek in April of 1987). (B) The accumulation of woody flood debris on the upstream side of trunks is common along aggrading reaches. This photograph shows a large debris pile that accumulated the previous day (photograph taken on 3 August 1996 along Dantz Creek in the NW ¼ of Section 23 in T 138 W/R 102 W). (C) As woody flood debris ages, the thinner twigs decompose first leaving remnants of only the larger twigs and branches. Fine-grained sediment is blown or washed into the woody debris pile and eventually vegetation grows through the pile. (D) Fine-grained sediment accumulates on the flood plain. When it dries it typically cracks. (E) Repeated overbank sedimentation in an aggrading reach leads to the thick accumulation of finely laminated, planar-bedded, vertical-accretion deposits. The laminae generally form a repeating sequence of flood couplets, in which slightly coarser sand beds are deposited during the waxing stages of the flood, and slightly finer mud beds are deposited during the waning stages of the flood. (F) Trees will suffocate if their roots are deeply buried. Cottonwood trees can survive in aggrading environments by sprouting adventitious roots that grow out of the buried tree trunk and into the alluvium at a shallow depth where gas exchange is better than at the depth of the buried root crown.

1930s show evidence of burial, including accumulations of woody flood debris on the upstream side of trunks (Fig. 14B and 14C), deposition of fine-grained, desiccation-cracked, overbank deposits surrounding the trunks of trees (Fig. 14D and 14E), and formation of adventitious roots that protrude from the trunks of trees above the original root crowns and into the over-bank sediment (Fig. 14F).

Samples were collected from five cottonwood trees along a small, unnamed tributary that joins Bear Creek along its lower alluvial reach. Three of these cottonwood trees were on remnants of a low terrace (Qt4) near the confluence of the tributary with Bear Creek, and two were 0.25 km upstream from the confluence (Fig. 13B). The trees on the Qt4 surface had dates of establishment ranging from 1819 to 1890, and the two on the Qal surface (an aggrading channel fan at the mouth of a tributary canyon) had dates of establishment in the late 1830s (Fig. 13B). These five trees indicate that the tributary was actively aggrading and reworking sediment from 1818 to 1890. Sometime after 1890, the tributary stream began to incise at its confluence with Bear Creek. However, the incision knickpoint has yet to migrate upstream the 0.25-km distance to where the two trees with establishment dates in the 1830s are partly buried by recent channel-fan sediments (Fig. 13B).

Dantz Creek and Toms Wash

Dantz Creek is the second largest drainage basin (65 km^2), and Toms Wash is one of the smaller basins examined (16.4 km^2) (Fig. 2). The data from the two basins are presented together, because both basins contain evidence of a recent episode of incision that occurred since 1979 along the downstream reaches. This recent episode of incision is similar to the recent incision that began in the 1950s along Jones Creek except that it apparently began later, since 1979, along Dantz Creek and Toms Wash. The recent incision in Dantz Creek and Toms Wash has led to local abandonment of the former flood plain (Qal) and to the creation of a new terrace (Qoal) and inset flood plain (Qyal) (*see* Fig. 15C).

The Dantz Creek basin has the largest population of cottonwood trees in this study. Hundreds of old trees are scattered along the lower 10 km of Dantz Creek; however, no living cottonwood trees were found along the upper 12 km. Increment cores were collected from 99 trees; 72 were within the flood plain (Qal), 16 from the Qoal surface, and 11 from the Qt4 surface (Fig. 15A; Table 8). None of the seedlings or saplings on the Qyal surface were large enough to core without causing severe injury. The majority (82 of the 99) established before European settlement in the area (Fig. 15A) with 69 trees becoming established during the 1860s and 1870s. Only 17 of the sampled trees established during historical time.

The downstream reaches of both basins contained many living cottonwood trees that established from 1773 through 1907 (Fig. 15B). Also, these reaches contain abundant evidence of vertical aggradation until at least 1979. The root crowns of most old (>100 years) trees are buried by one or more meters of alluvium. Woody flood debris has accumulated on the upstream side of most tree trunks (*see* Fig. 14B). An accumulation of fine-grained, mud-cracked, overbank sediment is evident on the flood plain (Figs. 14A and 14D) and in cutbank exposures (Fig. 14E). Along the middle reach of Dantz Creek, eight trees with dates of establishment from 1863 to 1877 were located on Qt4, and four trees with dates from 1935 to 1976 were located within the flood plain (Qal) or the channel (Fig. 15B).

Living cottonwood trees were confined to the lower 4 km of the Toms Wash valley and absent along the upper 6 km of Toms Wash, although there were many dead trees on the Qt4 surface. Cores from 30 trees along Toms Wash were examined: 19 established within the un-incised flood plain (Qal), 10 within the incised flood plain (Qoal) and one from the Qt4 surface (Figs. 16A and 16B; Table 9). Seedlings on the Qyal surface were too small to core. The absence of cottonwood trees larger than seedlings provides additional evidence that the Qyal

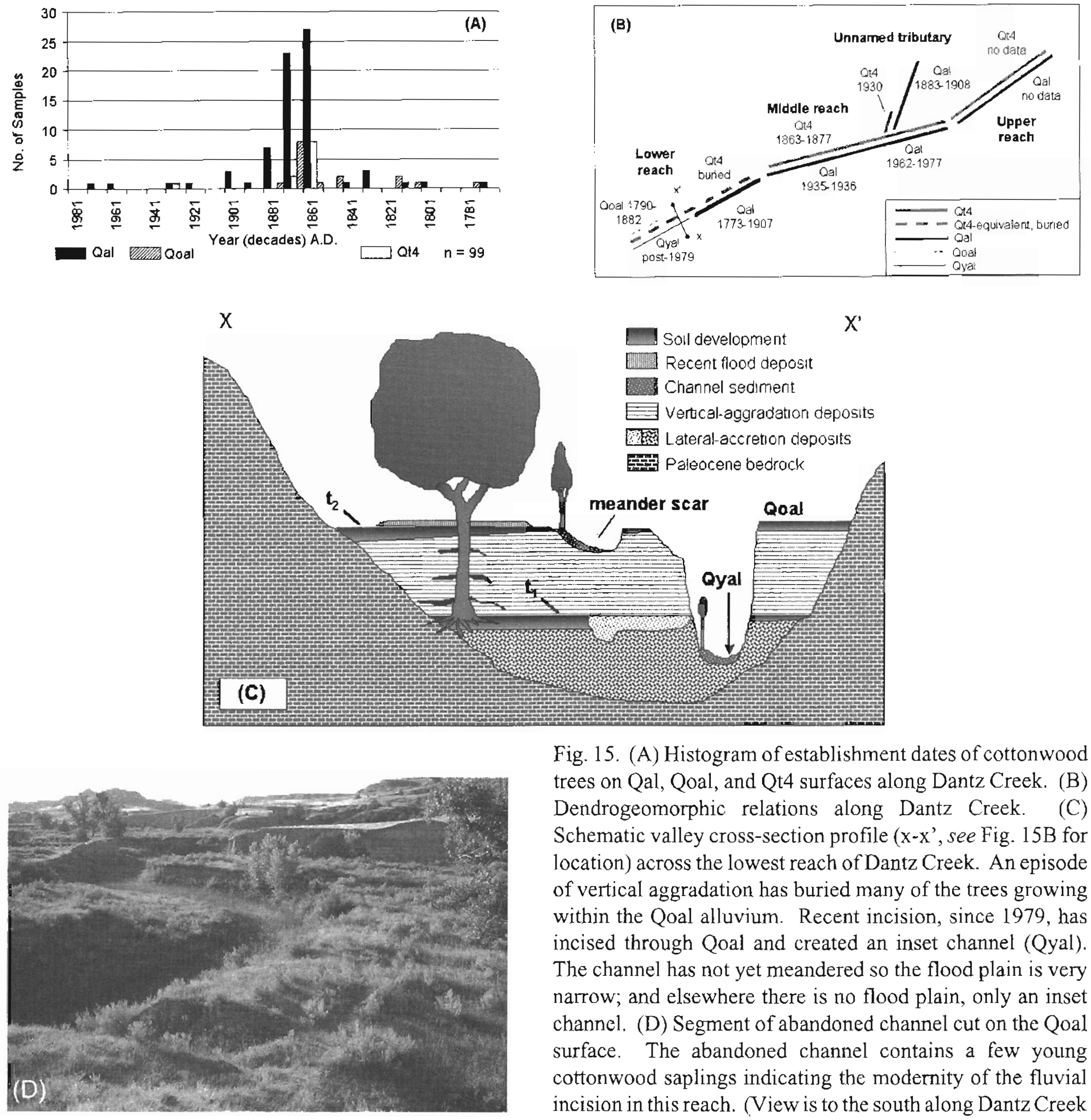

Fig. 15. (A) Histogram of establishment dates of cottonwood trees on Qal, Qoal, and Qt4 surfaces along Dantz Creek. (B) Dendrogeomorphic relations along Dantz Creek. (C) Schematic valley cross-section profile (x-x', *see* Fig. 15B for location) across the lowest reach of Dantz Creek. An episode of vertical aggradation has buried many of the trees growing within the Qoal alluvium. Recent incision, since 1979, has incised through Qoal and created an inset channel (Qyal). The channel has not yet meandered so the flood plain is very narrow; and elsewhere there is no flood plain, only an inset channel. (D) Segment of abandoned channel cut on the Qoal surface. The abandoned channel contains a few young cottonwood saplings indicating the modernity of the fluvial incision in this reach. (View is to the south along Dantz Creek in the SE ¼ of the NW ¼ of Section 20 in T 138N/R 102 W.)

surface is of recent origin.

Unlike other study basins where the streams have been aggrading along their lower reaches, parts of the lower 0.9 km of Toms Wash and the lower 1.4 km of Dantz Creek have incised since 1979. Both the Chimney Butte quadrangle (1:24,000-scale topographic map of the lower reach of Dantz Creek, published in 1979 by the U.S. Geological Survey) and the Cliffs Plateau quadrangle (topographic map of the lower reach of Toms Wash, published in 1982 by the U.S. Geological Survey) show highly sinuous channels with several large meander loops along the lower reaches of Dantz Creek and Toms Wash. In contrast, fieldwork in 1996 reveals that several of the largest meander loops have since been cut off and abandoned to form meander scars across the Qoal surface (Figs. 15C and 15D). Incision along Toms Wash probably began in the early to mid-1990s after a new bridge and road crossing were constructed 0.7 km from its mouth (K.A. Hansen,

Table 8. Dendrochronology of Dantz Creek

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
Middle reach								
805-A	1968	3	100 gs	1962	Qal	b	a	Sample from Juniper tree
805-B	1877	7	100 rc	1868	Qt4	v		Cross dated across break
805-C	1978	2	20 rc	1976	Qal	v		Many dead tree in vicinity
805-D	1881	2	80 rc	1877	Qt4	v		Cross dated across break
805-E	rot	N.D.	100 rc	N.D.	Qt4	v	wov	Many dead tree in vicinity
805-F	1873	3	70 rc	1868	Qt4	v		Cross dated across break
805-G	1886	7	100 rc	1877	Qt4	v		Many dead tree in vicinity
805-H	1869	2	70 gs	1865	Qt4	b	wo	Many dead tree in vicinity
805-I	1869	4	70 rc	1863	Qt4	v		
805-J	1868	1	100 rc	1865	Qt4	v		Many dead tree in vicinity
805-L	1875	5	100 rc	1868	Qt4	v		
805-M	1940	2	100 gs	1935	Qal	b	wr	
805-N	1941	3	20 gs	1936	Qal	b	wr	
804-Y	1867	2	40 rc	1864	Qt4	v		Many dead tree in vicinity
804-X	1878	7	100 rc	1869	Qt4	v		
Note: Qt4 terrace tread first appears here when traveling upstream. Numerous dead trees on Qt4 surface appear here and farther upstream, especially between 805B and 805J.								
Lower reach								
804-W	1893	11	70 rc	1880	Qal	v		
804-V	1872	2	100 gs	1867	Qal	b	a	
804-U	1870	0	70 gs	1868	Qal	b	a	
804-T	1871	5	100 rc	1864	Qal	v		
804-S	1881	2	70 gs	1877	Qal	b	a	
804-R	1883	4	100 gs	1877	Qal	b	a	
804-Q	1870	3	70 gs	1865	Qal	b	a	
804-P	1881	9	150 rc	1869	Qal	c (150)	a	
804-O	1877	0	>200 rc	1874	Qal	c(>200)	a	
804-N	1875	4	>200 rc	1868	Qal	c(>200)	a	
804-M	1871	1	100 gs	1866	Qal	b	a	
804-L	1871	2	70 gs	1867	Qal	b	a	
804-K	1877	5	100 gs	1869	Qal	b	a	
804-J	1874	5	100 gs	1866	Qal	b	a	Cross dated across breaks
804-I	1880	5	100 rc	1873	Qal	v	wr	
804-H	1882	3	45 gs	1877	Qal	b	a	
804-G	1879	2	45 gs	1875	Qal	b	a	
804-E	1880	8	75 gs	1870	Qal	b	a, wr	
804-D	1884	10	100 gs	1871	Qal	b	a, wr	
804-F	1870	0	100 gs	1867	Qal	b	a, wr	
804-C	1877	3	100 gs	1871	Qal	b	a	
804-B	1898	8	50 gs	1888	Qal	b	ar, wr	
804-A	1874	4	50 gs	1868	Qal	b	a, wr&o	Multiple flood events
803-K	1844	2	50 rc	1841	Qal	v		
803-J	1875	7	45 gs	1866	Qal	b	a	
803-I	1886	14	50 gs	1870	Qal	b	a	
803-H	1872	2	50 gs	1868	Qal	b	a	
803-G	1877	6	40 rc	1870	Qal	v		
803-F	1883	rot	30 gs	N.D.	Qal	b	ar	
803-E	1882	4	45 gs	1876	Qal	b	ar, wr	
803-D	1879	5	45 gs	1872	Qal	b	a	
803-C	1867	3	20 rc	1864	Qal	c (100)	ar	
803-B	1890	5	45 gs	1883	Qal	b	ar, wr	

Table 8. Dendrochronology of Dantz Creek, continued

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
803-A	1882	10	>50 standing water	1870	Qal	b	ar, wr	
831-A	1882	6	70 gs	1874	Qal	b	a	Rooted in natural levee
831-B	1870	2	50 gs	1866	Qal	b	ar, wr	
831-C	1879	4	65 gs	1873	Qal	b	a, wr	
831-D	1845	7	70 gs	1836	Qal	b	a	
831-E	1878	7	25 rc	1869	Qal	c (100)	a	
831-F	1877	3	50 gs	1872	Qal	b	ar, wr	
831-G	1842	4	40 gs	1836	Qal	b	ar, wr	
831-H	1872	5	60 gs	1865	Qal	b	ar, wr	
831-I	1877	8	150 rc	1866	Qal	c (150)	ar, wr	
831-J	1892	4(knot?)	80 gs	1886	Qal	b	p	
831-K	1868	5	20 rc	1863	Qal	c	a	
831-L	1877	4	90 gs	1870	Qal	b	ar, wr&o	
831-M	1881	2	50 gs	1877	Qal	b	p	
831-N	1916	rot	90 gs	N.D.	Qal	b	ar, wr	At mouth of tributary channel
831-O	1883	6	70 gs	1875	Qal	b	ar, wr	
830-O	1881	3	120 gs	1875	Qal	b	ard, wr	Rooted in natural levee
830-P	1913	4	60 gs	1907	Qal	b	a	Adventitious roots growing into alluvium
830-Q	1784	9	40 gs	1773	Qal	b	ar, wr	
830-R	1892	10	70 rc	1880	Qal	c (100)	ar	
830-S	1901	9	90 gs	1889	Qal	b	ard, wr	
830-T	1872	2	70 gs	1868	Qal	b	ard, wr	
830-U	1882	4	70 gs	1876	Qal	b	ard, wr	
830-V	1885	7	70 gs	1876	Qal	b	ar, wr	
830-W	1888	9	70 gs	1877	Qal	b	ar, wr	
830-X	1869	5	70 gs	1862	Qal	b		
823-Y	1895	3	30 rc	1892	Qal	c (130)	a, wr	
823-X	1817	5	50 rc	1811	Qal	c (100)	a, wr	
823-W1	1908	rot	100 gs	N.D.	Qal	b	a, wr&o	
823-W2	1914	7	100 gs	1901	Qal	b	a, wr&o	
823-V	1866	1	100 gs	1862	Qal	b	a	
823-U1	1916	rot	30 rc	N.D.	Qal	v	a, wr	Located on natural levee
823-U2	1890	3	30 rc	1886	Qal	v	a, wr	Located on natural levee
823-T	1994	3	100 gs	1888	Qal	b	a, wr	Located on natural levee
823-S	1878	5	100 gs	1870	Qal	b	a, wr	
823-R	1819	10	100 gs	1806	Qal	b	a, wr	
823-Q1	1873	7	50 gs; 150 rc	N.D.	Qal	c (100)	p, w	
823-Q2	1855	12		1840	Qal	c (100)	p, w	
823-P	1885	7	60 rc	1876	Qoal	v	wo	
823-O	1860	3	100 gs	1854	Qoal	b	a, wo	
823-N	1870	6	100 gs	1861	Qoal	b	w	
823-M	1802	9	100 gs	1790	Qoal	b	a	
823-L	1881	8	50 gs	1871	Qoal	b	a	
823-K	1825	5	80 gs	1818	Qoal	b	a	
823-J	1839	8	80 gs	1829	Qoal	b	a	
823-I	1892	12	70 rc	1878	Qoal	c (50)	a	
823-H	1878	2	100 gs	1873	Qoal	b	a	>2 m of incision; exposed adventitious roots
823-G	1875	2	60 rc	1871	Qoal	v	wo	

Table 8. Dendrochronology of Dantz Creek, continued

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
823-F	1877	3	70 rc	1872	Qoal	c (70)		Located at meander-neck cut off
823-E	1835	8	100 gs	1824	Qoal	b	a	Located along abandoned channel
823-D	1883	8	100 gs	1872	Qoal	b	a, wo	Located along abandoned channel
823-C	1894	9	140 rc	1882	Qoal	v	a, wr&o	Located along abandoned channel
823-B	1866	3	100 gs	1860	Qoal	b	a,w	
823-A	1878	3	60 gs	1873	Qoal	b	a, wo	
Tributary reach								
831-Q	1897	14	70 gs	1883	Qal	b		Reach of tributary is not incised
831-P	1910	2	50 rc	1908	Qal	v		Reach of tributary is not incised
831-R	1932	2	50 rc	1930	Qt4	v		Tree on Qt4; channel incised 2 m and cuts bedrock

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[1] 105 cores collected from 102 trees; 6 cores not analyzed due to rot, widely missed piths, or damaged cores

[2] Coring height affects age determination. Adjust age of trees 1 y for cores collected 30-50 cm above **rc**, root crown; 2 y 51-100 cm; and 3 y > 100 cm above the root crown. When root crown is not visible add a minimum of 10 cm of alluvium to determine age adjustment when core is collected above **gs**, ground surface.

[3] **N.D.** No data—establishment date uncertain; sample not dated due to rot, widely missed pith, or damaged to core

[4] Nature of root crown: **b** buried; **c (150)** exposed in cut bank (e.g., 150 cm beneath ground surface); **v** visible at ground surface

[5] Nature of flood debris if present around trunk: **a** overbank alluvium; **c** channel deposits; **d** desiccation cracks; **o** old, weathered; **p** point-bar deposits; **r** recent; **s** interstitial spaces of woody flood debris filled with sediment; **v** vegetation growing through debris pile; **w** woody flood debris on upstream side of trunk

Medora District of the Little Missouri National Grasslands, pers. comm.). The reach of channel immediately upstream of the new road crossing was channelized and reinforced with concrete and riprap. These human alterations to the channel apparently have initiated incision both up- and downstream of the road crossing. The modern channels are now relatively straight and incised through these reaches. The process of meander cutoff decreases sinuosity, increases channel slope, increases stream power, and increases the potential to incise along adjacent stream reaches.

Dendroclimatology in the Little Missouri Badlands

In an ongoing, separate study (M.A. Gonzalez and C.H. Garcia, unpublished data of a 470-year dendroclimatic record), cores and slabs were extracted from 82 nearby ponderosa pine (*Pinus ponderosa* Dougl. var. *scopulorum* Engelm; Stevens, 1950) with increment borers and a chainsaw. Samples were collected at mean-breast height, sanded to a fine polish, cross-dated, measured, and analyzed following the standard dendrochronologic conventions described by Fritts (1976) and Phipps (1985). Ring-width measurements were made with a precision linear encoder and analyzed using the CONVERT5, COFECHA, and CRONOL computer routines in the International Tree-ring Data Bank Library (ITRDBLIB) software program developed by researchers in the Laboratory of Tree-Ring Research at the University of Arizona. The raw measurements of tree-ring width were transformed in a two-pass technique. First, the raw data were transformed with a negative exponential curve to remove the biological growth trend typical of *Pinus ponderosa*. Second, the transformed indices were re-transformed using a 100-yr-long cubic smoothing spline. The second transformation was used to remove long-term trends in the tree-ring indices related to stand competition in the past century resulting from fire-suppression and evolution of the ponderosa forest from a park-like (sparsely treed) to a dog-haired (densely treed with thin, closely-spaced trees) stand.

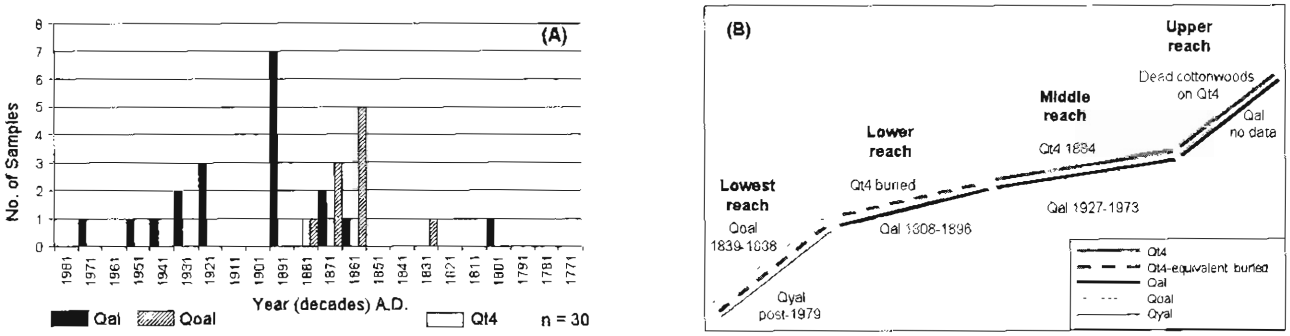

Fig. 16. (A) Histogram of establishment dates of cottonwood trees on Qal, Qoal, and Qt4 surfaces along Toms Wash. (B) Dendrogeomorphic relations along Toms Wash.

Table 9. Dendrochronology of Toms Wash

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
Middle reach								
811-E1	N.D	rot	20 gs	N.D.	Qal	b	ar, wr	
811-E2	1934	5	20 gs	1928	Qal	b	ar, wr	
811-F	1963	3	50 gs	1958	Qal	b	ar	
811-G	1964	rot	50 gs	N.D.	Qal	b	ar, wr	Largest tree in reach
811-H	1974	0	20 gs	1973	Qal	b	a, w	
811-I	1933	3	100 gs	1927	Qal	b	a	
811-J1	1945	rot	25 gs	N.D.	Qal	b	a, w	
811-J2	1942	5	40 gs	1935	Qal	b	a, w	
811-K	1934	5	50 gs	1927	Qal	b	wo	
811-L1	1896	9	20 rc	N.D.	Qt4	c	a	Adventitious roots growing in alluvium
811-L2	1891	7	20 rc	1884	Qt4	c	a	Adventitious roots growing in alluvium
811-M	1962	rot	70 gs	N.D.	Qt4	b	a	Channel incised 2.5 m along reach
811-N1	1951	rot	20 gs	N.D.	Qal	b	p	Flood-tipped tree
811-N2	1947	2	20 gs	1944	Qal	b	p	
811-O	1942	2	50 gs; 200 rc	1937	Qal	c (150)	a	Several dead trees nearby
Lower reach								
811-P	1873	4	50 gs	1867	Qal	b	wo	
812-A1	1902	5	50 gs	1895	Qal	b	a	
812-A2	1919	N.D.	50 gs	N.D.	Qal	b	a	Far off the pith
812-B	1897	2	50 gs	1893	Qal	b	a	
812-C	1912	rot	50 gs	N.D.	Qal	b	a, w	
812-D	1923	rot	100 gs	N.D.	Qal	b		
812-E1	1895	2	20 rc	1893	Qal	c (150)	a	
812-E2	1904	9	20 rc	N.D.	Qal	c (150)	a	
812-F	1902	4	70 gs	1896	Qal	b	a, wo	
812-G	1882	5	70 gs	1875	Qal	b	a	
812-H	1878	5	70 gs	1875	Qal	b	a	
812-I	1816	5	50 gs; 200 rc	1808	Qal	c (150)	a, wr	Adventitious roots in alluvium
812-J	1930	N.D.	70 gs	N.D.	Qal	b	a, wo	Core badly twisted
812-K	1902	7	70 gs	1893	Qal	b	w	Core broken, rings cross-dated across break
812-L	1902	4	70 gs	1896	Qal	b	w	
812-M	1900	2	60 gs	1896	Qal	b	a	
812-N	1887	5	70 gs	1880	Qoal	b	a	
812-O	1900	10	70 rc	1888	Qoal	v		
812-P	1881	6	40 gs	1874	Qoal	b	a	
812-Q	1874	0	40 gs	1872	Qoal	b	a	

Table 9. Dendrochronology of Toms Wash, continued

Sample[1]	Year of Inside Ring	Rings w/pith locator	Core height (cm)[2]	Est. Date[3]	Geom Surface	Root Crown[4]	Flood debris[5]	Comments
812-R	1879	8	70 gs	1869	Qoal	b	a	
821-E	1866	3	50 gs	1861	Qoal	b	wo	Located along abandoned meander
821-D	1871	3	50 gs	1866	Qoal	b	wo	Located along abandoned meander
821-C	1872	3	50 gs	1867	Qoal	b	wo	Located along abandoned meander
821-B	1877	5	50 gs	1870	Qoal	b	wo	Located along abandoned meander
821-A	1846	5	50 gs	1839	Qoal	b		Qal inset 2 m beneath Qoal; channel cut on bedrock

[1] 41 cores collected from 35 trees; 11 cores not analyzed due to rot, widely missed piths, or damaged cores

[2] Coring height affects age determination. Adjust age of trees 1 y for cores collected 30-50 cm above rc, root crown; 2 y 51-100 cm; and 3 y > 100 cm above the root crown. When root crown is not visible add a minimum of 10 cm of alluvium to determine age adjustment when core is collected above gs, ground surface.

[3] **N.D.** No data—establishment date uncertain; sample not dated due to rot, widely missed pith, or damaged to core

[4] Nature of root crown: **b** buried; **c (150)** exposed in cut bank (150 cm beneath ground surface); **v** visible at ground surface

[5] Nature of flood debris if present around trunk: **a** overbank alluvium; **c** channel deposits; **d** desiccation cracks; **o** old, weathered; **p** point-bar deposits; **r** recent; **s** interstitial spaces of woody flood debris filled with sediment; **v** vegetation growing through debris pile; **w** woody flood debris on upstream side of trunk

The standardized tree-ring indices are most strongly correlated with September through June precipitation (correlation coefficient, r = 0.68). These results indicate that ponderosa pine, and presumably many other plants of the region (*see* Epstein et al., 1997), are highly dependent on winter and spring moisture. Many plants become dormant during the hottest summer months; consequently, plant cover in this region is controlled primarily by cool season moisture.

Tree-ring data indicate that pronounced droughts, i.e., droughts comparable or more severe than the historic Dust Bowl drought of the 1930s, occurred approximately 3 to 4 times per century. Pronounced droughts occurred from 1529-1535, 1553-1563, 1591-1592, 1596-1600, 1603-1607, 1636-1640, 1648-1653, 1718-1725, 1756-1760, 1816-1823, 1863-1866, 1869-1875, 1897-1901, 1934-1937, 1952-1961, and 1988-1992 (Fig. 17). The period from 1863-1865 was the driest 3-year interval, and the period from 1863-1875 was the driest extended period of 10 or more years in the past 470 years (Fig. 17). The onset of incision in the studied streams coincided with the severe drought of the 1860s and 1870s.

The ring-width pattern from ponderosa

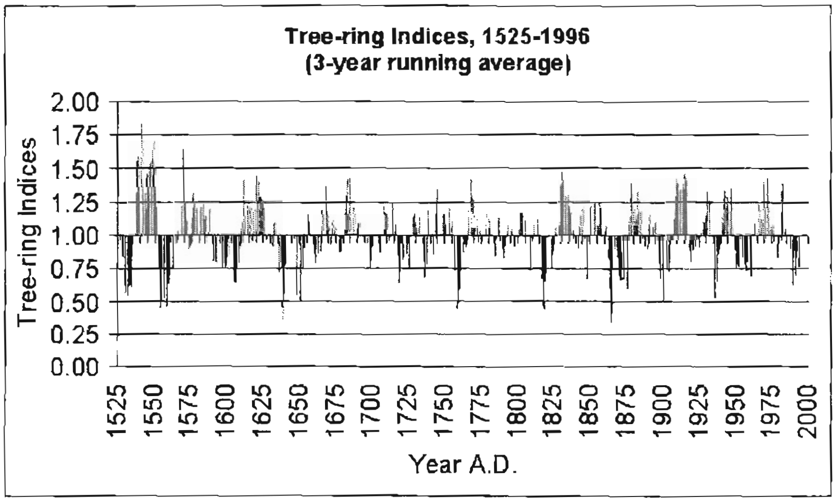

Fig. 17. A 470-year tree-ring record of precipitation reconstructed from a nearby stand of ponderosa pine (*Pinus ponderosa*) in Slope County, North Dakota. Tree-ring indices near 1.0 reflect near normal precipitation from September through June. Tree-ring indices well below 1.0 indicate periods of drought.

pine was mimicked to varying degrees in most cottonwood trees. Narrow rings in ponderosa pine, which served as reliable marker years in samples of cottonwood trees, corresponded to the years 1992, 1985, 1961, 1956, 1954, 1952, 1938, 1937, 1936, 1934, 1931, 1925, 1921-1919, 1911, 1900, and 1895. The marker years permitted cross-dating of cottonwood cores across broken, twisted, and rotten intervals.

DISCUSSION

Geomorphic responses of ephemeral streams to recent environmental changes

Model of arroyo evolution

Dendrochronologic data and dendrogeomorphic relations indicate times and types of channel adjustments along many stream reaches. When the periods of channel incision are well constrained, then it is possible to ascertain the cause(s) of incision by evaluating corresponding environmental conditions and land-use activities. Also, the dendrochronologic data and dendrogeomorphic relations permit construction of a four-stage model to illustrate the evolution of arroyos in the Little Missouri Badlands. The model comprises: (i) an initial period of relative geomorphic stability with pedogenesis in the flood-plain alluvium and low rates of lateral channel migration, (ii) a period of channel incision with subsequent flood-plain widening through "lateral corrasion" (term as defined by Mackin, 1937) along middle and upstream reaches (Figs. 8A and 18A), (iii) a concomitant period of downstream aggradation (Figs. 12D and 18B), and (iv) a period of downstream incision (Figs. 15C and 18C).

Period of relative stability

Under conditions of geomorphic stability, the stream channel is neither aggrading nor incising, and the longitudinal profile acquires a graded condition (Knox, 1976). The stream system maintains a steady-state equilibrium with a meandering channel pattern. Through time, lateral corrasion gradually reworks and widens the flood plain (Mackin, 1937). Soil develops in the flood-plain alluvium in the absence of vertical accretion. The degree of pedogenesis is variable across the flood plain and reflects the time since the alluvium was last reworked by lateral-accretion processes (*see* Fig. 12D). The flood-plain surface becomes vegetated with woody riparian shrubs and a mix of annual and perennial grasses and forbs. The vegetation cover inhibits germination of cottonwood seeds (Everitt, 1968; Johnson *et al.*, 1976; Nanson

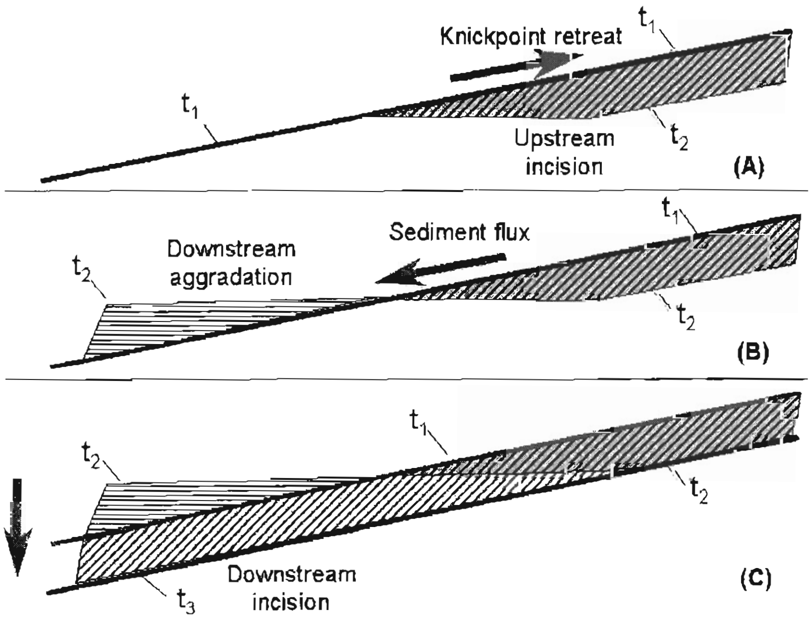

Fig. 18. Schematic diagrams illustrate the development of arroyos in small basins of the Little Missouri Badlands. (A) The longitudinal profile of the pre-incision, equilibrium channel is marked by the t_1 time line. Channel incision begins in the upstream reaches and is marked by the t_2 time line. (B) Concomitantly, sediment generated in upstream reaches is transported and stored as overbank deposits in aggrading downstream reaches as indicated by the t_2 time line. (C) Downstream incision eventually occurs either as predicted by Schumm's (1980) geomorphic threshold model and/or through oversteepening of reaches by meander cutoff process. Downstream incision creates an incised channel where the channel slope is in equilibrium along the entire stream, as indicated by the t_3 timeline.

and Beach, 1977; Scott *et al.,* 1996), and sites of germination are confined to point bars and channel bars where fresh increments of sediment are frequently deposited (Everitt, 1968; Friedman, 1993; Friedman *et al.,* 1996a; Scott *et al.,* 1996). Therefore, low rates of sediment flux and channel migration will correspond to low rates of cottonwood establishment.

Upstream incision

The period of geomorphic stability ends with initiation of channel incision (Fig. 18A). The distribution of terraces and dendrogeomorphic evidence indicate that incision does not initiate at the mouth or lower reaches of these badlands streams, but instead along a middle reach where a low terrace tread (Qt4) first appears along the streams. The Qt4 terrace tread emerges from and gradually gains height above the flood plain in an upstream direction. After incision of several meters depth, the channel expands the flood plain through lateral corrasion. Sites for germination of cottonwood trees are especially abundant during the period of flood-plain expansion.

The age structure of riparian cottonwood trees indicates that the Qt4 terrace observed today along the middle reaches was the active flood-plain surface well into the mid-19th Century. Beginning in the 1860s and 1870s, before European settlement of the region, the Qt4 terrace was abandoned as the active fluvial surface, and a lower inset flood plain (Qal surface) formed (Figs. 8A and 18A). Incision prevented inundation of the Qt4 terrace by low-magnitude, high-frequency floods. Germination of cottonwood trees ceased on the Qt4 surface due to the competition posed by other vegetation and the cessation of disturbances required to create a bare substrate. The inset flood plain and channel became the new locus of cottonwood germination, because large quantities of sediment moved and were deposited on these landforms, creating moist, bare substrates where cottonwood seeds could germinate.

Dates of establishment of cottonwood trees along upstream reaches suggest that fluvial incision lagged two to several decades behind incision of the middle reaches. Incision of upstream and headwater reaches began in the 1880s and 1890s, and it continued into the 1930s or later in some basins. Although incision of upper reaches coincides with the introduction of intensive grazing, it was not necessarily initiated by this activity. Upstream incision may have been exacerbated by grazing or may reflect the time-transgressive upstream migration of incision knickpoints.

Dendrochronologic evidence of pre-settlement incision and the general temporal conformity of incision among the basins suggest that the initial cause of the arroyos was related to a natural phenomenon, such as climate change. Previous work has shown that the response of a stream to climate change is complex and related in part to antecedent conditions (*e.g.,* the Langbein-Schumm sediment-yield curve (Langbein and Schumm, 1958)); to the direction of change (wetter to drier or vice versa); to temporal and/or spatial scales of analysis (Knox, 1983); and to inherent properties, such as the transport capacity versus sediment supply of various systems (Knox, 1972; Bull, 1991, pp. 112-116).

Langbein and Schumm (1958) showed that, in an arid environment, sediment yield increased with increase in effective precipitation (Fig. 19). The mere increase in precipitation would produce more runoff and more work on the arid landscape. In contrast, an increase in precipitation of similar proportion in a semiarid environment increases vegetation cover, thereby reducing sediment yield (Fig. 19). Therefore, the response of a stream to climate change is dependent on antecedent climatic and vegetative conditions.

Knox (1983) recounted the early debate between Huntington (1914) and Bryan (1928), who disagreed on the stream responses that would arise from a given climate change. For example, Huntington viewed a climatic shift to more arid conditions as causing stream alluviation, whereas Bryan argued that this same shift caused incision.

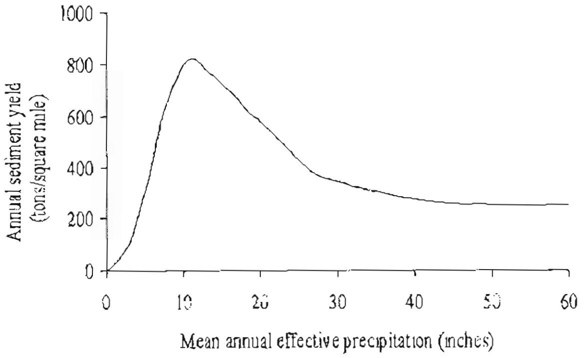

Fig. 19. The Langbein-Schumm sediment-yield curve illustrates the relation between sediment yield and effective precipitation (modified from Fig. 2 of Langbein and Schumm, 1958).

Knox suggested that the controversy related in part to differences in the temporal scales perceived by these investigators. Huntington viewed episodes of aggradation and incision as the consequence of long-term changes. In contrast, Bryan envisioned rapid incision as the result of intensified flooding during a drought with gradual aggradation during intervening periods. Bryan's model best fits the responses observed in the small (drainage area less than 100km^2), topographically steep, sparsely vegetated, highly-sensitive basins of the Little Missouri Badlands as discussed in detail below.

Knox (1972) and Bull (1991, pp. 112-116) illustrated how inherent characteristics of transport capacity and sediment supply affect stream response to climate change. Knox (1972) noted that a shift from arid to humid conditions in a humid environment increased erosion by increasing transport capacity. In contrast, Bull (1991) noted that a similar climatic shift in an arid environment led to an initial reduction in sediment largely because the hillslopes are sediment-supply limiting. The small, ephemeral streams of the semiarid Little Missouri Badlands fall somewhere between the examples provided by Knox (1972) and Bull (1991). The Little Missouri Badlands probably are not supply limiting, because sediment is obtained readily from the easily eroded, poorly lithified Paleocene bedrock. Other sediment is readily reworked from alluvial valley fills. The small, steep watersheds of the Little Missouri Badlands are sensitive to subtle changes in vegetation cover that result from short-lived changes in climate. Protracted drought would reduce vegetation cover and increase the erosion and runoff potential from hillslopes (Bull, 1991, pp. 112-116; and Bull, 1997). Infrequent thunderstorms become more effective agents of geomorphic change during drought because resisting forces, chiefly vegetative cover, are lower than under more humid conditions. Greater volumes of runoff during infrequent storms deliver copious supplies of sediment to the stream from hillslopes and could remobilize alluvial valley fill along upstream reaches.

The severe, protracted drought from 1863-1875 would have caused an appreciable reduction of vegetative cover. Any intense summer thunderstorm occurring during this and other severe droughts could have generated unusually large and powerful floods in the absence of runoff-retarding vegetative cover. Periods of renewed cottonwood establishment also coincide with the 1930s and 1950s droughts of the northern Great Plains (Fig. 17) when channels were incising and flood plains were widening along some upstream reaches. However, there are many reconstructed drought periods (Fig. 17) during which there is no corresponding period of channel incision. Therefore, severe drought alone is incapable of triggering channel incision. Rather, it is the occurrence of intense, spatially discrete thunderstorms during regional severe droughts that triggers channel incision locally. Furthermore, the limited aerial distribution of convection storms means that not all basins will necessarily have been affected by the same storms.

Downstream aggradation

Entrenchment of the channel and widening of the flood plain from the 1860s through the 1900s produced a copious supply of sediment that was transported from upstream to downstream reaches. Much of the sediment accumulated as vertical-accretion deposits along the lower reaches of all studied streams (Figs. 12D and 18B). Aggradation along the lower reaches results from a decrease in transport capacity as valley and channel slopes generally decrease in a downstream direction

(Table 3A). Deposition creates a self-enhancing feedback by further decreasing slope and inducing subsequent deposition.

Evidence of vertical aggradation is ubiquitous along downstream reaches. For example, where the roots of flood-plain trees are partly exhumed in channel cutbanks, the root collars are commonly several decimeters to meters below the surface of the flood plain. Adventitious roots commonly are found growing out of the buried trunks and into the encapsulating vertical-accretion deposits (*see* Fig. 14F). In addition, woody flood debris has accumulated on the upstream side of many trunks (Fig. 14B). Also, recent overbank deposition of desiccation-cracked mud cover is ubiquitous across flood plains (*see* Figs. 12D, 14A, and 14D).

The concomitant occurrence of upstream incision and downstream aggradation reflects disequilibrium conditions along ephemeral streams. The alluvial stratigraphy and the channel pattern observed in the Little Missouri Badlands indicate that a single meandering channel persists throughout the aggradational phase. This contrasts with the discontinuous ephemeral streams described by Bull (1997), in which valley aggradation produced coarse-textured channel fans with a braided distributary-channel pattern that eventually evolved into diverging sheetflow. The high suspended load and fine-grained deposits of ephemeral streams in the Little Missouri Badlands provide enough cohesion to maintain a single meandering channel throughout the aggradational phase. These observations of channel pattern in the Little Missouri Badlands are consistent with the relations between sediment load and channel pattern described by Schumm (1960, 1961).

Downstream incision

Jones Creek has incised through the vertical-accretion deposits along the lower reaches since 1950, and two other streams, Dantz Creek and Toms Wash, have done so since 1979 (Fig. 18C). Schumm (1973), Schumm and Parker (1973), and Bull (1997) described similar aggradation-degradation sequences. Bull's study of discontinuous ephemeral streams showed that aggradation and formation of a channel fan produced zones of positive (self-enhancing depositional processes) and negative (self-arresting depositional process) feedback (Fig. 20). Likewise, Schumm (1973) and Schumm and Parker (1973) have shown that when the downstream slope of the valley-floor fan reaches or exceeds a critical threshold, the channel incises. In subsequent work, Schumm (1980) referred to the critical slope as a geomorphic threshold that separates equilibrium from disequilibrium conditions.

In Bull's (1997) discontinuous-stream model and Schumm's complex-response model, the mechanism for incision was an increase in slope to or beyond a critical value. In these models, the increase in slope arose from depositional processes (Fig. 20). In Dantz Creek and Toms Wash, the slope increased by erosional processes when cutoff of meander loops occurred. Alternatively, channelization associated with recent culvert and road construction across Toms Wash may have increased slope as well. The cutoff process increases channel slope, stream power, and potential for channels to incise along adjacent reaches.

Schumm (1973) referred to the process of channel incision resulting from changes in valley slope as an intrinsic process, because each stream builds the accretionary channel fans at an independent rate unrelated to extrinsic factors. The cutoff of meander loops is an autogenic, or intrinsic, process as well, because the evolution of individual meander bends is independent of extrinsic factors and of the evolution of other meanders. Intrinsic processes should occur randomly and should not be simultaneous in all basins.

The modernity of this period of incision is evident from flood-plain geometry and dendrochronologic relations. The channel has not had time to widen the flood plain through lateral corrasion, and only young cottonwood seedlings and saplings established on the inset fluvial surface

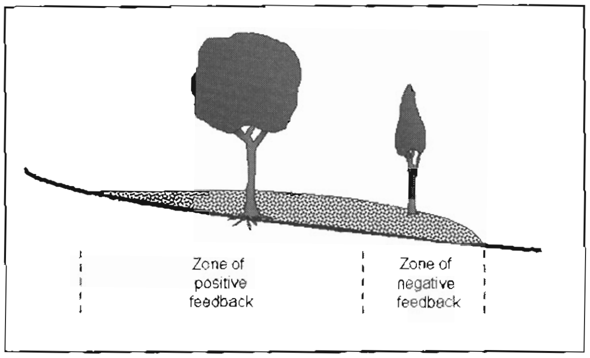

Fig. 20. Downstream aggradation creates zones of positive (self-enhancing) and negative (self-arresting) feedback. Eventually, the slope produced on the downstream end of the channel fan becomes over-steepened; *i.e.*, the slope exceeds a critical value, creating disequilibrium conditions with imminent change likely to occur (modified from Fig. 9 of Bull, 1997).

(*see* Fig. 15C). Whereas the channels in two study basins have now reached and undergone incision along parts of the downstream reaches, the channels in the other basins have yet to incise along the lower reaches. Incision along other downstream reaches should occur in the near future as slope increases locally by valley aggradation, natural meander cutoff, or anthropogenic channel straightening.

Geomorphic processes and the establishment of riparian cottonwood trees

Geomorphic-ecological relations

Previous investigators have illustrated the close relation between fluvial processes and the distribution, establishment, recruitment, and mortality of riparian species along perennial streams (*e.g.*, Sigafoos, 1964; Everitt, 1968; Osterkamp and Hupp, 1984; Hupp and Osterkamp, 1985; Hupp, 1988; Stromberg *et al.*, 1991; Scott *et al.*, 1996). Cottonwood establishment is particularly dependent on specific hydrologic and geomorphic processes. First, seed release in the spring must coincide with periods of ample moisture, produced by precipitation or flooding. Cottonwood seeds will fail to germinate if sufficient moisture is not available during a period of a few weeks when seeds are viable (*e.g.*, Moss, 1938). Second, the seeds germinate best on fresh mineral soils, devoid of competing vegetation and free of a shade-producing canopy (*e.g.*, Read, 1958; Everitt, 1968; Johnson *et al.*, 1976; Bradley and Smith, 1986). Fresh mineral soils are produced in the riparian zone by channel narrowing or in-channel sedimentation (Johnson, 1994; Friedman, 1993; Friedman *et al.*, 1996a, b), by point-bar accretion resulting from meander migration (Everitt, 1968; Bradley and Smith, 1986), and by deposition of flood-plain alluvium during overbank flows (Baker, 1990; Scott *et al.*, 1996, 1997). Third, once a plant has germinated, it must be protected from life-threatening disturbances for one or more years until it is large enough to withstand subsequent flooding and deposition. Finally, a source of moisture must be maintained until the plant develops a root system capable of extracting water from shallow alluvial aquifers (*e.g.*, Rood and Mahoney, 1990; Mahoney and Rood, 1992; Segelquist *et al.*, 1993; Stromberg *et al.*, 1996; Scott *et al.*, 1999).

Mortality of cottonwood trees along perennial streams results from fire, drought (Albertson and Weaver, 1945), and other causes of water-table decline (*e.g.*, Segelquist *et al.*, 1993; Stromberg *et al.*, 1996; Scott *et al.*, 1999), herbivory by beaver and cattle (Bradley and Smith, 1986; Baker, 1990), use of riparian zones by cattle (Brown *et al.*, 1977; Crouch, 1979b; Behan, 1981), and injury from ice heave (Scott *et al.*, 1996), floods, erosion, and deposition. Although some of these causes of mortality are universal along all types of streams, their role along ephemeral streams has yet to be studied in detail.

Many researchers have examined the relations between fluvial processes and the establishment of bottomland vegetation (*e.g.*, Sigafoos, 1964; Nanson and Beach, 1977; Osterkamp and Hupp, 1984; Hupp and Osterkamp, 1985; Hupp, 1988), particularly with respect to riparian cottonwood trees along perennial streams (*e.g.*, Everitt, 1968; Wilson, 1970; Johnson *et al.*, 1976; Crouch, 1979a, b; Noble, 1979; Fenner *et al.*, 1985; Bradley and Smith, 1986; Rood and Heinze-Milne, 1989; Baker, 1990; Rood and Mahoney, 1990; Stromberg *et al.*, 1991, 1993; Friedman, 1993;

Johnson, 1994; Stromberg *et al.*, 1996; Friedman *et al.*, 1996a, b; 1997; Scott *et al.*, 1996, 1997). These investigators among others have generally concluded that establishment of cottonwood trees requires a fluvial process to produce a seedbed along with several other factors to promote germination and survival of seeds, such as release of seeds concomitant with formation of a seedbed, maintenance of adequate soil moisture in the seedbed, and lack of competition from vegetation in the seedbed. Scott *et al.* (1996, 1997) summarized the findings of many investigators and noted that cottonwood establishment [along perennial streams] is related generally to one of three fluvial processes: (1) meander migration with point-bar accretion, (2) channel narrowing, and (3) flooding accompanied by overbank sedimentation.

Each fluvial process operates under a distinct magnitude-frequency regime; therefore, the establishment history and pattern should reflect the recurrence interval of events that produce seedbeds in combination with other edaphic (*i.e.*, soil-related) and non-edaphic factors that favor germination of seeds. For example, seedbeds suitable for cottonwood germination are commonly produced by point-bar accretion in a meandering river system (Everitt, 1968; Nanson and Beach, 1977; Bradley and Smith, 1986; Rood and Mahoney, 1990). Point-bar accretion can occur during flows that are slightly less than to greater than bankfull discharge. Bankfull discharge typically has a recurrence interval of one to two years in many streams in the humid parts of the United States (Wolman and Leopold, 1957; Leopold *et al.*, 1964). Other investigators suggest that bankfull discharge occurs less frequently and more irregularly along streams with highly variable streamflow (*e.g.*, Gregory and Walling, 1973) as happens along most streams in the western United States and the ephemeral streams in the Little Missouri Badlands. The hypothetical age distribution of trees established by meandering processes is depicted in a histogram of establishment dates (Fig. 21A). The number of living representatives from each decade would gradually decline with increasing age, reflecting senescence and the natural rate of mortality in an aging forest (Fig. 21A).

In some instances, the cottonwood trees established by point-bar accretion can be recognized by the pattern of their distribution across the flood plain. Everitt (1968) showed that cottonwood trees typically occur in arcuate-shaped, even-aged (*i.e.*, same age) stands when the trees germinate on point bars, which form on the inside bank of meander loops (Fig. 22A). As a channel migrates across the flood plain, erosion occurs on the cutbank side of the channel with concomitant deposition on the point-bar side (Fig. 22A). With time the channel moves progressively farther from the former point bars (Fig. 22A). The oldest point bars contain the oldest cottonwood trees in a given reach. Also, note that there are fewer trees on each progressively older point-bar deposit (Fig. 22A) as trees gradually die. Younger trees generally do not establish within pre-existing, even-aged, arcuate stands of cottonwood trees, because lack of moisture, shade produced by the overlying canopy, and competition with other vegetation diminishes seed success on older point-bar surfaces (*e.g.*, Johnson *et al.*, 1976; Friedman *et al.*, 1996b; Scott *et al.*, 1996).

Cottonwood establishment also results from channel narrowing, which commonly occurs after a catastrophic flood has enlarged a channel and reconfigured vast parts of a flood plain (Friedman, 1993; Friedman *et al.*, 1996a, 1997). Channel narrowing has also been observed following the construction of a dam, where regulated releases caused in-channel deposition in response to a decrease in the magnitude of peak discharges (Johnson, 1994). Catastrophic floods and alteration of the flow regime through the construction of a dam are relatively isolated events in the life span of trees. Each channel-narrowing event would hypothetically correspond to a discrete episode with high rates of cottonwood establishment (Fig. 21B). The ages of trees would decrease from the margin of the enlarged, post-catastrophe channel toward the banks of the smaller in-filled channel (Fig. 22B). The episode would potentially persist for several years, reflecting ongoing

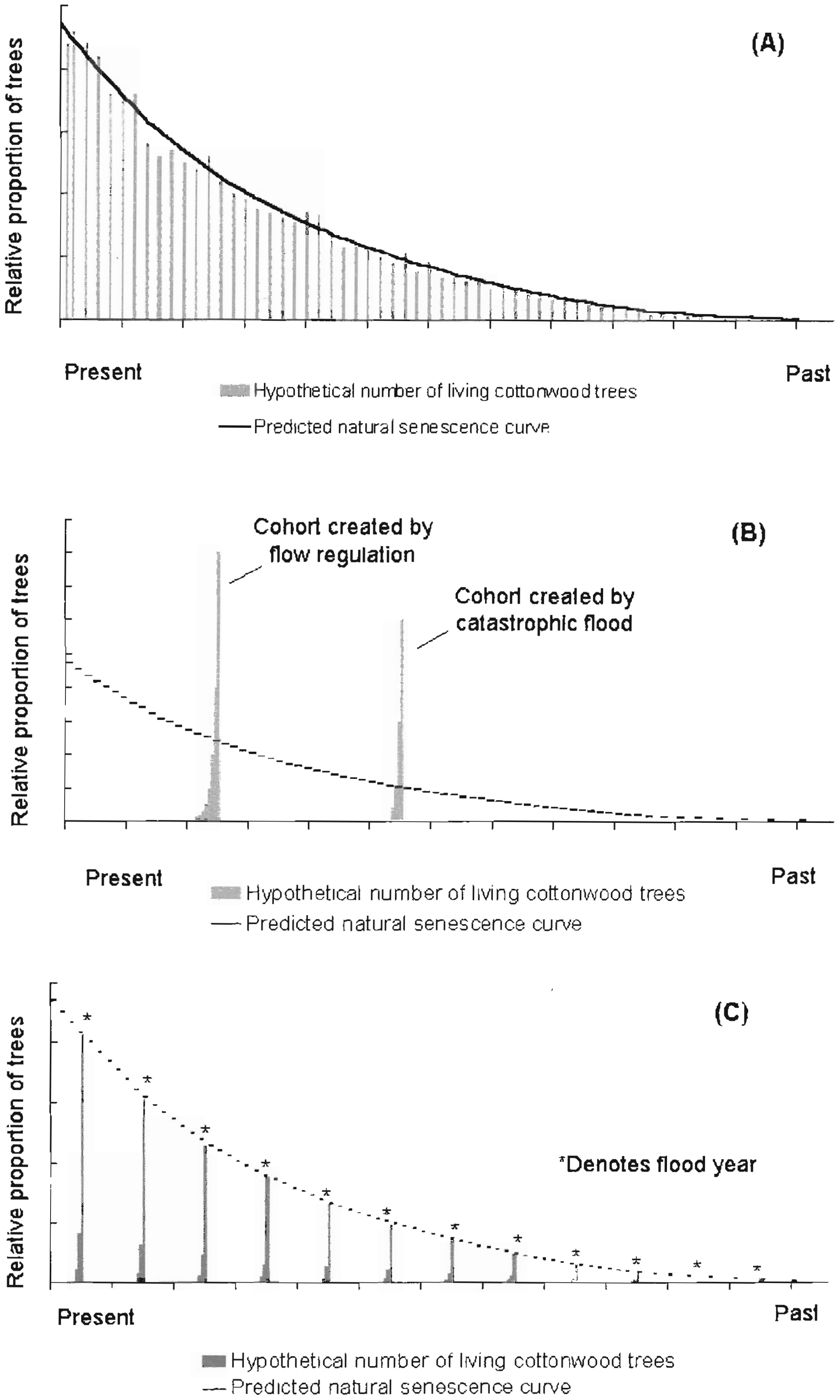

Fig. 21. Histograms illustrating the hypothetical dates of establishment of cottonwood trees resulting from (A) point-bar accretions along a meandering stream, (B) channel narrowing, and (C) floodplain deposition from large-magnitude floods.

deposition within a progressively narrowing channel (Figs. 21B and 22B). Cottonwood populations resulting from relatively infrequent processes of channel narrowing would also show the effects of senescence with a decline in the number of older cottonwood trees (Fig. 21B). Rates of establishment during intervening periods of channel stability would be relatively low, reflecting low rates of formation of seedbeds (Fig. 21B), perhaps by meander migration with point-bar accretion.

Riparian forests produced by large-magnitude floods tend to have even-aged stands (Baker, 1990; Scott *et al.,* 1996, 1997; Fig. 21C). Baker (1990) found that flood-related establishment along the Animas River had a mean recurrence interval of 9.2-10.6 years, and Scott *et al.* (1997) calculated a mean recurrence interval of 9.3 years along a reach of the upper Missouri River. Also, Scott *et al.* (1997) pointed out that cottonwood establishment by flooding is most likely to occur in reaches where the channel is relatively straight and the valley is narrow, precluding channel meandering or appreciable widening and narrowing. Seedbeds formed by a large-magnitude flood may persist for one or more years. Consequently, trees may establish in the year of the flood or in the few years immediately following the flood until the seedbeds become too dry or too vegetated for germination of cottonwood seeds (Fig. 21C).

Establishment of cottonwood trees along ephemeral streams

The distribution of cottonwood trees along ephemeral streams in the Little Missouri Badlands appears to be affected by several factors, including: (1) channel variables, particularly the gradient and

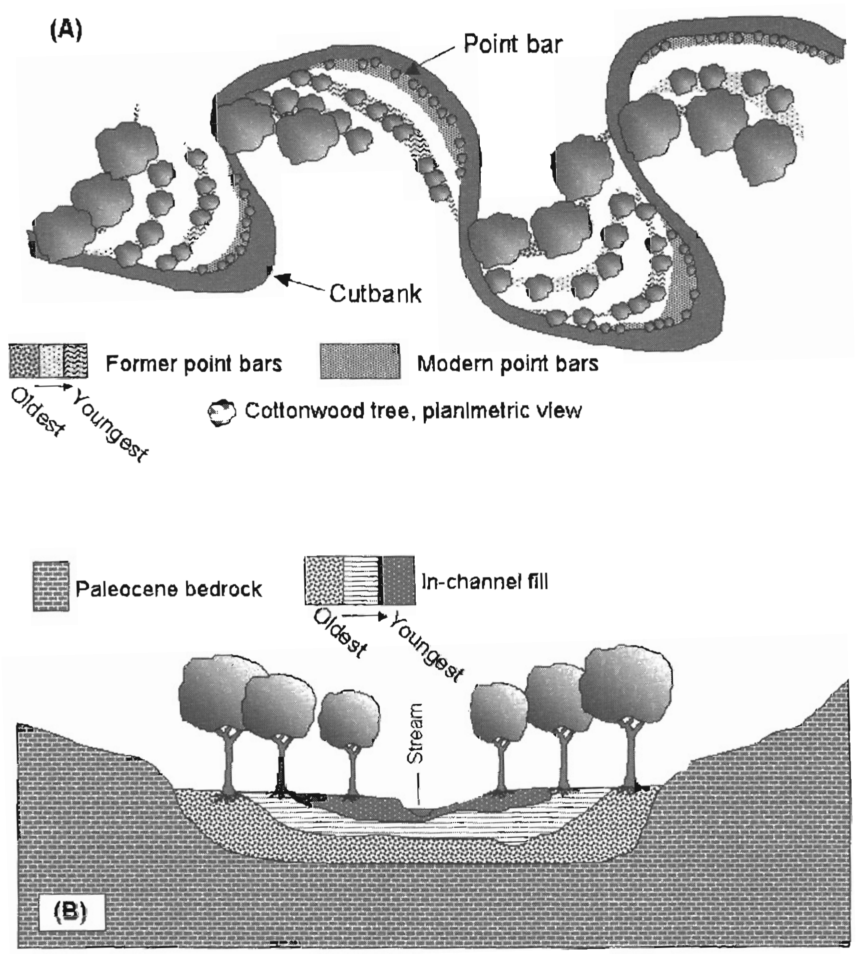

Fig. 22. Planimetric view illustrating the spatial and temporal distribution of cottonwood trees across a floodplain from (A) frequent point-bar accretion (B) channel narrowing.

sinuosity of the channel, (2) the relative geomorphic stability of the channel, chiefly the rates of channel incision, knickpoint migration, lateral channel migration, and flood-plain aggradation, (3) the rate of deposition along a reach, which is tied in large part to factors (1) and (2) above, and (4) the depth to groundwater. The roles of grazing by cattle and herbivory by beavers were not specifically tested, but field observations suggest that the latter may be an important factor that requires additional study.

Channel variables.—To facilitate discussion of establishment patterns of cottonwood trees, I have divided the ephemeral stream into four types of reaches: a headwater bedrock reach and upstream, middle, and downstream alluvial reaches (Fig. 23). Cottonwood trees occur extensively along the alluvial reaches of ephemeral streams in the Little Missouri Badlands. In contrast, the headwater bedrock reaches are generally devoid of cottonwood trees because the gradients of the valley axes are steep (> 1.5%), sinuosity is low (<1.20; Tables 3A and 3B) and sediment-transport capacity is high. Sediment is readily conveyed out of these reaches, the channel cuts directly into bedrock, and little or no alluvium accumulates. Few seedbeds are produced, and these are temporary, readily scoured by subsequent streamflows, leading to severe injury and probable mortality of any seedlings and saplings that might temporarily establish along bedrock reaches.

Geomorphic stability.—Along the small ephemeral streams of the Little Missouri Badlands, the majority (65%) of sampled cottonwood trees established in a 40-year (1861-1900) period and nearly half (51%) of the sampled trees established in the 1860s and 1870s (Fig. 9), a brief period when there was geomorphic instability marked by extensive channel incision, rapid headward migration of knickpoints, formation of inset flood plains, and rapid aggradation of flood plains along lower alluvial reaches (Fig. 18B). Geomorphic instability occurs more frequently in ephemeral than in perennial streams (Patton and Schumm, 1981). Geomorphic instability of the riparian corridor creates extensive areas and short-lived opportunities for cottonwood germination, resulting in periods of high establishment rates. These periods of high establishment rates in ephemeral streams are somewhat analogous to the recruitment period following low-frequency, catastrophic floods described by Friedman (1993) and Friedman *et al.* (1996a, b). Consequently, the decline in

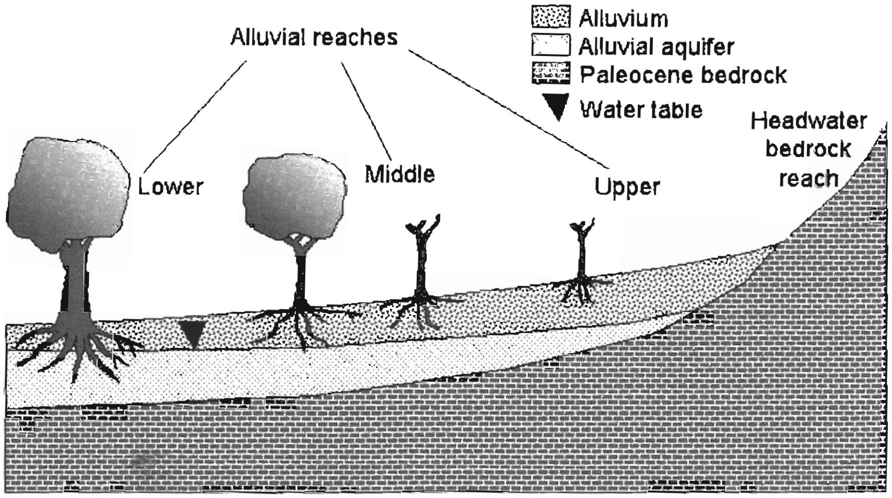

Fig. 23. The geomorphic processes, groundwater conditions, channel parameters, and cottonwood viability change systematically along ephemeral streams of the Little Missouri Badlands. Ephemeral streams are divided here into four reaches to explain spatial and temporal variability of cottonwood establishment: headwater bedrock reach, and alluvial upstream, middle, and downstream reaches. A fluctuating alluvial aquifer is typical of lower and middle reaches, and may extend intermittently upstream into the upper alluvial reaches of some ephemeral streams. Generally, the depth to the water table increases and the amount of groundwater decreases in an upstream direction.

cottonwood populations along ephemeral streams in the American West may be an artifact of the geomorphic processes operating during a discreet interval, and not necessarily due to human alteration of streamflow or riparian habitat. The apparent decline in cottonwood establishment may reflect the relative geomorphic stability during the past century and have little to do with human activities.

The pattern of establishment dates shows that the middle alluvial reaches of many ephemeral streams were incising and inset flood plains were forming during the 1860s and 1870s (Fig. 8A). The incised channels expanded into the upper alluvial reaches during the 1880s and 1890s and intermittently throughout the 20th Century. In contrast, the trees established before the 1880s are partly buried by vertical-accretion deposits (Figs. 5, 7A, 7B, 12D, and 14F) along the lower alluvial reaches.

Note that incision of ephemeral streams in the Little Missouri Badlands commenced in the 1860s and 1870s. This is before European settlement of the area, which began around 1883, when the Northern Pacific Railway completed its transcontinental rail, and large cattle companies began to operate around the newly formed boomtown of Medora (Robinson, 1966). Also, nearly synchronous incision in parts of all of the basins studied suggests that the formation of arroyos was related to an allogenic process, such as climate (Gonzalez, 1996, *in press*). A dendroclimatic study of precipitation patterns using nearby ponderosa pines (*Pinus ponderosa* Dougl. var. *scopulorum* Engelm; Stevens, 1950) indicates that the period from 1863 through 1875 was locally the driest, sustained interval in the past 470 years (Gonzalez, *in press*). Another 14% of the trees sampled established in the 1880s and 1890s. Generally the trees established in the 1880s and 1890s occur upstream of the trees established in the preceding decades, creating a spatial pattern consistent with diachronous, headward migration of a knickpoint through the middle and upper reaches of the ephemeral streams in the Little Missouri Badlands. Overgrazing and depletion of vegetative cover may have increased runoff and exacerbated knickpoint migration during the 1880s and 1890s. Alternatively, knickpoint migration may reflect ongoing diachronous processes that began in the 1860s and 1870s and had not yet concluded when cattle companies appeared in the region.

Cottonwood trees are relatively abundant along the lower reaches. Many of these trees germinated before the period of greatest geomorphic instability. They generally occur on point bars, or in arcuate bands within the flood plain, demarcating the position of former point bars that are now several decameters from the modern channel due to meander migration. These trees established on seedbeds created by either lateral-channel migration or by overbank storage of sediment transported from upstream reaches and deposited in lower reaches where transport capacity decreases due to reduced channel gradient (Figs. 12D and 18B).

The cottonwood trees found along upstream alluvial reaches generally postdate the period of greatest geomorphic instability. Their establishment appears to be related to episodic reactivation and headward migration of incision knickpoints with concomitant increase in sediment discharge and formation of an inset flood plain (Figs. 8A and 18A).

Groundwater.—Although this study was not designed to examine the effects of groundwater on establishment or mortality of cottonwood trees, observations made during fieldwork provided compelling visual evidence that groundwater is an important factor in the life cycle of cottonwood trees along ephemeral streams. Additional studies, using an extensive array of frequently monitored piezometers to specifically address the role of groundwater in ephemeral-stream ecosystems, are required. Albertson and Weaver (1945) summarized findings, which showed that decline in water tables, among other factors, led to high mortality of trees throughout the Great Plains during the drought of the Dust Bowl era. In the study area, the distribution of both living and dead cottonwood trees appears to be related to groundwater conditions, in part. Generally cottonwood trees are most abundant in the lower alluvial reaches and gradually decrease in number in an upstream direction. Some of the upper alluvial reaches have no cottonwood trees; others have only dead cottonwood trees (Fig. 24), indicating that their former range was greater than today's. The presence and survival of cottonwood trees along upper alluvial reaches might be related to the depth and fluctuation of the water table. Where the depth to saturation is great, seedlings may be unable to obtain sufficient moisture in the vadose zone. Consequently, the seedlings die before their embryonic root systems can develop and tap into the steady supply of moisture in an alluvial aquifer (Fig. 23). Also, seedlings may perish during the summer if the water table falls more rapidly than their root systems can expand downward (*e.g.*, Segelquist *et al.*, 1993). Alternatively, cottonwood trees that establish during a period of several wet years, when the alluvial aquifer is replenished and the water table is relatively shallow, may die during a subsequent protracted drought when the water table falls. Cottonwood trees along upper alluvial reaches are generally at greater risk from drought than those farther downstream, because the depth to water table fluctuates more where contributing areas are smaller, alluvial fills are coarser and hence have higher hydraulic conductivities, and hydraulic gradients are steeper, causing aquifers to drain more rapidly.

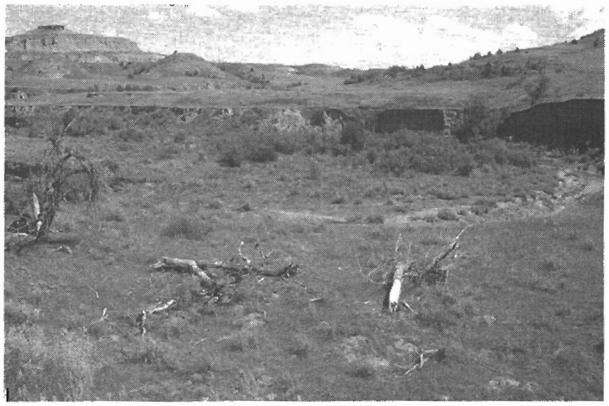

Fig. 24. Dead cottonwood trees are common along upstream reaches where the depth to and fluctuation in water table are great. (View is to the east in the NE ¼ of the SW ¼ of Section 19 in T 138 N/R 101 W along Dantz Creek.)

Along the middle and lower alluvial reaches, the valley gradients decrease to <0.9%, channels have moderate to high sinuosity (ranging from 1.3 to 3.0; Tables 3A and 3B) and long-term accumulation of sediment creates thick alluvial deposits. The alluvial aquifers in the lower reaches are fed by a larger contributing area than are the aquifers in upper reaches. Consequently, the cottonwood trees along lower reaches have a more dependable, more abundant supply of groundwater.

A high water table does not always promote the establishment of cottonwood trees. For example, in a separate study (Gonzalez and Miller, 1997) in the Willow Creek basin of northeastern Montana, a colleague and I observed that flood-detention dams had an adverse affect on cottonwood trees downstream of the dam. The structures were built to arrest knickpoint migration in an intermittent-stream channel by attenuating peak discharges and by promoting subtraction of surface water through infiltration and groundwater recharge. The alteration of streamflow and recharge of groundwater raised the water table until there was perennial streamflow downstream of the dam. Although Noble (1979) found that sustained discharges promoted germination and establishment of cottonwood trees and willows in south-central Minnesota, Gonzalez and Miller (1997) found that steady, perennial flow greatly favored colonization of channel fill and banks by willows (Salix spp.) in more arid northeastern Montana. No cottonwood trees were establishing along perennial-flowing reaches downstream from the dam. The dam attenuated discharge and reduced peak flows, thereby eliminating high flows that are required to disturb the riparian corridor and to deposit fresh sediment, prerequisites for germination of cottonwood seeds. Also, the dam trapped sediment, produced geomorphic stability, eliminated the formation of fresh seedbeds, and created consistent streamflow, factors which allowed willows to out-compete cottonwood trees in this setting.

Role of grazing.—The ephemeral streams in the Little Missouri Badlands are unregulated and exist in a relatively pristine condition. There are no dams, agricultural fields, municipalities, or industrial activities within the seven study sites to account for the decline in the population of riparian cottonwood trees. Grazing of livestock is the only anthropogenic activity that could affect the establishment of cottonwood trees in these basins. Livestock grazing has occurred in three basins (Dantz Creek, Bear Creek, and Toms Wash) from the 1880s to the present, and it occurred for a 50-year interval from the 1880s to the 1930s in the four other study basins (Jones Creek, Jules Creek, Paddock Creek, and Talkington Draw). Grazing by undomesticated buffalo, elk, and feral horses occurs in the South Unit of Theodore Roosevelt National Park, but the herds are closely monitored and are periodically culled to prevent overgrazing.

Cattle have little direct affect on trees (stem diameter >10 cm) but could affect seedlings (stem diameter <3 cm) through browsing or trampling. Cattle are drawn to riparian corridors to find water and shade beneath cottonwood trees. Consequently, some seedlings are in the direct path of cattle. However, as Johnson (1994) points out, cottonwood germination is less likely to occur under a canopy where light is reduced than on a fully lit seedbed. Therefore, the shady reaches with mature trees, which attract cattle, probably do not have as many seedlings to trample as sunlit reaches, which are not highly sought by cattle.

A comparison of the cottonwood establishment patterns between basins with short (1880s-1930s) and long (1880s-present) grazing history shows no obvious differences that can be directly related to grazing in the study area (Fig. 25). Furthermore, the highest rate of establishment occurred in the two decades immediately preceding European settlement in the area (Fig. 25), when channels were incising, knickpoints were migrating upstream rapidly, inset flood-plain deposits were being laid, and flood plains along lower alluvial reaches were aggrading. About one-half (51%) of the cottonwood trees dated in this study established in a brief period (1861-1880) before European settlement of the area. The lower rates of establishment during historic times reflect conditions of greater geomorphic stability along the ephemeral streams (Fig. 25). Establishment of cottonwood trees during the historic interval is tied closely to the rate of meander migration, or lateral point-bar accretion. Point-bar accretion occurs at a fairly constant rate and is related to moderately high frequency flows that are near or in excess of bankfull discharge.

Herbivory by beavers.—Although this study did not specifically set out to study the effect of herbivory, its role in cottonwood establishment rates and population dynamics of riparian forests may be important and requires additional study. Beavers were observed along all study reaches that had living cottonwood trees. In some reaches the population distribution of cottonwood trees was undoubtedly biased by recent harvests by beavers. Beavers have tremendous potential to decimate stands of cottonwood trees, especially now when their numbers have rebounded and the population of natural predators is low.

SUMMARY

Formation and evolution of arroyos

Dendrochronologic data and dendrogeomorphic relations provide a record of fluvial adjustments along seven ephemeral streams in the Little Missouri Badlands. These relations form the basis of a four-stage model of the formation of arroyos in the region. The four-stage cycle comprises: (i) a period of general geomorphic stability with pedogenesis in the flood-plain alluvium, (ii) channel entrenchment and flood-plain widening along the middle and upper reaches, (iii) concomitant channel and flood-plain aggradation along the lower reaches, and (iv) eventual channel incision and flood-plain widening along the lower reaches.

Three distinct episodes of channel incision are identified that differ temporally and spatially within and among the basins. Incision has resulted from allogenic and autogenic causes. For example,

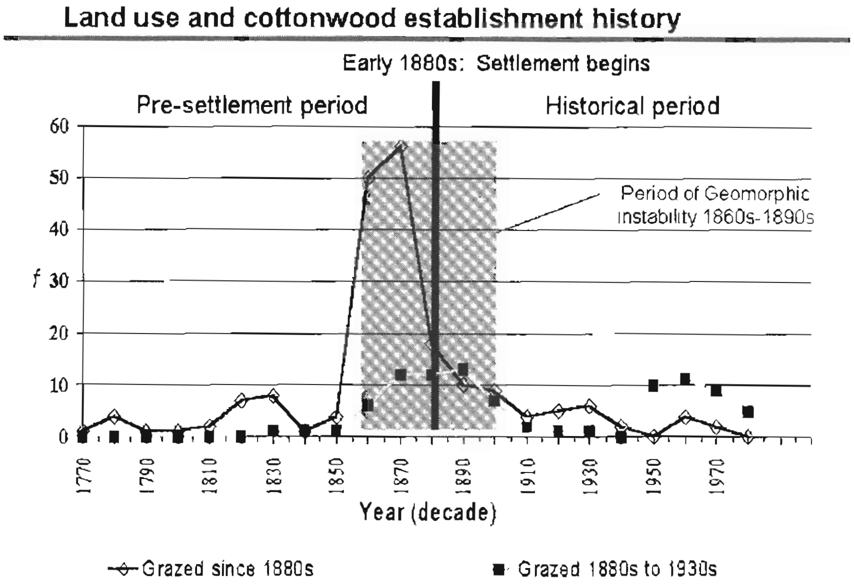

Fig. 25. Cottonwood establishment along the ephemeral streams of the Little Missouri Badlands is related to geomorphic stability of the channels. During a pre-settlement period of geomorphic instability (1861-1880) the rate of cottonwood establishment reached a maximum. Earlier and later periods, coincident with periods of relative geomorphic stability, have considerably lower rates of establishment. The establishment patterns are similar in those basins with long (1880s to the present) and short (1880s to mid-1930s) grazing histories, suggesting that grazing practices have not been the primary factor affecting the establishment of cottonwood trees in these basins.

incision along the middle reaches of the streams in this study commenced in the 1860s and 1870s before European settlement of the region (Figs. 10B, 12C, 13B, 15B, and 16B). This widespread incision coincides with the most protracted drought in the past 470 years (Fig. 17), suggesting that the pre-settlement period of incision resulted from an allogenic cause, *i.e.*, climatic fluctuations. The pre-settlement period of incision was preconditioned by drought that reduced vegetation cover and increased the vulnerability of the landscape to severe high-intensity storms capable of generating large volumes of runoff. Note that the mere occurrence of drought is not enough to initiate incision. Severe droughts occur a few times each century, and not all severe droughts were accompanied by channel incision. This climatic cause of incision is consistent with the model proposed by Bryan (1928). Bryan's model emphasized rapid incision of drought-ravaged areas by large floods. The geomorphic expression of this model is more likely in smaller, more sensitive basins, which respond more rapidly to environmental change, than larger, more complacent basins.

Another period of incision and headward expansion of arroyos occurred during the late 19th and the early 20th Centuries. This period has been well documented in the written accounts of early settlers, including Theodore Roosevelt (1888). Generally, this period of incision was confined to the upper reaches and was roughly synchronous in all basins where there is sufficient dendrochronologic data. This synchronous pattern would suggest an allogenic cause, but it is not evident if incision resulted from severe overgrazing in the region, or alternatively, from ongoing upstream migration of pre-existing incision knickpoints.

The period of incision along the lower reach of Jones Creek since 1952 is unique, suggesting that it is not related to climatic factors, which can potentially affect all the ephemeral streams in the Little Missouri Badlands simultaneously. It is possible that incision in this case was related to road construction and concentration of flow through a culvert that ran under the East River Road.

The period of incision along the lower reaches of Dantz Creek and Toms Wash since 1979 was triggered by an autogenic process. Schumm (1973) and Bull (1997) noted that the catalyst for autogenic incision is an intrinsic factor. They cited examples where accretion of channel fans locally over-steepened the downstream reach of the fans (Fig. 20). When the over-steepened reach attained or exceeded a critical slope, incision occurred. In the arroyos of the Little Missouri Badlands, the initial points of incision are not coincident with any channel fans. Instead, the process of meander cutoff, which locally increases channel slope, stream power, and incision potential, has triggered autogenic incision.

The model of arroyo evolution illustrates that the fluvial surfaces along the small, ephemeral streams are diachronous. Channel incision begins along the middle reaches, then migrates upstream, and affects headwater reaches one to several decades later. Also, while incision is removing sediment from middle and upper reaches, vertical accretion is storing overbank deposits along downstream reaches. These deposits bury the former flood-plain surface (Figs. 12D and 18B). After several decades to centuries of downstream aggradation, incision occurs along the downstream reach (Fig. 15C) and the channel is graded to a continuously incised longitudinal profile along its entire length (Fig. 18C). With time, the channel creates a wide flood plain along the lower reach through lateral corrasion.

Establishment of cottonwood trees

Cottonwood populations are in decline along many perennial streams in the western United States. The decline is attributed in many cases to human alteration of streamflow or riparian habitat. The ephemeral streams of the Little Missouri Badlands are relatively pristine and free from the alterations common in most other western streams. An examination of the spatial distribution and establishment history of riparian cottonwood trees, combined with the geomorphic processes operating in ephemeral streams, indicate that the most important factors affecting the population of cottonwood trees in ephemeral streams include: the degree of geomorphic stability, the discharge of sediment, properties of alluvial aquifers, and possibly herbivory by beavers. Grazing by domesticated cattle does not appear to be a primary control on cottonwood populations in this area.

Steep, straight reaches are generally devoid of cottonwood trees. These reaches effectively transport sediment downstream, have little meandering, and consequently have little to no accumulation of sediment as point-bar accretions. Channel scour of the few seedbeds and injury to seedlings is likely in these reaches, further precluding establishment of riparian cottonwood trees.

The greatest number of trees established during a period of geomorphic instability. Nearly two-thirds (65%) of the sampled cottonwood trees established during a 40-year (1861-1900) period of rapid vertical channel incision, headward migration of incision knickpoints, formation of inset flood plains along middle and upper alluvial reaches, and vertical aggradation of downstream reaches. Half (51%) of the sampled trees established in a brief period (1861-1880) before European settlement of the area. The episodic formation of arroyos leads to short-lived (decadal) intervals of high rates of establishment. These episodes of geomorphic instability along ephemeral streams lead to major reconfiguration of riparian habitat similar to that resulting from a rare, catastrophic flood on a perennial stream (Fig. 22B).

In contrast, during intervening periods (10^1 to 10^2 years) of relative geomorphic stability, the rate of establishment of cottonwood trees is low. Establishment during periods of geomorphic stability occurs primarily from point-bar accretion, an important process that creates seedbeds suitable for the germination of cottonwood seeds nearly annually (Fig. 22A). Activities that affect discharge of sediment, such as construction of earthen stock ponds, could affect rates of channel migration and point-bar accretion. Diminished rates of point-bar deposition would decrease the formation of seedbeds.

The depth to and fluctuation of water tables are important factors affecting the survival of cottonwood trees along ephemeral streams. Steep valley gradients and small contributing areas lead to widely and rapidly fluctuating water tables. Large drops in water table stress cottonwood trees severely during droughts. Seedling mortality may be high along ephemeral streams if the depth to saturation is great and seedlings cannot tap the alluvial aquifers for moisture, instead depending on generally sparse and unpredictable precipitation for moisture. The oldest and the greatest number of cottonwood trees occur along downstream alluvial reaches where the fluctuation of the water table is relatively small and the supply of groundwater is more consistent and copious than farther upstream (Fig. 23).

Grazing by domesticated cattle has no discernible effect on the establishment of cottonwood trees along ephemeral streams in the study area, though the study was not designed to control for this factor. Cursory comparison of populations of cottonwood trees in basins with short and long grazing histories shows that natural geomorphic events during pre-settlement time are a more important factor than grazing histories on the establishment of cottonwood trees in the study area (Fig. 25).

Herbivory by beavers was an unquantified factor that requires additional study based on casual field observations. All reaches with living trees showed signs of herbivory by beavers.

Effective management of cottonwood habitat should consider how geomorphic and ecological processes differ temporally and spatially within and between ephemeral and perennial streams. Cottonwood trees are disturbance dependent species. Widespread formation of arroyos during the 19th Century may have created a rare short-lived interval when the rate of establishment of cottonwood trees was great. The perception that cottonwood populations are in decline along some western streams may reflect the relative geomorphic stability that has persisted along many ephemeral streams during the past 120 years. The decline in some cases apparently is related to changes in geomorphic processes and not to human alteration of streamflow or riparian habitat. Therefore, management strategies aimed at maintaining geomorphic stability, such as lining channels with riprap, regulating streamflow, or controlling sedimentation of channels, or suppressing natural fires could adversely affect the population of cottonwood trees by altering the natural disturbance regime. The disturbances provide opportunities for cottonwood trees to establish along ephemeral streams.

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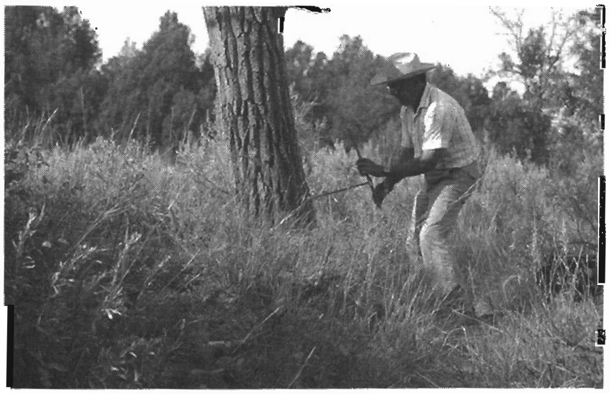

Fig. 26. Retired thoracic surgeon, Dr. Gilberto González, is illustrating his method for an invasive procedure on a cottonwood tree. He extracted a 50-cm-long core from the tree. The tree is purportedly doing well and has made a full recovery at the time of this writing.

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