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# Tree-ring record of hillslope erosion and valley floor dynamics: Landscape responses to climate variation during the last 400 yr in the Colorado Plateau, northeastern Arizona

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## Abstract

Dendrogeomorphologic approaches were used to study hillslope erosion and valley floor dynamics in a small drainage basin in the Colorado Plateau of northeastern Arizona, U.S.A. Root exposure in pinyon pines indicated hillslope erosion averaged 1.9 mm/yr over the last 400 yr, but erosion has been highly episodic. Negative increment growth anomalies in hillslope trees are interpreted as the consequence of rapid aerial exposure of roots by erosion. During the last 300 yr, two of three major episodes of these growth anomalies occurred after abrupt transitions from prolonged, multi-year droughts to sustained, lengthy periods of above-average precipitation. The most recent episode of these growth anomalies began within a few years after 1905 and was associated with the largest precipitation shift (drought to wet interval) in the last 400 yr. In contrast to trees on eroding hillslopes, increment growth of trees in more geomorphically stable landscape positions closely tracked the regional precipitation signal. Two major alluvial fills on the adjacent valley floor are also linked to the abrupt changes in precipitation regimes and the associated increases in delivery of runoff and sediments from slopes. The clay-cemented sandstones weather rapidly; rapid weathering and sediment production make slopes highly responsive to decadal precipitation changes. Significant vegetation declines on slopes during extreme drought make hillslope soils more prone to erosion if heavy precipitation follows soon thereafter.

*Keywords:* alluviation; arroyos; climate variation; Colorado Plateau; dendrogeomorphology; drought; erosion; hillslope dynamics; pinyon pine; soil

## 1. Introduction

Major climate transitions (e.g., Pleistocene to Holocene) generated considerable changes worldwide in landscape features (Bull, 1991), but influences of less extreme, more frequently occurring climate shifts are not as well understood. The capacity to predict the likelihood and magnitude of future geomorphic responses depends on a much better understanding of ways in which high-frequency, minor climate shifts affect landscapes.

Episodes of stream incision of basin floors (arroyo cutting) that have punctuated intervals of alluvial aggradation have produced some of the most pronounced landscape changes in semi-arid regions of the American Southwest. The most recent, region-wide episode of arroyo cutting during historical times captured the attention of geomorphologists in the early 1900s (e.g., Rich, 1911; Bryan, 1925; Swift, 1926) and

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cause(s) of that episode continue to be debated (Cooke and Reeves, 1976; Waters and Haynes, 2001). Geomorphic and stratigraphic evidence of regionally synchronous shifts between aggradation and incision in pre-settlement times point to climate variation as an important driver of these types of landscape changes (McFadden and McAuliffe, 1997; Waters and Haynes, 2001; Hereford, 2002). However, linkages between climate variables (e.g., precipitation amounts, intensities, seasonality, duration, etc.) and processes within drainage basins (e.g., weathering and sediment production, erosion and sediment transport) have not been resolved with the kind of detail needed to accurately predict responses of these landscapes to future climate variability.

Tree-ring analyses have demonstrated their utility in studies of long-term erosional dynamics of hillslopes. For example, LaMarche (1968) and Carrara and Carroll (1979) used dendrochronological techniques combined with measurements of root exposure to establish total vertical erosional losses from hillslopes over lifetimes of individual, long-lived trees. In this paper, we build on this basic approach by using dendrogeomorphological approaches to reconstruct the dynamics of a hillslope and adjacent basin floor in a small drainage basin in a semi-arid region of the Colorado Plateau, Arizona. Our study area is little used by livestock due to the steepness of slopes and lack of nearby livestock watering places. Consequently, the area provides a suitable site for investigating impacts of climate on landscape processes without the potentially confounding influence of historically recent, anthropogenic impacts. Hillslope trees provided a record of long-term erosion rates and the timing of erosion episodes. These data, paired with instrumental records of daily precipitation for the last century and the regional tree-ring reconstruction of annual precipitation for the last several centuries, provide a powerful means of pinpointing the timing of landscape-shaping events.

## 2. Study site

The study site is located 31 km west of Chinle, Arizona in an area where a series of small, 1–2 km wide erosional embayments are cut into soft sandstones, siltstones and mudstones of the Jurassic Morrison Formation and underlying Bluff Sandstone (San Rafael Group) (Figs. 1, 2; Table 1). Western margins of these embayments are escarpments capped in some places by more weathering resistant Cretaceous Dakota Sandstone. Starting with the northernmost in the series, the separate embayments were designated as Basins 0, 1 and 2. Each basin was further subdivided into sub-basins that generally corresponded to second-order tributary drainages. Work presented in this paper was conducted in Basin 1, sub-basins 1B and 1D (Fig. 1B). Pinyon pine trees (*Pinus edulis*) from Basin 0 were used to establish a local baseline tree-ring chronology.

## 3. Methods

### 3.1. Hillslopes

Pinyon pine trees on a north-facing hillslope of sub-basin 1D (Fig. 1B, location *a*; Fig. 2A; Table 1) provided information on the vertical extent of soil erosion over the lifetimes of individual trees. Within an area of approximately 60 × 150 m, GPS coordinates, trunk diameter directly above the base, and slope inclination were collected for each of the 27 trees on the slope using a 12-channel TRIMBLE *Pro XRS* unit. Field data was post-processed using the Trimble Pathfinder Office software and base station data from Flagstaff and Albuquerque. Post-processed positional accuracy is ~40 cm in the horizontal and 80 cm in the vertical.

Up to five increment cores from 25 trees were taken in October 1999 with a manual increment corer (two trees could not be cored), one in an east–west direction transverse to the slope inclination and one in a north–south direction parallel with the run of the slope. Direct ring counts were used as estimates of tree age. In cases where the increment core missed the pith, the number of missed rings was estimated and added to the direct ring count. Cores from 20 trees were used for detailed dendrochronological analyses; cores from the remaining five were excluded because long sections of those cores were extremely resinous, making ring boundaries difficult to precisely identify.

Lateral roots representing the oldest, original roots were selected to obtain sawn sections for pith height measurements. Roots on upslope and downslope sides of trees were not used. At a distance of 5–15 cm from the trunk, vertical sections were sawn through the selected roots; one root per tree was sampled. Vertical root exposure was measured as the height of a root's center axis of growth (the pith) above the ground surface (LaMarche, 1968). For smaller, younger trees that lacked exposed roots, lateral roots were excavated next to the trunk. The location of the pith centers of these smaller roots was estimated at half the root diameter and the depths of pith centers below the soil surface were recorded as negative values.

Soils and weathering patterns of the underlying Bluff sandstone were examined in 11 excavations on

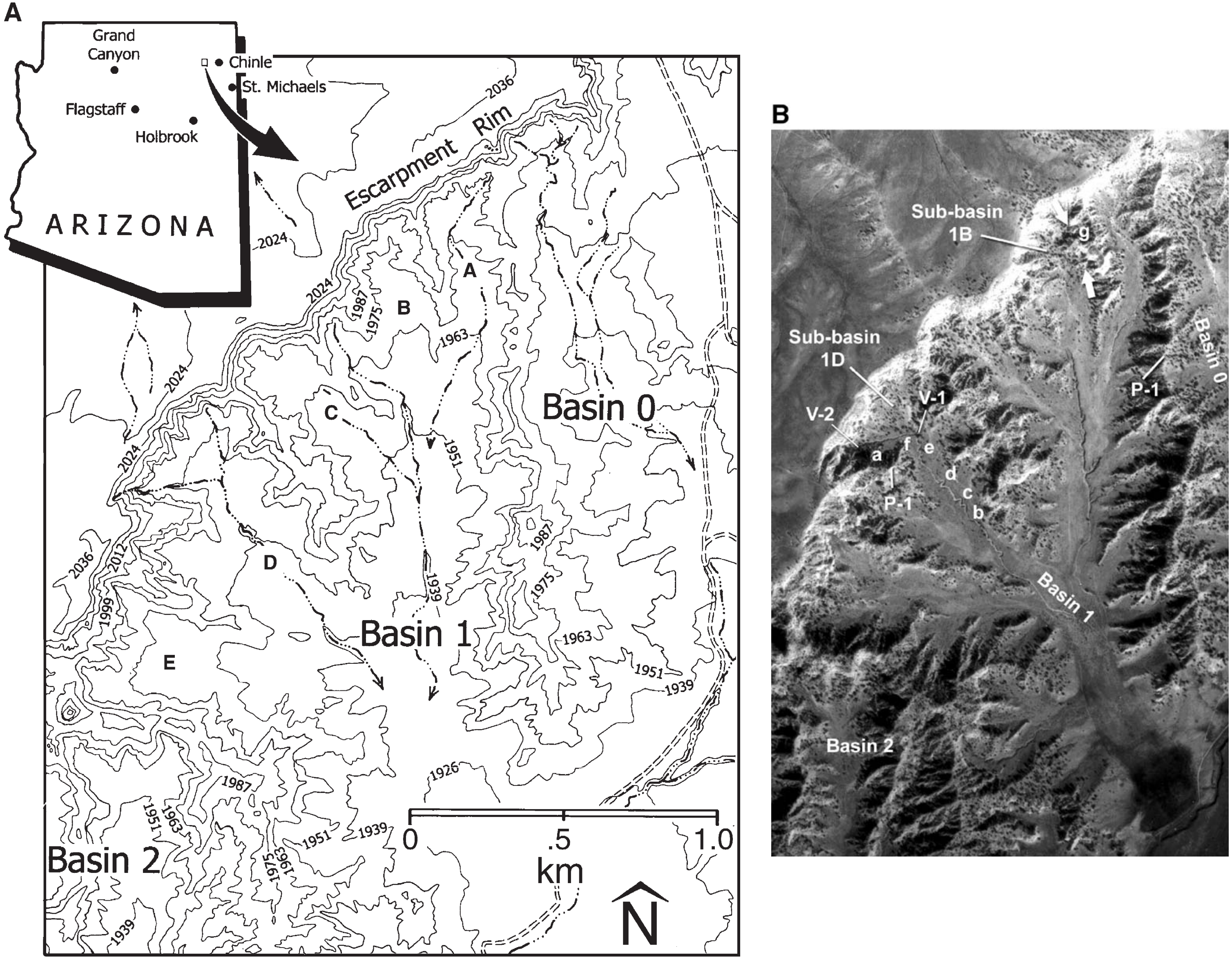

Fig. 1. (A) Map of study area and designations of basins and sub-basins; contour intervals in meters. (B) Aerial photograph of study area with labeled locations and features discussed in text.

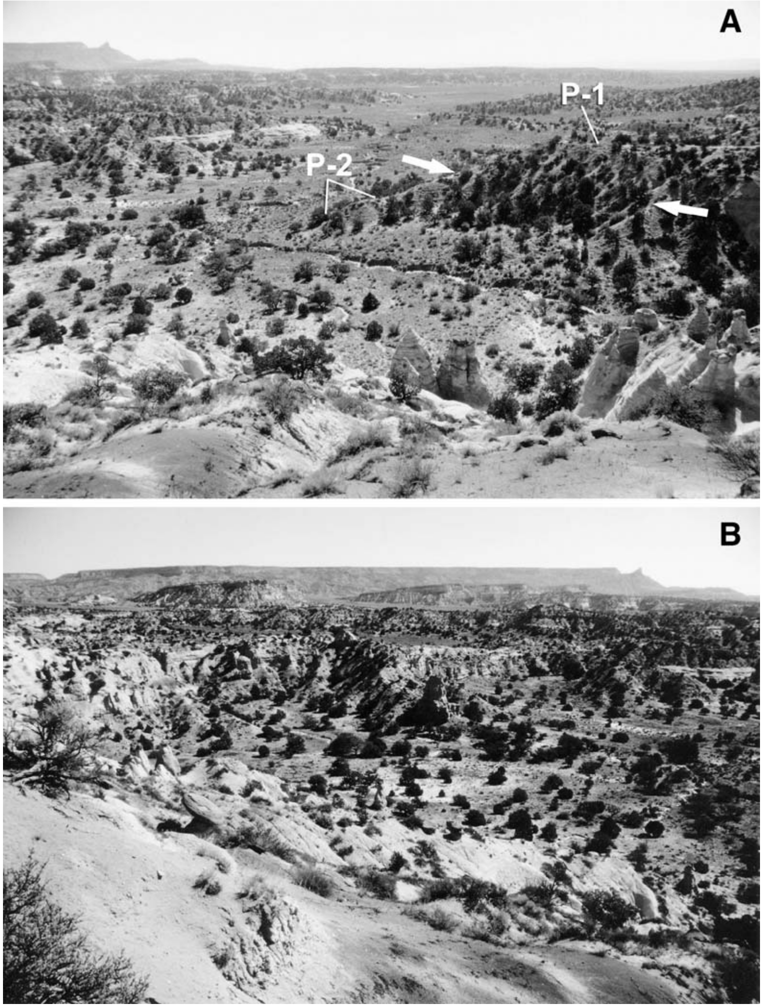

Fig. 2. (A) Overview of sub-basin 1D; view toward southeast from escarpment rim. The area between the two white arrows is the hillslope where erosion was studied (location *a* in Fig. 1B); P-1 and P-2 are ridgeline remnants of former pediment surfaces. These pediment remnants indicate past periods of valley floor stability that promoted pediment formation, punctuated by episodes of incision during which the pediment surfaces were abandoned. (B) View of southerly aspect exposures in sub-basin 1D; note predominance of barren bedrock surfaces lacking vegetation.

the hillslope and thickness, color, and morphology of soil horizons were recorded. Canopy cover of trees and shrubs on the hillslope was measured in five 200 $m^2$ circular plots on 6 October 1999 using the log-series sampling method (McAuliffe, 1991). Cover of perennial herbaceous plants in areas between widely separated tree and shrub canopies was measured in forty 0.1 $m^2$ plots placed at 2 m intervals along two 40 m transects oriented perpendicularly to the slope inclination. Those plot measurements were taken in the same area on two dates: 6 October 1999 following a year of abundant rainfall and 24 September 2002 following a lengthy, extreme drought. For each species, either the basal area (perennial grasses) or canopy area (broadleaf perennial plants) within each 0.1 $m^2$ plot was estimated visually and assigned to a cover class: Class 0: absent, no cover; Class 1: <1/16 of plot covered; Class 2: 1/16–1/8 cover; Class 3: 1/8–1/4 cover; Class 4: 1/4–1/2 cover; Class 5: 1/2–3/4 cover; Class 6: >3/4 of plot covered. Arithmetic midpoints of these cover intervals were used to calculate average cover per species.

Hillslopes with southerly aspect exposures in the upper portion of sub-basin 1B were also studied (Fig. 1B, location *g*; Table 1). The area examined was comparable in size (~1 ha) to the area of northern aspect exposures studied in sub-basin 1D. Cross-sections of trunks of dead pinyon and juniper trees located on exposed bedrock surfaces were collected for dendrochronological analyses.

Table 1
Site characteristics and geographic coordinates

| General site location (Basins 0 and 1) | 36.16°N, 109.90°W |
|---|---|
| Elevational range (basin floors to escarpment rim) | 1940–2025 m |
| Basin 1D, north-facing hillslope, location *a* | 36.1640°N, 109.9005°W |
| Basin 1B, south-facing hillslope, location *g* | 36.1713°N, 109.8924°W |
| Basin 0 baseline chronology (vicinity) | 36.1720°N, 109.8865°W |

### 3.2. Basin floor

Alluvial stratigraphy on the floor of sub-basin 1D was examined in exposures along the walls of a 1−km long incised channel that extends to the uppermost part of the basin (Fig. 1B). Buried, upright trunks of dead pinyon and juniper trees were excavated and samples of the outermost wood containing approximately 25 annual rings were used for radiocarbon dating. Increment cores (two per tree) from two living pinyon pines located next to or within the incised channel provided a more recent dendrochronological record of growth responses to episodes of alluviation and channel incision.

### 3.3. Dendrochronological analyses

Increment cores mounted in wood blocks and stem cross-sections were sanded and polished. Annual increment widths were measured under microscope magnification and skeleton-plotted to aid crossdating. In 19 of the 20 useable trees from Basin 1D, data recorded from multiple cores were used for internal cross-dating and as aid to identifying missing rings (zero-growth years). Crossdating with a regional pinyon pine chronology derived from 59 precipitation-sensitive pinyon chronologies within a 300 km radius of the study area in northeastern Arizona (Contributors of the International Tree-ring Data Bank, 2002) was used for complete identification and assignment of zero-growth years. Individual cores were standardized using a conservative linear detrending approach (Fritts, 1976; Wigley et al., 1987) and then combined to produce a chronology for each tree and a general slope chronology.

Increment cores collected in 1998 from 10 pinyon trees from relatively stable geomorphic settings in Basin 0 (Table 1) were used to construct a local, baseline chronology without the potentially confounding influence of tree responses to soil erosion and root exposure. The Basin 0 chronology was compared with the regional chronology to determine whether the Basin 0 record adequately reflected the regional climatic signal.

Anomalous growth reductions in trees from the sub-basin 1D hillslope were identified using two approaches. The first involved direct, visual, year-to-year comparisons of time-series plots of standardized increment widths for individual hillslope trees with the Basin 0 chronology. Using this approach, we could precisely identify the initiation of a growth decline in a hillslope tree that was out-of-phase with the Basin 0 tree-ring record. Times during which trees' standard growth increments were less than the Basin 0 chronology, but remained in phase with that of Basin 0 were not classified as anomalies, yielding a conservative identification of negative growth anomalies. Periods when growth trajectories were strongly out-of-phase but growth of a hillslope tree was greater, were designated as positive growth anomalies.

The second approach involved computation of year-by-year differences in standardized growth increments of individual hillslope trees and the Basin 0 chronology. Although this kind of comparison does not always indicate precisely when abrupt changes in growth trajectories began relative to the Basin 0 chronology, it provided quantitative information on the magnitude of the anomalies.

Regional dencroclimatological reconstructions and historical climate records were obtained from several on-line sources (Table 2).

## 4. Results

### 4.1. Hillslope erosion

The north-facing hillslope (Fig. 1B, location a) has an average inclination of 65% (median value of 28 measurements) and is moderately to deeply dissected by ravine-like drainages exceeding 2 m in depth (Fig.

Table 2
Climate data sources

| | |
|---|---|
| www.wrcc.dri.edu | Western Regional Climate Center; monthly total precipitation and daily record precipitation amounts |
| www.noaa.gov | NOAA United States Historical Climatology Network; daily precipitation and temperature |
| www.ncdc.noaa.gov/climate/onlineprod/drought | NOAA; data on the severity of the 2001–2002 drought |
| http://lwf.ncdc.noaa.gov/oa.climate/onlineprod/drought/main.html | Regional pinyon chronology reconstruction of annual precipitation for the last 400 yr based on Arizona Region 2 (northeastern Arizona) monthly precipitation and temperature averages |

2A). Large, old pinyon pines grow within these drainages as well as on the intervening spur ridgecrests (Fig. 3), indicating the hillslope's existing ridge and ravine topography predates the oldest trees.

#### *4.1.1. Erosion rates*

Ages of pinyons ranged from approximately 80 to 440 yr. Vertical root exposure is strongly correlated with tree age (Fig. 4). The regression slope provides an estimate of long-term, average annual vertical erosion rates (0.19 cm/yr) and the *Y*-intercept (−18.7 cm) accurately reflects the soil depth at which a young tree's first lateral roots grow. Substrate characteristics that constrain roots to this relatively shallow depth are presented in the next section.

Erosion rates were similar in different parts of the slope. There was no apparent difference in root exposure in trees from the lower versus upper halves of the slope. Root exposure was also similar in highly contrasting microtopographic settings. Most of the trees were located on planar sideslopes, but 2 trees were positioned directly on top of sharp spur ridgecrests and one was located at the bottom of a ravine-like, first order fluve (Fig. 3B). Despite the contrasting slope positions, vertical root exposure of those three trees did not deviate significantly from the average extent of root exposure (Fig. 4), indicating that hillslope retreat has been roughly parallel to the existing surface, at least over the lifetimes of the oldest trees.

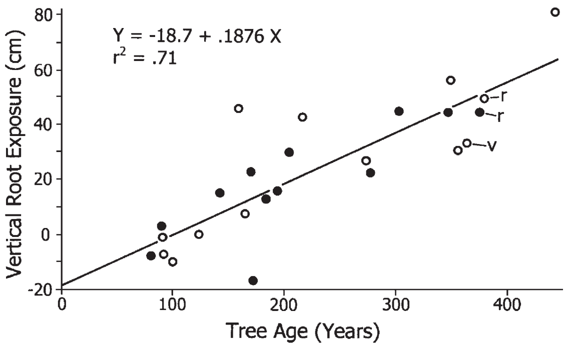

Fig. 4. Cumulative, vertical soil loss during the lifetimes of individual hillslope pinyon pine trees. Open and solid circles indicated trees on the upper versus lower halves of slopes, respectively. The two data points labeled "r" indicate trees on a spur ridgecrest; the point labeled "v" indicates a tree on the bottom of a V-shaped ravine (tree H-4, B).

Limited soil creep or erosion on higher parts of the slope has produced somewhat deeper accumulations of

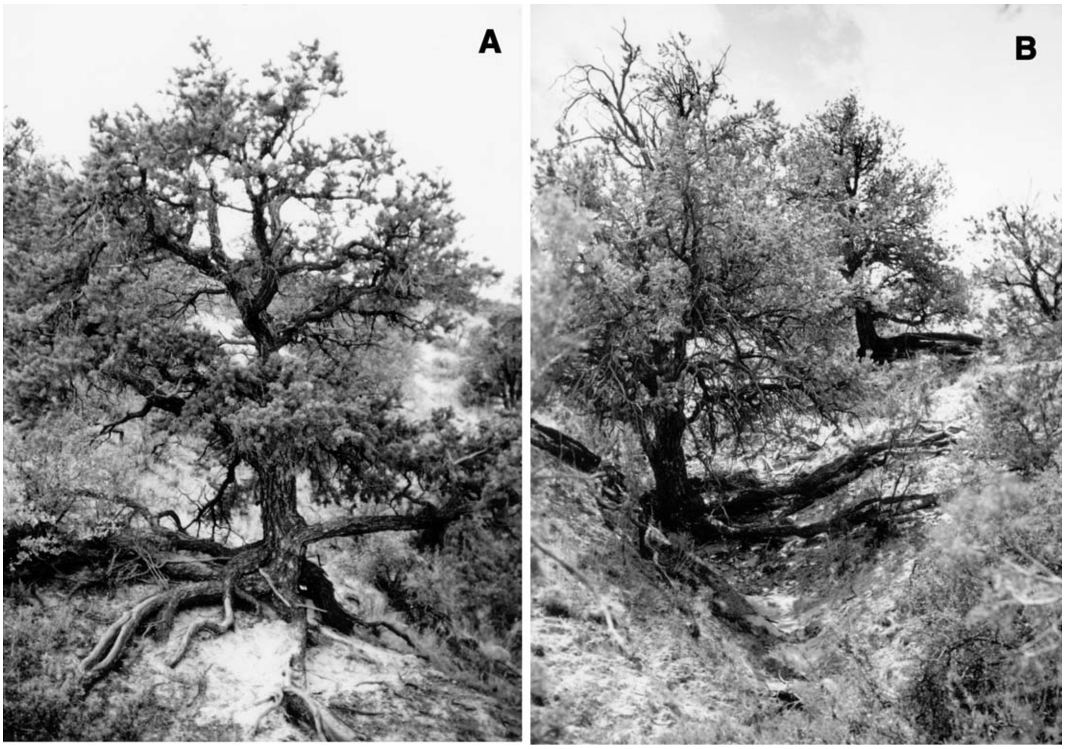

Fig. 3. (A) Hillslope pinyon pine (H-3; 302-yr-old) on planar sideslope with root exposure due to soil erosion. (B) Hillslope pinyon (H-4, 364-yr-old) rooted at bottom of a V-shaped ravine of a first-order fluve. Note considerable exposure of roots near and far from tree trunk indicating slope-parallel retreat.

soil on the upslope sides of tree trunks and apparently caused the sharp bending of the lowermost trunks of younger trees (<125-yr-old) when the trees were very young (Fig. 5A). Development of massive, laterally spreading roots prevents rotational tipping of trunks of older, larger trees on the shallow soils, but six of eight of the larger, older trees (trunks >40 cm diameter; ages 273–442 yr) also showed evidence that their lower trunks were bent when they were very young. The bent, basal sections of trunks of the oldest and youngest trees provide further evidence that movement of surface materials has occurred on this slope during the entire period of occupation by the existing trees (>400 yr).

### 4.1.2. Weathering, sediment production, and tree root distributions

The hillslope's thin soils are Entisols consisting of an A horizon directly overlying a Cr horizon and relatively unweathered bedrock (R); average depth to bedrock is approximately 20 cm (Table 3). The unweathered sandstone lacks carbonate cementation (non-effervescent in dilute HCl), but is weakly cemented by clays (principally smectite and kaolinite; Tillery et al., 2003). The Cr horizon and upper few centimeters of the bedrock contain prominent, laterally continuous fractures that are subparallel to the surface (Fig. 5B, C).

Table 3
Soil horizon depths, sub-basin 1D, north-facing hillslope

| Horizon | Depth of lower boundary | Description |
|---|---|---|
| Name | (range; mean ± 1 standard dev.) | |
| A | 2–18 cm;<br>9.1 ± 4.8 cm | Loose, noncohesive loamy sand; slightly darker than underlying horizons due to presence of organic matter. Surface with "popcorn" morphology due to shrink-swell behavior of clays. |
| Cr | 11–24 cm;<br>19.5 ± 5.8 cm | Highly weathered, intact bedrock; original bedding features are evident. Small animal burrows and root casts contain darker soil from A horizon. |
| R | | Relatively unweathered bedrock recognized by sharp increase in shear strength at boundary of Cr horizon and bedrock R (Tillery et al., 2003). |

Data from measurements taken at 11 profile excavations.

Fig. 5. (A) Relatively small, young pinyons showing evidence of limited surface creep (horizontally tipped trunks) and subsequent vertical stem growth; meter stick for scale. Tree H-10 (foreground, 90-yr-old), tree H-11 (background, 124-yr-old). (B) Excavated exposure across a spur ridgecrest located 7 m upslope from tree H-20. Note dark, continuous shrink-swell fracture sub-parallel to plane of surface. Dark body directly above the lower end of the hammer handle is a filled rodent burrow. (C) Close-up view of section showing shrink-swell fracture (f) and soil horizons.

These fractures apparently form in response to (1) expansion and contraction of clays in wetting and drying cycles, or (2) erosional removal of overlying materials and concomitant expansion owing to unloading, or, more likely, some combination of the two mechanisms. Roots of pinyons are usually no deeper than approximately 30 cm and occupy fractures within the Cr horizon, the interface between Cr and R horizons, and the upper few centimeters of the R horizon. Roots occasionally penetrate deeper vertical to subvertical fractures in unweathered bedrock, but such fractures are rare compared to the ubiquitous, surface-parallel fractures.

As soil erosion exposes older tree roots, younger roots colonize recently formed, deeper fractures. For example, erosion has exposed large lateral roots of a 165-yr-old tree (Tree H-13) on the soil surface. The largest exposed root (diameter = 7 cm) contained 144 growth rings and represents one of the tree's older roots. However, smaller lateral roots were found in deeper fractures at the boundary of the Cr and R horizons. The pith of the largest of these smaller roots (diameter = 1.7 cm) was 18 cm below the present soil surface and contained 57 growth rings. This younger, deeper root represents the recent colonization of a relatively new fracture. Occupation of these fractures by roots contributes further to mechanical and chemical weathering of bedrock as root diameters expand and organic materials accumulate.

### *4.2. Tree-ring growth anomalies and episodes of erosion*

#### *4.2.1. The hillslope tree-ring record*

The Basin 0 pinyon chronology closely matched the regional pinyon chronology compiled for 59 sites in northeastern Arizona (Fig. 6), indicating that Basin 0 trees in non-erosional settings closely tracked the regional precipitation signal. The Basin 0 chronology was therefore used as a local baseline against which growth of trees from the erosional hillslopes of sub-basin 1D could be compared. Because the Basin 0 and regional pinyon chronologies are so similar, analyses using the regional chronology as a baseline did not yield results significantly different than those presented below.

Increment growth of hillslope trees typically deviated greatly from the Basin 0 chronology. During the last 300 yr, hillslope trees exhibited three major episodes and one minor episode during which their growth declined relative to the Basin 0 chronology. All but two of the hillslope trees that germinated before 1900 A.D. showed marked declines in growth that began between 1907 and 1913 (Figs. 7, 8B, Table 4). This episode is also distinguished by the most negative quantitative growth anomaly recorded in the 400-yr record (Fig. 8C).

An earlier, major period of negative growth anomalies occurred just before 1830. All of the 12 trees that germinated before 1800 showed anomalous growth declines beginning in 1826 to 1830 (Fig. 8B). This period is marked by a corresponding, slight decline in quantitative growth anomalies (Fig. 8C). Another episode of negative growth anomalies began between 1708 and 1712 and is recorded in seven of nine of the oldest trees (Fig. 8B). This episode is also reflected by a period of moderate, negative quantitative growth anomalies beginning about 1708 (Fig. 8C). A less pronounced period of negative growth anomalies began in 1883–1884 when less than one-third (5 of 17 trees) showed anomalous growth declines (Fig. 8B). This episode, though, coincides with a relatively pronounced decline in quantitative anomalies (Fig. 8C). Another possible, but rather unpronounced episode of moderate negative growth anomalies, occurred around 1740, but is evident in only 4 of 10 trees that were present at that time.

#### *4.2.2. Precipitation, tree growth, and timing of growth anomalies*

Reconstructed mean annual precipitation (35.8 cm) for the region based on tree ring records from 1895

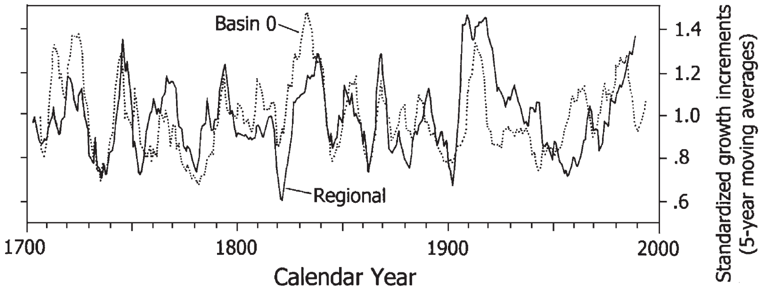

Fig. 6. Comparison of regional pinyon chronology and the chronology developed from pinyons sampled in Basin 0.

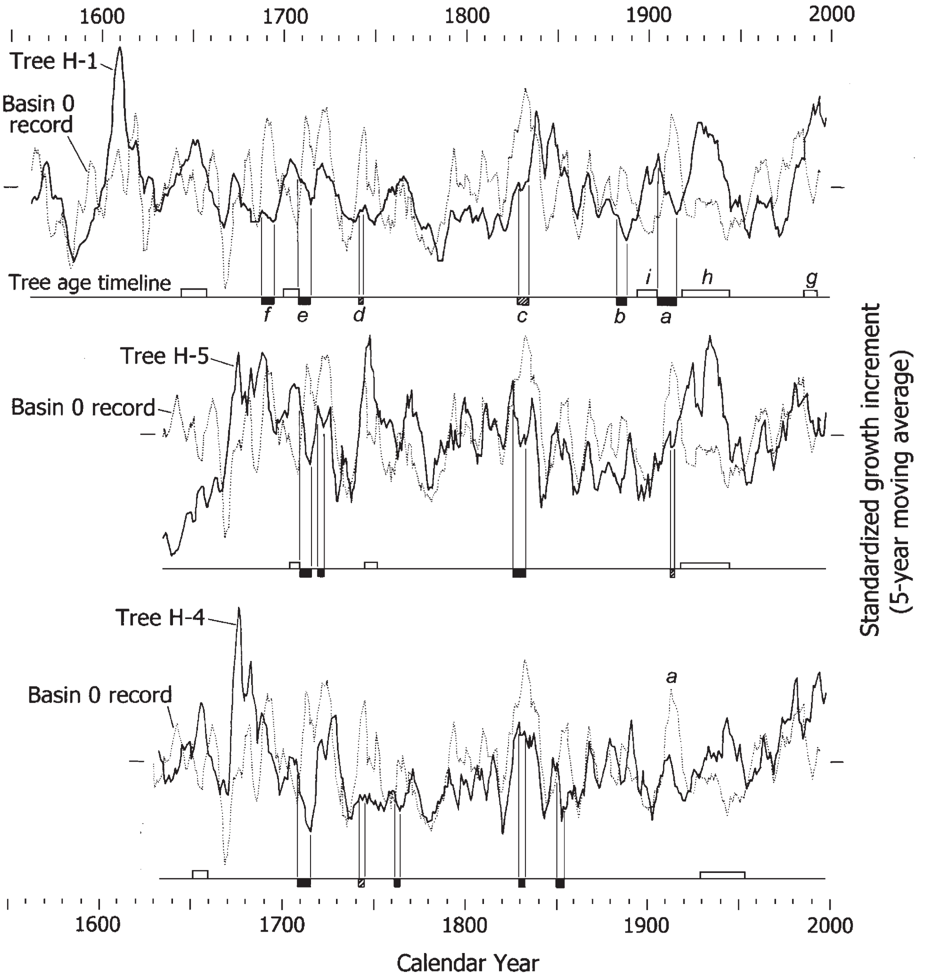

Fig. 7. Standardized growth increments of three hillslope pinyons (solid lines), each plotted against Basin 0 chronology (dotted line). *Top:* Tree H-1; pronounced episodes when tree growth declined relative to that predicted by the Basin 0 chronology (intervals *a, b, e, f*). Minor growth declines designated as intervals *c* and *d.* These intervals are represented as black and shaded bars (major and minor negative growth departures, respectively), below the line representing the tree's lifetime. Periods of time during which the tree showed positive departures are indicated by white bars above the line. *Middle:* Tree H-5. The early 1900s shows lower growth than predicted by the Basin 0 chronology. However, no pronounced, strongly out-of-phase decline in growth of tree H-5 occurred, with the exception of a very minor decline. *Lower:* Tree H-4. Although increment widths in this tree are below that predicted by the Basin 0 chronology from approximately 1910–1920, it is not out-of-phase with the Basin 0 baseline. Therefore this period is not designated as one in which an anomalous decline occurred as in tree H-1, above. The requirement for growth trajectories of hillslope trees be out-of-phase with those of Basin 0 (i.e., an anomalous growth decline when Basin 0 shows growth increases) provides a conservative designation of periods of anomalous, depressed growth. Only periods with severe departures from the expected growth pattern are designated as significant, negative growth anomalies.

through 1990 (Contributors of the International Tree-ring Data Bank, 2002) compares well with instrumental records for Region 2 in Arizona (36.8 cm) for the same period. The regional precipitation reconstruction indicates that during the past 400 yr there have been marked intervals of below-average and above-average precipitation (Fig. 8A).

One of the driest 5 yr intervals of the entire precipitation reconstruction was from 1900 through 1904 (annual average = 29.2 cm) and was soon followed by the wettest 5 yr interval from 1907 through 1911 (annual average = 45.3 cm/yr). Instrumental records also document this abrupt precipitation shift. Initiation of negative growth anomalies of Basin 1D hillslope trees from 1907 to 1913 (Table 4) began after this abrupt transition in precipitation (Fig. 8B). Whereas growth of trees in stable landscape settings (Basin 0) increased in response to the greater precipitation, the abrupt decline

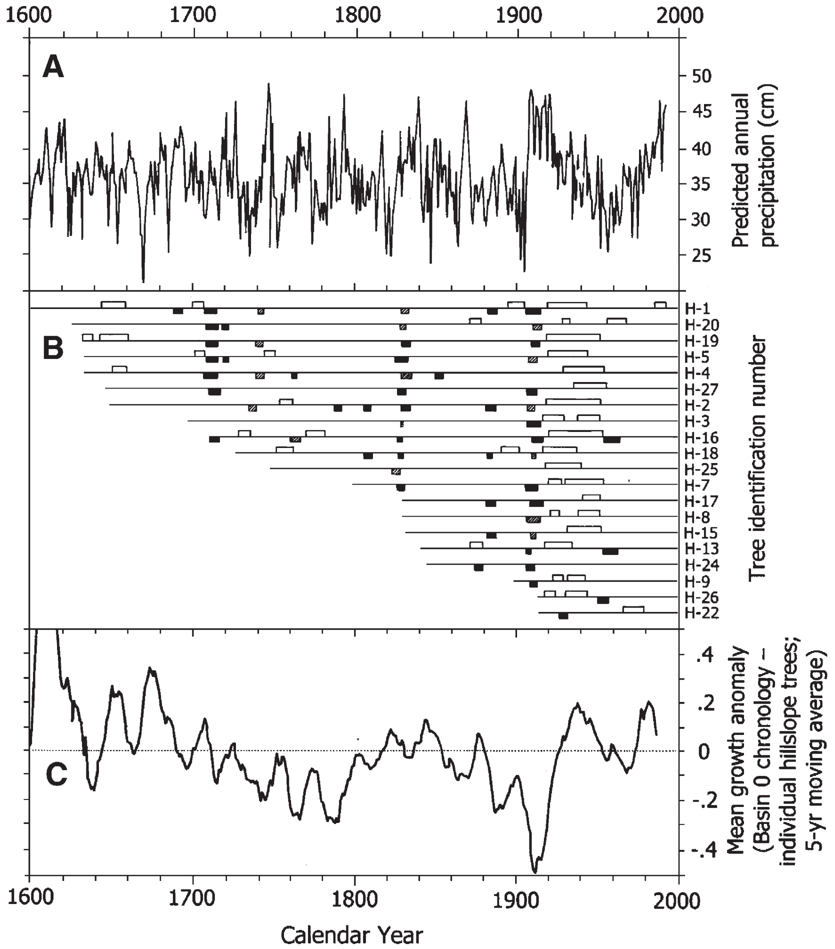

Fig. 8. (A) Reconstruction of annual precipitation (October–September hydrological year) based on regional pinyon chronology for northeastern Arizona (yearly data and 5-yr moving averages are plotted). (B) Major and minor intervals of depressed incremental growth (dark and shaded bars, respectively) and periods of positive growth anomalies (white bars) plotted on horizontal lines representing the lifetimes of individual hillslope trees (see Fig. 7 for description of derivation of these intervals). (C) Quantitative growth anomalies calculated by subtraction of the standardized increment width of individual hillslope trees (5-yr moving averages) from the 5-yr moving average of the Basin 0 chronology. The mean growth anomaly for all of the hillslope trees is plotted.

in growth of sub-basin 1D hillslope trees is attributed to stress caused by aerial root exposure due to soil erosion. The negative growth anomalies in the early 1900s are followed by a period lasting up to 25 yr during which trees exhibited positive growth anomies attributed to the compensatory growth of new roots after the earlier episode of root exposure stress.

Considerable precipitation in summer to early fall, 1907 could have triggered substantial hillslope erosion and the subsequent root exposure stress. Daily records for Holbrook and St. Michaels show frequent monsoonal inputs from mid-July through August, 1907. Large events on 20 and 29 August (26, 29 mm, respectively) were recorded at St. Michaels and represent record amounts for those dates. Similarly large precipitation events were not recorded, however, at Holbrook, a pattern consistent with the considerable spatial heterogeneity of summer monsoonal precipitation.

In October 1907, several multi-day precipitation events occurred, some of which may represent incursions of tropical Pacific cyclonic storms. The first began on 3 October and delivered a total of 30 mm precipitation in Holbrook in 2 days and 28 mm in St. Michaels in 3 days. Less than 2 weeks later, a second storm from 15 to 19 October delivered 26 mm of rainfall to Holbrook. (Only 1 mm was recorded at St. Michaels on 17 October, but the lack of precipitation data for this period may reflect failure to record, since temperature data were missing from the St. Michaels record for this period). A third storm hit the region on 23–24 October. St.

Table 4
Year of initiation of negative growth anomalies in sub-basin 1D hillslope trees, based on year-by-year comparisons of standardized increment measurements with the Basin 0 baseline chronology

| Year of initiation of anomalous growth decline | Number of trees |
|---|---|
| 1907 | 3 |
| 1908 | 6 |
| 1909 | 4 |
| 1910 | 0 |
| 1911 | 1 |
| 1912 | 1 |
| 1913 | 1 |

Michaels received 19 mm precipitation on these 2 days; Holbrook received 14 mm on 23 October (data missing for 24 October). Heavy precipitation during October was regional and was recorded in stations as far away as Flagstaff and Grand Canyon National Park (190 km west; Fig. 1A).

### 4.2.3. Impacts of recent drought on vegetation

For 3 yr starting in September 1999, monthly precipitation for all but 2 months were average to far below normal (Chinle records). By March 2002, Palmer Drought Severity indexes computed for Arizona Division 2 (northeastern Arizona) indicated severe drought (index values less than −4). This drought significantly affected perennial vegetation on the slopes. In areas between widely spaced trees and shrub canopies, perennial vegetation cover was significantly higher in 1999 than during drought conditions of 2002 (8.2% vs. 2.1% cover, *t*-test: $t=3.67$, $p<.001$). In 1999, perennial vegetation cover was completely absent in only 7 of the 40 plots, but in 2002, 27 of 40 plots lacked any vegetation cover (contingency test, $X^2=22.04$, $p<.001$; Table 5B).

The frequency of occurrence of live perennial grasses was much lower in 2002 than in 1999 (Table 5B) because of recent mortality. In 2002, dead perennial grass plants outnumbered live ones by a margin of more than two to one. Dead grass plants had all apparently expired within the year preceding the September 2002 sampling date, as indicated by the presence of dead leaves that remained from growth during the previous year (2001). Dead perennial grass plants included both C$_3$ (cool season) and C$_4$ (warm season) species. Herbaceous perennial plants were conspicuously absent from the September 2002 sample (Table 5B), reflecting an inability of plants to initiate vegetative growth from any below-ground plant parts that may have survived. Drought conditions continued through 2004. By March 2004, two large pinyon trees (52 and 32 cm trunk diameters) and many sagebrush plants (*Artemisia tridentata*) within the hillslope study area had also died, indicating that extreme, prolonged drought is also capable of eliminating larger woody shrubs and trees.

### 4.2.4. Erosion of south-facing hillslopes

Exposed bedrock with very thin, discontinuous regolith predominates on southerly slope exposures of Basin 1B (location *g*, Fig. 1B, Table 1; Fig. 9A). Dead remains of 22 large juniper and 11 pinyon trees were distributed across these slopes. Many of the dead trees

Table 5
Vegetation data from north aspect exposure, Basin 1D

(A) Data from 200 m$^2$ circular plots on large woody species (6 October 1999)

| Species | Canopy cover (percent of soil surface) (%) |
|---|---|
| *Pinus edulis* | 17.4 |
| *Amelanchier utahensis* | 3.4 |
| *Purshia stansburiana* (=*Cowania mexicana* var. *stansburiana*) | 6.6 |
| *Fendlera rupicola* | 1.9 |
| Others (4 species) | 0.4 |
| Total canopy cover | 29.7 |

(B) Data from 40 to 0.1 m$^2$ plots taken before and after extreme drought

| | Frequency of occurrence (number of plots in which each species occurred) | |
|---|---|---|
| | Oct. 1999 | Sept. 2002 |
| Perennial grasses | | |
| *Bouteloua gracilis* | 1 | 1 |
| *Mulhenbergia pungens* | 2 | 1 |
| C$_3$ grasses (*Stipa, Oryzopsis*) | 11 | 1 |
| Herbaceous perennials | | |
| *Artemisia ludoviciana* | 13 | 0 |
| *Astragalus ceramicus* | 8 | 0 |
| *Hymenopappus filiformis* | 4 | 0 |
| *Penstemon* sp. | 3 | 0 |
| *Thelesperma subnudum* | 3 | 0 |
| Small suffrutescent perennials | | |
| *Leptodactylon pungens* (Polemoniaceae) | 1 | 3 |
| *Machaeranthera grindeliodes* var. *depressus* (Asteraceae) | 3 | 1 |
| Plots lacking any vegetative growth | 7 | 27 |

were located on bare rock surfaces and their root systems were completely exposed, indicating that the soil/regolith mantle originally occupied by the roots had been completely stripped since the trees originally established and reached adult size (Fig. 9B).

Cross-sections of 8 dead juniper trees and one dead pinyon from this slope could be crossdated. The trees had establishment dates ranging from the early 1200s to the mid 1700s. Two junipers had outer dates (estimated years of death) of 1625 and 1797, but the remainder of the junipers died between 1860 and 1917. The pinyon germinated in 1765 and died in 1890. The many dead trees with completely exposed root systems on bare bedrock, especially those that established within the last 400 yr (the equivalent duration of the tree-ring record from the northerly Basin 1D exposures), indicate that, in marked contrast to the more mesic, northerly exposures, rates of erosion on the south-facing hillslopes have generally exceeded rates of weathering and formation of regolith and soils. This has led to increases in barren bedrock surfaces on southern exposures and the extensive mortality of large trees.

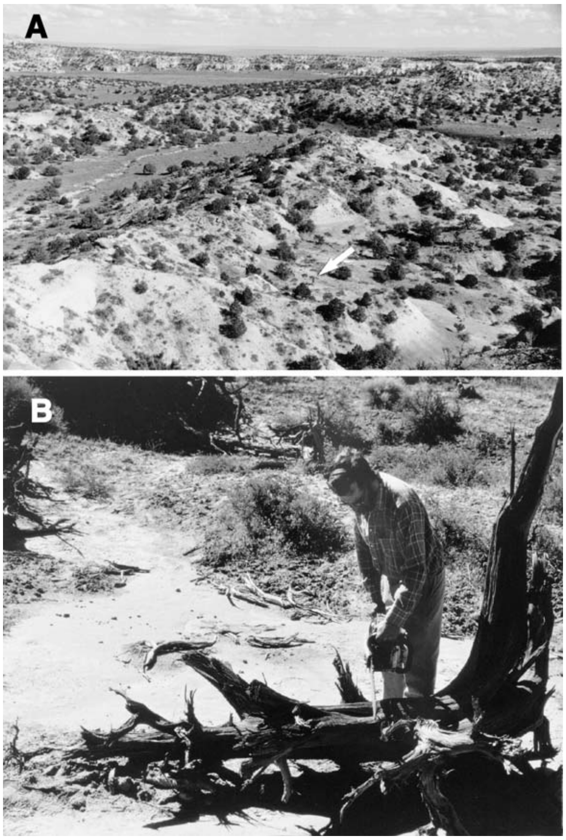

Fig. 9. (A) Portion of denuded, south-facing hillslopes in upper part of Basin 1B. Arrow indicates dead juniper shown in photograph below (12B). (B) One of the dead juniper trees found on Basin 1B slopes; this tree germinated in A.D. 1380 and died in A.D. 1797.

### 4.3. Valley floor deposits

#### 4.3.1. Basin floor stratigraphy and chronology

Five alluvial deposits (Units 1–5) were identified on the valley floor of Basin 1D. At location *b* (Fig. 1B), the upper boundary of Unit 1 is 2.3 m below the valley floor; the thickness of this unit is unknown (Fig. 10). The uppermost part of Unit 1 contains a soil that exhibits incipient Bw horizon development. The top of Unit 2, a 1.3 m thick deposit, also bears a weakly developed soil (A-Bwk horizons). The upper horizons of this soil are distinctly redder (7.5 yr 6/3) and finer-textured than the bulk of underlying sandy sediments of this unit (Figs. 10, 11A, B). The distinct soil at the top of Unit 2 can be continuously traced well up the arroyo from the vicinity of locations *b* to *f* (Fig. 1B) indicating Unit 2 once formed the surface of the valley floor. Calibrated radiocarbon dates of the outermost wood of pinyon and juniper trunks buried by Unit 2 alluvium (pinyon: A.D. 1300, $\pm 2\sigma$ range = A.D. 1240–1430, Beta-169825; juniper: A.D. 1420, $\pm 2\sigma$ range = A.D. 1320–1440, Beta-157062) show that that Unit 2 and all younger units were deposited during the last 700 yr.

Unit 3 is a 1 m thick deposit with a weakly developed soil and has formed most of the valley floor for perhaps as long as a few centuries. Pinyon V-1 is located 1.7 m from the edge of the arroyo (Figs. 1B, 11A, B) and channel incision has exposed major roots of this tree. Those roots project horizontally from the buried soil of Unit 2, 20–50 cm below the surface of that unit. The tree originally germinated and grew on the surface of Unit 2 before the lower part of the trunk was buried by Unit 3 alluvium (Fig. 10). Increment cores taken from the trunk 45 cm above the soil surface contained 235 annual rings. Since the increment cores were taken nearly 1.5 m above the surface (Unit 2) on which the tree germinated, the tree's age is probably is close to 300 yr, constraining the timing of deposition of Unit 3 to less than that age. The 65 yr estimated for the tree to reach 1.5 m height is based on ages of two pinyons from a similar valley floor environment located 45 km away (Qa2 surface of McFadden and McAuliffe, 1997). Those trees (heights = 2.25 m, 3.50 m; trunk diameters = 19 cm, 18 cm) were both approximately 125-yr-old. These trees and those on the sub-basin 1D valley floor are so slow-growing because their roots probably seldom, if ever, reach the water table; therefore they depend on mostly shallow, limited moisture that is derived from infiltration of incident precipitation, surface runon or, when nearby

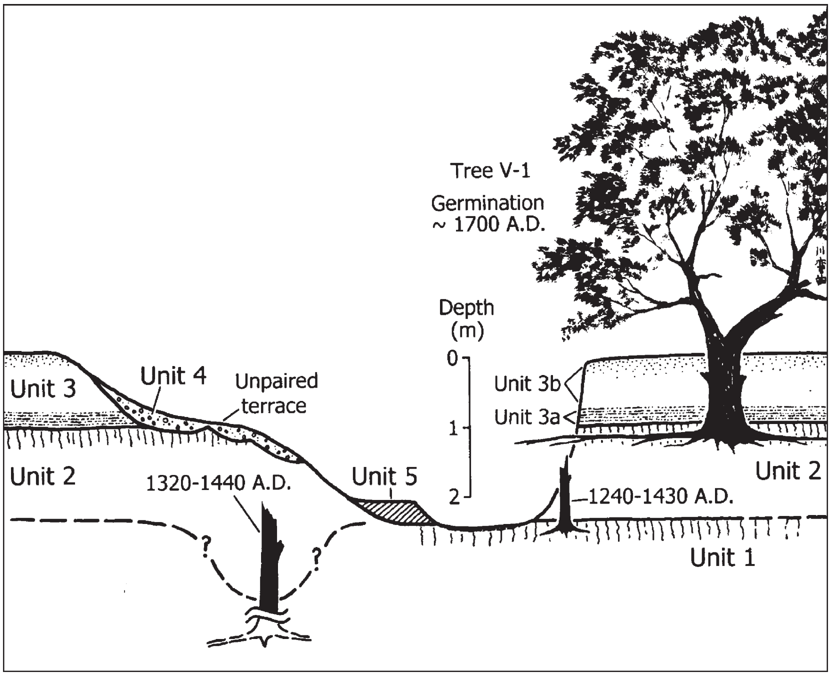

Fig. 10. Generalized cross-section of valley floor stratigraphy in Basin 1D based on studies from locations *b* to *f* (Fig. 1B).

channels are incised into the valley floor, lateral infiltration of stream channel discharge.

Unit 4 deposits are exposed in cut banks of the largest meander bends of the modern arroyo (locations *c* and *d*, Fig. 1B). This unit represents the backfilling of a channel cut into the valley floor through Unit 3 and into the uppermost 20 cm of Unit 2. The top of Unit 4 is approximately 40 cm below the surface of the valley floor at locations *c* and *d* (Fig. 1B). Unit 4 contains sandy to coarse gravelly alluvium with occasional large clasts (up to 8 cm diameter), indicating channel-confined transport of relatively coarse materials derived directly from the hillslopes. The unconformity between Unit 4 and underlying deposits is broadly scalloped, showing former positions of a deepening and laterally migrating, confined channel. A broad, nearly level, unpaired terrace remnant approximately 1.0–1.2 m above the level of the current channel that is associated with Unit 4 reflects the initial incision of the valley floor as noted above. Development of this terrace indicates a brief period of channel floor stability prior to renewed incision to the present channel depth (Fig. 10). Unit 5 consists of berms and other recent alluvial deposits associated with the modern active channel; surfaces of these deposits are elevated approximately 45–50 cm above the channel floor.

Steeply inclined fan aprons at the base of the north-facing hillslope in Basin 1D issue forth from the ravine-like drainages in that slope. The main valley floor has a slope of 5% but the slope of the fans directly beneath the hillslope is 13%. Near the base of the hillslope, the fan sediments bury the lower parts of trunks of living juniper trees by a meter or more. The fans thin in distal locations and stratigraphic exposures along the incised channel in the valley floor show the fan deposits overlie Unit 3, the unit that forms the present valley floor in more distal locations (Fig. 1B).

### *4.3.2. Dendrochronological reconstruction of recent alluviation and incision*

Tree-ring records from pinyons V-1 and V-2 provide a detailed record of valley floor behavior during the last 2 1/4 centuries. In the vertical stratigraphic exposure next to tree V-1, the lower 32 cm of Unit 3 consists of 5 relatively fine-grained, upward-fining deposits (Unit 3a, Figs. 10, 11B). This tree germinated on the surface of Unit 3 and the subsequent delivery of water associated with the repeated deposition of this fine-grained alluvium likely increased the local supply of plant-available moisture and produced the sharp spike of positive growth anomalies from about A.D. 1785 to 1800 (Fig 12).

The upper 65 cm of Unit 3 (Unit 3b) consists of coarser, sandier alluvium and weaker horizontal stratification, indicating rapid, uninterrupted deposition (Figs. 10, 11B). Roots of tree V-1 that originally grew

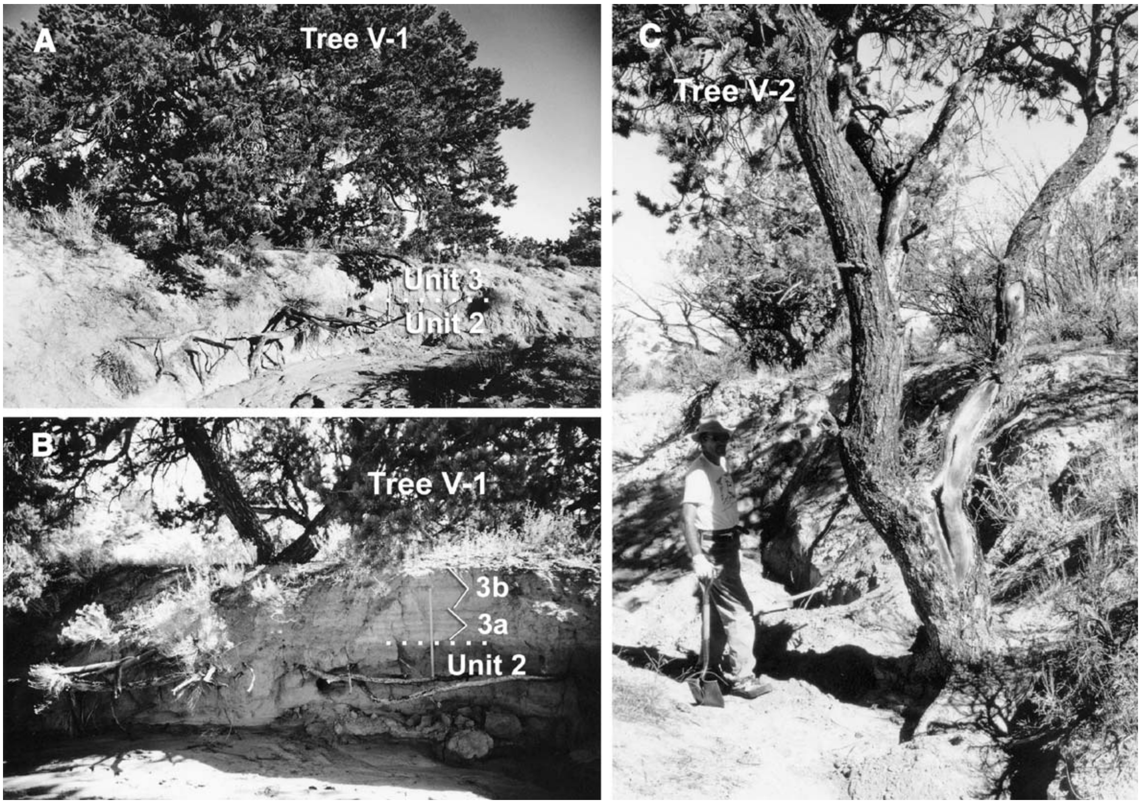

Fig. 11. (A) Tree V-1 with roots in Unit 2 exposed by incised channel. The exposed roots project from the vertical arroyo wall at a vertical depth of 20–50 cm below the surface of Unit 2 and 120–150 below the surface of the present valley floor. (B) Close-up view of vertical exposure along incised channel next to Tree V-1. Unit 3a consists of thin, multiple, upward-fining deposits whereas Unit 3b is a sandier deposit with weaker stratification, indicating more rapid, uninterrupted deposition. (C) Pinyon tree V-2. L.D. McFadden (height = 1.93 m) standing to left; note lack of branches on lower 3 m of trunk. The upper 60 cm depth of the terrace behind the tree consists of the highly inclined, sandy fan deposits derived from the nearby, north-facing hillslopes. In this proximal location, these fans lie on top of alluvial Unit 3.

20–50 cm below the surface of unit 2 when the tree was young were eventually buried more than 120 cm deep after unit 3B was deposited, well below the depth to which most surface moisture typically can percolate in this semi-arid environment. This reduction in delivery of moisture to the tree's roots probably caused the abrupt decline of incremental growth and the strongly negative growth anomalies that persisted for approximately 30 yr (~1794–1825). Slight negative growth anomalies persisted in this tree until shortly after A.D. 1900. This detailed tree ring record indicates that deposition of Unit 3 alluvium occurred at a time of heavy precipitation during the 1780s through the 1790s following a multi-year drought that occurred from about 1775–1780 (Fig. 8A).

The lengthy period of negative growth anomalies in tree V-1 ended abruptly after A.D. 1900 with a 20–30 yr long spike of positive growth anomalies (Fig. 12). Incision of the valley floor through Unit 3 and into the uppermost 20 cm of Unit 2 (Fig. 10) and lateral infiltration of confined channel flows at or below the surface of Unit 2 at the level of roots of tree V-1 would have produced the growth surge. Subsequent channel backfilling and deposition of Unit 4 alluvium probably did not diminish growth because that unit did not completely fill the previously incised channel, allowing channel-confined transport to persist, thereby continuing to supply roots of treeV-1 with abundant water. The episode of enhanced growth in tree V-1 ended abruptly around 1930, indicating that renewed entrenchment to the depth of the present-day channel left the tree's root system exposed in the arroyo wall, well above the level of confined channel flows (Figs. 10, 11A) but below the level to which most incident precipitation received on the valley floor could percolate.

Growth responses of a second pinyon pine located upstream (tree V-2; location shown in Fig. 1B) are generally opposite of those of tree V-1, especially during the last 100 yr. Instead of having originally established on a relatively high valley floor as did tree V-1, tree V-2

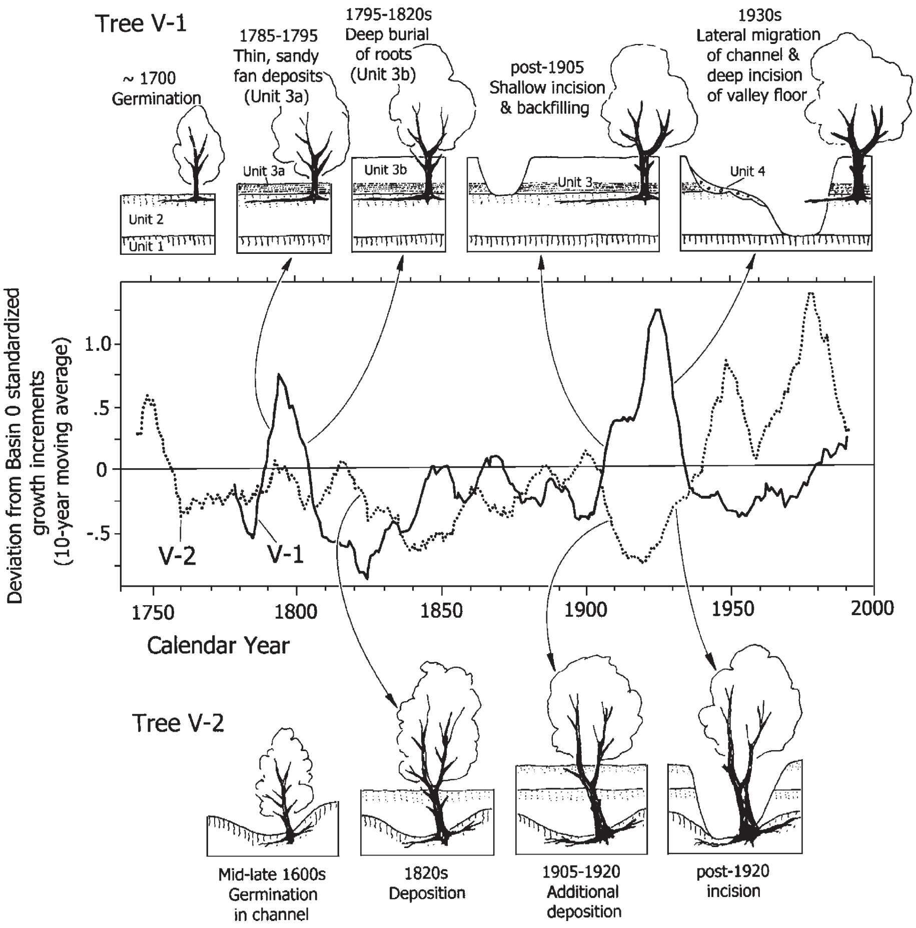

Fig. 12. Diagrammatic representations of depositional and incisional events that contributed to growth anomalies in basin floor pinyon trees V-1 (top) and V-2 (bottom). The central panel shows quantitative growth anomalies for the two trees (V-1 = solid line; V-2 = dotted line).

germinated in the mid-late 1600s in a wide, former channel at approximately the same elevation as the floor of the modern incised arroyo (Figs. 11C, 12). After the tree reached a relatively large size, the lower portion of its trunk was buried by at least 2 m of alluvium. The anomalous absence of branches on the lower 3 m of the forked trunk (Fig. 11C) provides evidence of this partial burial (i.e., smaller branches were killed when they were buried). That partial burial situated the roots in an effectively drier soil environment due to the limited percolation of moisture to the greater depth and the absence of channel-confined flows. Multiple depositional episodes may have occurred that progressively buried the roots at increasing depth, thereby producing several distinct periods of anomalous growth declines starting around 1750, 1820, and between 1900 and 1920 (Fig. 12). The growth decline in the first decades of the 1900s is synchronous with the 1907–1913 period when sediments were apparently eroded from the nearby north-facing hillslope. After 1920, incision of the modern channel to the level at which the tree originally germinated restored the roots to a far more favorable depth in terms of the receipt of soil moisture. The roots were once again positioned shallow enough to take advantage of infiltration of incident precipitation and, perhaps more importantly, moisture from the lateral infiltration of water from occasional channel discharge.

## 5. Discussion

Multiple lines of evidence (tree-ring records, root exposure, rapidity of weathering and sediment production) indicate that episodic sediment losses from the hillslope we studied have occurred at intervals of 80–120 yr during the last several centuries. Decadal changes in precipitation regimes, most notably shifts from multi-year droughts to wet intervals, apparently triggered those erosion episodes. During the last 300 yr, two of three major episodes of negative growth anomalies in hillslope trees occurred after abrupt transitions from prolonged, multi-year droughts to sustained, lengthy periods of above-average precipitation. The post-1905 episode of negative growth anomalies in hillslope trees was associated with the largest precipitation shift in the last 400 yr. An earlier, pronounced episode of negative growth anomalies in the 1820s also followed a precipitation shift from dry to wet that was nearly as great. The periods of anomalous, diminished growth in hillslope trees is most plausibly explained as the consequence of rapid exposure of roots by erosion at the onset of the wet climatic intervals. In contrast, increment growth of trees in non-eroding landscape positions (Basin 0) closely tracked the regional precipitation signal.

Erosion from the north-facing hillslope in sub-basin 1D would have been limited to the unconsolidated materials of the A horizon and underlying Cr horizon. In 2001, the combined thickness of those two horizons averaged about 20 cm. Approximately 100 yr have elapsed since the last major erosional episode indicated by negative tree growth anomalies. The existing, ~20 cm deep soil on these slopes may resemble the soils that were present immediately before past major erosional episodes spaced at approximately century intervals.

The two major alluvial fills (Units 3 and 4) that were deposited during the lifetimes of trees on the valley floor are best explained as stream channel responses to abrupt changes in precipitation regimes and the associated delivery of runoff and sediments from slopes. The timing of growth anomalies of tree V-1 on the valley floor (Fig. 12) suggests that valley floor incision was caused by increased runoff associated with the abrupt precipitation shift after 1904. The newly incised channel backfilled soon thereafter to within 40 cm of the valley floor. The coarse-grained texture of the backfill sediments strongly suggests that they were derived from the hillslopes and transported by confined channel flow, rather than by erosion and redeposition of finer-grained, valley floor sediments during unincised channel flow. Because the alluvium did not completely fill and overtop the incised channel, subsequent discharges were confined to the original width of the incised channel, favoring erosion of the bulk of Unit 4 alluvium as the channel deepened and increased in meander sinuosity. In addition to contributing to the backfilling of the channel (i.e., Unit 4), a substantial part of the sediments eroded from the north-facing hillslope during this period was deposited as relatively steep, slope apron fans.

Although no identifiable valley fill can be unambiguously linked to the 1820s precipitation shift and associated hillslope erosion, a pronounced, anomalous decline in growth of tree V-2 from the 1820s through 1840 (Fig. 12) indicates that sediments removed from the hillslope at that time accumulated and filled the channel near the base of the slope where this tree is located.

Although a pronounced precipitation shift occurred in the early 1780s, hillslope trees do not exhibit negative growth anomalies indicative of severe erosion (Fig. 8B). Nevertheless, growth of tree V-1 on the valley floor indicates that deposition of Unit 3 began at that time (Fig. 12). That depositional episode came within ~40 yr of two previous episodes of negative growth anomalies in hillslope trees (~1710, 1740; Fig. 8B) and it is possible that sediments removed from the slopes at that time originally accumulated and were temporarily stored in slope apron fans that subsequently yielded sediments contributing to the deposition of Unit 3.

The largest alluviation episodes recorded in basin floor stratigraphy are Units 2 and 3 and also probably Unit 1. Unit 2 was deposited around 700 yr ago; Unit 3 was deposited in the early 1800s. Within the last several centuries, sub-basin 1D has apparently made a transition from one of repeated depositional events on the valley floor to a predominantly incisional mode as the overall supply of sediments has been progressively reduced by sustained erosion on slopes with southerly exposures. Erosional episodes on the north-facing hillslope constitute transient changes due to the relatively rapid weathering of materials and the production and retention of new soils. In contrast, on the drier southerly exposures, the lower weathering rates (Churchill, 1982; Burnette, 2004) cannot compensate for high rates of erosion that have probably occurred throughout the Holocene. Consequently, the exposure of bedrock on the southerly exposures is apparently largely irreversible under the modern climate regime.

Today, the southerly exposures in Basin 1B consist largely of exposed bedrock (Fig. 2B); only thin, discontinuous patches of non-cohesive, sandy regolith remain in these areas. The widespread occurrence of dead trees on those denuded slopes indicates the progressive loss of soil mantles during the lifetimes of the trees. The denuded slopes would have yielded considerable runoff relatively devoid of sediment during the wet period of 1905–1915. The increased competency of the channel discharges produced by this presumably more sediment-poor runoff could have triggered the initial incision in distal valley locations (i.e., location of tree V-1) at the same time the very limited, proximal location directly below the north-facing hillslope experienced aggradation because of the locally abundant supply of sediments on that slope. Much sediment removed from the north-facing hillslope at that time apparently accumulated and remained at the foot of the hill in a steeply inclined fan apron. Because of the high permeability of the sandy sediments, those fan deposits probably inhibited further runoff and delivery of sediments to more distal locations on the valley floor.

The recent behaviors and current state of valley floors of various sub-basins in Basin 1 differ considerably (Tillery et al., 2003). Two possess long, continuous, entrenched arroyos (sub-basins 1B and 1D), one has discontinuous, less deeply entrenched channels (1A) and two almost entirely lack any kind of incision by major channels (1C and 1E) (Fig. 1B). In stark contrast to the modern incision of sub-basins 1B and 1D, the floor of basin 1C has experienced considerable recent aggradation, as indicated by partially buried, living trees throughout the entire valley floor. Differences among the sub-basins in the ratio of hillslope area with exposed bedrock versus hillslope area covered by highly weathered regolith may be a major determinant of the variable behaviors and requires more detailed study.

Elsewhere on the Colorado Plateau, Hereford (2002) related contrasting modes of valley floor behavior (aggradation vs. incision) to variation in flood frequency and intensity associated with the Little Ice Age (LIA; ~1400 A.D. to mid-late 1800s; Grove, 1988) and suggested that variation in the erosion of sediment and production of runoff from hillslopes was also related to variation in climate before, during, and after the LIA. In our study area, the most recent, large event involving hillslope erosion and an associated channel response was the post-1905 episode of erosion that clearly post-dates the LIA. Yet, that erosion event was preceded at least twice in the previous few centuries by similar events during the last half of the LIA. Therefore, we conclude that in our study area, variation in the production and erosion of sediments from slopes cannot be interpreted principally as a response to climate changes associated with the LIA, at least with those that occurred in the last half of this period and during the LIA to post-LIA transition. Multiple factors that control the production of sediments on slopes, including lithological controls of weathering and responses of vegetation must be clearly understood before hillslopes can be realistically linked to the behavior of the rest of the fluvial system.

Schumm (1977, 1991), Patton and Schumm (1981) and others clearly recognized the role of major climatic change as drivers of erosional and depositional events, but have generally downplayed the impact of minor climate change within the Holocene as a significant driver of fluvial system behavior. The results of our work contrast this view with evidence of how even decadal variation in precipitation has exerted a major control on the timing of erosional and depositional events within Basin 1D. This study shows that in some landscapes associated with particular lithologies, slope aspect, and vegetation, some changes in fluvial system behaviors that might be attributed to internal system adjustments (i.e., *complex response*) may actually be driven by decadal shifts in precipitation regimes. However, the identification of these more subtle influences of minor climate variability requires high-resolution dating of past fluvial events coupled with precipitation records (instrumental or proxy) such as tree-ring records.

Although climatic drivers of fluvial system changes versus complex response have sometimes been presented as mutually exclusive explanatory models (e.g., Hereford, 2002), the existence of one mode of operation does not preclude the other. A challenge in fluvial geomorphology is not to elevate one or the other, but rather determine accurately the extent to which each type of scenario contributes to various responses by a fluvial system, and the timing of those responses. For example, the variable behavior of the valley floor of Basin 1D in the 1–2 decades after 1905 (including incision, backfilling, and progressive downcutting) is best represented by an initial response to a climatic perturbation followed by internal adjustments (i.e., a type of complex response) that drove the backfilling and subsequent incision of the confined channel. The unpaired terrace remnants capped by Unit 4 alluvium are the same kinds of terraces attributed to this kind of complex response that produces a deepening and laterally migrating channel (Schumm, 1991). The potentially complicated relationships between phenomena occurring on hillslopes and on valley floors are most clearly resolved through detailed study of small-order basins (McFadden and McAuliffe, 1997; McAuliffe et al., 2001). Furthermore, such investigations are needed to better understand the behavior of much larger-order streams because the collective area of small upland tributary basins contributes a disproportionately large amount of runoff and sediments to the rest of the fluvial system (Lagasse et al., 1990).

In our study area, the high-resolution dating provided by tree rings combined with studies of various hillslope processes enabled us to date past episodes of geomorphic change and decipher linkages among processes responsible for those changes. Behaviors of slopes and the valley floor in Basin 1D have not been inherently stochastic, either temporally or spatially. Any conclusions about climate drivers of hillslope erosion must be considered, however, in the context of lithological controls on weathering. The propensity of materials to be removed by erosion depends on sediment availability, which in turn depends on mechanisms controlling weathering and the retention of colluvium and soils, which is in turn dependent on lithology and aspect-dependent plant responses.

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