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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 presettlement 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