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This thesis is approved, and it is acceptable in quality and form for publication:

Approved by the Thesis Committee:

, Chairperson

BIOGEOMORPHOLOGY AND SOIL GEOMORPHOLOGY OF SMALL SEMIARID BASINS, NORTHEASTERN ARIZONA: INFLUENCES OF TOPOCLIMATE AND CLIMATE VARIATIONS

BY

LEAH M ROBERTS

B.S., BIOLOGICAL SCIENCES,
COLORADO STATE UNIVERSITY

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science
Earth and Planetary Sciences

The University of New Mexico
Albuquerque, New Mexico

December, 2009

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Leah M Roberts

B.S., Biological Sciences, Colorado State University, 2002

M.S., Earth and Planetary Sciences, University of New Mexico, 2009

Abstract

In northeastern Arizona, on the Colorado Plateau, landscapes associated with weakly cemented sandstones are sensitive to Holocene climate changes on millennial to decadal scales. It is hypothesized that these climate changes affect processes of weathering, erosion and plant community establishment on hillslopes in this semiarid environment. In small basins formed at the base of Black Mesa escarpment west of Chinle, Arizona, Jurassic sandstones cemented mainly by clay minerals weather by hydration, favoring relatively high erodibility. Two end member slope forms related to aspect-induced topoclimates are present in this area: (1) transport-limited slopes mantled by 10-20 cm of weathered materials and (2) bedrock slopes lacking accumulations of weathered materials. In addition to being ideal end-members of a continuous hillslope morphology series, these two slope types and their associated plant communities can be considered end-member ecological systems. The zone of transition, or ecotone, between them represents a gradational change that, due to the slope form-aspect relations, may have shifted spatially during the late Holocene. We identified two sub basins that encompass the full range of aspects and analyzed the hillslopes by characterizing vegetation, measuring soil thicknesses and estimating erosion rates. In contrast to south-facing, more xeric slopes, north-facing, more mesic slopes have substantially thicker mantles, less exposed bedrock and the greatest tree and herbaceous cover. On the more transitional aspects, there is an intermediate amount of vegetation and bare bedrock cover and intermediate soil thicknesses compared to the aspect-related end member slope forms. Hillslope erosion rates vary by slope aspect and slope position. The soil geomorphic and dendrogeomorphic data indicate that, through feedback mechanisms linking weathering, erosion and vegetative growth, the hillslope transition zones are responding dynamically to late Holocene climate changes by shifting in the direction of bedrock-dominated slopes. Ultimately, this suggests that overall, the hillslopes are transforming away from the transport-limited end-member toward the bedrock-dominated end-member. With the predicted temperature increases and precipitation decreases in the desert southwest over the next 100 years, this slope transformation in areas with lithologically sensitive bedrock is most likely irreversible.

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CHAPTER ONE : Topoclimatic Influences on Vegetation in Hillslope Ecotones

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ABSTRACT

On the semiarid Colorado Plateau, northeastern Arizona, landscapes associated with weakly cemented sandstones are sensitive to climate changes on millennial to decadal scales. It is hypothesized that these climate changes affect processes of weathering and plant community establishment on hillslopes. In small basins formed at the base of Black Mesa escarpment west of Chinle, Arizona, Jurassic sandstones cemented mainly by clay minerals weather by hydration, favoring relatively high erodibility. Two end member slope forms related to aspect-induced topoclimates are present in this area: (1) north-facing, transport-limited slopes that form primarily in response to lower soil temperatures and enhanced soil moisture, conditions favoring development and accumulation of 10-20 cm of weathered materials, and (2) south-facing, bedrock slopes lacking accumulations of weathered materials due to warmer and drier soil conditions. In addition to being ideal end-members of a continuous hillslope morphology series, these two slope types and their associated plant communities can be considered end-member ecological systems. The zone of transition, or ecotone, between them represents a gradational change that, due to the slope form-aspect relations, may have shifted spatially during the late Holocene. We identified two sub basins that encompass the full range of aspects and produced 0.25 m resolution DEMs with LiDAR techniques, which allowed for a detailed aspect analysis. On each major hillslope aspect,

vegetation and bedrock cover were characterized in 3 different plot sizes placed along 50-m long transects. All piñon trees were cored to produce hillslope tree age distributions. In contrast to south-facing slopes, north-facing slopes have substantially thicker mantles, less exposed bedrock and the greatest tree and herbaceous cover. Piñon tree age ranges are greatest on the north-facing slopes. Tree and herbaceous vegetation cover is lower in the ecotones relative to the more mesic aspects but higher relative to the more xeric aspects. Bare bedrock is higher in the ecotones relative to the more mesic aspects but lower relative to the more xeric aspects. Shrub cover is relatively constant across all aspects. This data suggests that spatially and temporally (latest Holocene), the hillslope ecotones are responding dynamically to climate changes, ultimately shifting in the direction of bedrock-dominated slopes.

INTRODUCTION

Climate change exerts a major control on landscape evolution on glacial-interglacial timescales (e.g. Bull, 1991), but smaller-scale climate changes during the Holocene (e.g. Medieval Warm Period, Little Ice Age, other Neoglacial cold episodes, droughts) may be just as important in defining the nature of landscape evolution in many circumstances (Meyer et al., 1992; Meyer et al., 1995; McFadden and McAuliffe, 1997; Menking and Anderson, 2003; Pierce et al., 2004). In drylands of the southwestern US, fluvial systems can respond to minor climate changes on scales of millennia to centuries (Ely, 1997; McFadden and McAuliffe, 1997; Waters and Haynes, 2001; Hereford, 2002). While most of these studies dynamics of channels, few directly address the critical contributions of basin hillslopes – the primary source of runoff and sediments – to basin floor channel responses.

One important factor in determining how hillslopes respond to changes in climate is lithology. Many recent studies propose that hillslopes in certain types of bedrock are especially sensitive to minor climate changes (i.e. millennial or submillennial) (McFadden and McAuliffe, 1997; Tillery et al., 2003; McAuliffe et al., 2006; Burnett et al., 2008). Using tree ring records from the Blue Gap study area in northeastern Arizona, McAuliffe et al. (2006) found that periods of greatly increased erosion from highly erodible, weathered sandstone slopes correlates with climatic shifts from multi-year droughts to sustained periods of above average precipitation. The weathered surface materials that accumulate on the slopes form in response to rapid hydration of smectitic sandstone cements in the sandstones (Tillery et al., 2003; Burnett et al., 2008), so small changes in water availability can influence both the formation and erosion of these weathered materials.

In this same study area, differences in hillslope aspect lead to the development of different hillslope morphologies. Burnett et al. (2008) identified two slope form end members related to aspect-induced topoclimates, which they referred to as: 1) transport-limited slopes mantled by 10-20 cm of weathered materials and 2) bedrock slopes lacking accumulations of weathered materials. Southern aspects are dominated by the generally steeper bedrock slopes, including sub-vertical cliffs, where erosion rates exceed the rate of weathering, therefore little soil development occurs (Selby, 1993; Ritter et al., 2002). On these more xeric hillslopes where soil does exist, Burnett et al. (2008) found that soil temperature is higher, soil moisture is lower and plant cover is lower than on north-facing hillslopes. Those northern aspects have a much more extensive plant cover and continuous, thicker soil mantle. Here, soils form at a faster rate than most erosional processes (Selby, 1993; Ritter et al., 2002). These more mesic slopes have relatively lower soil temperatures and higher soil moisture levels (Burnett et al., 2008). These two dominant slope types, defined by their slope form, vegetation cover and degree of soil development, exist as ideal end members on the hillslope morphology continuum.

These end-member slope forms can also be considered as end-member ecological systems in this landscape. The composition of plant assemblages (species identity, cover, age structure, etc.) on xeric, southern aspects differs sharply from those on mesic, northerly aspects. However, intermediate hillslope aspects exist in the study area and they are characterized by gradational changes between the composition of the contrasting end members. These environmental gradients, or zones of transition, between adjacent ecological systems are defined as ecotones (Gosz, 1993, Kolasa and Zalewski, 1995, Risser, 1995). Ecotones are often associated with the transition zones between major biomes where climate is the main driving force, but they are also used to describe transitions at much finer scales, e.g. lake and forest edges (Gosz and Sharpe, 1989).

In the Blue Gap study area, we are investigating ecotones at the hillslope scale, where it is proposed that Holocene climate change has driven the transition of the ecological state on the mesic hillslopes to a more xeric ecological state; a consequence of these changes is the transition from transport-limited to detachment-limited slope forms (McAuliffe et al., 2006; Burnett et al., 2008). Building on the earlier research in this area, we are focusing on the hillslope plant communities to better understand the spatial and temporal nature of these slope-form transitions. Studies of both the biotic and abiotic variables of the hillslope system, and the processes that drive changes in these variables, should provide insight into the mechanisms underlying this landscape behavior and its connection to climate and climate change. Ultimately this study may help elucidate how these landscapes will respond to future climate changes caused by anthropogenic greenhouse warming (Alley et al., 2007).

STUDY AREA

The Blue Gap study area is located 31 km west of Chinle, Arizona in the central part of the Navajo Reservation on the Colorado Plateau (Fig. 1.1). The study area is named Blue Gap because it lies approximately 4 km southeast of the small settlement of Blue Gap, Arizona, in basins formed at the base of Black Mesa. This landscape is characterized by a semi-arid climate with an average annual precipitation of 23.3 cm, 47% of which occurs during July, August, September and October. Average annual snowfall is 14.5 cm, 88% of which occurs primarily in December through March. The average maximum temperature is 69.1°F (20.6°C), while the average minimum temperature is 37.9°F (3.28°C) (Western Regional Climate Center, 2009; data for Chinle recording station). Elevation in the study area ranges from 1910 m (6260 ft) in the lowest areas of the Blue Gap wash to 2050 m (6700 ft) at the highest elevation (Tillery et al., 2003).

The study area is includes a series of several 1-2 km wide basins draining the eastern margin of the Black Mesa escarpment. In this area, the 150-meter tall northeast-southwest trending escarpment cuts into mudstones, siltstones and sandstones of the

Jurassic Morrison Formation and underlying Bluff Sandstone (San Rafael Group). Although resistant Cretaceous sandstones cap most of Black Mesa, these are absent in the study area. The basins, separated by steep, narrow divides, are numbered 0-5 from north to south (Fig. 1.1). Each basin is subdivided in sub-basins, generally corresponding to second-order tributary basins (McAuliffe et al., 2006).

This study focuses on two sub-basins within Basin 2, referred to as the East and West Basins (Figs. 1.1, 1.2, 1.3). The West Basin varies in elevation from 1955 m to 2002 m, and the upper ridge line sits directly below the main escarpment. It consists of a triangular-shaped basin that opens to the northeast, as well as the northwest-facing hillslope on the opposite side of the northernmost sub-basin divide (Fig. 1.2). The East Basin varies in elevation from 1954 m to 1994 m, and it is the third subbasin to the south of the main escarpment. The shape of the East Basin is that of a slightly elongated circle that opens to the west (Fig. 1.3). The hillslopes of the study basins were divided into ~50 m long (perpendicular to slope inclination) segments according to the major facing direction, or aspect, of that segment. Each aspect described in the study covers 45° of an arc. In the West Basin, there are 4 major aspects: northwest (NW), east (E), northeast (NE) and north (N). In the East Basin, there are 5 major aspects: north (N), northwest (NW), west (W), southwest (SW) and south (S).

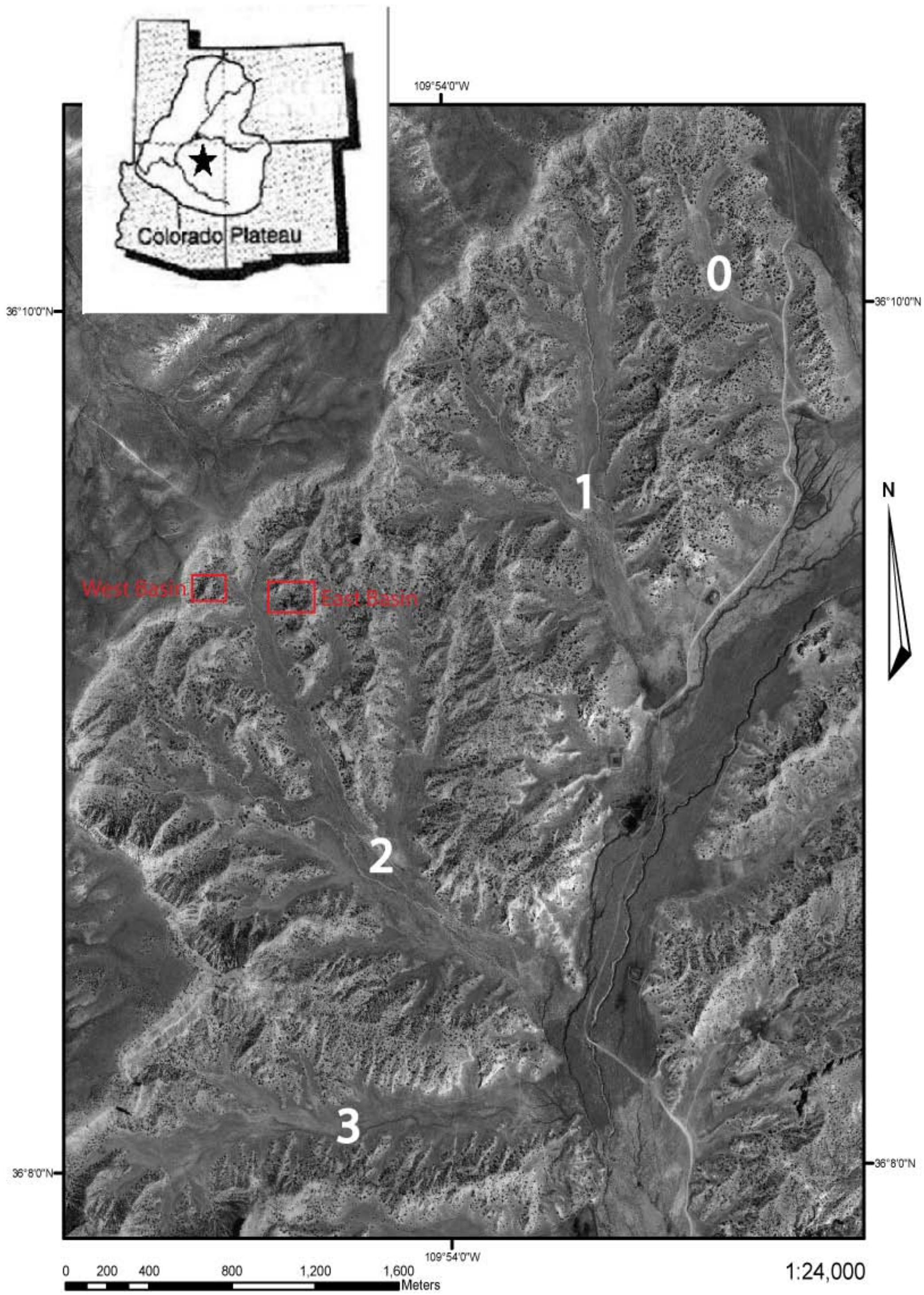

Fig. 1.1. Aerial photograph of Blue Gap Study Area with basins 0-3 labeled in white numbers and study basins labeled in red; inset map from Tillery et al., 2003.

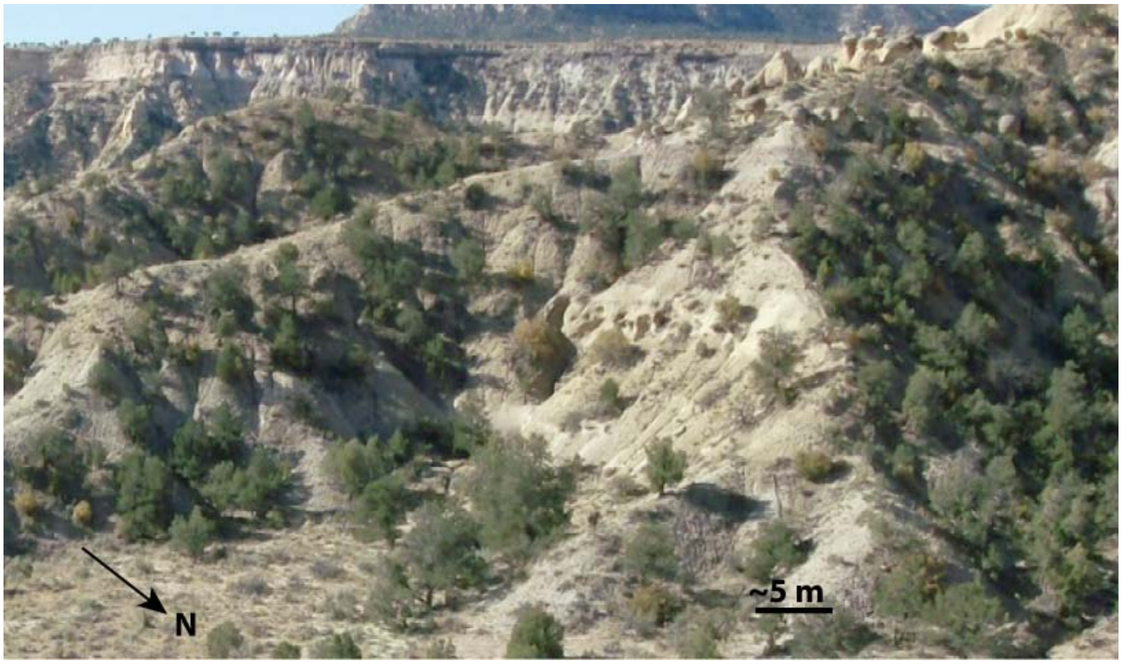

Fig. 1.2. Photograph of the West Basin, looking southwest. Note the abundance of trees on northern aspects as opposed to the lack of vegetation on the eastern aspect.

Fig. 1.3. Photograph of the East Basin, looking east. Note the abundance of trees on the northern aspects as opposed to the lack of vegetation and more bare bedrock on the western and southern aspects.

METHODS

LiDAR Scanning and Processing

LiDAR, an informal acronym for 'light detection and ranging', is a high-resolution scanning technology that is increasingly being used to obtain detailed measurements and images of landscape features. Originally developed for engineering purposes, terrestrial lidar scanners (TLS) can measure 1000-20,000 points per second over a surface and are capable of sub-centimeter precision and accuracy (Wawrzyniec et al., 2007). In this study, the University of New Mexico LiDAR Laboratory's Ilris 3D, grayscale intensity, TLS system was used to create detailed images of the study basins. In addition to serving as highly effective visual aids, the images provide a high-resolution 3-dimensional terrain model that can be analyzed in a geographic information system (GIS) software package.

Field-based data acquisition consisted of establishing 3-5 scanning stations per study basin, with 2-6 scans completed at each station. Each scan required calibration for the desired spacing of collected data points (5-35 mm) at the mean distance of the scan. At each station, scans were set to overlap ~5°. Each station was also located with a global positioning system (GPS) and the orientation of the scanner measured with a Brunton compass.

Post-collection processing consisted of merging scans into a single reference frame, removing bad/erroneous points (points lying above the ground surface as a result of scanned vegetation) and generating a digital elevation model (DEM). All merging and editing of scans was accomplished with the UNM LiDAR Laboratory's Polyworks v. 10.0 software. Multiple scans from a single station were merged into a common reference frame, followed by the merging of multiple scan stations into a single reference frame for each of the two study basins. Most of the editing of these scans was done after the merging process because the objective was to create a high resolution image of the hillslope surfaces. An image representing the ground surface required removal of points collected on the vegetation covering this ground surface. The most effective way to remove the vegetation data was to manually locate and delete anomalous high points. After fully merged and edited, the scans were translated to a UTM (Universal Transverse Mercator) coordinate reference frame. These georeferenced point cloud data sets were then loaded into GRASS GIS (GRASS Development Team, 2007), which interpolated the surfaces based on the lowest elevation point in each 0.25 m grid cell. The lowest elevation point was used in an effort to filter out any residual vegetation points situated above the ground surface. These submeter resolution DEMs of the study basins were then imported into ArcGIS v. 9.0 where aspect calculations were performed and total areal extent of each aspect was estimated.

Vegetation Surveys

The vegetation in the study area was characterized for each major slope aspect in both study basins during the fall 2007 field season. Within each of these hillslope segments (n = 9), two 50 m transect lines were established perpendicular to the slope inclination. One was placed 1/3 of the way up the slope from the basin floor and the other 2/3 of the way up, dividing the slope into lower, middle and upper sections.

Along each of the 18 transect lines, three different plot sizes were used for sampling vegetation. The amount of herbaceous canopy cover (non-woody perennial and annual vegetation) was visually estimated in 0.25 m^2 square plots placed every 1 meter along the transect line. For grasses, basal cover was estimated. These estimates were made for each species and assigned to a cover class: 0 = absent or no cover; 1 = < 1/16 of the plot covered; 2 = 1/16-1/8 cover; 3 = 1/8-1/4 cover; 4 = ¼-1/2 cover; 5 = ½-3/4 cover; 6 = > ¾ cover (McAuliffe et al., 2006). For data analysis, the midpoint of each of these cover intervals was used to calculate a mean percent cover for each species, for each herbaceous vegetation type (perennial grasses, herbaceous perennials and annuals) and for total herbaceous vegetation. In addition to the herbaceous vegetation, these 0.25 m^2 plots were also used to estimate exposed bare bedrock cover. The amount of bare bedrock in each plot was visually estimated to be in one of the previously described cover classes, and its mean percent cover for each slope aspect calculated the same way.

Woody vegetation was divided into two categories: shrubs and trees. Shrub cover was measured in 10 m^2 rectangular plots (5 m x 2 m) placed continuously along the length of each side of the transect lines (total of 20 plots per transect). At least half of the rooted base of a shrub had to be contained within the plot to be included as data for that particular plot. The canopy of each shrub species within these plots was measured along its short (a) and long (b) axis, providing a total canopy area of $\pi(½a)(½b)$. Based on this total canopy area and the size of the plots, a mean percent cover was calculated for each shrub species and for all shrubs on each slope aspect.

For the two tree species, piñon pine (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*), canopy diameter measurements were taken from 5 x 5 m contiguous plot placed along both sides of the transect lines (total of 20 plots/transect). In order for a tree to be included in a plot, the center of the rooted base of the tree had to be within the confines of the plot. The canopy of each tree was measured in the same way as the shrubs. A mean percent cover was calculated for each of the two tree species and for all trees on each slope aspect.

Piñon Tree Ages

Every accessible piñon tree on the hillslopes in the study basins with a trunk diameter > 5 cm was cored with an increment borer. For each tree separate cores were taken from opposite sides along an axis parallel with slope contours, yielding two cores per tree. Cores on upslope and downslope sides of trunks were not taken to avoid ring anomalies due to tilting of trunks. Each tree was cored twice, once on each lateral side relative to the slope. Cores were taken above the first roots and below the first branches, when possible. Each core was immediately extracted, transported in plastic straws, and allowed to dry for ~12-48 hours. They were then mounted and glued in grooved wooden blocks and allowed to dry for an additional 7-10 days. Once completely dry, the cores were sanded by hand with increasing sandpaper grit sizes: 220, 420 and 600. The rings on each core were counted under a stereo microscope. If the core did not include the pith, the number of missing rings was estimated by determining the approximate location of the pith center with respect to the core's end and visually extrapolating the ring count to that estimated center location. If the two cores from the same tree did not have an equal number of rings, the higher number was assigned as the age.

To obtain information on tree ages for trees with trunks < 5 cm in diameter, complete cross-sections were taken from four piñon pine saplings in the East Basin. Cross-sections were prepared in the same way as the tree cores, and the rings were counted. Based on these ages and their respective trunk diameters, a linear relationship was developed to estimate the age of all other piñon pines with trunks <5 cm in diameter.

RESULTS

LiDAR Imaging

The LiDAR scanning and image processing provided data to generate a 0.25 m digital elevation model (DEM) for both of the study basins (Fig. 1.4). Vegetation is not displayed in these DEMs, but the general characteristics of the hillslope surfaces are represented in finer resolution than any aerial photograph or DEM previously available. Using these DEMs in Arc GIS allows for a detailed analysis of the aspects of the hillslopes. Initially, to aid with data collection, the hillslopes of the study basins were divided into hillslope segments with each segment assigned a general aspect. Figures 1.5 and 1.6 show the variation in aspects that actually contribute to each of the assigned general aspects. The rose diagrams in these figures provide a visual breakdown of the relative proportions of the different aspects for each hillslope segment, based on the locations of the vegetation transect lines. These diagrams were created by compiling the assigned aspect of each 0.25 m^2 grid cell lying along the approximated transect lines that were drawn onto the DEM in ArcGIS. In the West Basin (Fig. 1.5), the E aspect has the least variability while the NE aspect has the most aspect variability. In the East Basin (Fig. 1.6), the N and NW hillslopes have much less aspect variability than the W, SW and S hillslopes.

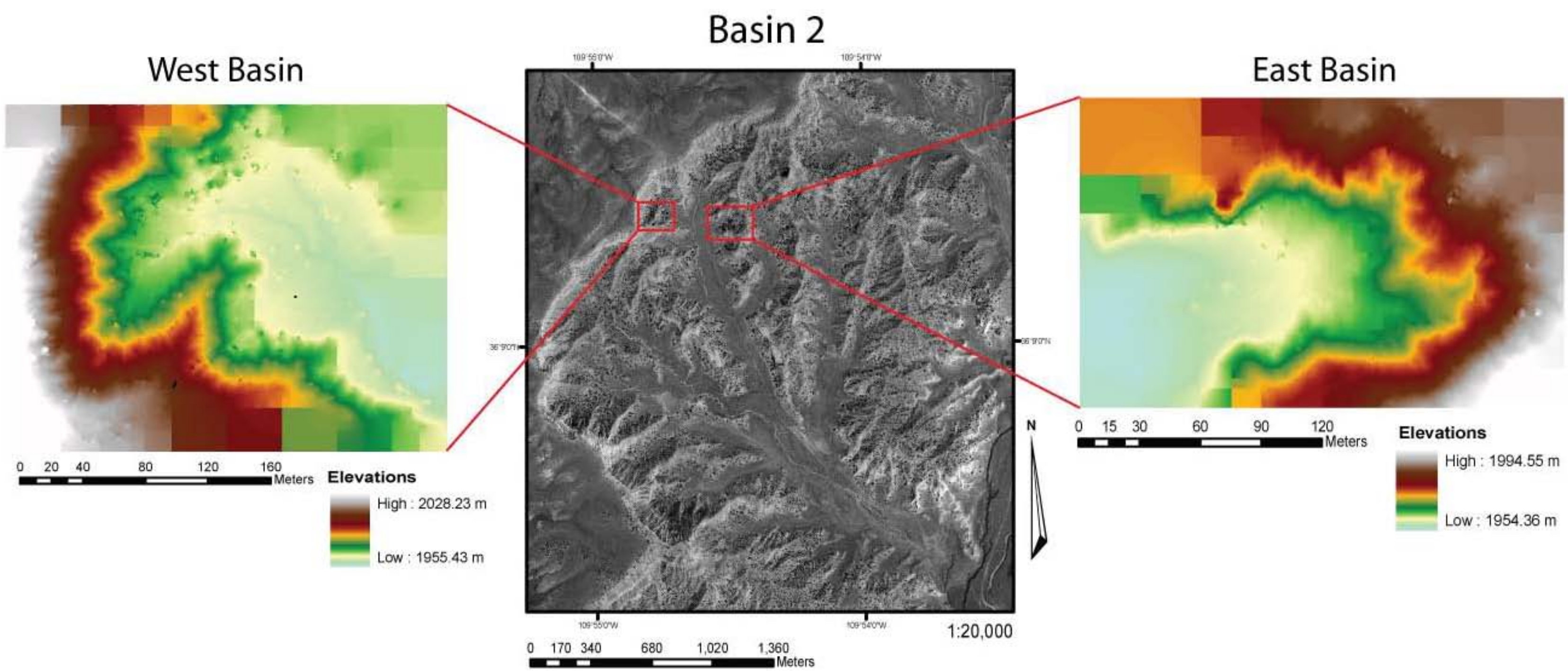

Fig. 1.4. Aerial photograph of Basin 2, with digital elevation models (DEMs) of the study basins expanded to either side.

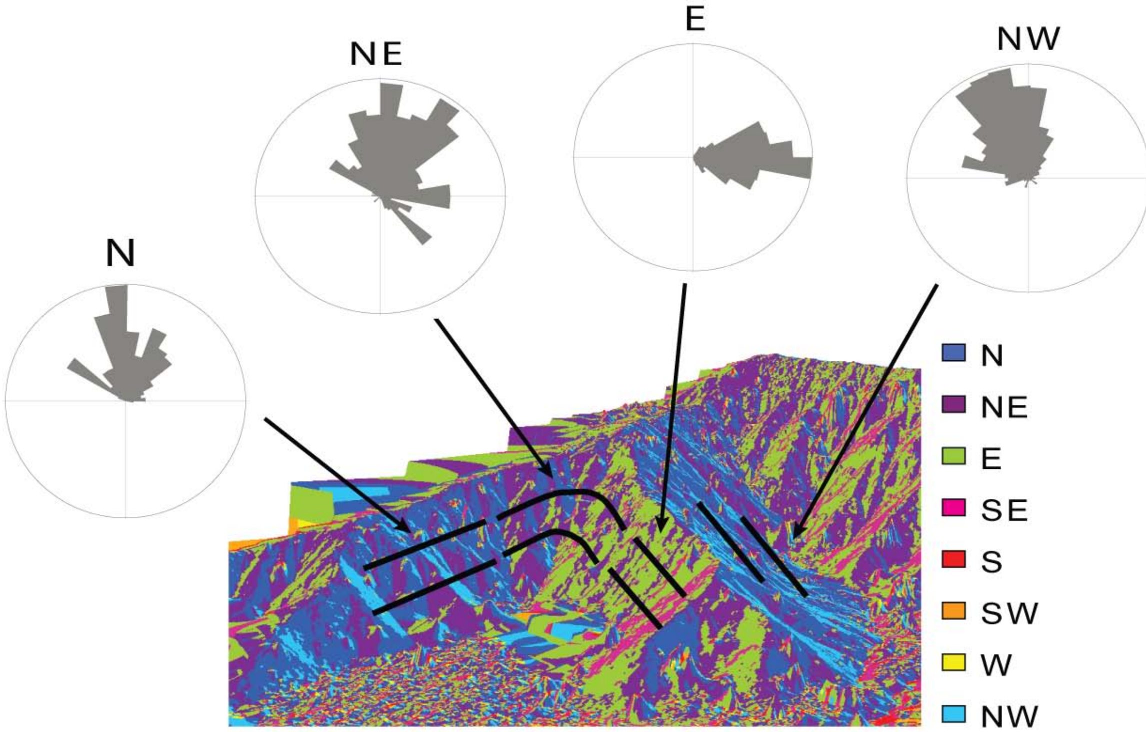

Fig. 1.5. 3-D DEM of the West Basin with aspects colored according to the legend. The rose diagrams describe the variability of aspects within each major hillslope segment, labeled with the major aspect direction above each one. The dark black lines represent approximate positions of vegetation transects.

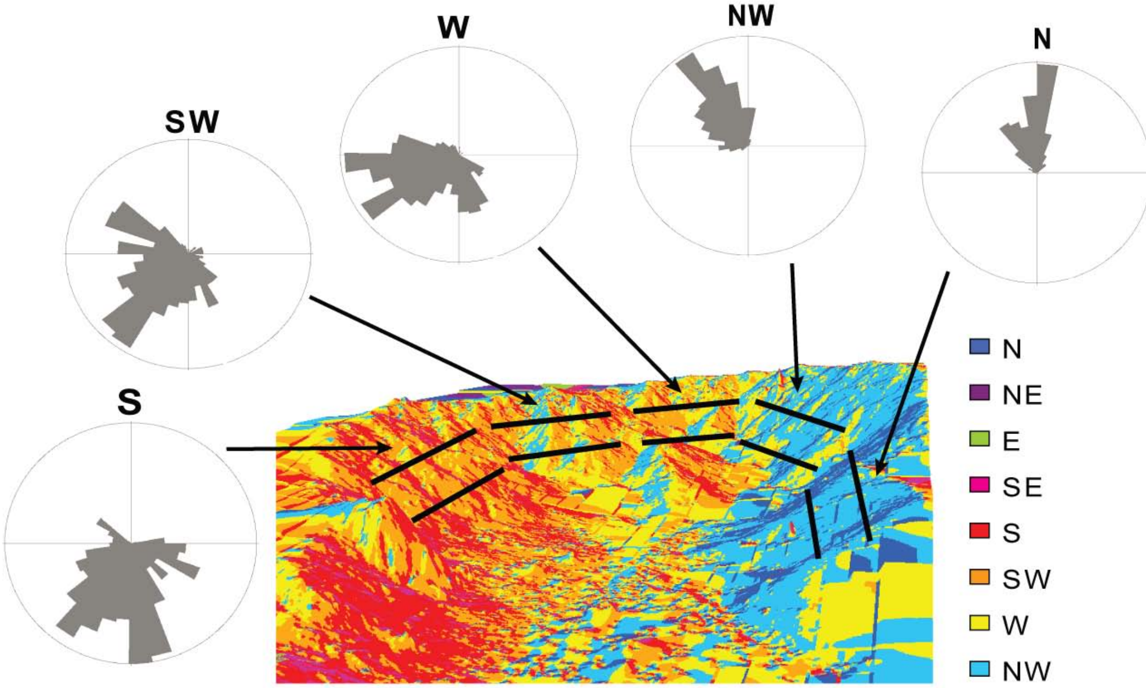

Fig. 1.6. 3-D DEM of the East Basin with aspects colored according to the legend. The rose diagrams describe the variability of aspects within each major hillslope segment, labeled with the major aspect direction above each one. The dark black lines represent approximate positions of vegetation transects**.**

Bedrock vs. Mantle

Soils on the hillslopes of the study basins are weakly developed with faint horizonation and would be classified as Psamments. Due to the lack of development, this soil has been referred to as the “weatherd mantle”, “soil mantle”, or more simply, “mantle” (Tillery et al., 2003; McAuliffe et al., 2006; Burnett et al., 2008) and these terms are also used in this study. These terms emphasize the fact that the soil mantle is forming through weathering of the bedrock below it, with the major difference being a lower shear strength, but little pedogenic change of these materials has occurred (Tillery et al., 2003, Burnett et al., 2008). The soil mantle is discontinuous or patchy on the more xeric aspects and more continuous on the mesic aspects (Tillery et al., 2003). On some areas of the slopes, particularly those with steep inclinations, a very thin (0.5-2 cm) soil mantle is often present. This mantle exhibits only Cr development and supports no vegetation, but since it is still weathered bedrock, it is included in the soil mantle category. Where the soil mantle is patchy, it is broken up by exposures of largely unweathered bedrock. Accordingly, for the purposes of this study, the hillslope surface was defined as either soil mantle or bare bedrock.

In the West Basin, the more mesic N and NW aspects have fewer areas of bare bedrock exposed on the surface, and the proportions are significantly lower than those on the more xeric NE and E aspects (Fig. 1.7). The mean percent of bare bedrock on the NE and E aspects is similar, and this amount is approximately 50 times greater than the amount of bare bedrock exposed on the more mesic slopes. In the East Basin, the S aspect has significantly more bare bedrock than the other aspects, and it decreases systematically around the basin to the N aspect, where exposed bedrock is absent (Fig. 1.8).

This percent of bare bedrock exposure is inversely related to the depth of the soil mantle. Mean soil mantle thickness in the East Basin is greatest on the N aspect and decreases systematically around the basin to the southerly aspects (Table 1.1). Comparing these two data sets suggests that when there is a thick soil mantle, there is little exposed bedrock and vice-versa.

Table 1.1. Soil mantle thicknesses in the East Basin (data obtained from Ch. 2).

Aspect	Mean (cm)	Range (cm)
N	20.0	6 - 41.5
NW	11.9	0 - 32
W	7.3	0 - 30
SW	4.2	0 - 18
S	4.4	0 - 26

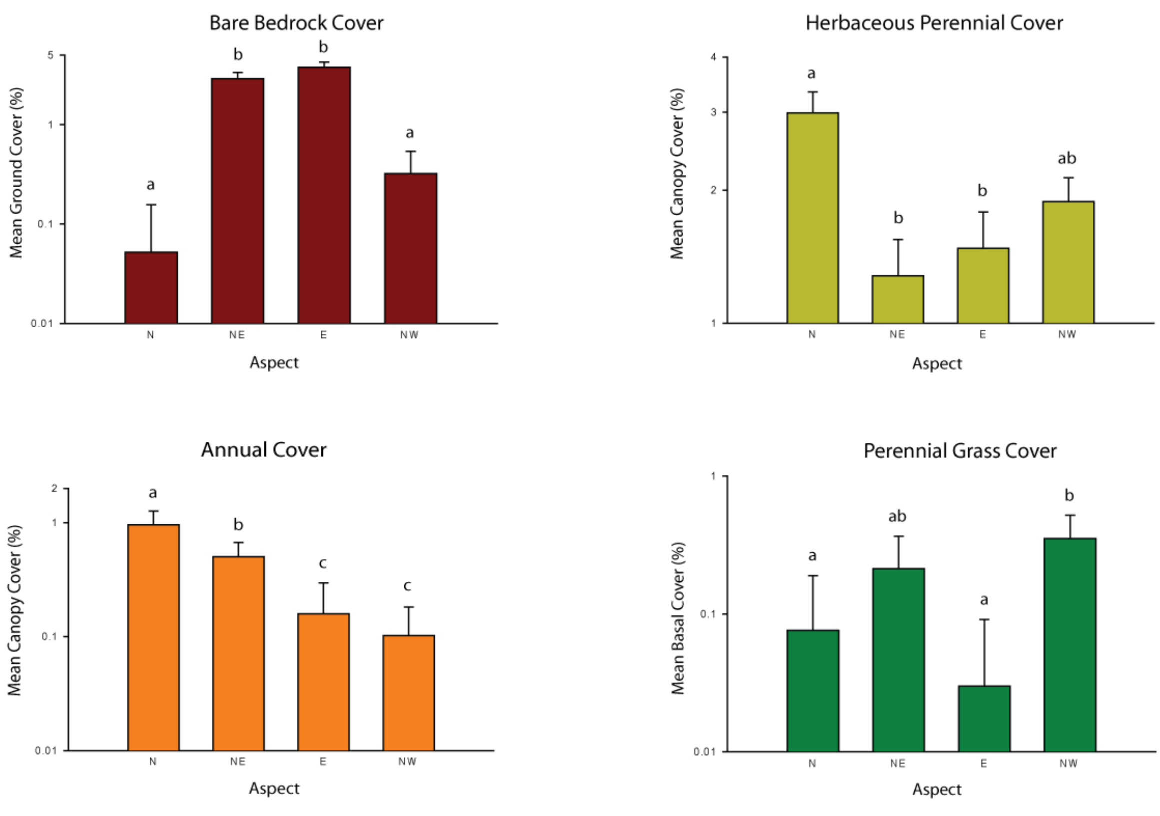

Fig. 1.7. Herbaceous vegetation cover and bare bedrock (no cover) on hillslopes of the West Basin. Error bars are 2 standard deviations from the mean. Small letters indicate significantly different groups ($p < 0.05$) when the letters are different. Note logarithmic scale on the y-axes.

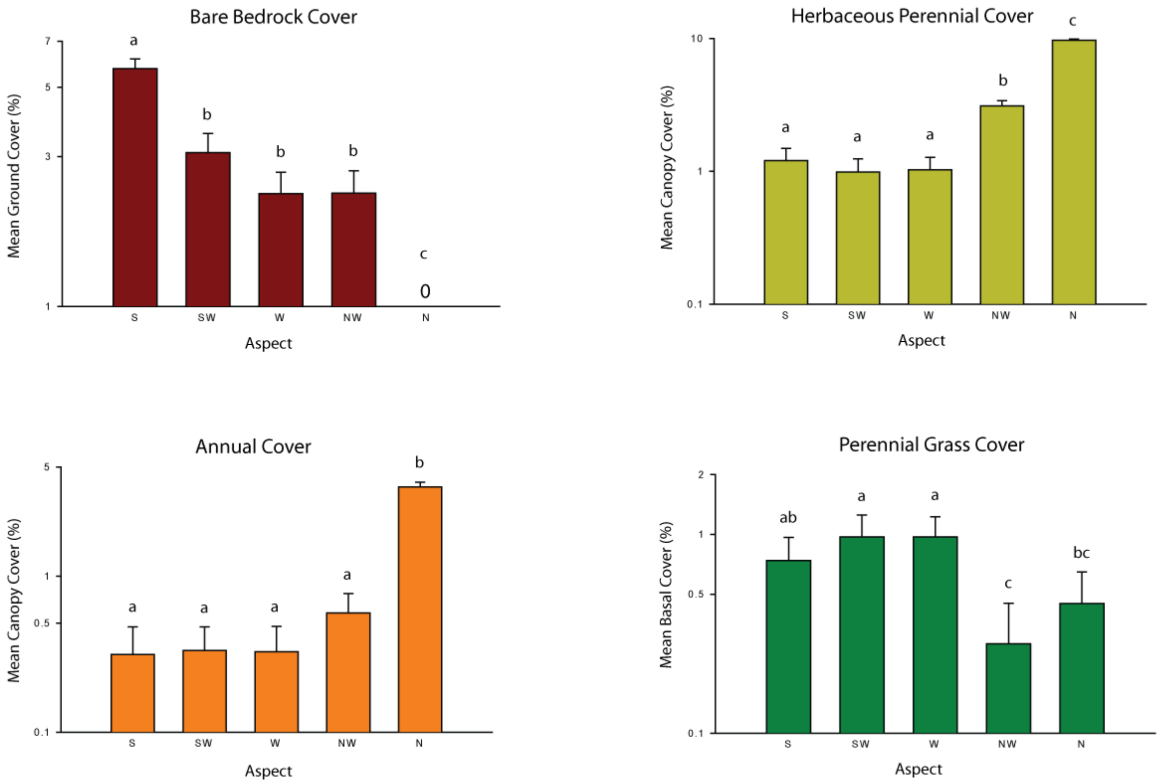

Fig.1.8. Herbaceous vegetation cover and bare bedrock (no cover) on hillslopes of the East Basin. Error bars are 2 standard deviations from the mean. Small letters indicate significantly different groups ($p < 0.05$) when the letters are different. Note logarithmic scale on the y-axes.

Vegetation Characterization

Herbaceous Vegetation Cover

The species composition and cover of herbaceous vegetation varied among the different aspects. Table 1.2 lists all the herbaceous species identified in the study basins. This is not a complete list as there were many plants that were unidentifiable due to a lack of seed heads and/or flowers. The mean percent cover of the total herbaceous vegetation in the West Basin is greater on the more mesic aspects compared to the more xeric aspects (Fig. 1.9 C). The N hillslope has the highest mean canopy cover, while the

E hillslope has the lowest. The NW slope herbaceous cover is not significantly higher than the herbaceous cover of the E or NE slope.

Table 1.2. List of herbaceous species identified in the study area

Herbaceous Plant Type	Genus	Species
Herbaceous pernnials	*Artemisia*	*ludoviciana*
	Artemisia	*campestris*
	Artemisia	*frigida*
	Astragalus	*mollissimus*
	Astragalus	*spp.*
	Boechera	*spp.*
	Castilleja	*spp.*
	Dasyochloa	*pulchella*
	Eriogonum	*microthecum*
	Gutierezzia	*microsephela*
	Hymenopappus	*filifolius*
	Leptodactylon	*pungens*
	Mirabilis	*spp.*
	Penstamon	*spp.*
	Phlox	*hoodii*
	Physalis	*spp.*
	Physaria	*spp.*
	Vicia	*americana*
	Xanthisma	*grindelioides*
Annuals	*Arida*	*parviflora*
	Bromus	*tectorum*
	Cordylanthus	*wrightii*
	Dimorphocarpa	*wizlizenii*
	Ipomopsis	*longiflora*
Perennial Grasses	*Acnatherum*	*hymenoides*
	Bouteloua	*gracilis*
	Muhlenbergia	*pungens*
	Poa	*spp.*
	Sporobolus	*flexuosus*

Total herbaceous canopy cover for the East Basin exhibits a similar trend (Fig. 1.10 C). The most mesic aspect, the N hillslope, has the highest mean percent cover compared to all the other aspects. While the mean percent cover for the NW slope is not significantly different from the more xeric aspects, it is slightly higher than the W, SW and S hillslopes.

For both study basins, values for mean canopy cover of herbaceous perennials and annuals are similar to that of the total herbaceous cover (Figs. 1.7 and 1.8). The N aspects have significantly greater mean percent cover of both than any of the other aspects. Annual cover decreases systematically from the more mesic N hillslope to the more xeric E slope in the West Basin. Perennial grass cover shows, however, a different pattern. In the West Basin (Fig. 1.7), mean basal cover of the grasses is highest on the NW slope, which is the hillslope that is on the outside of the main study basin. Within the main area of West Basin, the highest mean cover of perennial grasses is on the NE aspect, but this is not significantly different from the other aspects. In the East Basin (Fig. 1.8), the more xeric aspects (W, SW and S) have significantly higher mean basal cover of perennial grasses than the NW and N aspects.

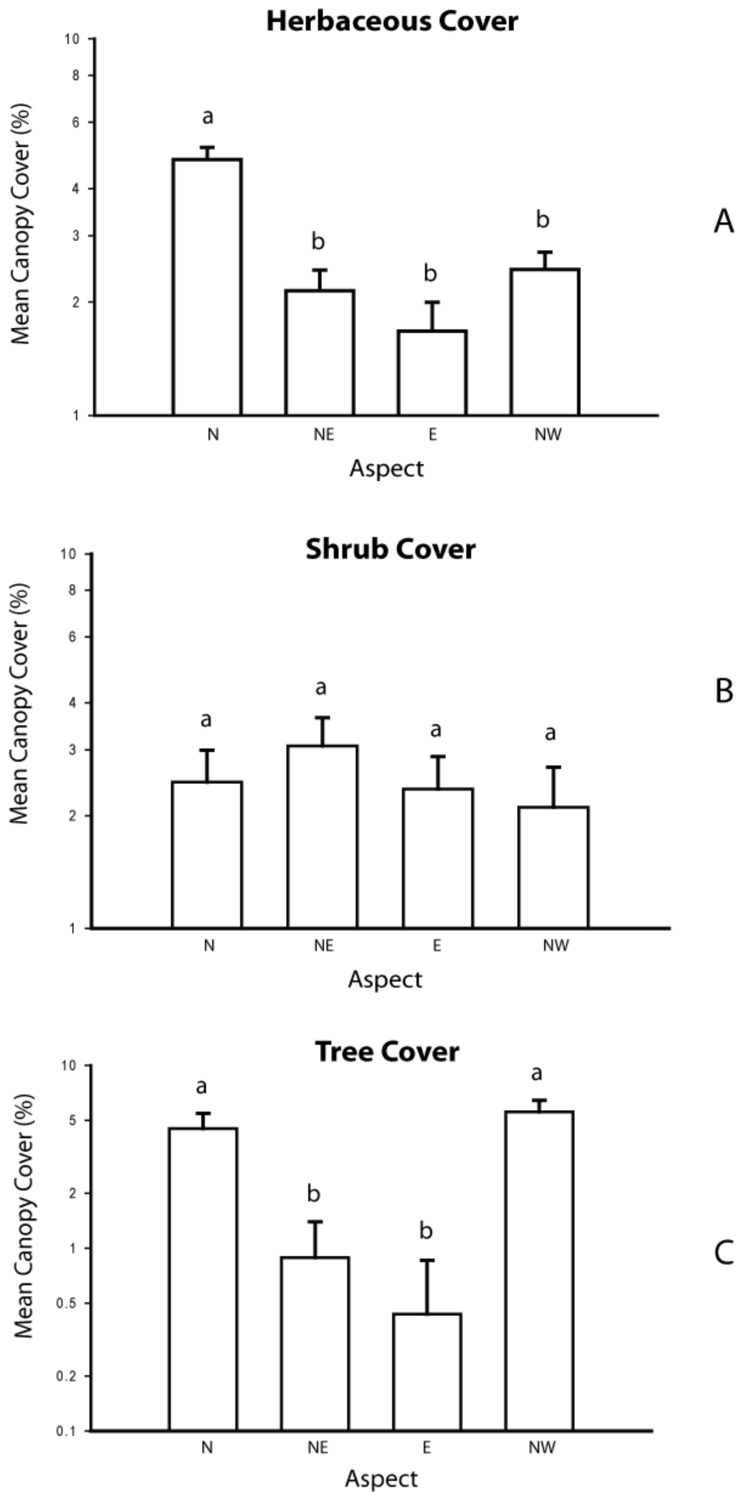

Fig. 1.9. Vegetation cover of the West Basin, classified into the following three categories: (A) herbaceous, (B) shrubs and (C) tree cover. Error bars are 2 standard deviations from the mean, while small letters above bars indicate significantly different means ($p < 0.05$) when the letters are different. Note logarithmic scale on the y-axes.

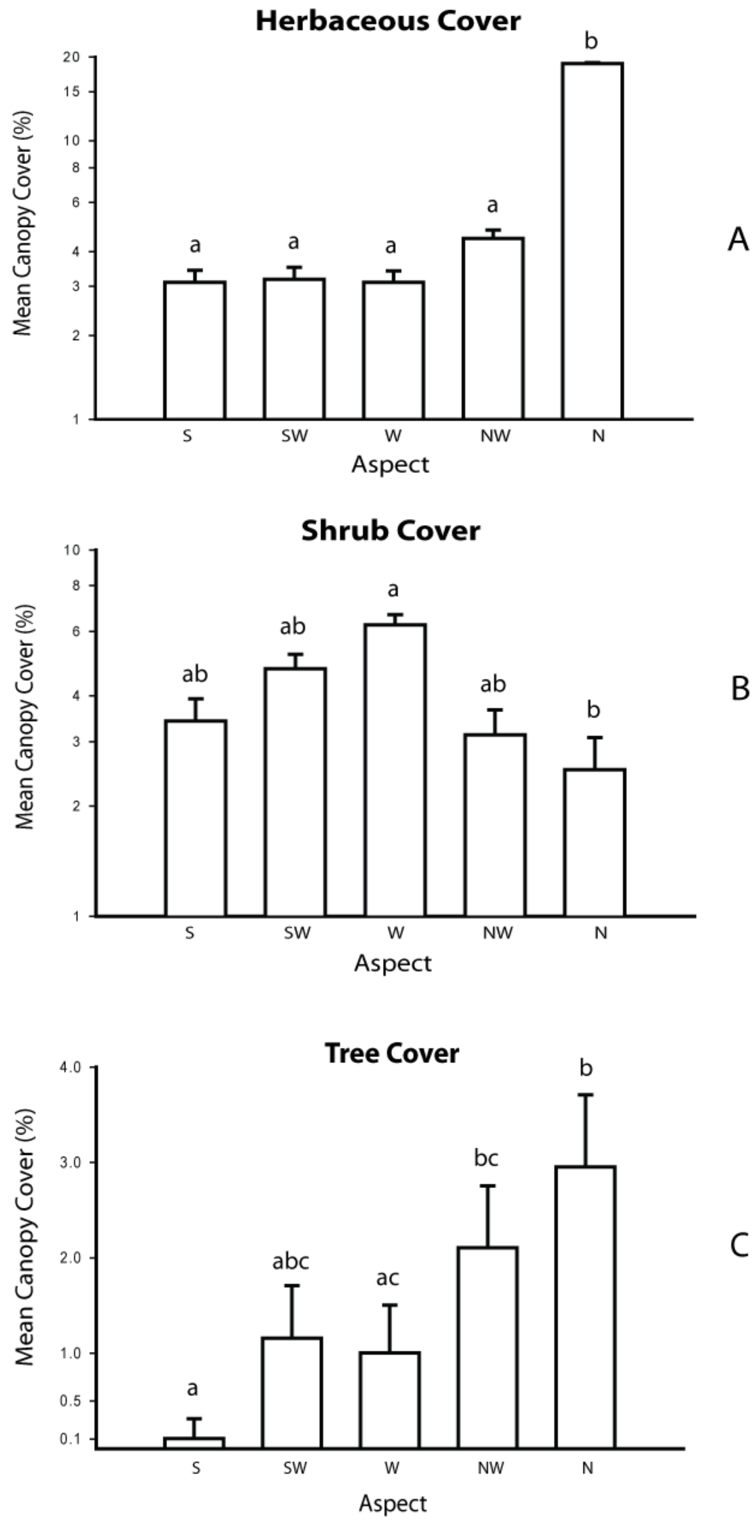

Fig. 1.10. Vegetation cover of the East Basin, classified into the following three categories: (A) herbaceous, (B) shrubs and (C) tree cover. Error bars are 2 standard deviations from the mean, while small letters above bars indicate significantly different means ($p < 0.05$) when the letters are different. Note logarithmic scale on the y-axes.

Shrub Cover

Shrubs included all perennial woody vegetation, excluding the two major tree species (piñon and juniper). Table 1.3 lists the shrub species occurring in the study area. The mean percent cover of shrub canopies for the West Basin is shown in figure 1.9 B. The NE aspect has a slightly higher mean than the other aspects, but none of the means are significantly different from each other. In the East Basin, the W aspect has the highest percent cover of shrubs, and it is significantly greater than the N aspect, which has the lowest percent cover (Fig. 1.10 B).

Table 1.3 Shrub species identified in the study basins.

Scientific Name	Common Name
Artemesia tridentata	big sage
Amelanchier utahensis	Utah serviceberry
Atriplex canescens	fourwing saltbush
Cylindropuntia arbuscula	Arizona pencil cholla
Ericamerica nauseosus	rabbitbrush
Fendlera rupicola	fendlerbush
Opuntia spp.	prickly pear cactus
Purshia stansburiana	Stansbury cliffrose
Tetradymia canescens	spineless horsebrush
Yucca glauca	soapweed yucca

While collecting shrub cover data, important characteristics about their growth pattern began to emerge. Based on observations, some of the root systems of these long-lived woody plants are exposed on the surface, particularly in the transitional areas and particularly with the roots of *Purshia stansburiana*. This is often not a continuous exposure as soil mantle covers part of the roots, but adjacent to where they are covered the roots are exposed on top of the Cr horizon (Fig. 1.11)

Fig. 1.11. Shrub roots exposed on the surface of the Cr horizon.

Tree Cover

In the West Basin, mean percent canopy cover is significantly greater on the N and NW aspects compared to the NE and E aspects (Fig. 1.9 A). Tree canopy cover decreases from the N aspect to the E aspect. This general trend also occurs in the East Basin. The N-facing slope has the highest percent tree canopy cover and cover decreases around the basin to the S-facing slope (Fig. 1.10 A). Tree cover is lowest on the S aspect.

Tree Ages

Piñon trees with trunk diameters > 5 cm ranged in age from 28 years to 560 years. The ages and locations of these trees are listed in Appendix A.

The locations and trunk diameters of all observed piñon saplings (< 5 cm in diameter) were recorded according to hillslope aspect. In the West Basin, the greatest number of saplings was observed in the head of the basin, on the NE aspect, with a total of 7 (Table 1.4). Density of saplings, however, varies systematically from the more mesic N aspect with the highest density decreasing to the xeric E aspect with the lowest density. The E aspect had the fewest number of saplings with only 1. Data was not collected on piñon saplings on the NW aspect of this basin. In the East Basin, the N aspect has the greatest number of piñon saplings, followed closely by the W aspect in the head of the basin (Table 1.5). The more xeric S and SW aspects have the fewest number of saplings. With the exception of the NW aspect, the density of saplings in this basin also decreases systematically from the mesic N aspect to the xeric S aspect.

Table 1.4 Piñon sapling distribution and density in the West Basin

Aspect	# of saplings	Density (#/m²)
E	1	1.00E-03
NE	7	3.85E-03
N	5	5.67E-03
NW	n/a	n/a

Table 1.5 Piñon sapling distribution and density in the East Basin

Aspect	# of saplings	Density (#/m²)
S	2	9.94E-04
SW	5	2.12E-03
W	8	3.23E-03
NW	5	2.08E-03
N	9	4.84E-03

Piñon saplings are too small to be cored, so a trunk diameter-age relationship was developed based on the actual ring count of four saplings from the East Basin (Fig 1.12). Ages of other trees less than 5 cm trunk diameter were estimated using the regression equation. The estimated ages of all saplings ranged from 8 to 88 years.

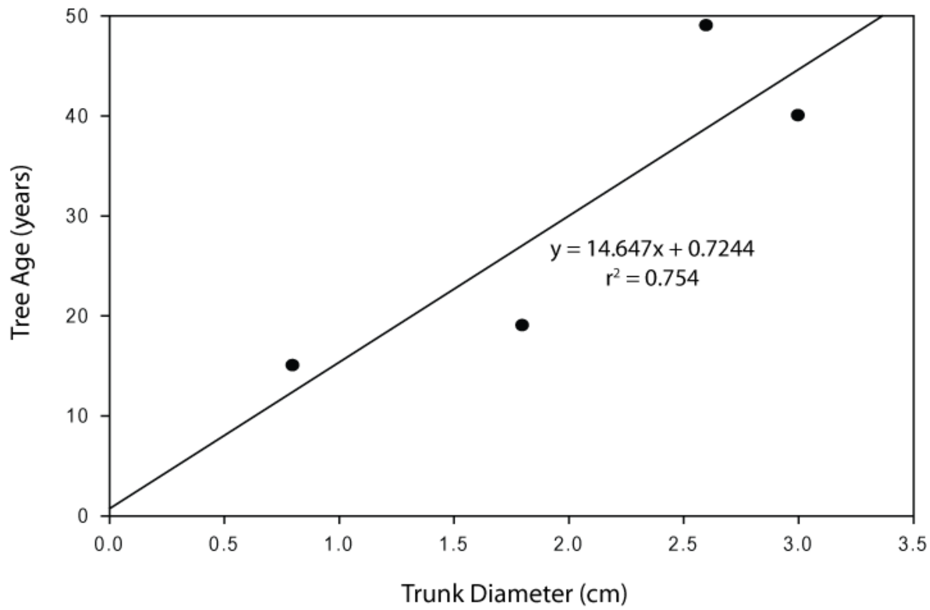

Fig. 1.12. Trunk diameters plotted against the ages of 4 selected piñon saplings with diameters <5 cm from the East Basin.

Combining the age data of all datable piñons of all sizes provides an overall age distribution for the study basins (Fig. 1.13). In the West Basin, the oldest trees are on the NW and NE aspects, but the mean tree age for each aspect is ~100 years. In the East Basin, this mean tree age of ~100 years is also observed on the more xeric S, SW and W aspects. However, average tree age is greater on more mesic aspects. The trees on the N aspect have the oldest mean age as well as the widest range of ages in the East Basin.

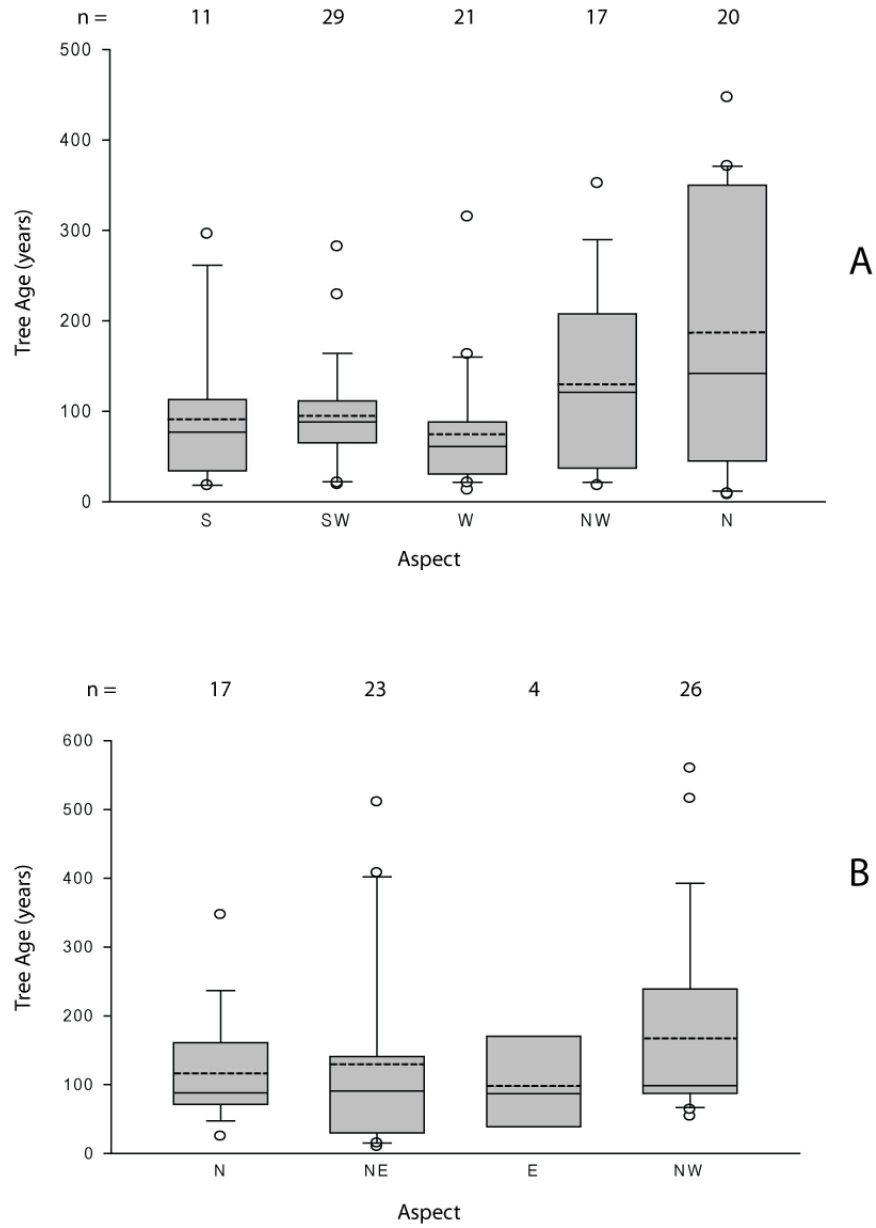

Fig. 1.13. Piñon tree age distributions by aspect on the (A) East Basin and (B) West Basin. The solid line within each box is the median, dashed line is the mean, upper box boundary is the 75th percentile, and the lower box boundary is the 25th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles, respectively. Open circles are outliers. The sample size for each aspect is given in the "n =" row above each plot.

DISCUSSION

Our findings suggest that hillslope plant communities respond to differences in aspect-related microclimate in identifiable ways. With warmer and drier hillslope microclimate (i.e. southern aspects as opposed to northern aspects), tree and herbaceous vegetation cover generally decrease while shrub cover does not significantly change. While overall vegetation cover decreases from the more mesic to more xeric aspects, the amount of unweathered bedrock exposed on the hillslope surface increases and soil mantle thickness decreases. These spatiotemporal relationships between plants, soils and slope form clearly reflect dynamic interrelationships between biotic and abiotic components comprising the hillslopes. Understanding hillslope evolution, therefore, requires understanding the nature of the linkages and feedbacks between those components.

Examining the hillslope subsystem through its component variables is an approach that emphasizes system connections and landscape responses (Bull, 1991). The independent variables are the main drivers of the system and are not affected by the hillslope environment, but they have direct impacts on it through the dependent variables (Fig. 1.14). Hillslope morphology and soil development are the abiotic dependent variables, while plants and animals comprise the biotic dependent variables (Fig. 1.14) (animals were not a focus of this study, so their effects on this system will not be discussed). Linkages between the dependent variables, represented by arrows in figure 1.14, represent cause-and-effect relationships that cause changes in those variables. Linkages between variables can be reciprocal, thereby leading to feedbacks within the system (positive or *self-enhancing* vs. negative or *self-arresting* feedbacks; Bull (1991)).

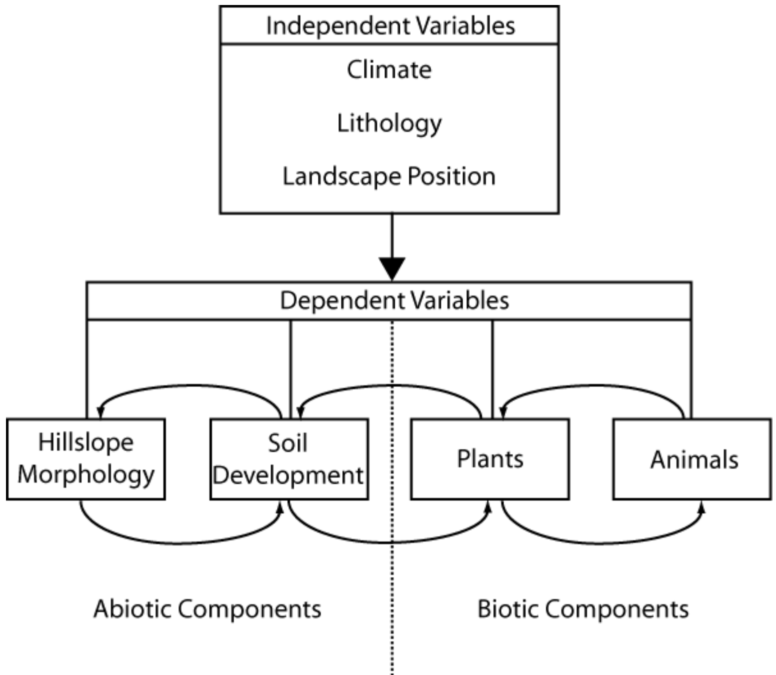

Fig. 1.14. Components of the hillslope subsystem model. Small arrows between dependent variables represents linkages and feedbacks that are discussed in the text.

The feedbacks between vegetation cover and soil development play a key role in understanding the behavior of this landscape. As pointed out above, in drylands such as the study area, where water is the limiting resource for plant growth (Noy-Meir, 1973), vegetation cover tends to be patchy with areas of relatively high vegetation cover interspersed with areas with little or no cover. The more xeric slopes have larger areas of little or no cover, while the more mesic slopes have greater vegetation cover. The redistribution of water and sediment by runoff between these areas can be an important feedback that contributes to further vegetation change and further modification in patterns of runoff (e.g. Schlesinger et al., 1990; Sanchez and Puigdefabregas, 1994; Bergkamp, 1998; Wilcox et al., 2003; Ludwig et al., 2005).

Precipitation or runon that infiltrates into the soil promotes greater plant growth as well as further weathering and soil development. At the Blue Gap site, increased weathering further increases the infiltration capacity and permeability of the substrate, which promotes increases storage of soil moisture and greater vegetative growth (Ludwig et al., 2005; Burnett et al., 2008). We see the expression of this feedback on the northern aspects, where there is the highest cover of tree canopies and herbaceous plants, the thickest soil mantles, and very little exposed bedrock. This self-enhancing feedback also occurs in the intercanopy areas in the opposite sense, i.e. there is no canopy to intercept precipitation, and so proportionally more water runs off and less infiltrates. This inhibits both plant growth and further soil development. This opposite pathway, also affected by self-enhancing feedbacks, is most readily observed on the southern aspects, where there is very little vegetation cover, very little soil mantle and large areas of exposed bedrock. Changes in precipitation, and thus soil moisture, will affect the strength of this feedback, thus modifying the hillslope environment.

Changes between the state where feedbacks lead to increased vegetation and increased soil development versus the one where feedbacks lead to increasingly diminished vegetation and soil loss should occur within the transitional zones, ecotones, between the end members of the slope aspect exposures and associated vegetation. The end-member hillslope ecological systems (i.e. northern vs. southern aspects) are relatively stable, at least on time scales of less than a century (McAuliffe et al., 2006), with more uniform distributions of dominant slope forms (Burnett et al., 2008) and microaspects (all of the aspects contributing to the overall hillslope aspect, as shown by the LiDAR results). Figures 1.4 and 1.5 also show that the ecotonal areas, in contrast, have the widest ranges of microaspects and a combination of the dominant slope forms. A key factor that strongly influences the ecotonal areas is the more variable microslopes and associated variations in slope form and soil depth. Ultimately, the plants tend to be within the more mesic patches in ecotones but their sustained survival depends on sufficient water availability. Available soil moisture, as described previously, also promotes continued bedrock weathering and mantle development.

However, if erosional rates increase greatly after unusually large runoff events, such as those hypothesized by McAuliffe et al. (2006) and Scuderi et al., (2008), documented by Wawrzyniec et al. (2007) and observed in the field, the soil patches and associated vegetation in the ecotones should be most strongly affected. Areas of bare bedrock both adjacent to and above areas of soil mantle produce and concentrate runoff that, when encountering mantle patches, causes their erosion. The roots of the vegetation help to retain the soil (Greenway, 1987), but only in limited areas influenced by the canopy or root systems of the plant. If subsequent precipitation-erosion events occur with sufficient frequency to inhibit reformation of a sufficiently thick mantle, then we hypothesize that such events would lead to continued decrease in overall mantle and herbaceous vegetation cover. In these basins, as well as other locations in the study area, where erosion has presumably removed much of the soil mantle and continues to inhibit its reformation, large root systems of shrubs, particularly cliffrose (*Purshia stansburiana*) are exposed on the surface of the Cr horizon (Fig. 1.11). These exposed roots demonstrate the historically recent loss of former, more continuous soil mantles in these transition zones. In areas of progressive loss of soil cover such as these, it is apparently more difficult for new piñons and other long-lived plants to establish. The lower density of piñon saplings consistently observed in the ecotones as compared to the mesic aspects supports this conclusion (with the exception of the NW aspect in the East Basin, which has an anomalously large bare bedrock exposure, see Chapter 2). If these ecotones were static, we would expect to see similar recruitment rates on the all aspects within the ecotonal areas, but this is not the case in the East Basin. Sapling density is lower on the SW aspect than on the W aspect, supporting the idea that the ecotone is an environmental gradient between the end-member ecological hillslope systems, and there is variability within the ecotone itself.

Climate, as characterized by temperature, precipitation and seasonal distribution of precipitation, is similar across all of the basins in Blue Gap, but many studies show climate has changed in the southwest US during the Holocene (Betancourt, 1984; Menking and Anderson, 2003; Scuderi et al., 2008). For example, according to Betancourt (1984), temperatures on the Colorado Plateau ca. 12 ka were 3-5°C cooler and there was 35-120% greater annual precipitation relative to modern conditions. Comparatively, the south-facing slopes in Blue Gap study area are currently 1.4-5.6°C warmer than north-facing slopes, well within the range of changing Holocene temperatures (Burnett et al., 2008).

Weltzin and McPherson (1999) suggest that ecotones shift due to abiotic changes, while biological constraints tend to stabilize them. The abiotic changes resulting from climate change that are occurring in Blue Gap that are shifting the ecotones are a decrease in soil moisture that leads to a decrease in weathering (soil depth), an increase in erosion (bedrock cover) and hillslope morphologies changing from more transport-limited to more bare bedrock-dominated. Plant distributions are changing along with the abiotic changes, so they are unable to stabilize the ecotones as Weltzin and McPherson (1999) suggest is the other way ecotones can behave. Herbaceous vegetation, specifically herbaceous perennial and annual cover, decreases with warmer soil temperatures. This is similar to results found by McAuliffe et al. (2006) where grass cover decreased after a 5-year drought. This loss of herbaceous cover helps to explain the difference in tree age distributions on these hillslopes. Less herbaceous cover results in a less stable soil mantle, which can be more readily eroded by episodic events that occur on a centennial time scale (McAuliffe et al. 2006). The older trees found on the mesic aspects suggest that the thicker soil mantle can withstand, or reform after, these erosion events and continue to support the trees. In the ecotones as well as the xeric aspects, however, the tree ages are younger (100 year average age), suggesting that the soil mantle is not stable enough to remain on the slopes, and cannot reform quickly enough due to the topoclimatic conditions, in order to support the persistence of long-lived trees. As these topoclimatic conditions persist, the loss of vegetation cover and soil mantle and exposure of bare bedrock is irreversible.

As global temperatures continue to warm in the Holocene (Alley et al., 2007), we predict that the ecotones will continue to shift towards the northern aspects. These present-day mesic aspects will no longer be cool enough or moist enough to support the relatively large plant community and relatively thick, continuous soil mantle. The feedbacks between vegetation, soil and slope form will continue in a way that favors the transformation of the more transport-limited slope morphology to the more detachment-limited slope morphology. This will result in a less productive landscape with the majority of hillslopes in the form of bare bedrock slopes and cliffs throughout much of the southwest US where similar weakly cemented, easily erodible rock types exist.

CONCLUSIONS

The main conclusions for this study are summarized as follows:

• Ecotones exist on hillslopes where topoclimatic differences produce an environmental gradient between ideal end-member hillslope ecological systems with respect to vegetation and soil development.

• Tree and herbaceous vegetation cover is lower in the ecotones relative to the more mesic aspects but higher relative to the more xeric aspects. Bare bedrock is higher in the ecotones relative to the more mesic aspects but lower relative to the more xeric aspects. Shrub cover is relatively constant across all aspects.

• Recruitment and age distributions of piñon pines provide the longest record and most useful insight into how the ecotones respond to changes in weathering and erosion. Piñon sapling density data suggests it is more difficult for piñons to establish in the ecotones compared to the more mesic aspects.

• Spatially and temporally, the hillslope ecotones are responding dynamically to Holocene climate changes, ultimately shifting in the direction of bedrock-dominated slopes.

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APPENDIX A – Cored piñon tree ages and locations

Study Basin	Aspect	Tree Age	Study Basin	Aspect	Tree Age
West	NW	38	West	NE	16
West	NW	54	West	NE	16
West	NW	61	West	NE	21
West	NW	64	West	NE	30
West	NW	68	West	NE	32
West	NW	74	West	NE	43
West	NW	86	West	NE	50
West	NW	86	West	NE	63
West	NW	88	West	NE	68
West	NW	89	West	NE	91
West	NW	92	West	NE	95
West	NW	93	West	NE	97
West	NW	93	West	NE	99
West	NW	93	West	NE	101
West	NW	96	West	NE	120
West	NW	101	West	NE	141
West	NW	116	West	NE	191
West	NW	117	West	NE	232
West	NW	134	West	NE	335
West	NW	135	West	NE	393
West	NW	193	West	NE	408
West	NW	239	West	NE	511
West	NW	239	West	N	25
West	NW	270	West	N	53
West	NW	294	West	N	59
West	NW	340	West	N	71
West	NW	516	West	N	72
West	NW	560	West	N	73
West	E	38	West	N	76
West	E	41	West	N	86
West	E	133	West	N	88
West	E	183	West	N	89
West	NE	10	West	N	109
West	NE	15	West	N	121

APPENDIX A (cont'd)

Study Basin	Aspect	Tree Age	Study Basin	Aspect	Tree Age
West	N	137	East	NW	85
West	N	185	East	NW	121
West	N	189	East	NW	133
West	N	209	East	NW	147
West	N	347	East	NW	184
East	N	8	East	NW	196
East	N	9	East	NW	219
East	N	34	East	NW	227
East	N	35	East	NW	274
East	N	43	East	NW	352
East	N	50	East	NW	465
East	N	51	East	W	13
East	N	51	East	W	21
East	N	57	East	W	22
East	N	67	East	W	25
East	N	72	East	W	30
East	N	212	East	W	31
East	N	225	East	W	31
East	N	245	East	W	34
East	N	275	East	W	44
East	N	335	East	W	57
East	N	350	East	W	61
East	N	350	East	W	67
East	N	353	East	W	70
East	N	370	East	W	73
East	N	371	East	W	84
East	N	447	East	W	87
East	NW	18	East	W	89
East	NW	22	East	W	100
East	NW	30	East	W	106
East	NW	33	East	W	145
East	NW	41	East	W	146
East	NW	44	East	W	163
East	NW	77	East	W	173

APPENDIX A (cont'd)

Study Basin	Aspect	Tree Age	Study Basin	Aspect	Tree Age
East	W	315	East	SW	98
East	W	317	East	SW	111
East	SW	19	East	SW	112
East	SW	21	East	SW	135
East	SW	22	East	SW	142
East	SW	28	East	SW	142
East	SW	47	East	SW	164
East	SW	53	East	SW	229
East	SW	63	East	SW	282
East	SW	67	East	S	18
East	SW	68	East	S	19
East	SW	73	East	S	34
East	SW	76	East	S	46
East	SW	81	East	S	56
East	SW	85	East	S	77
East	SW	85	East	S	98
East	SW	88	East	S	102
East	SW	88	East	S	113
East	SW	91	East	S	114
East	SW	92	East	S	122
East	SW	93	East	S	296
East	SW	94			

CHAPTER TWO: Linking Topoclimatic Variations in Soil Formation and Erosion Rates to Hillslope Evolution

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ABSTRACT

In order to fully understand dryland fluvial systems and their responses to Holocene climate change, a more complete understanding of the hillslope subsystem, including its geomorphic processes and how they are affected by climatic perturbations, is needed. This study focuses on weathering and erosion patterns of sandstone hillslopes in the Blue Gap study area in northeastern Arizona to test the hypothesis that the hillslopes are responding to late Holocene warming by transforming away from more vegetated, soil-mantled slopes toward more bedrock dominated slopes. These two slope form end members have been linked in previous studies to aspect related topoclimate differences. To assess weathering patterns, a soil toposequence was carried out on a north-facing slope, while soil mantle thicknesses were measured on all aspects of the study basin. Piñon tree ages combined with the amount of root exposure provide estimated hillslope erosion rates. The soil mantle is thicker on northerly, more mesic aspects compared to southerly, more xeric aspects. Soil profile depths increase from upslope to downslope positions on a continuous soil-mantled slope. Hillslope erosion rates vary according to hillslope aspect and hillslope position. Topoclimate differences help explain the variations in soil mantle thickness and erosion rates due to feedbacks involving soil moisture, degree of weathering, and runoff and erosion. This soil geomorphic and dendrogeomorphic study indicates that warmer, drier conditions are

conducive to thinner soils, more bare bedrock exposure and heterogeneous erosion rates on the hillslopes of this study area. This leads to the hypothesis that when climate changes to warmer and drier conditions, transitional areas on hillslopes are affected the most through loss of soil, loss of vegetation and increased erosion. Ultimately, this suggests that slopes are transforming away from the transport-limited end-member toward the bedrock-dominated end-member.

INTRODUCTION

Fluvial systems can be divided into two distinct subsystems that show variable degrees of connection: the streams and the hillslopes (Bull, 1991). Fluvial system drivers, such as climate and anthropogenic activities, influence the behavior of both of the subsystems, which in turn, influence each other. In the southwestern US, many studies have focused on how climate and climate change have caused stream subsystems to respond either by degradation (arroyo cutting) or aggradation (arroyo filling) (McFadden and McAuliffe, 1997; Waters and Haynes, 2001; Hereford, 2002). To fully understand the dryland fluvial system and its response to climate change, however, requires a more complete understanding of the hillslope subsystem, including its geomorphic processes and how they are affected by climatic perturbations.

Weathering and erosion are important geomorphic processes that play a key role in shaping the hillslope landscape, and how they respond to climate changes is, in part, determined by hillslope lithology. McFadden and McAuliffe (1997) proposed that hillslopes underlain by particularly sensitive rock types in the southern Colorado Plateau have responded to climate changes during the Holocene. On another highly weatherable, easily erodible rock in the southwest, McAuliffe et al., (2006) documented centennial scale, episodic erosion events, which they argue resulted from multi-year droughts followed by above average precipitation.

McAuliffe et al. (2006) focused their studies on a north-facing hillslope in the Blue Gap study area of northeastern Arizona. Here, weathered material on the sandstone slopes forms in response to rapid hydration of the smectitic clay cement (Tillery et al., 2003; Burnett et al., 2008). McAuliffe et al. (2006) suggested that, in contrast to the mesic, north-facing slopes, the rockier, more xeric, south-facing slopes should be characterized by greater erosion rates and lower soil-forming rates. In different basins in the same study area, Burnett et al. (2008) noted that depending on aspect and the associated topoclimate, weathering and erosional processes tend to push slopes toward two end members: (1) transport-limited slopes mantled by 10-20 cm of weathered materials and (2) bedrock slopes lacking accumulations of weathered materials. The transport-limited slopes are more commonly associated with mesic, northerly aspects, whereas more xeric, southerly aspects have a substantially greater proportion of bedrock slopes. Other studies have documented these two contrasting slope forms and likewise considered that they are end-members of a continuous hillslope series (e.g. Schumm, 1956).

The McAuliffe et al. (2006) and Burnett et al. (2008) studies strongly suggest the possibility that many hillslopes in Blue Gap study area have been, and are actively moving away from the transport-limited end of the series toward the bedrock-dominated end member. If so, the hillslopes with aspects between these end-members should exhibit transitional characteristic between the two. From a biological point of view, these transitional areas can also be defined as ecotones, and the nature and hypothesized behavior of these ecotones in response to topoclimate and regional climate change is addressed in Chapter One.

The key goal of this study is to determine how the hypothesized slope transformation occurs on the basis of observed changes in soil development and erosion rates as functions of slope aspect and slope position. By understanding how topoclimate variation influences both abiotic and biotic variables and the geomorphic processes that link them, we hope to gain a greater understanding of these interdependent relations that should elucidate the impacts of past and future climate changes on this landscape. In order to do this, the three main objectives of this study are: (1) to compare the data McAuliffe et al. (2006) collected on erosion rates, soil development and slope form on a north-facing hillslope to other north-facing slopes in the study area; (2) to characterize and evaluate erosion rates and soil development in transitional and xeric hillslope aspects; and (3) to assess the relationships between soil development and slope forming processes that are well documented in other areas (e.g. Birkeland, 1999).

STUDY AREA

The Blue Gap study area is located 31 km west of Chinle, Arizona in the central part of the Navajo Reservation on the Colorado Plateau (Fig. 1.1). It is approximately 4 km southeast of the settlement of Blue Gap, Arizona, in basins draining a small north-south trending section of Black Mesa escarpment. This landscape is characterized by a semi-arid climate with an average annual precipitation of 23.3 cm, 47% of which occurs during July, August, September and October. Average annual snowfall is 14.5 cm, 88%

of which occurs in December, January, February, and March. The average maximum temperature is 69.1°F (20.6°C), while the average minimum temperature is 37.9°F (3.28°C) (Western Regional Climate Center, 2009; data for Chinle recording station). Elevation in the study area ranges from 1910 m (6260 ft) in the lowest areas of the Blue Gap wash to 2050 m (6700 ft) at the highest elevation (Tillery et al., 2003).

The study area includes several 1-2 km wide basins draining the eastern margin of the Black Mesa escarpment. This 150-meter tall northeast-southwest trending escarpment cuts into mudstones, siltstones and sandstones of the Jurassic Morrison Formation and the underlying Bluff Sandstone (San Rafael Group). Although resistant Cretaceous sandstones cap most of Black Mesa, these are absent in the study area. The basins, separated by steep, narrow divides, are numbered 0-5 from north to south (Fig. 2.1). Each basin is subdivided in sub-basins, generally corresponding to second-order tributary basins (McAuliffe et al., 2006).

This study focuses on two sub-basins within Basin 2, referred to as the East and West Basins (Fig. 2.1). The West Basin varies in elevation from 1955 m to 2002 m, and the upper ridge line sits directly below the main escarpment. It consists of a triangular-shaped basin that opens to the northeast, as well as the northwest-facing hillslope on the opposite side of the northernmost sub-basin divide. The East Basin varies in elevation from 1954 m to 1994 m, and it is the third sub-basin to the south of the main escarpment. The shape of the East Basin is that of a slightly elongated circle that opens to the west. The hillslopes of the study basins were divided into ~50 m long (perpendicular to slope inclination) segments according to the major facing direction, or aspect, of that segment (Ch. 1). In the West Basin, we categorized hillslopes into 4 major aspects, with each aspect covering 45° of an arc: northwest (NW), east (E), northeast (NE) and north (N). In the East Basin, 5 major hillslope aspect categories were defined, again with each aspect covering 45° of an arc: north (N), northwest (NW), west (W), southwest (SW) and south (S). Throughout this study, the hillslopes are described and referred to as these dominant aspects, i.e. NW aspect means the entire hillslope with the dominant northwest aspect.

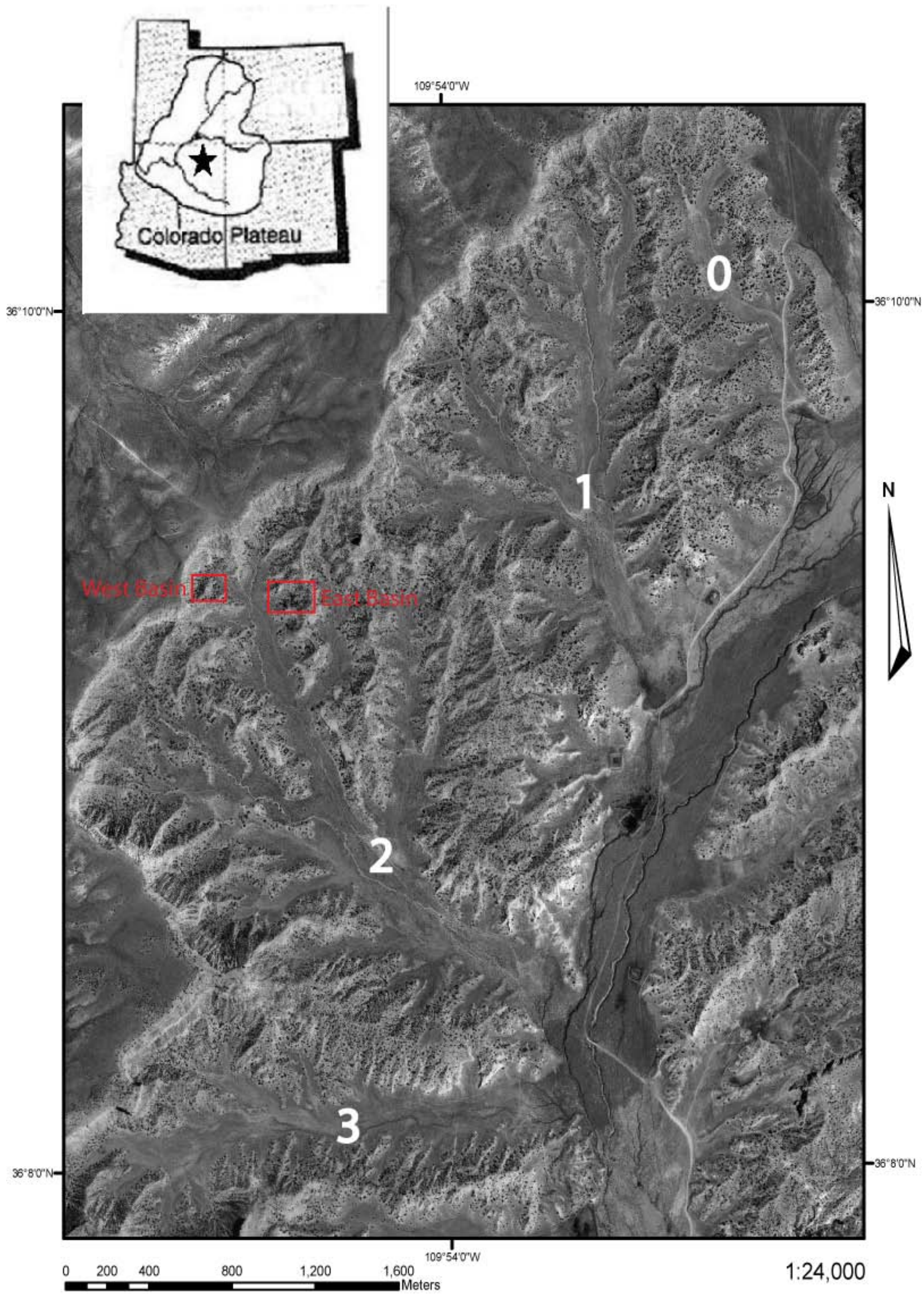


Fig. 2.1. Aerial photograph of Blue Gap Study Area, with major drainage basins labeled in white numbers. Study sub-basins included in this study are outlined and labeled in red. Inset map modified from Tillery et al. (2003).

METHODS

Soil Mantle Thickness

The thickness of the soil mantle was measured on all aspects of the East Basin. Four transects were established on each major slope aspect, placed parallel to the slope inclination from the base of the slope to the ridge top. Beginning at the bottom of the slope, the thickness of the soil mantle was measured at 1.5 m vertical intervals (measured with a Jacob staff), with the location of each sampling point recorded with a handheld GPS unit. The number of sampling points differed for each transect, due to differences in the elevational ranges of the transects. Adopting a simplified version of the cone penetrometer method from Tillery et al. (2003), soil mantle thickness could be very rapidly measured at each sampling point using a ½ inch (1.27 cm) diameter, 2 foot (61 cm) long steel rod (concrete reinforcement bar). One key soil thickness, the A horizon, was derived empirically on the basis of releasing the rod from a set height (10 cm), the distance necessary to penetrate through the mantle to the A/C horizon boundary. Preliminary investigation showed that by using this technique, the actual thicknesses of the A horizon determined by direct field examinations could be estimated within +/- 1 cm. The depth to the C/Cr horizon boundary was determined by pushing the rod into the soil after it had been dropped to the bottom of the A horizon, until it could not be pushed any further without using extreme force. Empirically, this was estimated to require a force of approximately 130 Newtons.

Soil thickness data from the mantle transects were log-transformed prior to statistical analyses. Mean A and C horizon thicknesses were calculated for each slope aspect (S, SW, W, NW and N) using the log-transformed data. These means were then compared using a one way analysis of variance (ANOVA).

The locations of the soil mantle measurements were plotted on a 0.25 meter resolution DEM of the East Basin (Ch. 1). An inverse distance weighted interpolation was executed on the depths to the C/Cr boundary to estimate the soil mantle thickness throughout the basin.

Soils Upslope vs. Downslope of Trees

In order to help determine the impacts of large trees on processes and patterns of slope material movement and soil development, soil profiles were characterized immediately above and below 9 trees on the N aspect of the East Basin. The trees were chosen along 3 transect lines running the length of the slope on the N aspect, with each transect consisting of 1 mature tree in each slope position: the upper, mid and lower slope. Soil pits were excavated within 0.5 meter upslope and downslope of each tree trunk, down to the bottom of the Cr horizon (unweathered bedrock). Thicknesses of the A, C and Cr soil horizons were measured in each soil pit. Soil thickness data from above and below the trees were log-transformed prior to analysis. Mean horizon thicknesses were compared using t-tests.

Toposequence

A soil toposequence was described on the NW slope of the East Basin. Soil pits were excavated to unweathered bedrock in six slope positions: summit, above the shoulder, shoulder, below the shoulder, backslope and footslope. The toeslope position was not included in the toposequence because of its location on the slope apron where loose, sandy sediment >1 m thick has very recently accumulated, and in which no significant soil development has occurred. In all other pits, however, standard soil description techniques were used to describe each soil profile (Birkeland et al., 1991). Small samples (~100 g) were collected from each horizon for particle size analyses in the laboratory (modified from Day, 1965 and Jackson, 1969).

Piñon Trees

Every accessible piñon tree on the hillslopes in the study basins with a trunk diameter > 5 cm was cored with an increment borer. For each tree, separate cores were taken from opposite sides along an axis parallel with slope contours, yielding two cores per tree. Upslope and downslope sides of trunks were not cored to avoid ring anomalies due to tilting of trunks. Each tree was cored twice, once on each lateral side relative to the slope. Cores were taken above the uppermost lateral roots (representing the tree's first developed roots). Each core was immediately extracted, transported in plastic straws, and allowed to dry for ~12-48 hours. They were then mounted and glued in grooved wooden blocks and allowed to dry for an additional 7-10 days. Once completely dry, the cores were sanded by hand with increasingly finer sandpaper (grit sizes 220, 420 and 600). The rings on each core were counted under a stereo microscope. If the core did not include the pith, the number of missing rings was estimated by determining the approximate location of the pith center with respect to the core's end and visually extrapolating the ring count to that estimated center location. If the two cores from the same tree did not have an equal number of rings, the higher number was assigned as the age.

To obtain information on ages for trees with trunks < 5 cm in diameter, complete cross-sections were taken from four piñon pine saplings in the East Basin. Cross-sections were prepared in the same way as the tree cores, and the rings were counted. Based on these ages and their respective trunk diameters, a linear relationship was developed to estimate the age of all other piñon pines with trunks <5 cm in diameter (Ch. 1).

The age of each tree, together with the amount of vertical root exposure, provides an estimate of an erosion rate at that point on the hillslope (LaMarche, 1967; Carrara and Carroll, 1979). For trees with roots exposed above the ground surface, the uppermost root was identified and, if dead, cut off. If the root was alive, a notch was cut out of the root close to the trunk. In both of these cases, the vertical distance from the root pith to the ground surface was measured on a lateral side of the tree. These distances were recorded as positive values. For trees with roots covered by the soil mantle, the roots were excavated and the distance from the center of the uppermost lateral root up to the soil surface was measured. These distances were recorded as negative values.

At each sample tree, other measurements were made to aid with interpreting hillslope processes. The presence, or lack thereof, of trunk curvature was noted. The slope location (i.e. upper, middle, lower) of each tree was recorded, while the location was identified with a handheld GPS unit with an accuracy of approximately ± 3 m.

RESULTS

Soil Toposequence

Analyses and descriptions of soils along a toposequence provide information on soil forming processes along a hillslope. The results of the toposequence study, including soil morphological data and silt and clay contents for each of the six slope positions, are shown in table 2.1 and figure 2.2. Because the parent material is dominantly well sorted sand and the soils are very weakly developed, the main size fractions that change largely in response to weathering and soil development are silt and clay. Therefore, only the percentages of clay- and silt-sized particles are graphically displayed in this figure.

The soil development is strongl dependent on slope position on the NW aspect. First, the thickness of the entire soil profile, as well as the thickness of each horizon, decreases from lower to upper slope positions. The footslope has the thickest soil profile (37 cm), while the summit has the thinnest profile (15 cm). Second, the silt + clay content changes with topographic position and soil depth. The silt + clay content throughout the entire profile is lowest in the footslope position. Additionally, as soil depth increases in each profile, the silt + clay content generally decreases; however, no obvious, consistent relations between soil depth and percent clay or soil depth and percent silt are recognized.

Table 2.1. Selected soil descriptions and laboratory data from NW aspect toposequence in East Basin

Horizon#	Depth (cm)	Dry color	Moist color	Structure†	Dry consistence‡	Texture§	Silt (%)	Clay (%)
Summit								
A	0-1.5	5Y7/3	5Y6/4	1m sbk	so	LS	7.25	13.01
C	1.5-8.4	5Y7/3	5Y6/4	1c sbk	so	LS	6.98	8.59
Cr	8.4-15.1	5Y8/3	5Y7/3	1msbk	so	LS	4.24	8.23
Above Shoulder								
A	0-2.1	5Y6/4	5Y5/4	2m sbk	so	LS	8.69	12.96
C	2.1-6.4	5Y6/4	5Y5/4	1c sbk	so	LS	10.30	12.69
Cr	6.4-16.9	5Y7/3	5Y6/3	2m pl	so	LS	10.30	8.37
Shoulder								
A	0-2	2.5Y6/4	2.5Y5/4	1 m sbk	so	LS	10.99	9.98
C	2-12.4	2.5Y6/4	2.5Y5/4	1m sbk	so	LS	9.14	8.74
Cr	12.4-18.9	2.5Y6/4	2.5Y5/4	m-vf gr	lo	LS	8.98	1.53
Below Shoulder								
A	0-3.1	5Y6/4	5Y5/4	1c sbk	so	LS	8.89	8.73
C	3.1-22.8	5Y6/4	5Y5/4	1c sbk	so	LS	11.80	1.43
Cr	22.8-34	5Y6/4	5Y5/4	2c sbk	sh	LS	3.85	7.25
Backslope								
A	0-2	2.5Y6/4	2.5Y5/4	1c sbk	so	LS	4.52	6.18
C	2-18.4	5Y6/3	5Y4/3	1c sbk	so	LS	0.00	7.22
Cr	18.4-28.5	5Y7/3	5Y6/3	1c sbk	sh	LS	2.17	4.32
Footslope								
A	0-5.6	2.5Y5/4	2.5Y4/3	1c sbk	so	LS	4.52	7.51
C	5.6-27	5Y6/3	5Y6/3	1c sbk	so	LS	0.64	7.24
Cr	27-35.8	5Y5/4	5Y5/4	2m pl	so	LS	1.06	6.05

#Horizon nomenclature follows Birkeland (1999) and references therein; r represents weathered or soft bedrock that is hard enough that roots only penetrate along cracks but soft enough that it can be dug with a spade or shovel (Buol et al., 1997).

†Structure codes: Strength/abundance: 1-3. Size: vf - very fine; f - fine; m - medium; c - coarse. Shape: sbk - subangular blocky; pl - platy.

‡Dry consistence codes: lo - loose; so - soft; sh - slightly hard.

§Texture code: LS - loamy sand.

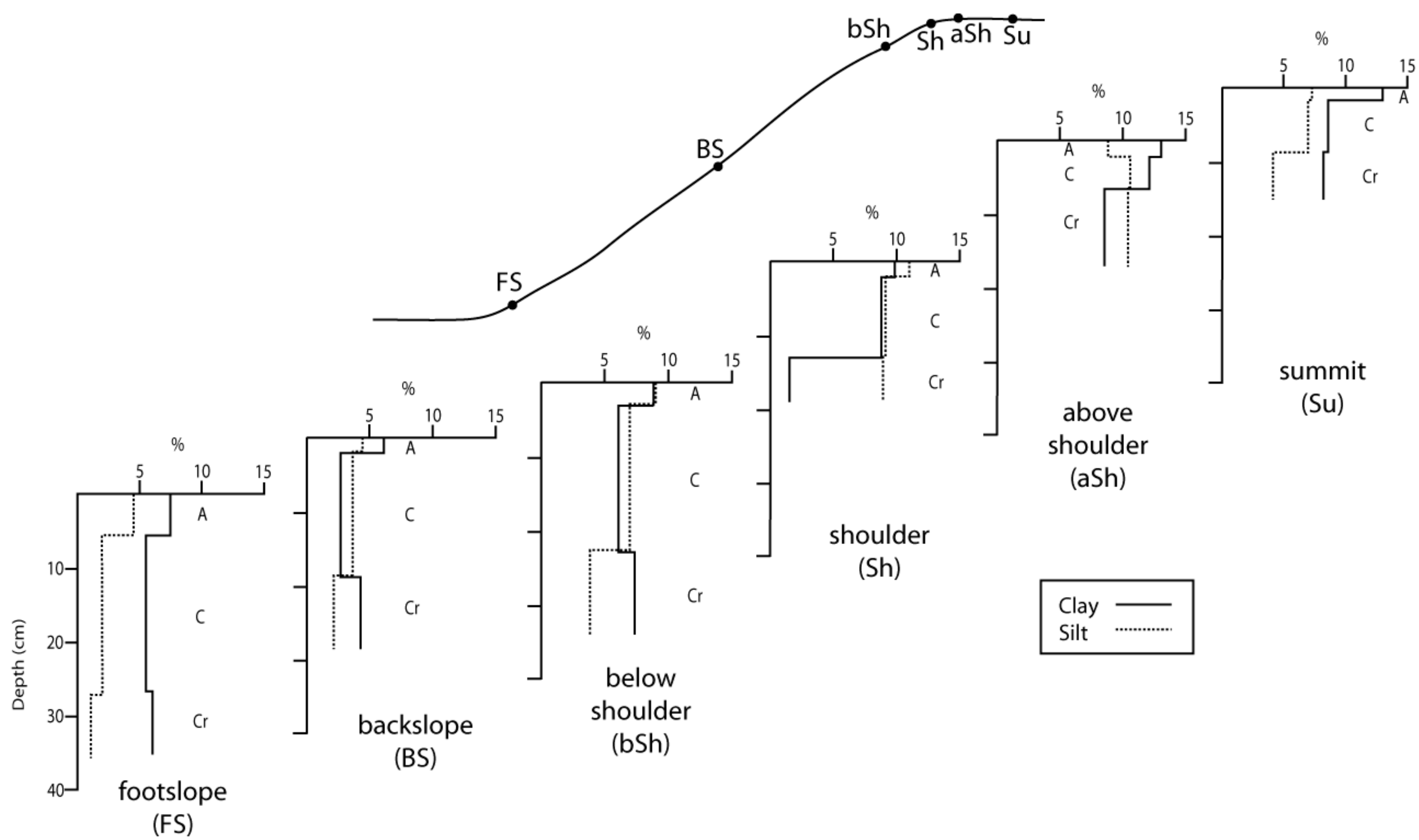


Fig. 2.2. Amount of silt and clay in soil profiles of soil toposequence. Each profile corresponds to a distinct slope position located on the slope profile illustrated above.

Soil Mantle Thickness

Mean mantle thickness systematically increases on the hillslopes of the East Basin from the south to north aspect. This trend is apparent with respect to both the A and C horizons (Fig. 2.3 A). A horizons of the S and SW aspects are significantly thinner than all other aspects in the East Basin (Fig. 2.3 B). The mean A horizon thickness of soils on the N aspect is significantly thicker than on all other aspects. The mean C horizon thicknesses on the S and SW aspects are again significantly thinner than those of soils on all other aspects. Mean C horizon thickness increases progressively on the W, NW and N aspects, respectively, and the thickness differences are statistically significant (Fig. 2.3 C).

The relative large number of points for which soil thickness has been measured enables estimation of mantle thickness variation (defined as the thickness of the A + C horizons) over the entire East Basin using interpolation methods (Fig. 2.4). The results of this procedure show the same general trends with slope aspect as described above: the N aspect has the thickest soils and the S aspect has the thinnest soils. Some anomalies in soil thickness are evident, however. On the S aspect, for example, where the majority of the mantle thicknesses are less than 5 cm, soils in one area near the top of the ridge are much thicker than the surrounding soils. Similarly, a bedrock-dominated region occurs on the lower slope area on the NW aspect that elsewhere exhibits a thick, continuous soil mantle (Fig. 2.5). Mantle thicknesses of zero are either bedrock-dominated areas, similar to that described above, or surface exposures of calcite-cemented concretions.

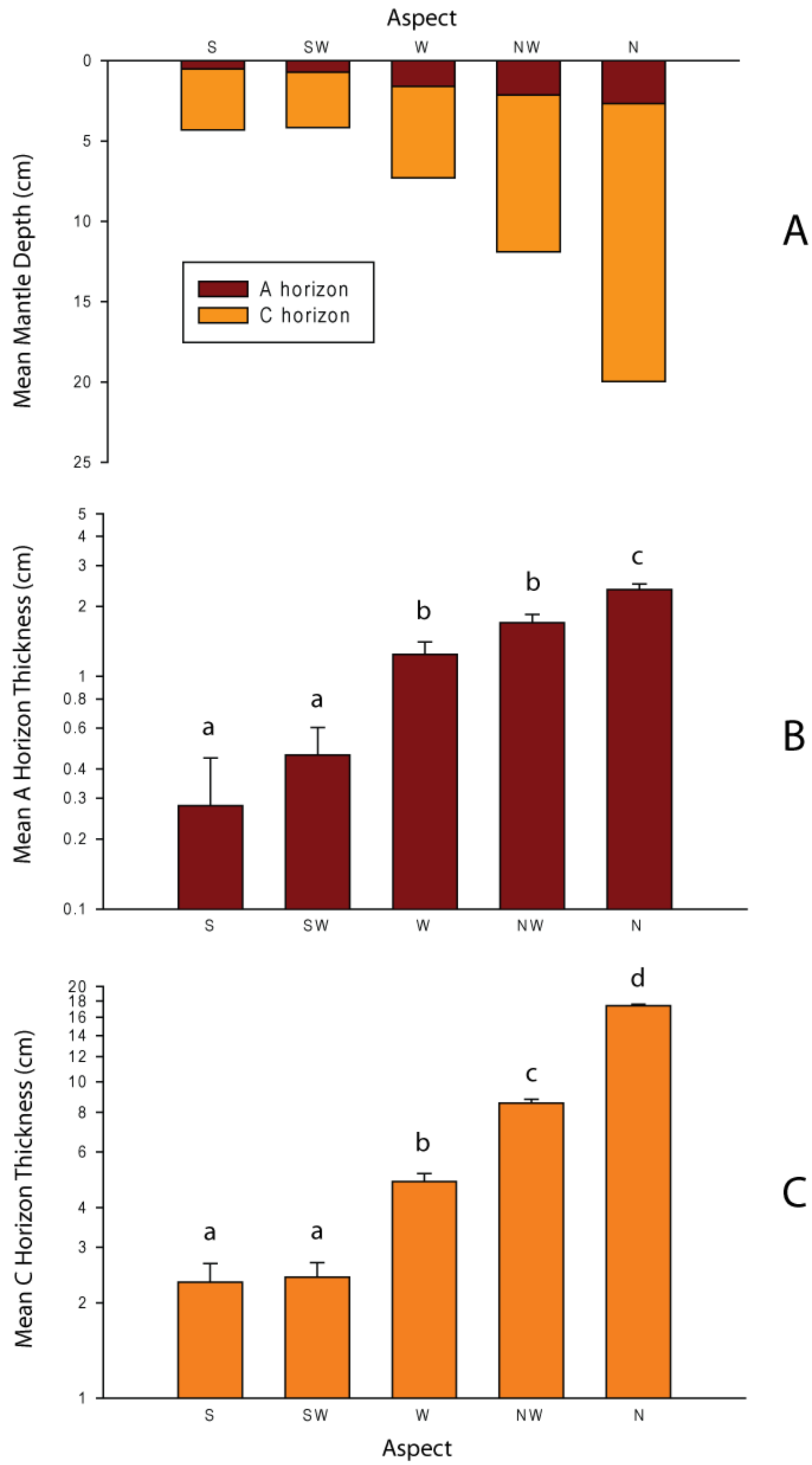


Fig. 2.3. Mean soil mantle thickness on all aspects of the East Basin, displayed by (A) combined mean depths of the A and C horizons, (B) mean A horizon thickness and (C) mean C horizon thickness. Error bars are 2 standard deviations from the mean, while small letters above bars indicate significantly different means ($p < 0.05$) when letters are different between bars.

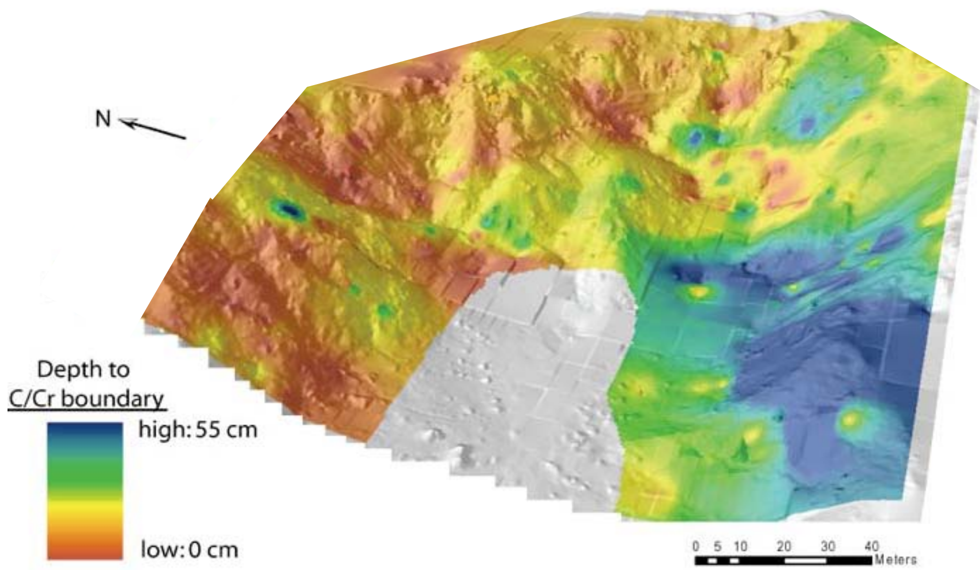


Fig. 2.4. Soil thickness variation in the East Basin. Interpolation is based on a sample size of n = 271. Gray colors represent areas where there is no data. Grid cell size = $0.25m^2$.

Fig. 2.5. Large area of bare bedrock on NW aspect of East Basin. Active channel is located at the base of the slope, just below the lower margin of this photograph

Soils Upslope vs. Downslope of Trees

Soil horizon thicknesses around large, mature trees varied according to slope position and position relative to the tree (immediately upslope or above tree vs. downslope or below tree trunks). There are 3 trees, thus 6 soil profiles, in each slope position (i.e. lower, middle, upper). While this sample size is relatively small, differences and similarities in soil development across the hillslope are evident. The mean thicknesses of soil horizons directly above tree trunk generally increase moving from upper to lower slope positions (Fig. 2.6 A). The mean thicknesses of soil horizons below tree trunks also increase from upper to lower slope positions (Fig. 2.6 B). At each slope position, the mean thicknesses of the A, C and Cr horizons are generally greater above the trees compared to the same slope position below the trees (Fig. 2.6 C).

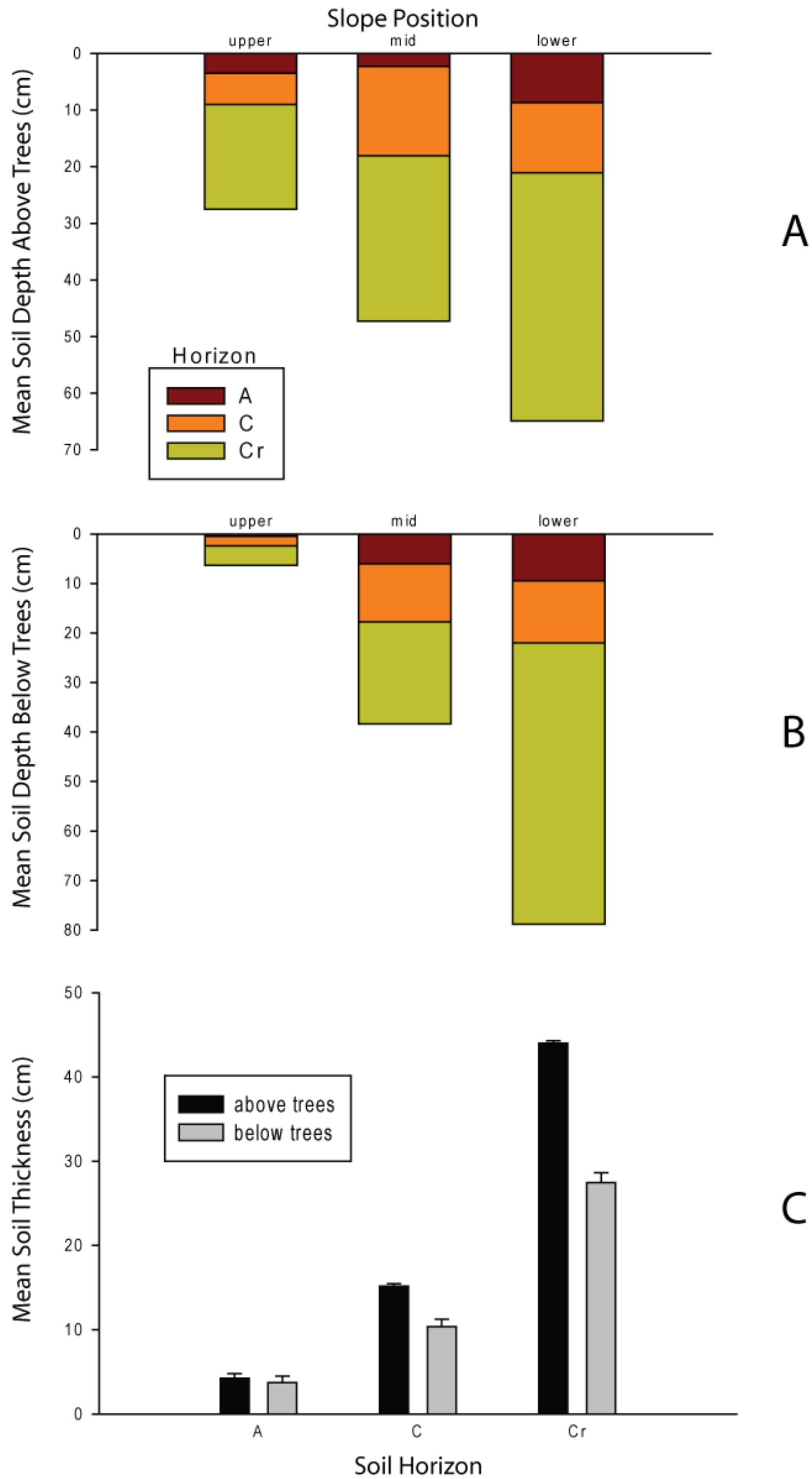


Fig. 2.6. (A) Mean soil horizon depths above trees, (B) Mean soil horizon depths below trees, (C) Comparison of mean soil horizon thickness in all slope positions above vs. below trees. Error bars are 2 standard deviations.

Erosion Rates

Erosion rates around individual trees can be used collectively to estimate long-term hillslope erosion rates (LaMarche, 1968; McAuliffe et al., 2006). Positive erosion rates indicate a net loss of material throughout the life of the tree, indicated by exposure of the uppermost lateral roots. "Negative erosion rates" actually indicate either net accumulation of surficial material around the base of the tree, with no roots exposed above the ground surface, or reflect the initial depth of root germination below the initial ground surface, or some combination of both (McAuliffe et al., 2006). Many of the trees that yielded negative erosion rates in this study were growing within 1 meter of calcite-cemented concretions that confer stronger resistance to weathering and erosion than the clay cemented bedrock.

Scatterplots of the age of each tree against its respective height of vertical root exposure provide information about hillslope erosion (Figs. 2.7, 2.9). Regression lines fit to the data points help explain variation within the data, as well as estimate the depth below the surface of initial root germination and estimate a long-term hillslope erosion rate. The y-intercept of the regression equation estimates an average depth of root germination for all trees on one slope aspect while the slope value estimates an entire hillslope erosion rate, as long as there is a positive relationship between vertical root exposure and tree age (LaMarche, 1968; McAuliffe et al, 2006). Most of the aspects in this study display this type of relationship, but there are exceptions that are described below.

Relationships between vertical root exposure and tree age vary as a function of aspect and slope location (Figs. 2.7, 2.9). On the NW aspect of the West Basin, there is a pronounced non-linear relationship between root exposure and tree age, and there are no apparent differences between root exposure in various slope positions (upper, mid, lower). The non-linear pattern consists of two distinct data groups, however: for trees less 150 years in age, the slope of the relationship between root exposure and age is extremely steep (Fig. 2.8). In contrast, for trees greater than 150 years old, the slope of the relationship is nearly horizontal, with very little increase in net root exposure over a time span of approximately 450 years.

This relationship does not exist on the NE aspect, where there is a linear relationship between root exposure and tree age (Fig. 2.7). On the N aspect, which is less mesic than the NW aspect because of its more exposed position, the correlation between root exposure and age is weaker than at the other two sites ($r^2 = 0.283$). However, this relatively weak relationship consists of different erosion rates for trees in lower slope and upper slope positions. The relationship for trees in the upper slope position has a steeper slope than the lower slope position (0.141 vs. 0.079, respectively), although there are relatively few data points in each separate group.

In the East Basin, similar relationships between vertical root exposure, tree age and slope position are observed (Fig. 2.9). On the N aspect, which is the most mesic slope in this basin, there is a relatively constant relationship between root exposure and tree age, regardless of slope position. On the slightly less mesic NW aspect in the East Basin, there is a pronounced difference in the relationship between root exposure and tree age for trees in the upper and lower slope positions (Figs. 2.9, 2.10). The slope of the relationship is positive and the correlation is relatively strong ($r^2 = 0.314$) for trees on the upper slope (Fig. 2.10). For trees on the lower slope, the slope of the relationship slightly negative but is not significantly different than zero, though there are relatively few trees on the lower slope alone.

The more xeric slopes in the East Basin on W, SW and S aspects all show positive, linear relationships between vertical root exposure and tree age (Figure 2.9). These relationships are similar to the NE aspect in the West Basin, except they all have weaker correlations ($r^2 < 0.2$). Differences between root exposure on upper vs. lower slope positions on these aspects are not as apparent as they are on the NW aspect. Almost all of the trees on all three aspects are less than 150 years in age and none are greater than 350 years in age.

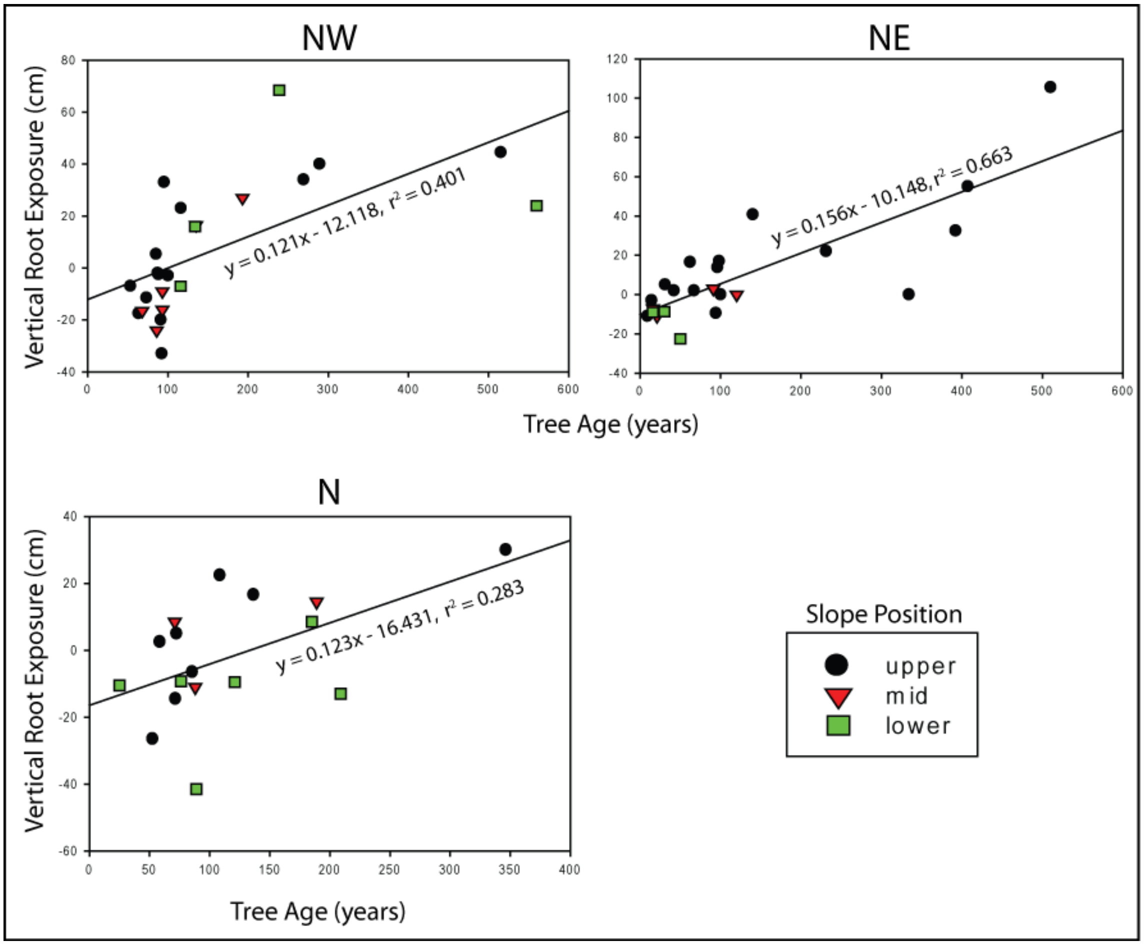


Fig. 2.7. Vertical soil loss, or apparent accumulation, during the lifetimes of individual hillslope piñon pine trees in the West Basin. Each plot represents a major hillslope aspect.

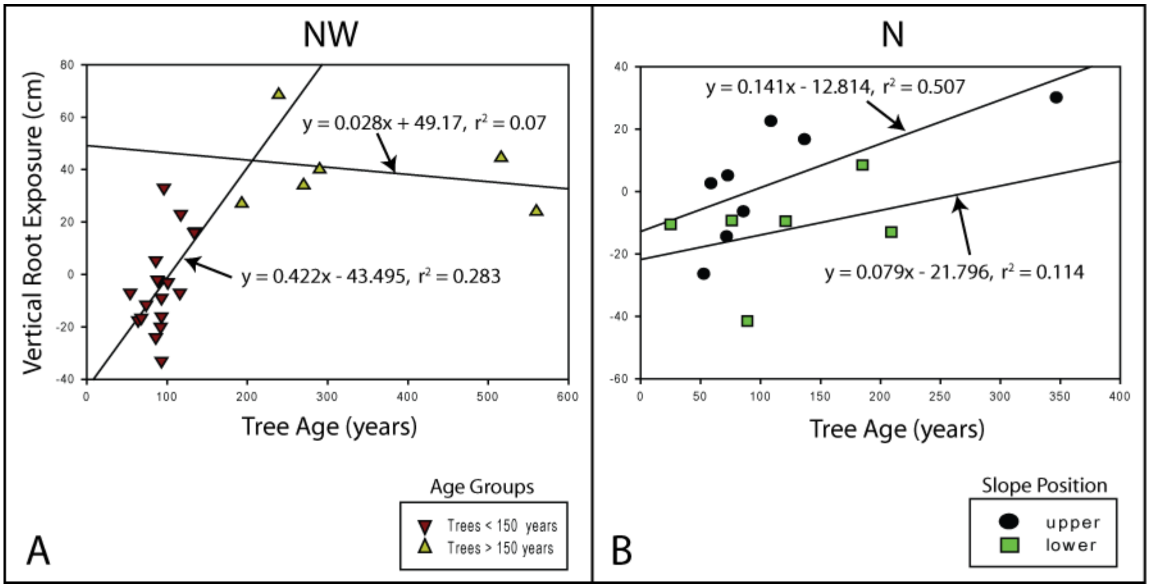
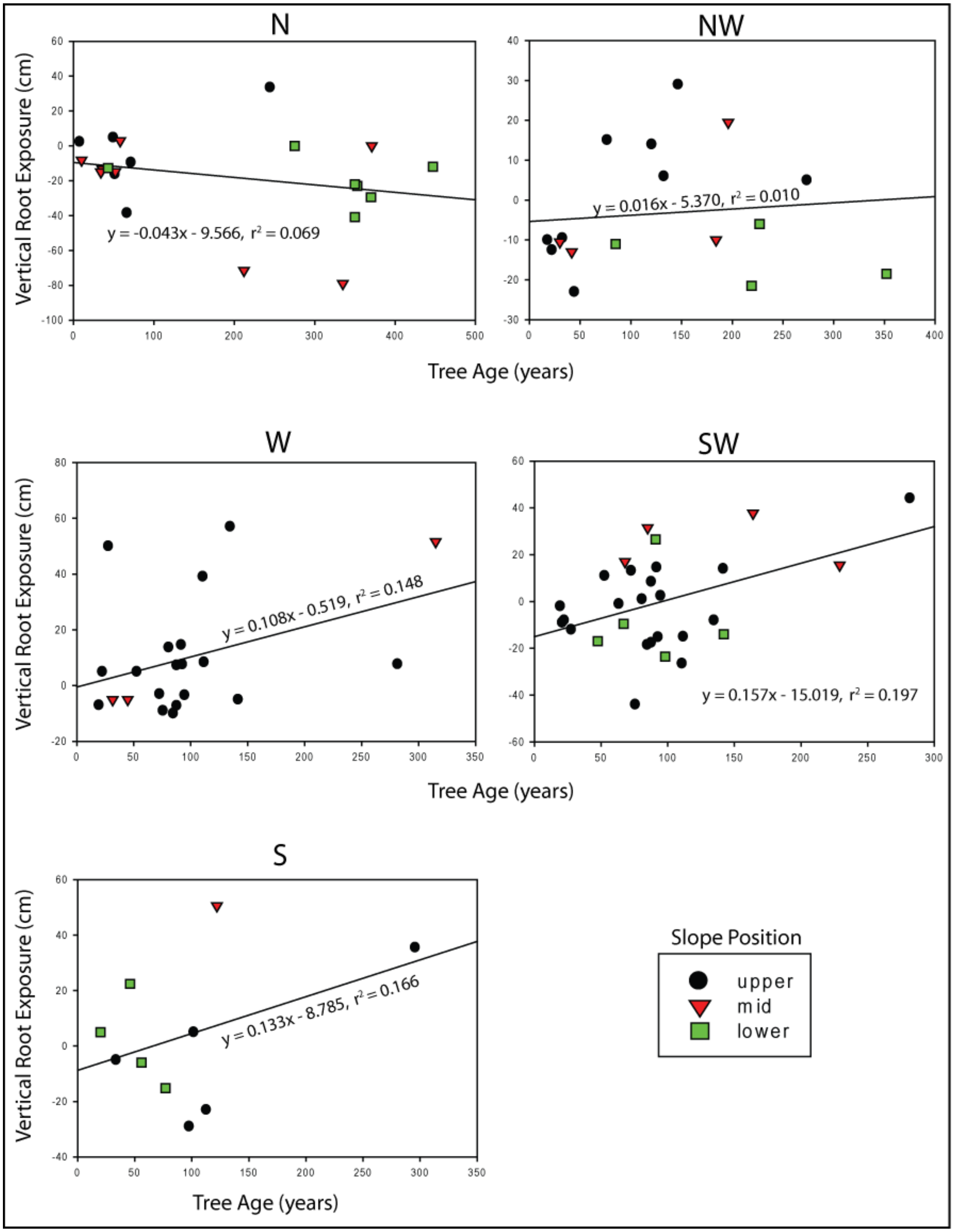


Fig. 2.8. Vertical soil loss, or apparent accumulation, of individual hillslope trees on two selected aspects from the West Basin. (A) Regression lines fit to trees of different age groups on the NW aspect: <150 years and >150 years. (B) Regression lines fit to trees in different hillslope positions on the N aspect: upper slope and lower slope. Data for trees on the mid slope have been excluded from this analysis.



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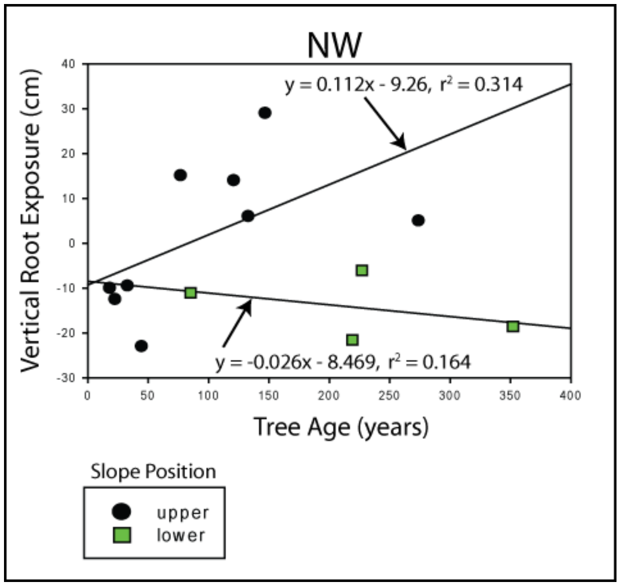

Fig. 2.10. Vertical soil loss, or apparent accumulation, of individual hillslope trees on the NW aspect of the East Basin. Trend lines are fit to trees in upper and lower slope positions. Data for trees on the mid slope have been excluded from this analysis.

DISCUSSION

The soils and dendrogeomorphic data in this study provide insight into how soil development (in this case, primarily from bedrock weathering) and soil erosion differ according to slope aspect and slope position in this study area. Soil toposequence data revealed that soil depth varies with slope position, with thicker soils forming on lower slope positions. Soil mantle thickness throughout an entire sub-basin depends on hillslope aspect, with thicker soils forming on more northerly aspects. Long-lived woody vegetation on the hillslopes affects soil development, as soil depth varies immediately upslope and downslope of trees. Trees are also used to estimate erosion rates, revealing that the removal of the soil mantle from the hillslopes varies as a function of both aspect and, in some cases, slope position.

In semi-arid regions, variations in geomorphic processes over a relatively small area can often be explained by hillslope aspect-induced differences in water availability (Churchill, 1982; Burnett et al., 2008). Churchill (1982) documented differences in weathering and erosion patterns on north- vs. south-facing aspects in the South Dakota badlands. Burnett et al. (2008) documented the actual differences in soil temperature and moisture regimes that ultimately lead to those patterns. They found that soil temperatures are cooler and soil water potential is greater on northern aspects as opposed to the warmer temperatures and lower soil water potential on southern aspects.

These topoclimate differences help explain the variations in soil mantle depth as a function of slope aspect. On the more mesic northern and eastern aspects, greater soil water content enhances both weathering of the clay-cemented bedrock and vegetation cover to maintain a thicker soil mantle. On more southerly and westerly aspects, the more xeric conditions decrease soil water availability, plant growth, and weathering, favoring a thinner mantle. The presence of thinner mantles or bare bedrock, however, should produce greater runoff that aids in the expansion of bare bedrock areas by stripping the thin, readily erodible mantle. Through positive feedback mechanisms, this acts to eliminate the mantle over larger and larger areas (Burnett et al., 2008; Ch. 1).

The N aspect comprises the most mesic slopes within the East Basin and consequently, has deeper soils due to more rapid weathering than less mesic aspects. The NW aspect is the most mesic location within the West Basin and, based on the soils data from the East Basin, also has deeper soils than the other, less mesic aspects. In the previous section, it was demonstrated that tree trunks impede the downslope movement of soil materials, which tend to accumulate immediately above tree trunks. The steep slope of the relationship between root exposure and age on the NW aspect of the West Basin is interpreted as the relative ineffectiveness of small trees (< ca. 10 cm diameter trunks) to impede the downslope movement of materials. Instead, there is a net loss of soil materials around young trees until those trees are approximately 100 years of age and the oldest roots, originally located at 10-20 cm depth, are subsequently much nearer the surface. This also helps to explain the concentration of trees less than 100 years of age on the N aspect of the East Basin. Most of the root exposure measurements here are between the original rooting depths (10-20 cm below the surface) and 5 cm above the surface. Without accumulating material behind their trunks and the lack of a large erosional event in the last 100 years (McAuliffe et al., 2006) results in very little accumulation or erosion around these trees. In contrast, larger trunks as well as extensive lateral roots of older trees act as effective dams that intercept and retain sediment moving downslope. The interception and accumulation of materials by large trees, in turn, probably promotes further weathering of underlying bedrock because of moister soil conditions. This feedback is strongest on the more mesic slopes within the study area.

On the more transitional and xeric W, SW and S aspects of the East Basin, the soil mantle is thinner while the relationship between root exposure and tree age becomes more positive and linear, relative to the mesic aspects. In addition, the trees are generally less than 150 years in age. These results indicate that there is overall less weathering and more erosion over these hillslope aspects. Though many of the older trees are able to accumulate material upslope of their trunks and lateral roots, there is not as much material available to accumulate as there is on the more mesic aspects due to the lower rates of weathering. The thinner soil mantles and more erosion on the xeric aspects compared to the mesic aspects also inhibit the trees from remaining on the slopes to attain ages greater than 350 years. The older trees that are present on these aspects display the greatest amounts of erosion. Fewer older trees results in less accumulation of material around their trunk and roots. Less accumulation results in less weathering of the mantle and a thinner mantle leads to increased erosion. This positive feedback is most evident on these transitional and southerly aspects.

The greater abundance of long-lived woody vegetation on the northern aspects and the older ages of piñon trees on these hillslopes suggests that even during the late 19^{th} and early 20^{th} century drought and episodic erosion events proposed by McAuliffe et al. (2006), the conditions on these aspects remained favorable for piñon establishment and growth. On the more transitional slopes (W, SW and NE), the trees do not live as long as on the more mesic aspects and there is a predominance of trees around 100 years old. During times of high erosion, these slopes are no longer able to support the majority of their piñon population except those trees in very favorable locations. It appears as if the piñons in the transitional areas are cycling on the same centennial scale as the episodic erosion events. The most xeric, southern aspect, supports very few trees older than 100 years old, suggesting that the erosion events are even more pronounced here. The systematic increase in density of piñons saplings from more xeric to more mesic aspects also supports these conclusions in terms of long-lived woody vegetation recruitment of the slopes (Ch. 1).

Soil forming processes are affected by hillslope aspect and the presence of trees through the feedbacks and weathering patterns just described, as well as by hillslope position. The soil toposequence data from the NW aspect of the East Basin shows that soil development varies as a function of slope position on these mesic hillslopes where there is a continuous soil mantle.   The thicker soils present in lower slope positions suggest that more weathering is occurring here, as has been observed in other semi-arid hillslope studies that show a downslope increase in soil moisture and leaching intensity (Yair, 1990). However, considering the clay + silt percentages as a proxy for the degree of weathering suggests that the soils in the upper slope positions are weathering to a greater degree, albeit over a smaller soil thickness. If so, a few explanations for the observed differences in thickness, and by implication weathering, are possible. One is that the weathering front is not progressing down as far into the soil profile in the upper slope position as compared to those in lower slope profiles. This explanation is supported by the study of Puigdefabregas et al. (1999), who concluded that higher clay + silt content of soils on upper slopes cause moisture content there to remain higher during the dry season compared to the lower, sandier hillslope segments. The increased sand content of the lower slope soils may reflect greater sand accumulation on the lower slopes due to downslope erosion, favoring greater permeability of the accumulated sandy materials. If this is the case, the thicker soils in these slope positions also reflect, to some extent, cumulic soil development as well as deeper infiltration and weathering.

Analysis of soils upslope and downslope of mature trees on a N aspect supports the conclusion that the presence of long-lived woody vegetation on the hillslope affects slope and soil forming processes. This analysis also begins to provide explanations for the weak relationships between root exposure and tree age in this study on mesic aspects as opposed to the strong correlation between the same variables on a N aspect in

McAuliffe et al. (2006). Assuming that material is transported downslope mainly by some combination of diffusive processes, the thicker A and C horizons observed in soils upslope of trees relative to those in the downslope position suggests that the trees themselves are acting as impediments to downslope transport. During the lifetimes of the trees, this process promotes sediment accumulation above the trees, which would likely favor development of cumulic A and C horizons. An increasingly thicker A and C horizon, in turn, may increase soil water retention, favoring increased overall weathering as well as a thicker Cr horizon. At this spatial and temporal scale, the continued downslope transport that produces sediment accumulation and the observed topographically elevated slope immediately above the tree would presumably be balanced by the development of a topographically lower slope area below the trees (Fig. 2.11). These results also suggest the possibility that when large, infrequent precipitation events (or a sequence of closely spaced precipitation events) produce enough runoff to generate surface flow, the modified slope form and presumably changed patterns of runoff might cause changes in patterns of surface erosion and sediment movement around and below the trees. Further studies on the effects of trees on hillslope processes are needed in order to substantiate the results from the relatively small sample size in this study.

Fig. 2.11. Examples of piñon trees on north-facing hillslopes with net accumulation of material upslope of the tree and net apparent removal of material downslope of the tree. Dashed line projects upslope soil surface elevation downslope of the tree. Solid line estimates present soil surface elevation downslope of tree. Vertical solid line with arrows depicts estimated depth of sediment storage upslope of tree.

Other geomorphic processes, such as base level changes in the basin floors, may also account for the variations from the expected mantle thicknesses and erosion rates. Anomalously thin mantles on northern aspects may be attributable to processes that affect local base level at the base of the slope. For example, a channel draining a large area of the East Basin is located at the base of the NW slope. The position of this active channel strongly suggests active erosion at the base of the slope by removal of basal slope material and steepening of the basal part of slope. Ultimately, this removal of basal slope material has propagated up the slope, produced an expanding, large, bare bedrock outcrop (Fig. 2.5). Conversely, no channel exists at the base of the hillslope studied by McAuliffe et al. (2006); instead, the active channel is located away from the slopes, along the slope pediment. The incision of the main channel in this basin likely caused abandonment and subsequent incision of the pediment, favoring the development of deeper drainage lines on the slopes. Also unlike the north-facing hillslope studied in McAuliffe et al. (2006), there are deeply buried trees on the north aspects in the current study basins, particularly in lower slope positions. Based on the depth of the soil mantle above the roots of many older piñon trees, material seems to be moving downslope and accumulating at the base, perhaps as a result of base level rise of active channels near the base of the slopes. In McAuliffe et al. (2006), where the active channel is farther away from the base of the slope, the entire hillslope was undergoing erosion, whereas the hillslopes in this study do not exhibit this uniform erosion. Alternatively, sediment may not be moving out of the basin as quickly in these study basins, which acts to accumulate material on the basin floor as well as at the base of the slopes (Tillery et al., 2003). These examples suggest that the position of the active channel relative to the hillslopes affects hillslope erosion processes.

On the upper parts of some aspects, the presence of calcite-cemented concretions on the slopes also appears to affect important hillslope processes. On transitional and southerly aspects, emerging concretions are observed to be associated with greater heterogeneity in slope form. These concretions in the otherwise homogeneous sandstone lead to local areas of relatively low slope gradients as well as localized traps of eolian sediment. During infrequent high intensity rainfall events (McAuliffe et al., 2006, Wawrzyniec et al., 2007, Scuderi et al., 2008) overland flow has more time to infiltrate and permeate through the soil profile in these relatively flat areas. This increases soil moisture in these areas, which increases weathering of the bedrock below, thus increasing the permeable soil mantle depth. Also, if the laterally moving water was carrying sediment with it, this sediment will most likely be deposited as the water slows and infiltrates, also acting to increase the amount of material and thus depth of the soil mantle. In areas where the concretions are acting as eolian traps, the extra, sandy material builds up on the surface and contributes to an overall thicker soil mantle. A greater depth to the less permeable bedrock below reduces the potential of these areas to produce runoff, and increases the soil moisture potential. It is in most of these areas on the transitional slopes that we find the majority of piñon trees growing, especially the ones without exposed roots. The accumulation of material on top of the roots explains some of the variation in individual tree erosion rates and the weak correlation between overall root exposure and tree age in the transitional areas. Conversely, concretions do not generally produce areas of positive relief on north aspects. Preliminary studies suggest that generally higher soil moisture content and greater soil depths favor a greater magnitude of weathering of the concretions, precluding their emergence. The lack of preserved concretions on these mesic slopes, therefore, indicates that this factor cannot account for variations in erosion rates on the mesic aspects.

While the northern aspects in the West Basin support some piñons with roots that are not exposed, the long-term erosion rates for these hillslopes are much more similar to that found by McAuliffe et al. (2006) compared to the East Basin. One possibly significant difference between the West Basin and East Basin is the distance from the main escarpment. The West Basin is directly below the escarpment, as is the hillslope studied by McAuliffe et al. (2006), but the East Basin is approximately 0.5 km away from the local topographic high. This position relative to the main escarpment likely results in greater daily insolation for the East Basin, and this presumably produces variations in soil temperature and soil moisture potential between the basins that may be sufficient to affect weathering and erosion patterns, as observed by Burnett et al. (2008).

The soil geomorphic and dendrogeomorphic studies indicate that warmer, drier conditions are conducive to thinner soils, more bare bedrock exposure and heterogeneous erosion rates on the hillslopes of this study area. These results combined with the results of the biogeomorphic study (Ch. 1) leads to the hypothesis that when climate changes to warmer and drier conditions, transitional areas on hillslopes are affected the most through loss of soil, loss of vegetation and increased erosion. Ultimately, this suggests that slopes are transforming away from the transport-limited end-member toward the bedrock-dominated end-member. This transformation occurs through the changes in microclimate that lower piñon survival rates, lower weathering rates and increase erosion rates through the redistribution of runoff. As weathering rates decrease, less soil mantle is produced, even on the mesic aspects, leading to fewer areas able to support piñons and to a greater chance that this weathered material will be removed during an episodic erosion event.

As soil temperatures on the mesic aspects approach those currently on the xeric aspects, the soil mantle will not be able to reform, permanently exposing more unweathered bedrock that is unable to support long-lived woody vegetation and changes the geomorphic processes. Once there is exposure of bare bedrock, as observed on the xeric and transitional aspects in this study, the soil mantle cannot easily reform, especially in a semi-arid environment (e.g. Wahrhaftig, 1965). In this area of the southwestern US, approximately 40% of the precipitation is in the form of flashy, monsoon thunderstorms. Temporally, the monsoon weather phenomenon has been affecting this landscape throughout the Holocene (Adams et al., 1997). These short, intense precipitation events generate runoff on the exposed bedrock areas rapidly, further eroding any weathered material that may be adjacent to the bedrock. As such, monsoonal precipitation is not conducive to infiltration and deeper weathering that is necessary for the reformation of eroded mantle.

Although capped by resistant Cretaceous Dakota sandstone, the 60 m cliffs observed by Burnett et al. (2008) on xeric aspects in the same Jurassic bedrock as this current study further supports the conclusion that the slope transformation has been largely unidirectional within the Holocene. The distinct aspect-related slope morphologies in the Burnett et al. (2008) study have likely developed over glacial-interglacial timescales, and there is no evidence that during the Holocene the tall cliffs and exposed bedrock areas on xeric aspects began to reform a soil mantle and lower their slope gradients. According to Yair (1990), "Any important change in the extent and properties of the surficial mantle in semi-arid and arid environments is usually linked to a climatic change." The change in the extent of the soil mantle between the different hillslope aspects in Blue Gap is no exception. With the predicted temperature increases and precipitation decreases in the desert southwest over the next 100 years (Alley et al., 2007), this slope transformation in areas with lithologically sensitive bedrock is most likely irreversible.

CONCLUSIONS

The main conclusions of this study are summarized as follows:

• Soil mantle thickness is generally greater on northerly, more mesic aspects than on southerly, more xeric aspects, mainly as a result of topoclimate differences and the related weathering and erosion feedbacks.

• On northerly aspects with a continuous soil mantle and relatively dense piñon canopy cover, soil profile depths increase from upslope to downslope positions as a result of more material accumulating at the base of the slopes through creep processes. On these same slopes, soil horizon thicknesses are greater immediately upslope of mature tree trunks compared to immediately downslope as a result of material creeping downslope and accumulating above the trunks. This accumulation promotes greater weathering.

• Hillslope erosion rates, as estimated from root exposure and age of trees, vary according to hillslope aspect, hillslope position, and geomorphic processes related to base level changes and heterogeneities in the bedrock.

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