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Non-equilibrium hillslope dynamics and irreversible landscape changes at a shifting pinyon–juniper woodland ecotone

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ABSTRACT

Pinyon–juniper woodlands of the western United States frequently exist within topographically complex landscapes where varied slope aspect yields substantial, local microclimate variation. Vegetation composition and cover typically change markedly along the gradient of relatively mesic northern aspects to more xeric southern aspects. Ecohydrological processes including precipitation runoff, soil moisture storage, and erosion are strongly influenced by vegetation. In certain cases, reduction of plant cover may set self-enhancing feedbacks in motion that lead to further declines of both vegetation and soils, and in some cases, replacement of woodlands with more xerophytic vegetation. The first place such change is likely to occur is in the ecotone between the drier southern aspects and moister north aspects. We studied vegetation, soils, and soil erosion in two small (1–2 ha) drainage basins in northeastern Arizona where pinyon–juniper woodlands occupy northern aspects, grading to shrub-dominated vegetation on more xeric southern aspects. Mapping of soil thickness, use of tree-root exposure to measure long-term soil erosion rates, and data on tree mortality and establishment indicate that the ecotone between woodland and more xerophytic vegetation has apparently been shifting for centuries, with a reduction in woodland vegetation. Erosion rates on xeric aspects ranged from 14 to 23 cm per century in one basin and as much as 60 cm per century in the other basin. In contrast, mesic aspects showed either no net soil losses over the last several centuries or rates significantly less than on the xeric aspects. Exposure of small roots (<5 mm diameter) of cliff rose (*Purshia stansburiana*) directly overlying bare bedrock surfaces indicates that the process of denudation is ongoing and probably expanding in ecotonal areas. Mesic and xeric aspects exemplify “conserving” vs. “non-conserving” ecohydrologic systems in terms of their capacities to retain water and soils. The contrasting sets of self-enhancing feedback dynamics on xeric vs. mesic aspects not only produce different states in vegetation and soils, they also set in motion the production of pronounced geomorphic contrasts that probably require centuries to millennia to develop. The ongoing ecohydrological transitions in the more xeric aspects are in the process of transforming those hillslopes from smooth, curvilinear, soil-mantled, sediment transport-limited slopes to detachment-limited slopes characterized by an expanding area of bare bedrock steps and cliffs, and this transition is probably irreversible. Predicted temperature increases over the next century for the region are comparable to the present-day soil temperature differential on xeric vs. mesic aspects at the site. Soil temperature is the principal driver of soil water evapotranspirative losses, and because of the interdependent linkages between soil temperature, soil moisture, weathering, production and retention of soil, vegetation, and hydrological response, relatively small temperature increases will likely accelerate the ongoing environmental changes in this and similar areas.

1. Introduction

Within the last 25 years, ecologists and earth scientists have increasingly recognized the complex and interdependent linkages between biotic and physical components of landscapes and how these linkages affect current system states and potential future trajectories of landscape change (e.g., Schlesinger et al., 1990; Bull, 1991; Viles et al., 2008; Gutiérrez-Jurado et al., 2013; Persico and Meyer, 2013). Collaborations among ecologists and earth scientists in deciphering

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these linkages are contributing to a growing understanding of how both climate change and land use can set significant landscape transitions in motion (McAuliffe et al., 2006; Monger and Bestelmeyer, 2006; Peters et al., 2006).

Sparsely vegetated, semiarid landscapes are especially prone to change because small alterations of vegetation caused by either climate or land use can have large effects on hydrological responses and soils. Because of the interdependence of soils, vegetation, and other dynamic components of the landscape, such changes may produce either self-arresting (negative) feedback that tend to return the system to the pre-disturbance state, or self-enhancing (positive) feedback that can produce irreversible state transitions (Schlesinger et al., 1990; Bull, 1991; Monger and Bestelmeyer, 2006; Peters et al., 2006).

Semiarid, pinyon–juniper woodlands are the most geographically extensive biotic community of the western United States, occupying more than 22 million hectares (Mitchell and Roberts, 1999). Extreme and regionally extensive mortality of pinyon trees in response to prolonged severe drought has recently been documented (Breshears et al., 2005, 2009; Royer et al., 2011). Pinyon mortality rates up to 90% in some locations demonstrate the capacity for drought coupled with slightly elevated temperatures to greatly impact these ecosystems (Adams et al., 2009) as well as coniferous forests in general (Williams et al., 2013). Abrupt vegetation changes such as these can potentially trigger a cascade of interdependent responses including soil erosion (Davenport et al., 1998), altered hydrological behavior (Wilcox et al., 1996, 2003), and increased near-ground solar radiation and associated soil water evaporative losses (Royer et al., 2011, 2012) that can inhibit or prevent ecosystem recovery.

Considerably larger average temperature increases of 3 to 4 °C are predicted for the southwestern United States within the next century (Gutzler and Robbins, 2011). Drought conditions comparable in intensity and duration to recent, historic droughts, but occurring under elevated temperature regimes, will probably have very large impacts on pinyon–juniper woodlands (Breshears et al., 2005; Adams et al., 2009). Many sites in pinyon–juniper woodlands appear to lie near or have crossed a critical threshold for soil erosion, and may be on a trajectory of irreversible change. Investigations of landscape dynamics in pinyon–juniper woodlands can further our knowledge about the kinds of terrains that are susceptible to change. Such investigations can contribute to the prediction of the responses of landscapes subjected to future, altered climate regimes.

Since the late 1990s, as part of a diverse multidisciplinary team of geomorphologists, soil scientists, ecologists, and dendroclimatologists, we have investigated vegetation and landscape dynamics of a series of small drainage basins at a site in northeastern Arizona (Blue Gap site). Mesic slope exposures at the site are covered with pinyon–juniper woodlands grading to shrub-dominated vegetation in more xeric exposures. The body of work conducted at the site includes dated, late Holocene chronologies of aggradation and incision of valley floor alluvial deposits in two basins (Tillery et al., 2003; McAuliffe et al., 2006); lithologic and microclimate controls on weathering of bedrock, sediment production, and morphology of slopes (Tillery et al., 2001; Burnett et al., 2008); high-resolution records derived from tree-ring data and tree-root exposure to determine the magnitude and timing of hillslope erosion and adjacent valley floor responses during the last 400 years (McAuliffe et al., 2006; Scuderi et al., 2008); and use of LiDAR imaging to document the magnitude of slope erosion during a single, large precipitation event (Wawrzyniec et al., 2007).

The work of McAuliffe et al. (2006) was largely focused on a single mesic, northern aspect slope covered by pinyons and junipers. Measurements of pinyon root exposure indicated long-term erosion rates of 19 cm per century; ring-growth anomalies indicated three episodes of erosion at approximately century intervals. The most recent and pronounced of those episodes occurred slightly more than 100 years ago in what was the largest precipitation shift (dry to wet) during the last 2000 years (Scuderi et al., 2008). However, despite substantial, episodic losses of soil from the north-facing slope, those losses have been compensated by rapid weathering of underlying bedrock and production and retention of a new soil mantle, thereby enabling the persistence of pinyon–juniper woodland. This apparent resilience of the north aspect contrasted strongly with xeric, south-facing hillslopes in the same basin, where substantial areas of exposed bedrock predominate. In those areas of exposed bedrock, the remains of large, dead juniper and pinyon trees with their root systems completely exposed indicate a relatively recent loss of soils. The many dead trees on this slope, especially those that had established within the last 400 years but died a century or more ago, indicate that a threshold was apparently passed centuries ago on the xeric exposures, where erosion began to outpace rates of weathering and formation of regolith and soils, leading inexorably to increased exposure of barren bedrock surfaces and a progressive elimination of most trees and vegetation.

The contrasting mesic and xeric aspects at this site appear to represent end members of a continuum of responses from a resource-conserving (north aspect) to resource non-conserving or "leaky" system (south aspect) (Wilcox et al., 2003), in which the latter has undergone a relatively recent and irreversible transition leading to the loss of soil, moisture storage, and a capacity to support woodland vegetation. Although this irreversible transition apparently began many centuries ago on the more xeric southern aspects, we hypothesize that some hillslopes along a continuum ranging from mesic north aspects to xeric south aspects should exhibit soil characteristics, erosion rates, and vegetation responses indicating a closer approach to, or more recent transition across, a threshold leading to irreversible system change.

In this paper, we build on the foundation of our earlier work to examine in detail the relationships between changes in hillslope vegetation, soils, and soil erosion along a topoclimatic gradient produced by variation in aspect exposure in two drainage small basins. This gradient includes the ecotonal transition from relatively mesic pinyon–juniper woodland to more xeric, shrub-dominated vegetation. Through analyses of aerial root exposure of pinyon pine trees, we investigate differences in erosion rates over the last several centuries in various parts of the basins. This approach, used previously in McAuliffe et al. (2006), is combined with studies of root exposure of a small shrub, cliff rose (*Purshia stansburiana*), on bare bedrock surfaces in order to decipher more recent trajectories of bedrock exposure and landscape change in various parts of one of the basins. Finally, we examine how the contrasting erosional behavior of mesic vs. xeric aspects is in the process of generating pronounced geomorphic contrasts within different parts of this landscape.

2. Study site

The Blue Gap site is located 31 km west of Chinle, Arizona in the central part of the Navajo Reservation, 3.5 km east–southeast of the small settlement of Blue Gap. A map showing the general location of the site is contained in McAuliffe et al. (2006, Fig. 1). The climate is semiarid and receives an annual average of 233 mm precipitation, 47% of which occurs from July through October. Average maximum temperature is 69.1 °F (20.6 °C), and the average minimum temperature is 37.9 °F (3.28 °C) (Western Regional Climate Center, 2009; data for Chinle recording station).

The area includes a series of 1–2 km wide, eastward-draining basins bounded on the west by a 150 m-tall escarpment. The six basins are numbered 0 (north end) through 5 (south). Basins 0, 1, and 2 were the locations of studies by Tillery et al. (2001, 2003), McAuliffe et al. (2006), Scuderi et al. (2008), and Wawrzyniec et al. (2007); Basins 3, 4, and 5 were the locations of research by Burnett et al. (2008). The present study was conducted in Basin 2. Hillslopes of this basin are formed on mudstones, siltstones and sandstones of the Jurassic Morrison Formation and underlying Bluff Sandstone (San Rafael Group). Research was focused on two sub-basins within Basin 2, referred to as East Basin