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Viewpoint: Sustainability of piñon-juniper ecosystems—a unifying perspective of soil erosion thresholds

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Abstract

Many piñon-juniper ecosystems in the western U.S. are subject to accelerated erosion while others are undergoing little or no erosion. Controversy has developed over whether invading or encroaching piñon and juniper species are inherently harmful to rangeland ecosystems. We developed a conceptual model of soil erosion in piñon-juniper ecosystems that is consistent with both sides of the controversy and suggests that the diverse perspectives on this issue arise from threshold effects operating under very different site conditions. Soil erosion rate can be viewed as a function of (1) site erosion potential (SEP), determined by climate, geomorphology and soil erodibility; and (2) ground cover. Site erosion potential and cover act synergistically to determine soil erosion rates, as evident even from simple USLE predictions of erosion. In piñon-juniper ecosystems with high SEP, the erosion rate is highly sensitive to ground cover and can cross a threshold so that erosion increases dramatically in response to a small decrease in cover. The sensitivity of erosion rate to SEP and cover can be visualized as a cusp catastrophe surface on which changes may occur rapidly and irreversibly. The mechanisms associated with a rapid shift from low to high erosion rate can be illustrated using percolation theory to incorporate spatial, temporal, and scale-dependent patterns of water storage capacity on a hillslope. Percolation theory demonstrates how hillslope runoff can undergo a threshold response to a minor change in storage capacity. Our conceptual model suggests that piñon and juniper contribute to accelerated erosion only under a limited range of site conditions which, however, may exist over large areas.

Key Words: Pinyon, piñon, juniper, soil erosion, threshold, site erodibility, percolation theory, catastrophe theory, scale dependence, runoff, grazing, drought, understory, canopy, intercanopy

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Resumen

Algunas ecosistemas de piñon-juniper tiene erosion que es acelerada, mientras en otras hay poca erosion. Por eso, hay controversia sobre el effecto de la invasion de estos arboles a la sustentabilidad de los suelos. Aqui, presentamos un modelo conceptual que es consistente con los dos lados de la controversia. Las perspectivas diferentes surgen por causa de diferencisas importantes en la potencia de erosion en los suelos. Se puede ver erosion de suelo como una funcion de (1) potencia de erosion (PE), la cual es afectada por caracteristicas de los suelos, el clima, y la geomorfologia; y (2) la cobertura vegetal. Modelaciones del USLE demuestran las interacciones de esas dos cosas. Por ejemplo, cuando el PE es alto, la erosion de suelo tiene mucha sensibilidad a los cambios de la cobertura vegetal. En esa caso, la proyeccion de erosion cambia mucho con muy pocos cambios del cobertura vegetal. Teorias de catastrofe y percolacion son muy util para apoyar nuestro modelo conceptual. Segun nuesto modelo, piñon y juniper causa una acceleracion de la erosion, solamente bajo unas condiciones muy limitadas, sin embargo esas condiciones puede exister sobre areas grandes.

Piñon-juniper ecosystems—woodlands dominated by species of piñon and/or juniper—have expanded dramatically both in areal extent and density during the last century, and now occupy 20 to 30 million hectares in the western United States (Johnsen 1962, Miller and Wigand 1994). Sustainability of these ecosystems ultimately depends upon the sustainability of the soil resource (Jenny 1980, National Research Council 1994). Accelerated erosion has been documented in some of these woodlands (Carrara and Carroll 1979, Van Hooser et al. 1993, Wilcox et al. 1996a, 1996b). The increase in erosion rates in some cases has been so dramatic that the soil resource will be lost within a matter of decades if the processes are not halted or reversed (Wilcox et al. 1996a, 1996b). These ecosystems, then, appear to have crossed a threshold between a state with low erosion rates and a sustainable soil resource to one with high erosion rates and a degrading and unsustainable soil resource.

Piñon and juniper are often viewed as harmful invading species that cause erosion and ecosystem degradation (cf. Belsky 1996). Studies have demonstrated that piñon and juniper utilize moisture (Breshears et al. 1997a) and nutrients (Doescher et al. 1987, Padien and Lajtha 1992) from intercanopy soils, and that as woody biomass increases, understory biomass decreases (Aro 1971, Clary 1971, 1974, Everett and Sharrow 1985, Pieper 1990). Because ground cover has a primary effect on erosion rates (Wood et al. 1987), reductions of herbaceous intercanopy plants as a result of competition from piñon and juniper can cause erosion rates to increase. Other processes, however, can also contribute to reductions in herbaceous cover, including livestock grazing, short-term climate fluctuations (e.g., drought), fire, and off-road vehicle use. Although reductions in ground cover resulting from either land use or competition with piñon and juniper may lead to accelerated erosion (Wilcox et al. 1996a, 1996b), some piñon-juniper ecosystems can experience reductions in herbaceous cover without increases in erosion (Renard 1987, Schmidt 1987). Hence, ground cover alone is not an adequate predictor of soil erosion.

A recent review by Belsky (1996) pointed out that the perception of piñon and juniper as "harmful weeds" that lead to land degradation is not strongly supported by existing scientific literature. There are 2 widely held but divergent perspectives with regard to piñon-juniper ecosystems (Brown and McDonald 1995, Belsky 1996): (1) piñon and juniper trees negatively impact the sustainability of a site by triggering high erosion rates; hence the recent expansion of piñon and juniper is problematic; (2) piñon and juniper trees do not negatively impact the stability of a site; hence the recent expansion is not problematic. These very different perspectives probably arise from the wide range of conditions encompassed by piñon-juniper ecosystems. Piñon and juniper are found in widely varying climates, on sites with different geology, geomorphic setting, soil properties, and land use histories (West et al. 1978, Leonard et al. 1987). In addition, piñon-juniper ecosystems include a number of species of both piñon and juniper: piñon species include *Pinus edulis* Engelm., *P. monophylla* Torr. & Frém., and *P. cembroides* Zucc.; juniper species include *Juniperus monosperma* [Engelm.] Sarg., *J. osteosperma* [Torr.] Little, *J. occidentalis* Hook., *J. scopulorum* Sarg., and *J. deppeana* Steud. Similarly, herbaceous components vary greatly (Harner and Harper 1976). Further, the woody species have been long established at some sites but have recently invaded others, and the densities of the trees vary widely. Thus, the widely differing perspectives of soil sustainability in piñon-juniper woodlands may reflect accurate assessments of woodland conditions in widely differing environments.

Problems can arise when management practices developed for a particular site are applied at other sites with very different conditions. Management practices in piñon-juniper ecosystems often focus on a specific resource, particularly forage or fuel wood. However, both of these resources, as well as many other ecosystem resources and processes, are ultimately dependent on the capacity of the soil to support the plant community. Hence, it is critical that management of these ecosystems focus on maintaining the soil resource at a level that allows sustainable use (Baker et al. 1995).

Use of even simple erosion models such as the Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978, Nyhan and Lane 1986) allow prediction of erosion under a variety of conditions, including high and low erosion states, but neither simple nor complex models provide a clear conceptual framework explaining the occurrence of erosion thresholds. Our objective is to develop a conceptual model of soil erosion thresholds in piñon-juniper ecosystems that is consistent with observations of erosion and is applicable across sites and regions. We address this objective by using USLE, recent studies of erosion in piñon and juniper ecosystems, and non-linear conceptual models.

General Determinants of Soil Erosion Rates

We view the numerous factors that affect soil erosion rates as belonging to 1 of 2 general determinants: (1) site erosion potential (SEP), which is a function of climate, geomorphology, and soil erodibility; and (2) ground cover, which is most directly linked to vegetation patterns and may change rapidly in response to land management practices and climatic variations.

Site Erosion Potential

Site erosion potential may be thought of as an index combining a number of site-specific characteristics that, in rangeland settings, are not readily subject to alteration by management practices. These characteristics are inherently scale dependent, and can be placed in 3 categories in order of decreasing scale: climate, geomorphic setting, and soil erodibility. Climate, as discussed here, has its influence at intersite scales, in that an entire watershed or region is likely to experience relatively similar precipitation and temperature dynamics. Specific amounts of precipitation and temperatures may vary from one part of a site to another, but the seasonal distribution and type of events are likely to be relatively similar across the entire site. Climatic factors include total annual precipitation; temporal variability and seasonal distribution of precipitation, including proportions received as rain and snow; intensity and duration of individual precipitation events; and diurnal and seasonal variability of soil and air temperatures. Geomorphic setting tends to be more site specific than climate. Geomorphic conditions can vary dramatically for sites that are in close proximity to one another. In geomorphic setting, we include factors such as slope gradient, shape, length, and aspect; topographic relief; and drainage system characteristics (e.g., highly channelized or more diffuse). Soil erodibility can be very site specific, often varying significantly at a scale of a few meters or less. Erodibility of specific soils is influenced by many factors, including soil texture, porosity and bulk density; hydraulic conductivity; surface crusts; soil structure; organic matter content; rooting patterns and density; and rock fragment content.

The Three Site Erosion Potential (SEP) categories—climate, geomorphic setting, and soil erodibility—vary greatly among piñon-juniper ecosystems. A major difference in climate among different piñon-juniper regions is between those dominated by winter precipitation vs. those with a summer monsoon pattern. Climate also differs along elevational gradients, causing changes in plant community composition (Barnes 1986, Allen 1989, Padien and Lajtha 1992). The geomorphic setting of piñon-juniper ecosystems can vary substantially even for sites in close proximity, particularly with respect to slope and aspect. Soil erodibility is also highly variable within piñon-juniper ecosystems. Although it has been suggested that piñon and juniper trees can trigger high erosion rates, it is not clear that these trees have important direct effects on soil erodibility. Recently, Davenport et al. (1996) studied the effects of *P. edulis* and *J. monosperma* on some soil morphological properties that could affect soil erodibility. In that study, the effects of trees on soil morphology appear to be minor: soil depth, topsoil organic carbon content, and percentage of coarse fragments differed only slightly between canopy and intercanopy soils in a woodland with mean tree age of about 135 years and with low erosion rates. Other studies in piñon and juniper woodlands have shown differences in soil chemistry (e.g., soil pH, nutrient availability) between canopy and intercanopy locations (Barth 1980, Doescher et al. 1987, Covington and DeBano 1990, McDaniel and Graham 1992, Padien and Lajtha 1992, Evans and Ehleringer 1994) attributed to accumulation of litter beneath woody canopies. Infiltration rates are generally higher for soils with litter on the surface (Wood et al. 1987), and therefore one effect of canopy patches that may be important in terms of soil erodibility is the accumulation of litter layers beneath the trees.

Ground Cover

The amount of ground cover (e.g., understory vegetation, plant litter, and gravel) at a site is an important factor determining erosion rates, so the relationship of ground coverage and density of piñon and juniper to understory vegetation is fundamental to the trees' impact on soil erosion. There is substantial evidence that, in general, as piñon and juniper increase in density the understory vegetation cover decreases (Tausch et al. 1981, Schott and Pieper 1987, Pieper 1990, Tausch and West 1995). Juniper species in particular tend to reduce or in some circumstances virtually eliminate understory vegetation (Tausch and Tueller 1990), probably due to their greater ability to extract shallow intercanopy soil moisture (Breshears 1997a). Conversely, it has been shown that herbaceous vegetation increases dramatically when piñon and juniper are removed from a site by chaining (Aro 1971), burning (Jameson 1962, Dweyer and Pieper 1967, Clary 1971, Everett and Sharrow 1985, Everett 1987, Bates et al. 1994) or thinning (Clary 1974, Bledsoe and Fowler 1992).

Water availability is a fundamental limiting factor for herbaceous plant productivity in piñon-juniper ecosystems. Although climate and soil properties determine the vertical heterogeneity of soil moisture, the presence or absence of tree canopies determines important horizontal heterogeneity in soil moisture. In a *P. edulis-J. monosperma* woodland with low erosion rates, Breshears et al. (1997b) found that soil moisture was greater on average in intercanopy than in canopy locations (when averaged over 6-month intervals). An experiment in which water was added to intercanopy locations at shallow depths (0–30 cm) confirmed that both *P. edulis* and *J. monosperma* are able to obtain this soil moisture (Breshears et al. 1997a). In addition, the spatial pattern of piñon and juniper trees indicates use of resources from surrounding intercanopy spaces (Welden et al. 1990, Martens et al. 1997). Clearly, these woody species compete with intercanopy herbaceous species for the most abundant source of soil moisture, located in shallow intercanopy soil locations.

Soil Erosion Thresholds

Our viewpoint on soil erosion in piñon-juniper ecosystems has been influenced by the dramatic contrast between 2 sites that we have examined in some detail over the past several years (Wilcox 1994, Wilcox and Breshears 1995, Wilcox et al. 1996a, 1996b, Davenport et al. 1996, Breshears et al. 1997a, 1997b). These sites, located within 6 km of each other near Los Alamos in north-central New Mexico, have very similar soil properties, climate, and density of piñon and juniper. One site, however, is experiencing very high erosion rates while the other site is experiencing little or no erosion.

The rapidly eroding site (located in Bandelier National Monument and hereafter referred to as the Bandelier site) appears to have entered its current high erosion state (~9 Mg ha^{-1} yr^{-1} net soil loss; Wilcox et al. 1996b) only within the past 30 to 40 years, perhaps in response to cover changes arising from a severe regional drought in the 1950s (Allen 1989, Betancourt et al. 1993). Although recurrent droughts are a normal feature of the regional climate, the 1950s drought was one of the most severe in the Southwest within the last millennium (Grissino-Mayer 1996). The region affected by the 1950s drought also encompassed the stable site (located at Technical Area 51 of Los Alamos National Laboratory, hereafter referred to as the Mesita del Buey site) but did not trigger similarly accelerated erosion rates there (0.025–0.10 Mg ha^{-1} yr^{-1} net soil loss; Wilcox 1994, Wilcox et al. 1996a). Both sites are atop mesas at similar elevations, although the slope gradient is higher at Bandelier (7–8%) than at Mesita del Buey (3–4%). The only other apparent difference in current site conditions is that intercanopy ground cover (including litter) is considerably lower at Bandelier (~30%) than at Mesita del Buey (~50%). The histories of the 2 sites, however, are somewhat different in that prior to the 1950s drought, much of the Bandelier site was dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), with a widespread piñon and juniper understory and some clumps of older piñon and juniper contributing to the overstory. The drought, combined with a concurrent outbreak of pine bark beetles (*Dendroctonus* sp.), eliminated all ponderosa pines from the site within a period of a few years, leaving piñon and juniper as the dominant woody plants (Allen 1989). While harder to demonstrate definitively, the severe drought on this relatively dry (west-southwest aspect) site probably significantly reduced herbaceous ground cover as well, perhaps pushing the site across an erosion threshold. In addition, heavy grazing by feral burros may have contributed to reduction of herbaceous cover (Earth Environmental Consultants 1974, Koehler 1974) and achievement of the threshold. In contrast, the relatively mesic Mesita del Buey site appears to have been continuously dominated by piñon and juniper for at least the past 150 years (Davenport et al. 1996), with stable low erosion rates. Apparently, the effects of the 1950s drought alone on herbaceous cover were insufficient to cause significantly accelerated erosion rates at the Mesita del Buey site.

The contrast between these 2 sites, and the rapid change in the Bandelier site, suggest that threshold effects are operating with respect to soil erosion in piñon-juniper ecosystems. Figure 1A illustrates this concept; as ground cover decreases, the erosion rate increases gradually, until it crosses a steep threshold at which a relatively small decrease in cover corresponds to a large jump in erosion rate. The threshold corresponds to a transition in the relative dominance of biotic and abiotic processes in determining erosion rates (a similar transition has been identified in the process of desertification–Schlesinger et al. 1990). The Mesita del Buey site seems to be an example of a site on the upper part of the curve, above the threshold, and the Bandelier site seems to be on the lower part of the curve, having crossed the threshold into a high erosion state. The widely divergent reports of the effects of piñon and juniper on soil erosion (and ecosystem health in general) are consistent with such a phenomenon (Friedel 1991,

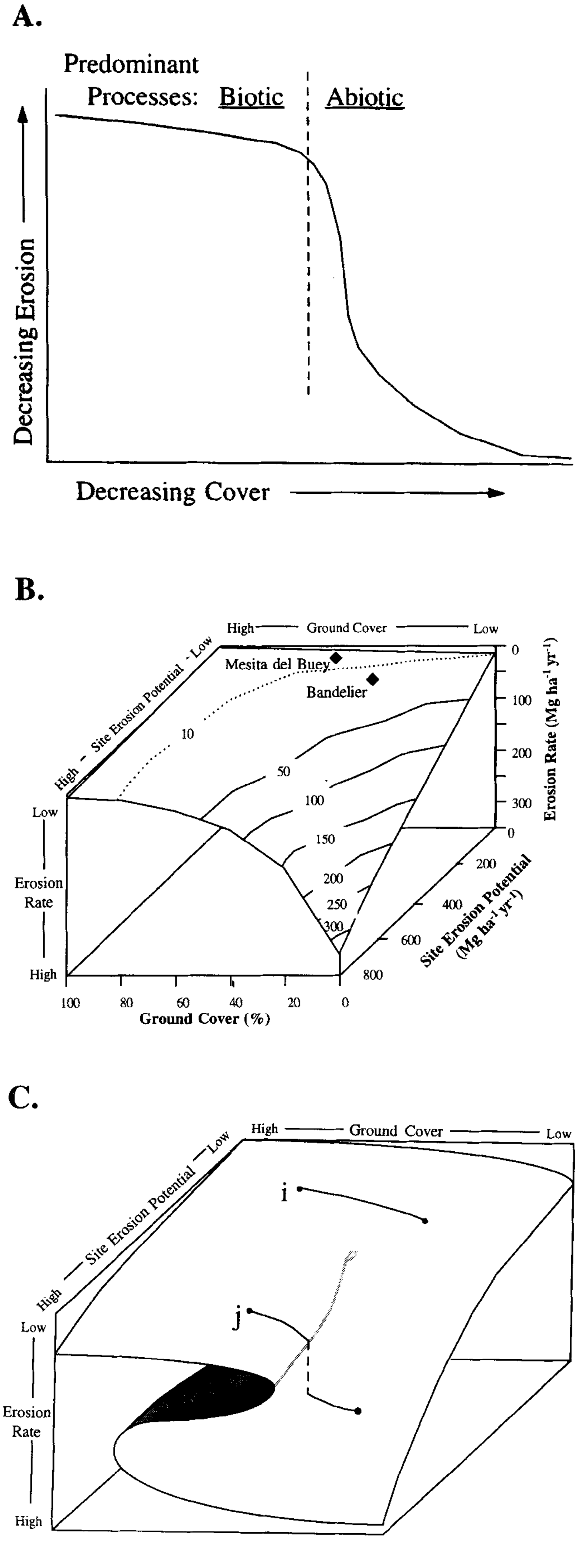

Fig. 1. (A). Threshold in erosion rate as a function of ground cover. Under conditions of low erosion rate, biotic processes are relatively dominant, whereas under high erosion, abiotic processes become relatively dominant. (B). Predicted erosion rates from the Universal Soil Loss Equation (USLE), based on a combined parameter for soil erosion potential (SEP)–from climate, slope and slope length, and soil erodibility–and ground cover for sites with 50% woody canopy cover and grass-like understory. Contour lines show erosion rate in Mg ha^{-1} yr^{-1}. Closer contour spacing indicates increasing sensitivity to ground cover and SEP. Seventy percent of sites have erosion rates less than 50 Mg ha^{-1} yr^{-1}. (C) A cusp catastrophe surface representing stability of erosion rates as a function of SEP and ground cover. Under conditions of low SEP, changes in cover lead to gradual, continuous changes in erosion rates (e.g., line i); under conditions of high SEP, rapid and effectively irreversible changes in erosion rates occur (e.g., line j) due to the feedbacks between erosion rate and cover. The infolded portion of the surface represents a region of inaccessibility; hence the system following line j crosses the threshold as ground cover decreases, and very rapidly jumps to a much greater erosion rate.

Laycock 1991, Tausch et al. 1993), in which the majority of piñon-juniper sites exist in either relatively stable or rapidly eroding conditions, with few examples of intermediate states.

To examine this threshold concept and evaluate its implications for piñon-juniper ecosystems in general, we have utilized the Universal Soil Loss Equation (USLE), an empirical model for estimating soil loss (Wischmeier and Smith 1978). USLE is one of the earliest, and perhaps one of the simplest, models for predicting soil erosion, and is best applied to agricultural lands in the more humid eastern portion of the United States. Although a number of other empirical and process-based soil erosion models have been developed that are able to more specifically address the rangeland conditions of piñon-juniper ecosystems (e.g., RUSLE–Renard et al. 1991; WEPP–Nearing et al. 1989; KINEROS–Smith et al. 1994), the concepts within the USLE are embedded within these other models. Despite the shortcomings of USLE, it provides a simple but useful framework for comparing and illustrating the potential erosion response to Site Erosion Potential (SEP) and cover among diverse sites.

Evidence for Soil Erosion Thresholds from the Universal Soil Loss Equation

The factors used in USLE can be readily categorized as part of the 2 general determinants of erosion discussed earlier—Site Erosion Potential (SEP) and ground cover. USLE estimates erosion (A) using the equation

$$A = R\,L\,S\,K\,C\,P.$$

The factors R, L, S, and K represent site erosion potential characteristics that are not generally subject to manipulation: climate (R), geomorphic setting (L, S), and soil erodibility (K). The cover factor (C) represents the ground cover conditions of a site, and is subject to manipulation, both in agricultural fields and piñon-juniper woodlands. For our purposes of estimating erosion under different piñon-juniper ecosystem conditions, the P factor can be ignored because the management practices included (e.g., contouring, terracing) do not generally apply in rangelands.

For each of the USLE parameters, we estimated a range of potential values likely to be encountered in piñon-juniper ecosystems. We assumed R ranges from 85 to 700 Mj mm ha^{-1} hr^{-1} yr^{-1} (based on R values for cities in RUSLE database that are bordered by piñon and juniper ecosystems); LS (often determined as a product) ranges from 0.133 to 12.90, corresponding to slopes from 2% to 20% and slope lengths from 7.6 m to 305 m; and K ranges from 0 to 0.08 Mg hr Mj^{-1} mm^{-1}, corresponding to a range from 20% silt and very fine sand with 0% sand to 70% silt and very fine sand with 30% sand. We evaluated these relationships using C values for woody canopy cover of 50% with grass-like understory ranging from 0 to 100%. (Evaluations using different proportions of woody canopy cover indicated that the predicted value of erosion rate was not highly sensitive to the woody canopy cover percentage, and that the shape of the resultant surface was very similar.)

Figure 1B shows the three-dimensional surface that results when we plot site erosion potential (R*LS*K) vs. cover (C). This plot illustrates that most combinations of Site Erosion Potential (SEP) and ground cover result in relatively low erosion rates, and that at low values of SEP the predicted erosion rate is quite insensitive to cover. Thus, we can see how many sites experience little or no increase in erosion due to piñon or juniper, even if ground cover is drastically reduced. In contrast, at high values of SEP the predicted erosion rate is very sensitive to percent cover–as ground cover decreases, the erosion rate increases very sharply. Similarly, under high cover conditions, increases in SEP have little effect on erosion, but under low cover conditions the erosion rate is very sensitive to increasing SEP. The striking feature of this plot is the very rapid increase in erosion as SEP increases and cover decreases. This rapid increase in erosion occurs only under limited conditions (only 30% of SEP/cover combinations result in erosion rates greater than 50 Mg ha^{-1} yr^{-1}).

We are able to compare the USLE-predicted erosion rates for different sites on the surface shown in Fig. 1B. For our 2 study sites, the parameter values are as follows: Mesita del Buey—R = 650 Mj mm ha^{-1} hr^{-1} yr^{-1}, LS = 0.621 (100 m slope length, 4% slope), K = 0.062 Mg hr Mj^{-1} mm^{-1} (50% very fine sand + silt with 35% sand; 1% organic matter; structure class 4; permeability class 3), and C = 0.065 (based on 50% woody canopy cover with 50% grass-like understory); Bandelier–R = 650 Mj mm ha^{-1} hr^{-1} yr^{-1}, LS = 2.43 (200 m slope length, 8% slope), K = 0.065 Mg hr Mj^{-1} mm^{-1} (50% very fine sand + silt with 40% sand; 0.5% organic matter; structure class 3; permeability class 3), and C = 0.135 (based on 50% woody canopy cover with 30% grass-like understory). Placing these sites on Fig. 1B shows that the Bandelier site is predicted to be closer to the steep portion of the plot surface than is the Mesita del Buey site, reflecting its higher SEP (steeper and longer slope, slightly higher soil erodibility) and lower ground cover. The USLE predictions for erosion rates at these 2 sites are close to measured erosion rates (Mesita del Buey, 1.6 Mg ha^{-1} yr^{-1} predicted vs. 0.1 Mg ha^{-1} yr^{-1} measured; Bandelier, 14 Mg ha^{-1} yr^{-1} predicted vs. 9 Mg ha^{-1} yr^{-1} measured).

Soil Erosion Feedbacks Produce a Cusp Catastrophe Surface

The USLE is intended to estimate long-term annual average soil loss for specified sets of Site Erosion Potential (SEP) and cover conditions. However, it does not predict the temporal stability of different sets of conditions, which depends not only on the effects of SEP and ground cover on soil erosion rates, but also on feedbacks that result from the converse–the effects of soil erosion rates on SEP and ground cover.

Piñon-juniper ecosystems that differ in high and low erosion rates also differ with respect to several other physical, biotic, and water balance factors that interrelate soil erosion rates with SEP and cover (Table 1). Changes in the water balance of sites undergoing a shift in erosion rates are likely to affect the biotic and physical characteristics of the site (Schlesinger et al. 1990). High erosion rates can increase SEP through channelization and decrease cover through removal of ground cover, particularly litter; these relationships provide the basis for a feedback (Gottfried et al. 1995). This feedback can be exacerbated by erosion around individual herbaceous plants, that leaves them pedestalled and isolated, in a harsher microclimate, and less able to capture runon. In addition, decreases in ground cover can lead to increases in evaporative rates, which effectively reduce the amount of water available to plants and the probability of establishment and

Table 1. Directional changes in semiarid site characteristics associated with a shift from low to high erosion rates.

Site Characteristic	Change Associated with Shift from Low to High Erosion Rates
	Physical Characteristics
Erosion	Increased
Runoff	Increased
Soil profile	Decreased thickness, possible loss of A horizon
Channel formation	Increased
Raindrop impact energy in intercanopy areas	Increased
Slope length between components of ground cover	Increased
Intercanopy soil surface temperature	Increased maximum and variance
	Biotic Characteristics
Intercanopy ground cover	Reduced
Herbaceous seed pool	Reduced
Ratios of woody-to-herbaceous biomass and productivity	Increased
	Water Balance Characteristics
System evapotranspiration	Slightly reduced
Intercanopy evapotranspiration	Slightly reduced
Intercanopy water storage	Reduced
Canopy water storage	Increased or reduced, dependent on topography changes
Plant-available water in intercanopy locations	Reduced
Relative use of shallow intercanopy water by woody plants	Increased
	General characteristics
Importance of biotic processes	Reduced
Importance of physical processes	Increased

survival of herbaceous seedlings; this process provides an additional feedback between erosion rates with SEP and cover. Erosional loss of microphytic soil crusts can further increase erosion rates (West 1990). These feedbacks are discussed in greater detail in Allen (1989) and Gottfried et al. (1995). In shifting from a state of low erosion to one of high erosion, then, the relative importance of biotic processes in maintaining the system decreases while the role of physical processes increases (Fig. 1A). This type of non-linear feedback behavior has been proposed previously for semiarid ecosystems for erosion (Abrahams et al. 1995, Baker et al. 1995, Gottfried et al. 1995, Ludwig and Tongway 1995, Wilcox et al. 1996a, 1996b) and for dynamics of rangeland vegetation (Clary and Jensen 1981, Jameson 1987, Westoby et al. 1989, Schlesinger et al. 1990, Laycock 1991, Tausch et al. 1993).

We hypothesize that the feedbacks between erosion rate and its determinants—SEP and cover—are enhanced at high erosion rates. That is, under conditions of high erosion, cover is decreased and Site Erosion Potential (SEP) is increased. Because the erosion rate under these conditions is sensitive to change in cover and SEP (i.e., the steep part of the surface in Fig. 1B), the erosion rate increases and the positive feedback continues. Modifying our conceptual model of erosion thresholds (Fig. 1A) in terms of soil erodibility and cover yields a non-linear surface with the properties of a cusp catastrophe surface (Fig. 1C—Saunders 1980, Lockwood and Lockwood 1993, Loehle 1985). Under conditions of low SEP, changes in cover lead to gradual continuous changes in erosion rate (e.g., line i), whereas for conditions of high SEP, a rapid change in sustainability and erodibility occurs (e.g., line j), corresponding to a shift over the cusp of the surface. This surface is similar to that predicted by USLE (Fig. 1B) except that it contains a fold where USLE predicted high sensitivity to SEP and cover. The part of the cusp catastrophe surface that is folded (Fig. 1C) represents a region of inaccessibility, meaning that the system cannot be stable within that region (Lockwood and Lockwood 1993). For sites with high SEP and high cover, erosion is low, but if the cover is decreased beyond a threshold (e.g., moving along line j), the erosion is sufficient to further reduce the cover (e.g. through loss of nutrients and moisture storage capacity) to an even lower amount; this corresponds to moving over the cusp.

Although non-linear feedback behavior for erosion processes have been hypothesized for semiarid woodlands previously, our approach makes the synergy between SEP and cover explicit. This conceptual model is useful in comparing sites of differing erosion rates. However, this model alone is insufficient to explain the mechanisms behind the hypothesized threshold.

Percolation Theory as an Approach for Understanding Threshold Mechanisms

The mechanisms behind the shift from low to high erosion rates on the cusp catastrophe surface can be understood more readily using another type of conceptual model—one based on percolation theory, which is spatially explicit. Percolation theory is used to predict the probability that a network of patches is interconnected (Stauffer 1985; see Gardner et al. 1987 and 1992 for related applications in ecology). For our purposes, we can view this as the probability that a quantity of water generated as small-scale local runoff in one part of the woodland is interconnected with other patches within the network, forming a spanning cluster, such that it exits the woodland as hillslope runoff. Indeed, recent work in piñon-juniper woodlands defines ecosystem structure on the basis of spanning clusters of intercanopy patches (Milne et al. 1996). In a percolation network, each cell within the network is viewed as being in an "on" or "off" state. We can view this in terms of storage capacity: the cell either does or does not have the capacity to store more moisture under current conditions. Within this framework, we can view woodland sites at the hillslope scale as a network of grid cells at 2 resolutions: a primary grid differentiates between canopy and intercanopy cells, and, nested within intercanopy cells, a secondary grid differentiates between areas of low and high ground cover (Fig. 2).

Within the primary grid, most of the runoff is generated from intercanopy rather than canopy patches (Blackburn 1975, Roundy et al. 1978. Wilcox 1994, Wilcox and Breshears 1995), a pattern common to other semiarid ecosystems (Ludwig and Tongway 1995, Seyfried and Wilcox 1995). Canopy patches may provide a source of storage for some of the runoff generated in the intercanopy patches due to the high infiltration capacity of the litter layer; that is, intercanopy runoff may become canopy runon. Measurements of soil moisture support this assumption–soil moisture is greater in canopy than intercanopy locations following runoff-generating storms (Breshears et al. 1997b). However, the potential for storage by canopy locations can be reduced by microtopography differences, particularly if channelization within intercanopy locations is occurring, leaving pedestalled canopy patches literally high and dry.

A secondary finer-scale grid exists within intercanopy patches that distinguishes between areas with low and high proportions of ground cover (Wilcox and Breshears 1995, Seyfried and Wilcox 1995, Wilcox et al. 1996a, 1996b). At this finer-scale, patches with low ground cover generate runoff and patches with high ground cover provide storage. Ongoing field studies support this perspective (Wilcox et al 1996a, 1996b).

Percolation theory is relevant to the cusp catastrophe surface that we have proposed because the theory predicts that the probability of the cells within the network becoming interconnected–corresponding to the probability of a parcel of water leaving the system as hillslope runoff in our application–has a sharp non-linear threshold (Gardner et al. 1992). At some critical density for which a certain number of cells are "on", a threshold is crossed such that the probability of the cells being interconnected shifts from low to very high (Fig. 2). Hence, if a piñon-juniper ecosystem is viewed as a network of grid cells, each with its own storage capacity, a transition between low and high erosion rates is readily understood. This conceptual approach should enable us to improve our predictive capability relative to erosion thresholds.

The behavior of percolation networks is consistent with scale-dependent differences in runoff and erosion that we have observed in piñon-juniper ecosystems (Wilcox 1994, Wilcox and Breshears 1995, Wilcox et al. 1996a, 1996b). For hillslopes with low amounts of runoff, measurements of runoff per unit area decrease with increasing spatial scale–runoff per unit area for small intercanopy patches with low ground cover is much greater than that measured for larger intercanopy plots, and runoff per unit area for larger intercanopy plots is much greater than that measured for a hillslope comprised of canopy and intercanopy patches. Hence, storage by adjacent patches appears to be important in causing a decrease in runoff per unit area with increasing spatial scale. In cases where hillslope runoff is high, these scale-dependent differences are reduced because storage at the finer scales is greatly reduced (Wilcox and Breshears 1995, Wilcox et

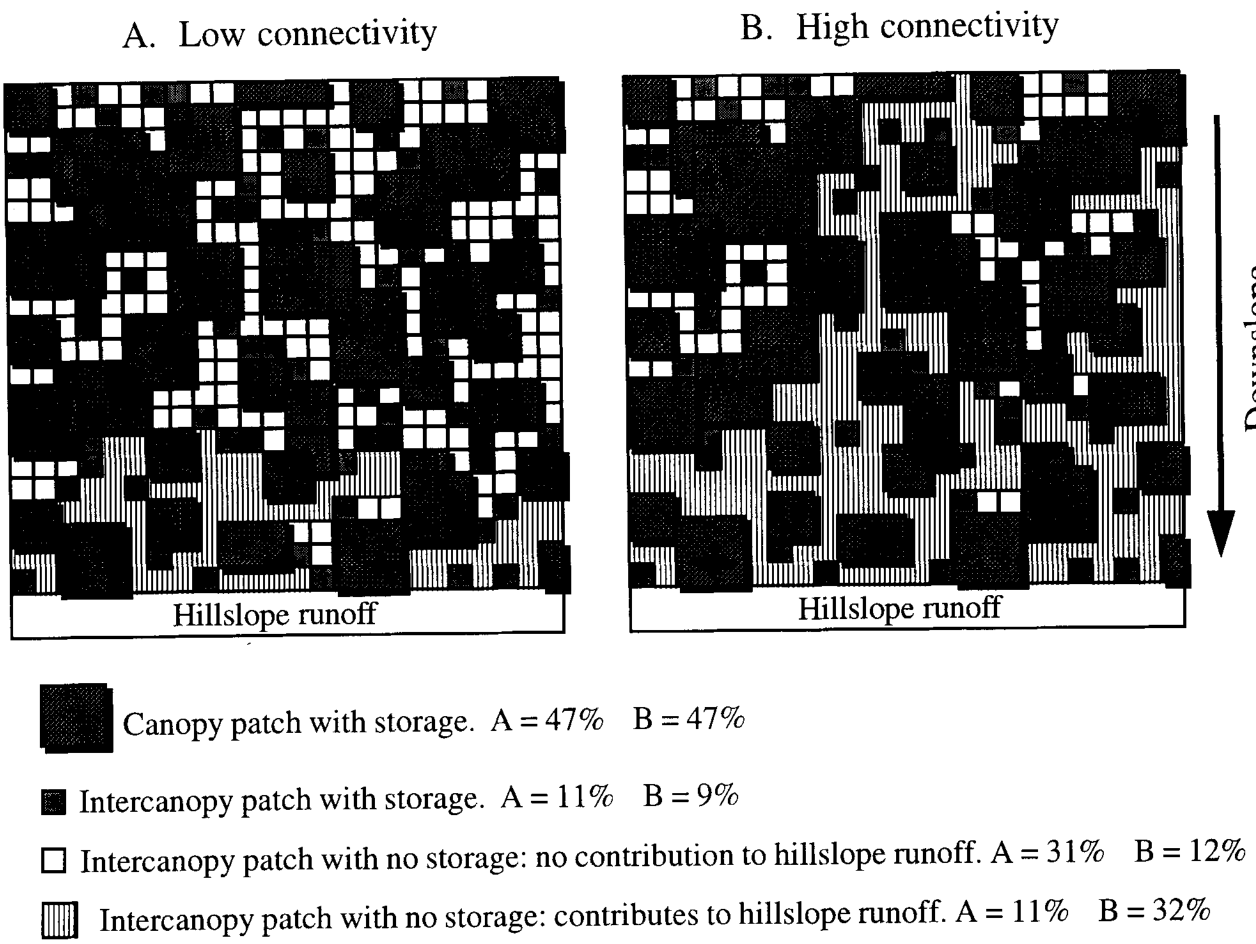

Fig. 2. A runoff threshold mechanism illustrated by the use of percolation theory. Patches with storage are areas where water infiltrates or ponds; patches with no storage generate runoff due to saturation or exceeded infiltration rate. Runoff that is able to flow laterally or downslope to other patches without storage continues as runoff; runoff that flows onto canopy or intercanopy patches with storage will infiltrate. In order for the runoff from any particular patch to contribute to the total hillslope runoff collected at the base of the slope, a linked series (spanning clusters) of patches with no storage must exist such that the flow is not intercepted by patches with storage. A small decrease in the number of intercanopy storage patches can have a large influence on the proportion of patches that are in spanning clusters, resulting in a transition from low connectivity (A) to high connectivity (B). In this example, a 2% decrease in intercanopy patches with storage capacity results in a 21% increase in patches without storage contributing to hillslope runoff.

al. 1996 a, 1996b). In terms of percolation theory, the probability of forming a "spanning cluster" of runoff is low when storage is high and, conversely, is high when storage is low. Further, the storage capacity of each patch varies temporally as a function of soil moisture and precipitation rate, and hence the fold in the cusp catastrophe surface (Fig. 1C) also varies temporally.

These conceptual models (Figs. 1 and 2) each contain a threshold and help unify different perspectives on erosion rates in piñon-juniper ecosystems. The simple threshold model (Fig. 1A) highlights the relative importance of biotic processes in ecosystems with low erosion rates and, in contrast, the relative importance of abiotic processes in ecosystems with high erosion rates. The USLE, which is based on a large set of field data, demonstrates the presence of an erosion threshold as a synergistic function of Site Erosion Potential (SEP) and cover (Fig. 1B). The cusp catastrophe surface (Fig. 1C) highlights the importance of feedbacks in determining the different stable states within the system–high erosion rates reduce cover and increase SEP, which in turn increase erosion rates. Not only do some changes occur rapidly, they are also not directly reversible. The percolation model (Fig. 2) provides a mechanistic understanding of thresholds in terms of water storage capacity of the hillslope network. The percolation model also highlights the importance of spatial heterogeneity within the hillslope in determining runoff, as have other recent papers (Wilcox and Breshears 1995, Seyfried and Wilcox 1995, Tarboton et al. 1992, Ludwig and Tongway 1995). It is a two dimensional approach that is similar to the one dimensional approach of subdividing the hillslope length into subunits, as done in the Revised Universal Soil Loss Equation (Renard et al. 1991).

Implications and Applications

The conceptual models developed here can be applied to a wide variety of sites and conditions within piñon-juniper ecosystems and provide insights into how land management practices can affect the sustainability of piñon-juniper ecosystems. For example, the catastrophe cusp surface (Fig. 1C) can be used to contrast the sensitivity of erosion rates to cover in juniper woodlands of the Pacific Northwest with piñon-juniper woodlands of the Southwest. In the northwestern juniper woodlands, precipitation events are generally of lower intensity and therefore these sites generally have relatively low Site Erosion Potential (SEPs); erosion rates are relatively insensitive to changes in cover (e.g., line i in Fig. 1C). In contrast, southwestern piñon-juniper woodlands experience more high intensity precipitation events and therefore have generally higher SEPs; erosion rates are more sensitive to changing cover and can more readily cross a threshold (e.g., line j in Fig. 1C).

USLE-derived predictions (Fig. 1B) are a simplification of erosion rates over longer time frames, but they clearly highlight the synergistic effects of SEP and cover on erosion rates. This simple model can be used to evaluate the potential of a site to cross a threshold, and to compare sites in terms of potential for high erosion rates. For example, extensive livestock grazing is typically the predominant land use in piñon-juniper woodlands. Grazing can directly move a piñon-juniper site across an erosion threshold by concurrently reducing intercanopy vegetation cover and soil water infiltration capacities through trampling effects. Grazing also can indirectly contribute to moving a site across an erosion threshold because reduction of herbaceous vegetation reduces competition to woody plant establishment and suppresses fires, which can lead to an increase in the dominance of woody plants which, in turn, can further reduce herbaceous cover through competitive interactions (Gottfried et al. 1995). These thresholds explain why reductions in livestock grazing are not sufficient to reverse accelerated erosion in certain piñon-juniper systems (Allen 1989, Laycock 1991), although in other systems changes in grazing regimes may suffice to bring a system back to a sustainable state.

Similarly, land management practices which alter tree densities (e.g. fuelwooding, thinning, chaining/pushing, herbicide applications) may directly or indirectly alter soil sustainability in piñon-juniper woodlands. Reductions in tree density may increase herbaceous cover and reduce hillslope erosion for locations with low Site Erosion Potential (SEP), but may be insufficient to reduce erosion at sites with high SEP that have crossed the threshold. Restoration of such high-erosion sites likely will require concurrent reductions in SEP and increases in ground cover. Some restoration techniques, such as thinning of woody plants and seeding of herbaceous species, serve primarily to increase herbaceous cover, while others, such as slashing, mulching, and imprinting the soil surface, can effectively decrease SEP as well as increase herbaceous ground cover (Clary and Wagstaff 1987, Johnsen 1987, Chong 1994). Sites with the most severe erosion may require a greater emphasis on reducing SEP before cover can be increased and erosion stabilized. Indeed, the principle of reducing SEP has been used for millennia in varied landscapes to enhance soil sustainability by terracing agricultural fields (Lowdermilk 1953). In southwestern piñon-juniper woodlands, prehistoric Native American agriculturalists effectively reduced SEP through the use of check dams and gravel mulches (Periman 1996).

To summarize, a shift from the relative importance of biotic to abiotic processes accompanies a transition from low to high erosion rates. The mechanisms associated with a rapid shift from low to high erosion rate can be illustrated using percolation theory to incorporate spatial, temporal, and scale-dependent patterns of water storage capacity on a hillslope. When the relationships among SEP, ground cover, and erosion rate are viewed as a cusp catastrophe surface, the different perspectives of erosion in piñon-juniper woodlands are consistent and compatible with one another. Under conditions of high SEP, the system will be in either a low- or high-erosion state, and the change from low to high erosion may be rapid. Where SEP is low, piñon and juniper should have only a limited effect on soil erosion. Matching management practices to site SEP can provide a basis for greater sustainability of piñon-juniper ecosystems.

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