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Spatial patterns of soil erosion and deposition in two small, semiarid watersheds

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[1] This work investigates spatial patterns of hillslope erosion and sediment yields in a semiarid ecosystem considering influences of vegetation, slope, rocks, and landscape morphology. The ^{137}Cs inventories were measured on one shrub and one grassed watershed in southeastern Arizona. Calculated mean erosion rates in eroding areas were 5.6 and 3.2 t ha^{-1} yr^{-1}, and net erosion rates for the entire watershed, including depositional areas, were 4.3 and nearly 0 t ha^{-1} yr^{-1} for the shrub and grass watersheds, respectively, over the past four decades. Differences in hillslope erosion rates between the two watersheds were apparently due to vegetation: while on the shrub site, runoff pathways were unobstructed, on the grass site, runoff was obstructed by vegetation patches and litter. Hillslope erosion rates within the watersheds were not correlated to slope gradient or curvature but were correlated to rocks in the upper soil profile. These results are interpretable in terms of slope-velocity equilibrium wherein overland flow velocities became independent of slope gradient because of differential rock cover, which evolved as a result of preferential erosion of fine material on the steeper slopes prior to ^{137}Cs deposition. Watershed morphology and channel incision controlled sediment yield. Most of the eroded soil was deposited in swales of the grassed watershed. Most of the soil eroded in the shrub watershed was exported from the watershed outlet by way of a well-incised channel system. The study shows that measurement of sediment yield from a watershed can be a poor indicator of erosion taking place within the watershed.

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1. Introduction

[2] Surface cover associated with vegetation and rocks is known to be an important influence on the generation of sediment in semiarid landscapes. It is well documented that in a wide variety of ecological systems, greater vegetative cover relates to a more protected soil surface and decreased erosion rates. In semiarid regions with patchy vegetation, not only the percent coverage of the surface, but also the patchiness of the vegetative cover may influence both runoff generation and sediment production on slopes. It has been documented that in some cases greater patchiness translates to greater runoff and erosion [*Puigdefabregas*, 2005]. Vegetation patches may act as sinks of sediment because of the reduction of flow velocity that occurs as surface water runoff encounters the patches [*Ludwig et al.*, 2005]. In many grassland areas the patches of vegetation tend to be relatively contiguous, which can result in less connectivity in runoff pathways and hence flow broadening. This contrasts with many shrubland environments wherein the plants tend to be more isolated and have a much lesser area of basal cover, which induces less obstruction to the overland flow. Another difference is that in wind erosion prone areas shrubs can act as sediment sink areas for wind-blown materials [*Ritchie et al.*, 2003]. While wind deposition can happen on any landscape, its occurrence is not well documented specifically for grasslands, and the effects of the grassland vegetation itself on the deposition process is not as dramatic as for shrubs.

[3] Slope gradient is generally considered to be a factor that influences soil erosion in most environments [*Wischmeier and Smith*, 1978]. In uncultivated environments, however, the situation can be more complex. *Riebe et al.* [2000] used cosmogenic ^{26}Al and ^{10}Be to measure erosion rates at seven sites in the Sierra Nevadas. They found erosion to be highly correlated to slope gradient at three sites, while erosion at four of the sites was less sensitive to slope.

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A part of the reason for this may be due to the mechanics of erosion caused by overland flow on relatively undisturbed sites. Studies of flow induced erosion in southeastern Arizona have indicated that the hydraulic roughness of slopes of different gradients may evolve in such a way that a slope-velocity equilibrium is established through differences in rock cover on different slopes [*Nearing et al.*, 1999]. Those measurements have shown that overland flow velocities became independent of slope gradient because of differential rock cover, which had evolved as a result of previous, preferential erosion of fine material.

[4] The effects of surface rock fragments on soil erosion at various scales were discussed in a review paper by *Poesen et al.* [1994]. An analysis of data from 133 erosion plots at the macroplot scale (10^1-10^4 m^2) showed that rill and interrill sediment yield decreased as an exponential decay function of percent rock fragment cover. They attributed this decrease largely to three factors: (1) protection against raindrop impact and flow detachment, (2) reduction of physical degradation of the underlying soil, and (3) retardation of flow velocity caused by greater hydraulic roughness associated with the rock cover.

[5] Correlations between rock cover and slope steepness have been observed in studies in Arizona and Nevada [*Simanton and Toy*, 1994; *Simanton et al.*, 1994; *Nearing et al.*, 1999] and Spain [*Poesen et al.*, 1998]. *Simanton et al.* [1994] also found correlation between rock cover and the percentage of rock fragments in the upper part of the soil profile. The explanation for these correlations has been attributed to past erosion. Steeper portions of the slope are thought to have experienced more intensive erosion in the past, which left the soil with lesser fine material and a greater proportion of rock cover. To take this logic a step further, one can hypothesize that as the hillslopes evolve and come to a state of slope-velocity equilibrium, erosion rates will tend to become more uniform along the hillslope.

[6] The purpose of this study was to evaluate and compare the rates and spatial patterns of soil erosion and deposition in two small, semiarid watersheds by using ^{137}Cs measurements. ^{137}Cs was measured on a 1.9 ha grass-dominated watershed (Kendall), and a 3.7 ha shrub-dominated watershed (Lucky Hills), both located in the Walnut Gulch Experimental Watershed, southeastern Arizona, USA. A portion of the results of the study in the Lucky Hills watershed was reported previously [*Ritchie et al.*, 2005]. In an attempt to understand the processes controlling the erosion and sediment yield in these watersheds, we also investigated the relationships between erosion and slope gradient, slope curvature, and the percent of rock fragments in the soils.

2. Methods

2.1. Study Watersheds

[7] The Lucky Hills watershed (SW63.103) and the Kendall watershed (SW63.112), which are subwatersheds of the larger Walnut Gulch Experimental Watershed, are located in southeastern Arizona, USA, within a few kilometers from the town of Tombstone (31° 43′N, 110°41′W). The mean annual temperature at the Walnut Gulch Experimental Watershed is approximately 18°C. Approximately two thirds of the annual precipitation occurs in the "monsoon" season from July to September [*Nichols et al.*, 2002]. For the time period of 1963 through 2004, the measured mean annual precipitation measured at Lucky Hills was 292 mm and that at Kendall was 315 mm. The main branch of Walnut Gulch is dry approximately 99% of the time.

[8] The Lucky Hills watershed has an area of 3.7 hectares and the Kendall watershed has an area of 1.9 hectares. The mean hillslope gradients of the Lucky Hills and Kendall watersheds are 7.7% (4.4°) and 12.3% (7.0°), respectively. The Lucky Hills watershed is a shrub dominated, semiarid rangeland. Canopy cover during the rainy season is approximately 25%, and the ground has approximately two thirds rock cover and one third bare soil. Dominant shrubs include Creosote (*Larrea tridentata* (Sessé & Moc. ex DC.) Coville) and Whitethorn (*Acacia constricta* Benth.). The Kendall watershed is largely vegetated with grass at approximately 35% canopy cover, with a trace of shrubs and forbs. Ground cover during the rainy season has been measured at 28% rock, 42% litter, and 14% basal cover. The dominant vegetation types are blue grama (*Bouteloua gracilis* (Kunth) Lag. ex Griffiths), black grama (*B. eriopoda* (Torr.) Torr.), snakeweed (*Gutierrezia sarothrae* (Pursh) Britton & Rusby), and false Mesquite (*Calliandra eriophylla* Benth.).

[9] In addition to distinctly different vegetation cover, the character of the drainage network connecting the hillslopes to the watershed outlet is unique to each of the watersheds. The Lucky Hills watershed is drained by a well developed, incised channel network that efficiently delivers entrained particles to the watershed outlet. The Kendall watershed is drained by concentrated flow paths that terminate in a swale above the outlet. The swale is a site of deposition and thus sediment storage within the watershed.

[10] The soil at Lucky Hills is a gravelly sandy loam with approximately 52% sand, 26% silt, and 22% clay. At Kendall the soil is gravelly sandy loam with approximately 55% sand, 20% silt, and 25% clay. The organic carbon contents of the soils from the Lucky Hills and Kendall watersheds are approximately 0.8 and 1.1%, respectively.

[11] Both of these watersheds have historically served as grazing land for cattle and horses. Though some managed grazing has occurred in the area since the establishment of Spanish ranches in the early 1800s, intensive grazing in the Tombstone area began in the 1880s [*Hamilton*, 1884; *Wagoner*, 1952]. During the last century there has been a general change from grasslands to shrublands in the southwestern United States [*Hastings and Turner*, 1980; *Humphrey*, 1987]. Though historic records of the condition of the land on the WGEW are not extensive or specific, anecdotal reports from the early 1900s indicate that the area was relatively well covered with grasses in the mid to late 1800s. Currently, traveling east in the Walnut Gulch watershed from its confluence with the San Pedro River toward higher elevations, one moves from an area that is dominated by shrubs and sparse vegetative cover to grassland with significantly more vegetative cover.

[12] Although several causes for the general change from grass to shrubs, including climate, fire, grazing, and urbanization have been suggested [*Hastings and Turner*, 1980; *Humphrey*, 1987], in essence, the study area that is shrubland today is located within walking distance for cattle and horses to drinking water in the San Pedro River. Most of that land today is too degraded to support vegetation

sufficient for grazing, whereas the land further from the river is used today as active ranch land. The Lucky Hills watershed is located in the shrubland nearer the San Pedro River, while the Kendall watershed is located in the grasslands farther from the San Pedro. The implications of this fact in terms of soil erosion are that the Lucky Hills shrubland was probably severely eroded and degraded by the early 1900s, while the Kendall watershed may have experienced less severe degradation during the intensive ranching phase from approximately 1880 until 1930. However, while the Lucky Hills watershed is currently not being used for agricultural purposes, the vegetation in the Kendall watershed continues to be influenced by current grazing.

2.2. Soil Sampling

[13] Soil surface samples to measure ^{137}Cs inventories were collected at 68 sampling points in the Lucky Hills watershed on 5 May 2003 and at 62 points in the Kendall watershed on 9 June 2003 by using a bucket corer with 50 mm diameter to a depth of 25 cm. Sample locations were uniformly distributed over both watersheds on an approximate 25 m grid pattern in the Lucky Hills watershed and a 17 m grid pattern in the Kendall watershed.

[14] Twenty reference soil surface samples were taken at sites with minimal physical disturbance (with assumed negligible erosion) of the surface in Walnut Gulch by using a bucket corer with 50 mm diameter to a depth of 25 cm. The ^{137}Cs inventories for these sites were used as the reference inventory for the Lucky Hills and Kendall watersheds. The reference sites were chosen in two different areas. One site was a graveyard where samples could be collected on marked and dated grave sites (with the permission of the town of Tombstone). The second site was located on a flat, plateau area located near the town's airport, which we knew had not been disturbed since the installation of the airport several decades previous. Two soil profiles were sampled for ^{137}Cs with 5 cm depth increments, along with a sample of the top one cm, in order to examine the ^{137}Cs depth profile.

2.3. The ^{137}Cs Analyses

[15] Soil samples were dried at 80 °C and sieved using a 2 mm screen to separate the rock fragment fraction (>2 mm) and soil fraction (<2 mm). The less than 2 mm soil fraction was placed into Marinelli beakers and sealed for ^{137}Cs analyses. Analyses for ^{137}Cs were made by gamma ray spectrometry using a Canberra Genie-2000 Spectroscopy System that received input from three Canberra high-purity coaxial germanium crystals (High purity Germanium: HPGe >30% efficiency) into three 8192-channel analyzers. The system was calibrated and efficiency determined using an Analytic^2 mixed radionuclide standard (10 nuclides) whose calibration could be traced to U.S. National Institute of Standards and Technology. Measurement precision for ^{137}Cs was ±4–6%.

2.4. Estimation of Net Soil Erosion and Deposition Rates

[16] The Diffusion and Migration Model for Erosion and Deposition on Undisturbed Soils [*Walling and He*, 1999], which accounts for the time-dependent behavior of both the ^{137}Cs fallout input and its subsequent redistribution in the soil profile, was used to convert from ^{137}Cs inventories to net soil erosion and deposition rates for the Kendall and Lucky Hills watersheds. The net soil erosion and deposition rates were calculated by comparing the ^{137}Cs inventories of the soil samples collected over the watersheds to the mean ^{137}Cs inventory of the soil samples taken at the uneroded reference sites. According to *Walling and He* [1999], the variation of the ^{137}Cs inventory $C_u(t)$ (Bq kg^{-1}; 1 becquerel (Bq) is the activity of a quantity of radioactive material in which one nucleus decays per second. It replaces the curie (Ci), and 1 curie is equal to 3.7×10^{10} becquerels) for surface soil with time t (year) can be described as

$$C_u(t) \approx \frac{I(t)}{H} + \int_{t_0}^{t-1} \frac{I(t')e^{-R/H}}{\sqrt{D\pi(t-t')}} e^{-V^2(t-t')/(4D)-\lambda(t-t')} dt' \qquad (1)$$

where t_0 is the effective year for the original ^{137}Cs deposition from the atmosphere (1963), $I(t)$ is annual ^{137}Cs deposition flux (Bq m^{-2} yr^{-1}), H is the relaxation mass depth of the initial distribution (kg m^{-2}), R is erosion rate (kg m^{-2}), λ is decay constant (yr^{-1}), D is a diffusion coefficient (kg^2 m^{-4} yr^{-1}) and V is the downward migration rate of ^{137}Cs in the soil profile (kg m^{-2} yr^{-1}).

[17] Erosion rates were calculated from the loss in the ^{137}Cs inventory $A_{ls}(t)$ (Bq m^{-2}) at the sites where the measured total ^{137}Cs inventory was less than the reference inventory. The ^{137}Cs inventory in the surface soil, $C_u(t)$, was calculated based on equation (1), and $A_{ls}(t)$ was calculated as

$$\int_{t_0}^{t} RC_u(t')e^{-\lambda(t-t')}dt' = A_{ls}(t). \qquad (2)$$

Net deposition rates (R') were calculated as

$$R' = \frac{A_{ex}}{\int_{t_0}^{t} C_d(t')e^{-\lambda(t-t')}dt'} \qquad (3)$$

where $A_{ex}(t)$ (Bq m^{-2}) is the excess in the ^{137}Cs inventory at the sample points where the measured total ^{137}Cs inventory was greater than the reference inventory, and $C_d(t')$ is the weighted average of the ^{137}Cs concentrations of the sediment generated from the upslope contribution area S (m^2). Generally, the ^{137}Cs concentration $C_d(t')$ of deposited sediment can be assumed to be represented by the weighted mean of the ^{137}Cs concentration of the mobilized sediment from the upslope contribution area [*Walling and He*, 2001]. $C_d(t')$ can be calculated from

$$C_d(t') = \frac{1}{\int_S RdS} \int_S C_u(t')RdS \qquad (4)$$

2.5. Assessment of Parameter Values for the Cesium Model

[18] Three parameters are required to run the diffusion and migration model for erosion and deposition on undis-

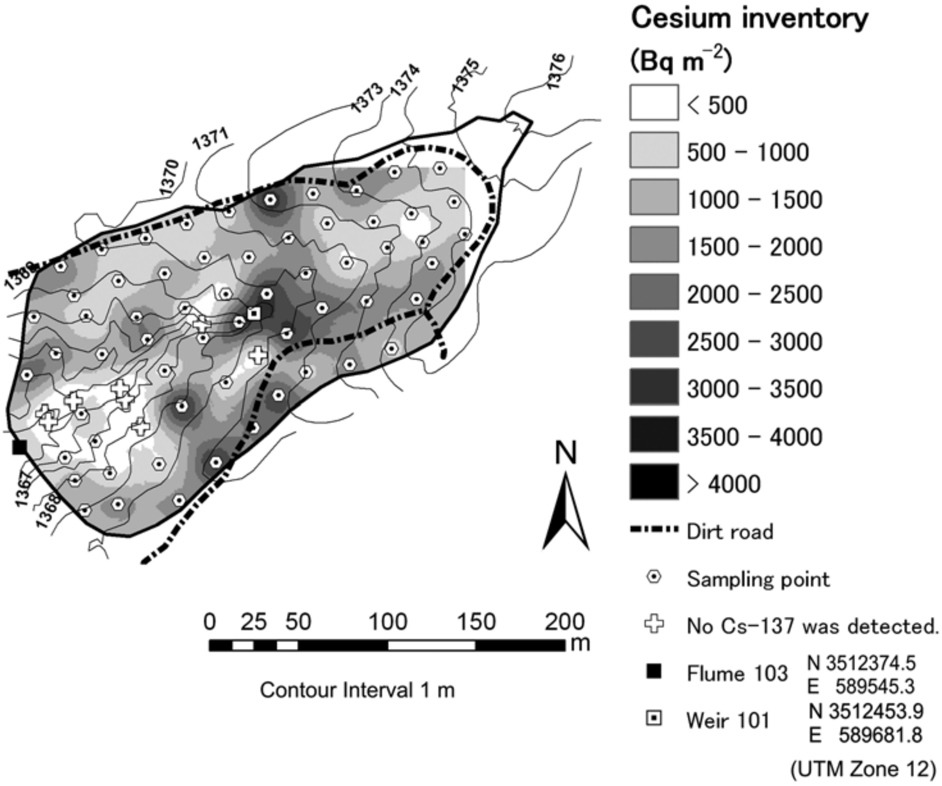

Figure 1. Spatial pattern of ^{137}Cs inventories for the sampling points in the Lucky Hills watershed.

turbed soils [*Walling and He*, 1999]: *H*, *D*, and *V* (see equation (1)). Under optimum circumstances the values for *D* and *V* may be determined following the procedures outlined by *Walling and He* [1999]. Determination of *H* requires extensive field experimentation, thus we used the model default value for H of 5 kg m^{-2} [*Walling and He*, 1999]. The parameters *D* and *V* can be determined if one has depth samples of ^{137}Cs concentration from the tested area. We attempted to take such samples on undisturbed areas near the Lucky Hills and Kendall sites, but because of the fragile nature of the soil we were successful in obtaining samples only in 5 cm increments, plus one sample of the top one cm of soil. While this did not provide sufficient information to estimate the values of *D* and *V*, we were able to ascertain that the default values suggested for the model [*Walling and He*, 1999] were within their possible ranges based on the depth concentrations samples that we collected. Thus we used default values of 40 kg^2 m^{-4} yr^{-1} for *D* and 0.5 kg m^{-2} yr^{-1} for *V*.

[19] However, it should be noted that due to the limitations of our depth profile sampling capabilities, the resultant estimates of erosion that we calculated using the default model parameters represent a maximum value for the actual erosion rates for these sites. On the basis of a comparison between the concentration of the 0–5 cm and 0–1 cm samples, and an idealization of the shape of the depth concentration curve for typical ^{137}Cs profiles, the "best" parameter values for the location could be as much as 25–30% less than the default parameter values. In order to obtain a feel for the accuracy of the erosion and deposition estimates using the default model parameter values we performed a sensitivity analysis of model results for our data using perturbations of ±25% and ±50% for each model parameter.

2.6. Spatial Patterns of ^{137}Cs Inventories and Net Soil Erosion and Deposition Rates

[20] ArcMap 8.3 [*Ormsby et al.*, 2001] was used to show the spatial distributions of ^{137}Cs inventories and net soil erosion and deposition rates. Contour maps of ^{137}Cs inventories and net soil erosion and deposition rates were produced by using a kriging interpolation method.

2.7. Topographical Factors for the Sampling Points

[21] Slope and Curvature were computed by ArcGIS 9.0 to examine the impacts of topographical factors on net soil erosion and deposition rates. Slope at each sampling point was described as a percentage. A positive curvature indicates that the surface was upwardly convex at that cell, while a negative curvature indicates that the surface was concave at that cell. A value of zero indicates that the surface at the sampling point was flat.

2.8. Calculating the Confidence Range for Net Erosion and Deposition Estimates

[22] We used the variability of the reference soil surface samples computed with data from sites with minimal physical disturbance of the surface near Tombstone to calculate the confidence limits for our methodology. To do this, we ran the values of the twenty ^{137}Cs reference measurements through the diffusion and migration model

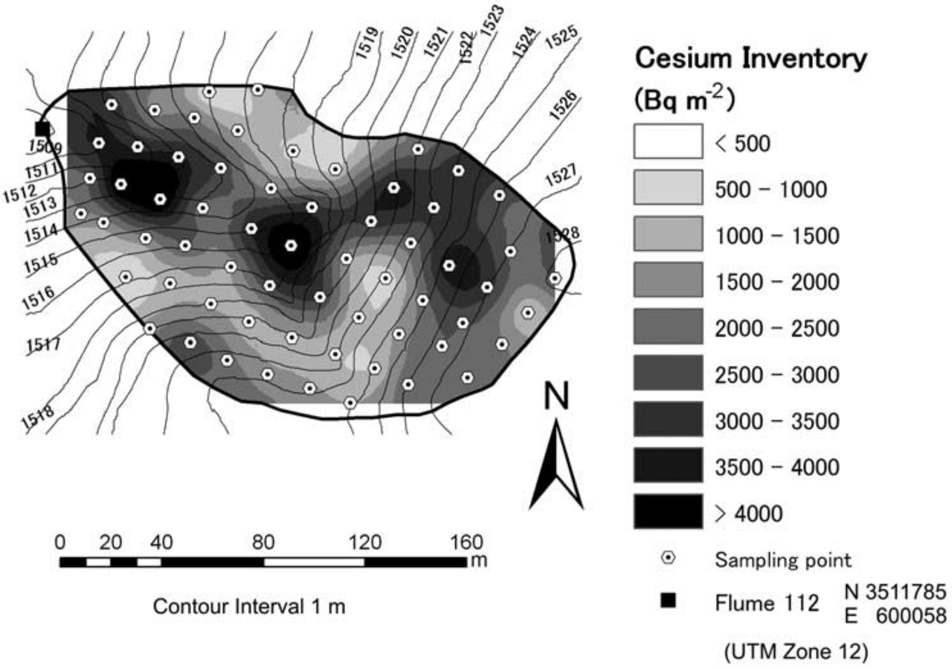

Figure 2. Spatial pattern of ^{137}Cs inventories for the sampling points in the Kendall watershed.

for erosion and deposition on undisturbed soils [*Walling and He*, 1999], and computed the confidence range for the value of zero erosion represented by the reference soil surface samples. We then assumed that net erosion rates from the watersheds that fell in that range were not significantly different from zero.

3. Results

3.1. The ^{137}Cs Inventories

[23] The spatial patterns of ^{137}Cs inventories at the sampling points in the Lucky Hills and Kendall watersheds are shown in Figures 1 and 2. A weir (SW63.101) was located in the middle of the Lucky Hills watershed, and a road is located along the boundary of the watershed (Figure 1). The white crosses in Figure 1 are the sampling points in the Lucky Hills watershed where no ^{137}Cs was detected. Table 1 summarizes the ^{137}Cs inventories for the references sites near the Walnut Gulch Watershed and at the sampling points in the Lucky Hills and Kendall watersheds. Outlier data points with the highest ^{137}Cs inventory in each watershed (8293.2 Bq m^{-2} for the Lucky Hills watershed, 6496.0 Bq m^{-2} for the Kendall watershed) were removed from the further analysis, because these high inventories were significantly greater than the next highest inventories (3643.7 Bq m^{-2} for the Lucky Hills watershed, 4823.5 Bq m^{-2} for the Kendall watershed) and the reliability of those data was not clear. The mean reference inventory was 2245.0 Bq m^{-2} for the 20 samples with a coefficient of variation (CV) of 50.0% (Table 1). The variation in the reference samples translated to a confidence in the zero value of erosion of ±1.2 t ha^{-1} yr^{-1}.

[24] The mean ^{137}Cs inventory at the sampling points in the Lucky Hills watershed was 1227.7 Bq m^{-2} for the 68 samples, while that in the Kendall watershed was 2277.5 Bq m^{-2} for the 62 samples. The standard deviation of the ^{137}Cs inventory was approximately the same in both watersheds.

3.2. Parameter Values and Erosion and Deposition Rates

[25] Figure 3 shows the means and variations of the ratio of computed erosion and deposition rates for each model parameter perturbation of ±25% and ±50% to that for the case of using default values in computing erosion and deposition (see Methods section). As pointed out by *Walling and He* [1999], the model was more sensitive to *D* than to *V* and *H* (Figure 3). The maximum mean ratio calculated was 1.19, and the minimum was 0.74, both for the case of parameter *D*. On the basis of these results we cannot exactly quantify the confidence range for the erosion estimates that we calculated in this study, but as noted above, the erosion (and deposition) rates calculated probably represent maximum values. We suggest based on the sensitivity analysis conducted, as well as an assessment of the comparison between the ^{137}Cs concentration for the upper one cm of soil compared to the upper 5 cm of soil, that a reasonable confidence range for our erosion estimates that used the

Table 1. The ^{137}Cs Inventories for the Samples From the Reference Sites and for the Sampling Points in the Lucky Hills and Kendall Watersheds

	Reference Site	Lucky Hills	Kendall
Mean, Bq m^{-2}	2245	1228	2278
Minimum, Bq m^{-2}	1245	0	390
Maximum, Bq m^{-2}	5086	3644	4824
Standard deviation, Bq m^{-2}	1123	999	1067
Coefficient of variation, %	50	81	47
Number of samples	20	68	62

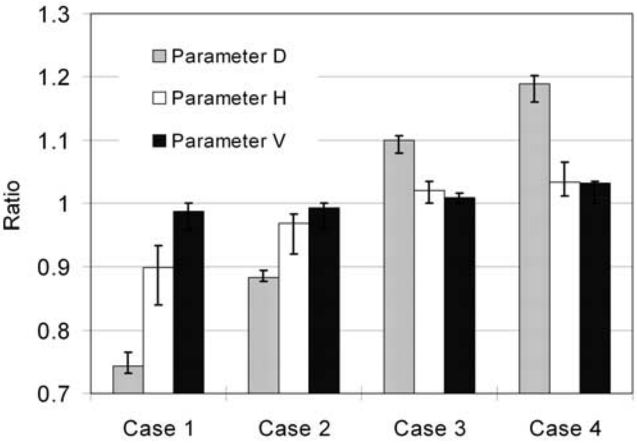

Figure 3. Sensitivities of the parameter values used in the diffusion and migration model for erosion and deposition on undisturbed soils [*Walling and He*, 1999] on calculated erosion and deposition rates in the Lucky Hills watershed. Results are shown as the ratio of the erosion or deposition rates computed using the perturbed parameter values to the same values computed using the default parameter values. Default values for H, D, and V were 5 kg m^{-2}, 40 kg^2 m^{-4} yr^{-1}, 0.5 kg m^{-2} yr^{-1}, respectively. Perturbed values were 50% of the default values for case 1, 75% for case 2, 125% for case 3, and 150% for case 4. Error bars represent the ranges of values computed for the data points.

default model parameters may range from 100% to as low as 75% of the values reported in this study.

3.3. Rates and Spatial Patterns of Soil Erosion and Deposition

[26] The spatial patterns of computed soil erosion and deposition rates at the sampling points in the Lucky Hills and Kendall watersheds are shown in Figures 4 and 5. Figure 6 shows the relative frequency of the soil erosion and deposition rates at the sampling points in the Lucky Hills and Kendall watersheds. Mean, minimum and maximum rates of soil erosion and deposition for the sampling points in the Lucky Hills and Kendall watersheds were shown in Table 2. Table 3 summarizes the mean and variation of erosion rates from areas in the watersheds where erosion (loss) was measured, and mean and variation of deposition rates from areas in the watersheds where deposition (gain) was measured. The values indicated in Tables 2 and 3 were computed by using erosion and deposition rates on individual sampling points, and not on the interpolated, kriged results.

[27] There were five basic results with respect to the measured erosion rates for the two watersheds.

[28] 1. The percent of area that had experienced erosion in the Lucky Hills watershed was greater, and the percent area of deposition less, than in the Kendall watershed (Figures 4, 5, and 6). Eighty-five percent of all of the sampling points in the Lucky Hills watershed showed erosion, while the corresponding value for the Kendall watershed was 53% (Table 3). conversely, this implies that deposition occurred at 15% of all of the sampling points in the Lucky Hills watershed and 47% for the Kendall watershed.

[29] 2. There was more net soil loss from the Lucky Hills watershed than from the Kendall watershed. The mean of the calculated values of soil erosion and deposition rates from all the sampling points in the Lucky Hills watershed was −4.3 t ha^{-1} yr^{-1}, while the mean in the Kendall watershed was +0.1 t ha^{-1} yr^{-1} (Table 2). The mean net erosion value calculated for the Kendall watershed was less than the accuracy range for the method as calculated by the variation in the reference samples (±1.2 t ha^{-1} yr^{-1}), which suggests that its value was not greatly different from zero.

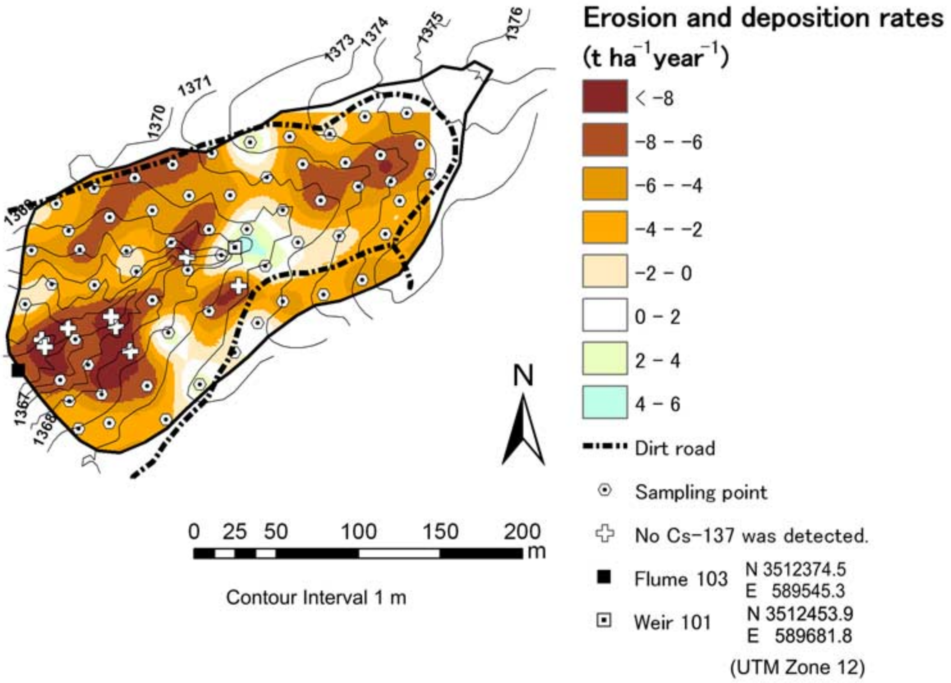

Figure 4. Spatial pattern of calculated erosion and deposition rates in the Lucky Hills watershed.

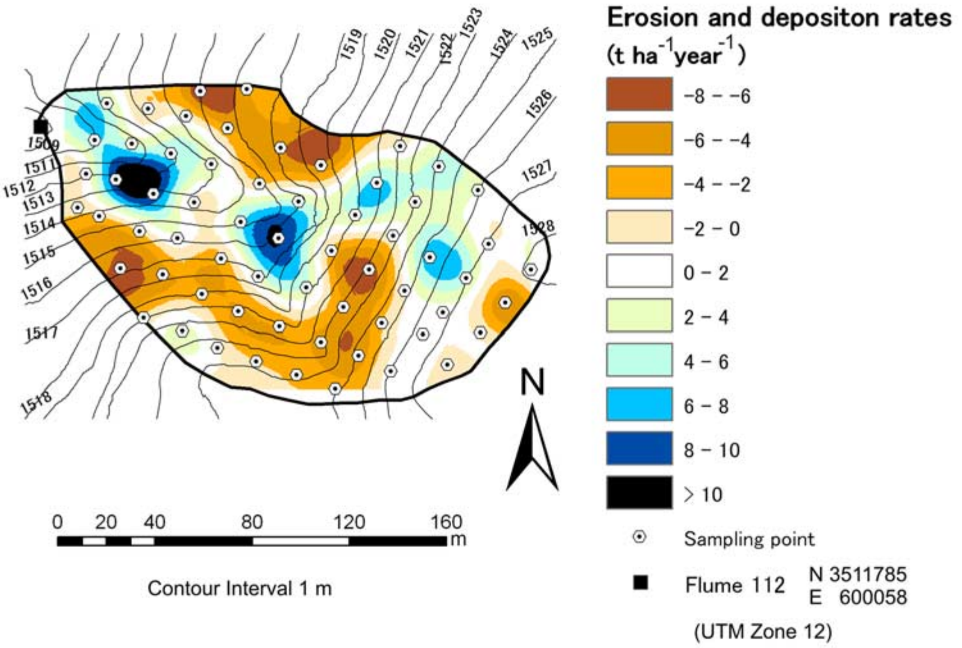

Figure 5. Spatial pattern of calculated erosion and deposition rates in the Kendall watershed.

[30] 3. Erosion rates were greater in the Lucky Hills watershed than in the Kendall watershed. The mean value for the points that had experienced erosion in the Lucky Hills watershed was -5.6 t ha^{-1} yr^{-1}, and the value for the Kendall watershed was -3.2 t ha^{-1} yr^{-1} (Table 3).

[31] 4. Deposition rates were slightly greater in the Kendall watershed than in the Lucky Hills watershed. The mean value for the points that experienced deposition in the Lucky Hills watershed was +3.4 t ha^{-1} yr^{-1}, and the value for the Kendall watershed was +3.9 t ha^{-1} yr^{-1} (Table 3).

[32] 5. The hillslope erosion rates within the watersheds were not indicative of net sediment yield from these watersheds. The annual average sediment yield measured in the Kendall watershed from 1973 through 1976 was 0.14 t ha^{-1} yr^{-1}, while that for the Lucky Hills watershed was 5.8 t ha^{-1} yr^{-1} [*Osborn et al.*, 1978]. In the case of the grassed watershed (Kendall), our calculated net sediment yield from the watershed was negligible (Table 2), while hillslope erosion rates within the watershed (on areas of loss) averaged -3.2 t ha^{-1} yr^{-1} (Table 3), with values as great as -7.9 t ha^{-1} yr^{-1} (Table 2).

[33] The deposition areas in the Lucky Hills watershed were located in the middle of the watershed and in small areas around the north and south rims of the watershed (Figure 4). Visual inspection of the area suggested that the deposition in the middle of the watershed was induced by the presence of the weir (SW63.101). The deposition around the north and south rims of the watershed was possibly due to runoff from the road along the watershed boundary. These results suggest that much of the sediment accumulation in the Lucky Hills watershed was probably due to human activities.

[34] No ^{137}Cs inventory was detected at eight sampling points in the Lucky Hills watershed (Figure 4). All of these eight points were located near the main channel in the watershed. Lack of ^{137}Cs means that the erosion rates at those points were too high for the ^{137}Cs method to measure. Hence these points were assigned the maximum value of erosion that the method could calculate for this situation, which was -9.8 t ha^{-1} yr^{-1}. Obviously, the true erosion rate at these points was possibly greater than -9.8 t ha^{-1} yr^{-1} since the ^{137}Cs inventory was completely depleted.

[35] Deposition of greater than +10.0 t ha^{-1} yr^{-1} was measured in the Kendall watershed on the toeslopes and in the swale where the two upper channel forks converged (Figure 5). The deposition pattern showed that eroded sediments accumulated in areas where the slope gradients decreased before exiting the watershed outlet, as would be expected. The deposition around the southwest rim of the watershed could have been caused by disturbance from

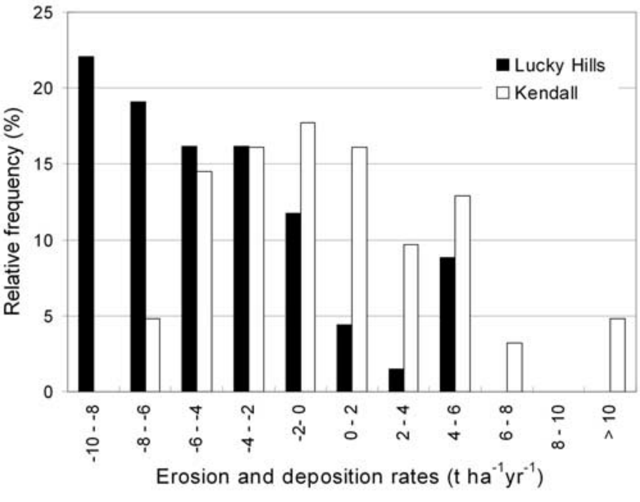

Figure 6. Relative frequency of calculated erosion and deposition rates for the sampling points in the Lucky Hills and Kendall watersheds.

Table 2. Mean, Minimum, and Maximum Rates of Calculated Erosion and Deposition for the Sampling Points in the Lucky Hills and Kendall Watersheds

	Lucky Hills	Kendall
Mean, t ha^{-1} yr^{-1}	−4.27	0.12
Minimum, t ha^{-1} yr^{-1}	−9.83	−7.87
Maximum, t ha^{-1} yr^{-1}	5.74	10.12
Standard deviation, t ha^{-1} yr^{-1}	4.3	4.3
Number of samples	68	62

Table 3. Mean and Variation of Calculated Erosion Rates From Areas in the Watersheds Where Erosion (Loss) Was Measured and Mean and Variation of Calculated Deposition Rates From Areas in the Watersheds Where Deposition (Gain) Was Measured

	Lucky Hills	Kendall
Sample Points From Areas of Erosion		
Mean, t ha^{-1} yr^{-1}	−5.6	−3.2
Standard deviation, t ha^{-1} yr^{-1}	3.0	2.1
Coefficient of variation, %	54	66
Number of samples	58	33
Sample Points From Areas of Deposition		
Mean, t ha^{-1} yr^{-1}	+3.4	+3.9
Standard deviation, t ha^{-1} yr^{-1}	2.0	2.9
Coefficient of variation, %	59	74
Number of samples	10	29

rainfall simulation experiments that were conducted on this area several years in the past.

[36] Theoretically, the mean of the calculated values of soil erosion and deposition rates from all the sampling points in a watershed should be negative since no soil should have been imported across the watershed boundaries and into the watershed as a function of water erosion. An exception to this could be a net importation caused by wind erosion. In general, wind erosion rates in this area are not considered to be significant by the scientists who have worked at Walnut Gulch over the past 40 years (Kenneth Renard, personal communication), however, wind erosion rates have not been documented at Walnut Gulch. Also, areas in the valley on the other side of the Dragoon Mountains, which constitute the eastern, upper portions of Walnut Gulch, as well as areas further east into New Mexico are noted for high wind erosion rates. It is possible that wind deposition may have placed some sediment into the Kendall watershed.

[37] Both the Lucky Hills and Kendall watersheds are currently monitored for runoff and sediment yield by water. The Lucky Hills watershed is outfitted with a supercritical flume and traversing slot sampler, and the Kendall watershed has a broad-crested V notch weir and pump sampler. Unfortunately, the sediment record for both of these watersheds over the past 30 years is spotty, however, available measured sediment yields from the Kendall watershed are generally quite small, while sediment yields from the Lucky Hills watershed are rather large. For example, the annual average sediment yield measured in the Kendall watershed from 1973 through 1976 was 0.14 t ha^{-1} yr^{-1}, while that for the Lucky Hills watershed was 5.8 t ha^{-1} yr^{-1} [*Osborn et al.*, 1978].

3.4. Impacts of Slope, Curvature, and Percent Rock Fragments on Erosion

[38] The measured slopes at the sampling points ranged from 1.5 to 24.0% for the Lucky Hills watershed and from 1.5 to 25.2% for the Kendall watershed. The curvature ranged from −33.6 to 53.5 m^{-1} for the Lucky Hills watershed and from −11.7 to 16.8 m^{-1} for the Kendall watershed. There were no significant relationships between soil erosion and slope gradient in the Lucky Hills watershed, nor between erosion and curvature in either the Lucky Hills and Kendall watersheds (Figures 7 and 8). There was a weak negative, but significant, relationship between soil erosion and deposition rates and slope gradient (i.e., steeper slopes correlated to greater erosion) in the Kendall watershed (F = 5.3, p = 0.03, r^2 = 0.08; Figure 7). However, the relationship between slope and erosion on the Kendall watershed is related to the patterns of erosion versus deposition in that watershed. The swale areas, which had experienced net deposition, were flatter while the hillslopes, which in general experienced soil loss, were steeper. An analysis of only the points of erosion (net loss) for the Kendall data shows no statistically significant relationship. In other words, the slope gradient relationship for Kendall does not correlate to erosional loss per se, but rather is a statistical statement of the fact that areas of erosion were on the hillslopes and areas of deposition were in the flatter swales. Thus the results indicated that the hillslope soil erosion rates were controlled neither by slope curvature nor slope gradient in either the Lucky Hills or Kendall watersheds.

[39] The mean value for rock fragments in the soil profile (top 25 cm) at the sampling points was 37.0% for the Lucky Hills watershed and 30.7% for the Kendall watershed (Table 4). There was a significant positive linear relationship between soil erosion and percent rock fragments in both the Kendall watershed (F = 44.2, p = 0.00000001, r^2 = 0.42) and the Lucky Hills watershed (F = 13.1, p = 0.0004, r^2 = 0.17) (Figure 9). This suggested that the patterns of net soil erosion and deposition rates were probably influenced by the percent of rock fragments for both dominant vegetation types. The significant positive relationships between soil erosion and deposition rates and percent rock fragments

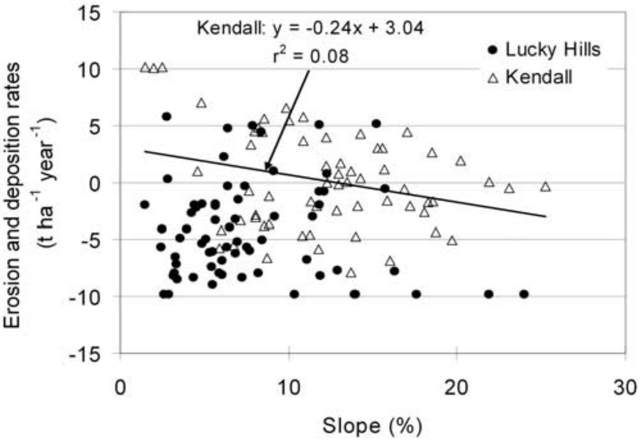

Figure 7. Relationships between slope gradients and calculated erosion and deposition rates in the Lucky Hills and Kendall watersheds.

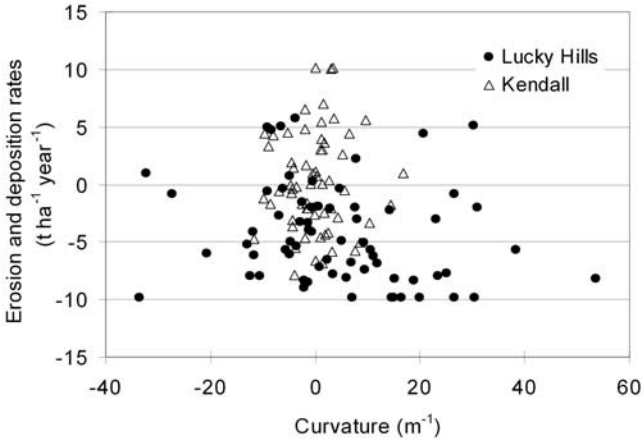

Figure 8. Relationships between slope curvatures and calculated erosion and deposition rates in the Lucky Hills and Kendall watersheds.

in the two watersheds supports the conclusions of previous work that has shown the importance of rock fragments relative to erosion [*Poesen et al.*, 1994]. Less erosion in the areas with higher percentages of rock fragments may be explained by the reduction of sediment transport capacity of flow with increasing hydraulic resistance on stony surfaces [*Nearing et al.*, 1999; *Poesen et al.*, 1999].

3.5. Sediment Delivery Ratios

[40] These two semiarid watersheds, with their relatively similar size, under essentially the same climatic conditions, and located only a few kilometers apart, had very different sediment delivery ratios. The sediment delivery ratio, as used in this case, is the ratio of total erosion from the hillslopes to the net sediment yield from the watershed (i.e., we had no method for accounting for channel scour in the calculations). The sediment delivery ratios calculated from the ^{137}Cs data were 0.89 for the Lucky Hills watershed and −0.07 for the Kendall watershed. The Kendall watershed value is within the error limits of the measurements as discussed previously, and therefore is not greatly different from zero. The results indicate that for all practical purposes the sediment delivery ratio for Kendall is quite small. If we used the sediment yield for the Kendall watershed reported by *Osborn et al.* [1978] of -0.14 t ha^{-1} yr^{-1}, the ratio would be 0.04 (although we recognize that the sediment yield calculated by *Osborn et al.* [1978] was for a period of only 4 years). In the case of the Lucky Hills watershed, the areas where deposition was observed were largely due to human disturbance, so one can argue that in a less disturbed state the sediment delivery ratio for the Lucky Hills watershed would be close to one.

4. Discussion

[41] On the basis of the historical land use on the two study sites, as well as descriptions of the two sites by research scientists working in this area over the past 40 years (Ken Renard, personal communication), it is probable that the general environmental conditions have not substantively changed over the last 40 years, which is the time range associated with the ^{137}Cs measurements. Over the last 40 years, the Lucky Hills site has been a degraded shrubland site with low vegetative cover and essentially no grass cover, while Kendall has been a grass dominated site, with canopy cover probably not significantly different from the current value of approximately 35%. In other words, the stage was set for these two sites before the ^{137}Cs was deposited in the 1950s and 1960s and the erosion rates and patterns that were observed in this experiment occurred under relatively constant vegetative conditions over the time period of study.

Table 4. Percent of Rock Fragments in the Soil Profile (Upper 25 cm) for Soils From the Lucky Hills and Kendall Watersheds

	Lucky Hills	Kendall
Mean, %	37.0	30.7
Minimum, %	18.2	9.8
Maximum, %	56.6	49.7
Standard deviation, %	9.4	9.6
Coefficient of variation, %	25.3	31.5
Number of samples	68	62

[42] The evidence here suggests that the differences in hillslope erosion rates between the two watersheds were controlled largely by the vegetation differences. Other factors between the two watersheds were relatively similar or might actually tend toward causing greater erosion in the Kendall watershed, rather than less as was observed. Slopes in the Kendall watershed were somewhat greater than those for the Lucky Hills watershed, and rainfall was slightly greater in the Kendall watershed, with 315 mm annual average, as compared to 292 mm in the Lucky Hills watershed. Soils are similar between the two watersheds.

[43] The interpretation that vegetation is a primary controlling factors makes sense based on the previous works conducted in the Walnut Gulch Experimental Watershed showing that the erosion rates on shrublands were greater than that on grasslands [*Parsons et al.*, 1996; *Wainwright et al.*, 2000]. It is also consistent with the interpretations

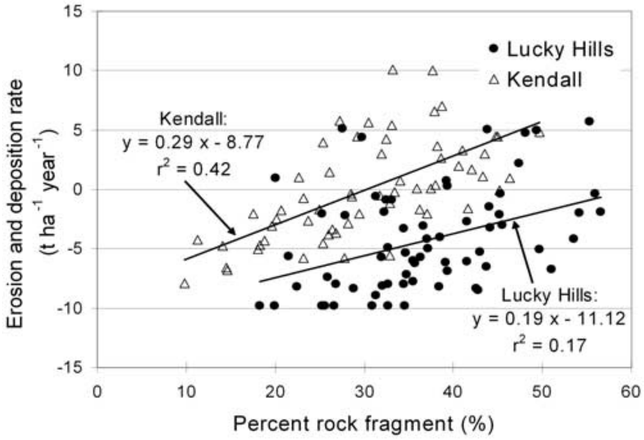

Figure 9. Relationships between percent rock fragments in the upper 25 cm of the soil profile and calculated erosion and deposition rates in the Lucky Hills and Kendall watersheds.

suggested by *Puigdefabregas* [2005] for data from Spain related to the degree of patchiness of the vegetation. The grass cover in the Kendall watershed was certainly less patchy than that of Lucky Hills, wherein the shrubs were essentially lone plants separated by relatively wide interplant open spaces. Observations of rainfall simulation experiments by the authors on sites immediately adjacent to both of these watersheds clearly have shown some of the hydrologic response differences between the watersheds. For the Lucky Hills shrub site, runoff pathways on small plots have been observed to be well connected and unobstructed by any kind of live vegetation or litter. Flows from the Lucky Hills area plots come from small concentrated flow pathways. From plots in the Kendall area, observed runoff from plots is obstructed by vegetation and small debris dams. Flow pathways tend to alternate down the slope from regions of flow concentration between vegetative patches to regions of diffusion and spreading when flow reaches vegetative patches or debris dams. Flows from the Kendall area plots tend to emerge as diffuse, broad sheet flow, as opposed to concentrated flow for the Lucky Hills area plots.

[44] These hydrologic response differences as a function of vegetation differences are probably largely responsible for the differences in hillslope erosion rates between the two watersheds. If flows are more concentrated and vegetative cover is less, as on the Lucky Hills site, flow shear stresses and stream power will tend to be greater, resulting in a greater hydrologic potential for erosion. Also important is probably the higher litter cover and plant basal area cover on the grassland site that would have a direct protective effect against erosion. The vegetative effects would probably be partly offset by erosion resistance from the higher rock cover on the Lucky Hills site (67%) versus Kendall (28%), but on balance the rates appear to be greater at Lucky Hills, which suggests the dominance in this case of vegetation over rock cover in controlling differences in hillslope erosion rates between the watersheds.

[45] Within watersheds, however, variation in hillslope erosion and deposition rates appeared to be dominated by variation in rocks. Slope at sampling points and slope curvature, on the other hand did not appear to be the dominant influence on the hillslope erosion rates. The results related to rocks may reflect back to what we know about the processes of hillslope evolution, since the historic erosion of fine materials on an uncultivated site and the original rock content of the soil profile determines rock cover. (In our case we did not measure rock cover directly, so we are assuming a correspondence between rock cover and rock fragment content in the upper soil profile.) The dependence between erosion and rocks shown here, and the apparent independence of direct control of slope gradient over erosion rates, are interpretable in terms of hydraulic controls by the rocks and initial conditions of the sites and the associated slope-velocity equilibrium that develops on uncultivated slopes. Experiments suggest [*Nearing et al.*, 1999], that overland flow velocities on these hillslopes are slope-gradient-independent, and that hydraulic roughness is greater for greater rock cover. Given that the slope characteristics had probably been largely determined prior to the time period spanned by this experiment, it is reasonable that more rock at a sampling point correlated to less erosion between 1963 and the present. The energy (and hydraulic shear) of flow available for erosion and transport of sediment is reduced as a function of increased hydraulic roughness of soil surface cover because of the energy lost on the roughness elements [*Nearing et al.*, 2001].

[46] The delivery of eroded soil to the outlet of each watershed appears to have different controls than those controlling hillslope erosion rates. Watershed sediment yield and sediment delivery ratios provide an integrated measure of erosion, transport and deposition processes. The difference in deposition between the two watersheds was due to differences in the watershed and drainage network morphology. The Lucky Hills watershed has a strongly incised channel network which facilitates transport of eroded sediments from the watershed. Conversely, the Kendall watershed has a swale area in which runoff slows, allowing much of the sediment in the runoff from the hillslopes to deposit before it leaves the watershed outlet.

[47] These differences in hillslope erosion rates measured from the Lucky Hills watershed, at -5.6 t ha^{-1} yr^{-1}, compared to the Kendall watershed, at -3.2 t ha^{-1} yr^{-1} (Table 3), can explain a portion of the different sediment yields between these two watersheds as measured by *Osborn et al.* [1978], but the majority of the difference in sediment yields can only be explained by the much greater area and higher rates of deposition at Kendall. In addition, the incised channel network in the Lucky Hills watershed also contributes bed scour material, while the Kendall watershed does not have incised channels to act as a sediment source.

[48] An important implication of the results of this study is that sediment yield from a watershed may have little to do with the rates of erosion within the watershed. The results from this study for the Kendall watershed are illustrative of the point. Even though the net erosion in the watershed was small, and even though past measurements show sediment yield rates to be quite small, there was net erosion taking place on 50% or more of the Kendall watershed area at rates as high as 7.9 t ha^{-1} yr^{-1} (Table 2). Hillslopes at Kendall have been eroding over the past 40 years, even though very little sediment is being exported.

[49] **Acknowledgment.** Trade names do not imply endorsement by the USDA or by the Agricultural Research Service.

References

Hamilton, P. (1884), *The Resources of Arizona. Its Mineral, Farming, Grazing and Timber Lands; Its History, Climate, Productions, Civil and Military Government, Pre-historic Ruins, Early Missionaries, Indian Tribes, Pioneer Days, etc., etc.*, 414 pp., A. L. Bancroft, San Francisco, Calif.

Hastings, R. H., and R. M. Turner (1980), *The Changing Mile*, 334 pp. Univ. of Ariz. Press, Tucson.

Humphrey, R. R. (1987), *90 Years and 535 Miles, Vegetation Changes Along the Mexican Border*, 448 pp., Univ. of N. M. Press, Albuquerque.

Ludwig, J. A., B. P. Wilcox, D. D. Breshears, D. J. Tongway, and A. C. Imeson (2005), Vegetation patches and runoff erosion as interacting ecohydrological processes in semiarid landscapes, *Ecology*, *86*, 288–297.

Nearing, M. A., J. R. Simanton, L. D. Norton, S. Y. Bulygin, and J. Stone (1999), Soil erosion by surface water flow on a stony, semiarid hillslope, *Earth Surf. Processes Landforms*, *24*, 677–686.

Nearing, M. A., L. D. Norton, and X. Zhang (2001), Soil erosion and sedimentation, in *Agricultural Nonpoint Source Pollution*, edited by W. F. Ritter and A. Shirmohammadi, pp. 29–58, Lewis, Boca Raton, Fla.

Nichols, M. H., K. G. Renard, and H. B. Osborn (2002), Precipitation changes from 1956–1996 on the Walnut Gulch Experimental Watershed, *J. Am. Water Resources Assoc.*, *38*, 161–172.

Ormsby, T., E. Napoleon, R. Burke, C. Groess, and L. Feaster (2001), *Getting to Know ArcGIS Desktop*, 541 pp., ESRI Press, Redlands, Calif.

Osborn, H. B., J. R. Simanton, and K. G. Renard (1978), Sediment yields of rangeland watersheds, paper presented at the First International Rangeland Congress, Soc. for Range Manage., Denver, Colo.

Parsons, A., A. D. Abrahams, and J. Wainwright (1996), Responses of interrill runoff and erosion rates to vegetation change in southern Arizona, *Geomorphology*, *14*, 311–317.

Poesen, J. W., D. Torri, and K. Bunte (1994), Effects of rock fragments on soil erosion by water at different spatial scales: A review, *Catena*, *23*, 141–166.

Poesen, J. W., B. van Wesemael, K. Bunte, and A. S. Benet (1998), Variation of rock cover and size along semiarid hillslopes: A case study from southeast Spain, *Geomorphology*, *23*, 323–335.

Poesen, J., E. De Luna, A. Franca, J. Nachtergaele, and G. Govers (1999), Concentrated flow erosion rates as affected by rock fragment cover and initial soil moisture content, *Catena*, *36*, 315–329.

Puigdefabregas, J. (2005), The role of vegetation patterns in structuring runoff and sediment fluxes in drylands, *Earth Surf. Processes Landforms*, *30*, 133–147.

Riebe, C. S., J. W. Kirchner, D. E. Granger, and R. C. Finkle (2000), Erosional equilibrium and disequilibrium in the Sierra Nevada, inferred from cosmogenic ^{26}Al and ^{10}Be in alluvial sediment, *Geology*, *28*, 803–806.

Ritchie, J. C., J. E. Herrick, and C. A. Ritchie (2003), Variability in soil redistribution in the northern Chihuahuan Desert based on ^{137}Cs measurements, *J. Arid Environ.*, *55*, 737–746.

Ritchie, J. C., M. A. Nearing, M. A. Nichols, and C. A. Ritchie (2005), Patterns of soil erosion and re-deposition on Lucky Hills Watershed, Walnut Gulch Experimental Watershed, Arizona, *Catena*, *61*, 122–130.

Simanton, J. R., and T. J. Toy (1994), The relation between surface rock-fragment cover and semiarid hillslope profile morphology, *Catena*, *23*, 213–225.

Simanton, J. R., K. G. Renard, C. M. Christiansen, and L. J. Lane (1994), Spatial distribution of surface rock fragments along catenas in semiarid Arizona and Nevada, USA, *Catena*, *23*, 29–42.

Wagoner, J. J. (1952), History of the cattle industry in southern Arizona, *Soc. Sci. Bull. 20*, 132 pp., Univ. of Ariz., Tucson.

Wainwright, J., A. J. Parsons, and A. D. Abrahams (2000), Plot-scale studies of vegetation, overland flow and erosion interactions: Case studies from Arizona and New Mexico, *Hydrol. Processes*, *14*, 2921–2943.

Walling, D. E., and Q. He (1999), Improved models for estimating soil erosion rates from cesium-137 measurements, *J. Environ. Qual.*, *28*, 611–622.

Walling, D. E., and Q. He (2001), Models for converting ^{137}Cs measurements to estimates of soil redistribution rates on cultivated and uncultivated soils, and estimating bomb-derived ^{137}Cs reference inventories (including software for model implementation), report, 32 pp., Univ. of Exeter, Exeter, U. K.

Wischmeier, W. H., and D. D. Smith (1978), *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning*, *Agric. Handbk.*, vol. 537, 58 pp., US. Gov. Print. Off., Washington, D. C.

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