



Contents lists available at ScienceDirect

## Journal of Environmental Radioactivity

journal homepage: [www.elsevier.com/locate/jenvrad](http://www.elsevier.com/locate/jenvrad)

## Sediment budgets and source determinations using fallout Cesium-137 in a semiarid rangeland watershed, Arizona, USA

Jerry C. Ritchie<sup>a</sup>, Mark A. Nearing<sup>b,\*</sup>, Fred E. Rhoton<sup>c</sup><sup>a</sup> USDA ARS, Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705, USA<sup>b</sup> USDA-ARS, Southwest Watershed Research Center, Tucson, AZ 85719, USA<sup>c</sup> USDA-ARS, National Sedimentation Laboratory, Oxford, MS 38655, USA

## ARTICLE INFO

## Article history:

Received 23 January 2009

Received in revised form

4 May 2009

Accepted 12 May 2009

Available online 25 June 2009

## Keywords:

Cs-137

Erosion

Soil redistribution

Arid rangelands

Watersheds

Sediment budgets

Sediment sources

## ABSTRACT

Analysis of soil redistribution and sediment sources in semiarid and arid watersheds provides information for implementing management practices to improve rangeland conditions and reduce sediment loads to streams. The purpose of this research was to develop sediment budgets and identify potential sediment sources using <sup>137</sup>Cs and other soil properties in a series of small semiarid subwatersheds on the USDA ARS Walnut Gulch Experimental Watershed near Tombstone, Arizona, USA. Soils were sampled in a grid pattern on two small subwatersheds and along transects associated with soils and geomorphology on six larger subwatersheds. Soil samples were analyzed for <sup>137</sup>Cs and selected physical and chemical properties (i.e., bulk density, rocks, particle size, soil organic carbon). Suspended sediment samples collected at measuring flume sites on the Walnut Gulch Experimental Watershed were also analyzed for these properties. Soil redistribution measured using <sup>137</sup>Cs inventories for a small shrub-dominated subwatershed and a small grass-dominated subwatershed found eroding areas in these subwatersheds were losing  $-5.6$  and  $-3.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ , respectively; however, a sediment budget for each of these subwatersheds, including depositional areas, found net soil loss to be  $-4.3 \text{ t ha}^{-1} \text{ yr}^{-1}$  from the shrub-dominated subwatershed and  $-0.1 \text{ t ha}^{-1} \text{ yr}^{-1}$  from the grass-dominated subwatershed. Generally, the suspended sediment collected at the flumes of the six other subwatersheds was enriched in silt and clay. Using a mixing model to determine sediment source indicated that shrub-dominated subwatersheds were contributing most of the suspended sediment that was measured at the outlet flume of the Walnut Gulch Experimental Watershed. The two methodologies (sediment budgets and sediment source analyses) indicate that shrub-dominated systems provide more suspended sediment to the stream systems. The sediment budget studies also suggest that sediment yields measured at the outlet of a watershed may be a poor indicator of actual soil redistribution rates within these semiarid watersheds. Management of these semiarid rangelands must consider techniques that will protect grass-dominated areas from shrub invasion to improve rangeland conditions.

Published by Elsevier Ltd.

## 1. Introduction

Degradation of semiarid and arid rangelands is a major concern and is usually described in terms of soil movement/erosion and changing plant communities (Havstad et al., 2006; Tongway et al., 2003; de Soyza et al., 2000; Herrick and Whitford, 1995). A National Research Council (1994) report cited a need to develop methodology to monitor and assess this degradation and its impact on rangelands and rangeland conditions. Understanding the patterns of soil erosion, soil redistribution, and sediment yield are key

factors for monitoring and assessing soil quality, rangeland condition, water quality, and managing semiarid rangelands (Whitford et al., 1998). Maintaining or improving soil quality or rangeland conditions requires managing soil erosion, soil organic carbon movement and loss and vegetation at the field and watershed scale (Verity and Anderson, 1990; Whitford et al., 1998; Lal et al., 1998; Ritchie and McCarty, 2003). Recent studies indicate that soil erosion and subsequent redeposition of this eroded material within the same field play a significant role in soil organic matter patterns and therefore soil quality at field and landscape scales (Van Oost et al., 2007; Ritchie et al., 2007; Ritchie and McCarty, 2003; McCarty and Ritchie, 2002; Verity and Anderson, 1990). The stability of semiarid rangeland ecosystems has been defined as the capability of a site to limit redistribution and loss of soil resources (including

\* Corresponding author. Tel.: +1 301 504 8717; fax: +1 301 504 8931.  
E-mail address: [jerry.ritchie@ars.usda.gov](mailto:jerry.ritchie@ars.usda.gov) (J.C. Ritchie).

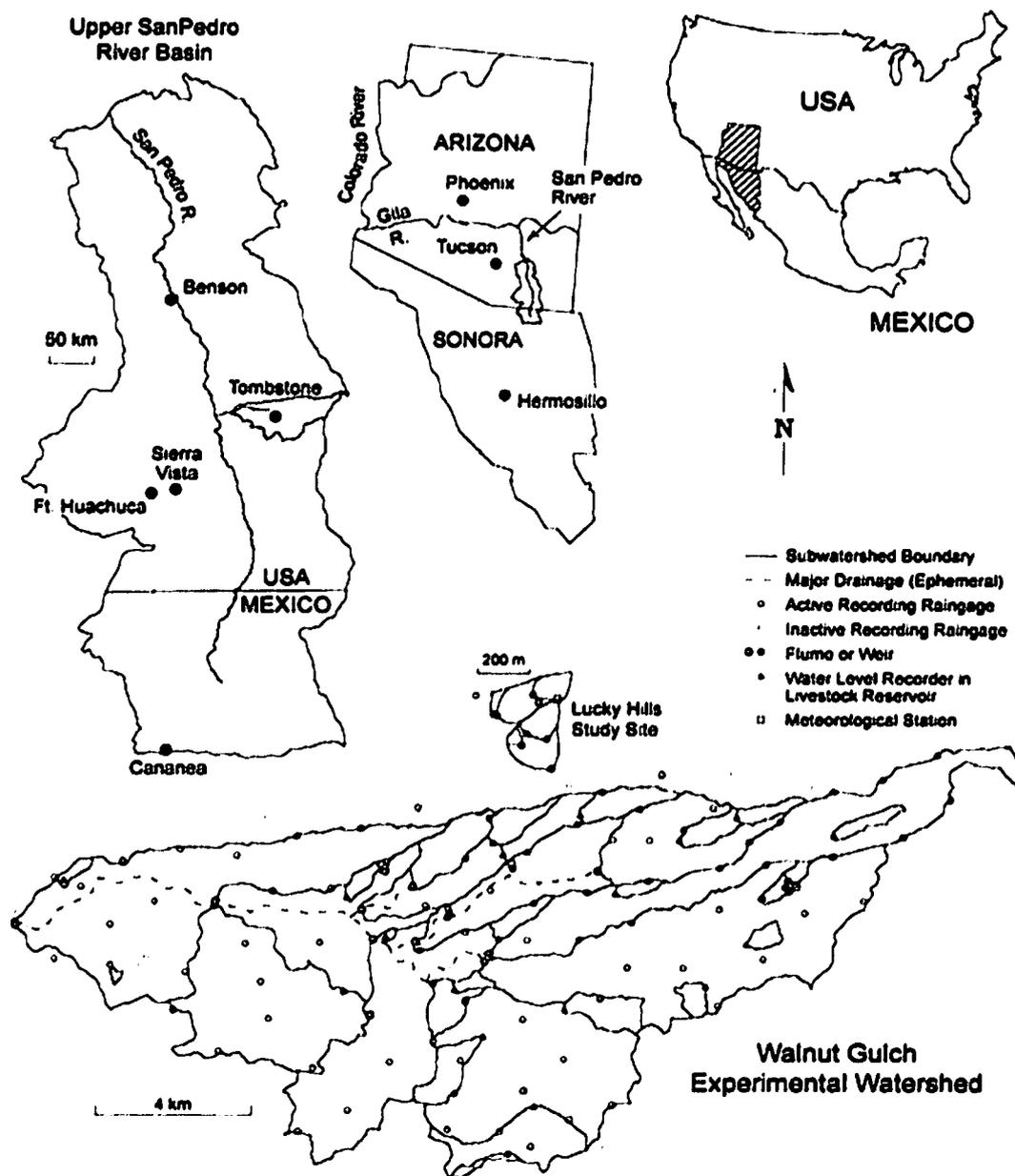


Fig. 1. Map of Walnut Gulch Experimental Watershed, Tombstone, Arizona, USA showing the subwatersheds used in this study. [Adapted from <http://www.tucson.ars.ag.gov>].

nutrients and organic matter) by wind and water (Ritchie et al., 2003; Schlesinger et al., 1990).

Soil losses are a major concern around the world with degradation of both onsite and off-site resources (Boardman and Poesen, 2007; Pimentel, 2006; Pimentel et al., 1995). With the growing recognition of the enormity of this problem, determining soil redistribution patterns in watersheds is needed, for relating suspended sediment to source areas in the watershed, and for determining the effectiveness of management practices on the runoff and soil redistribution. With the growing concern about degradation of semiarid and arid rangelands (National Research Council, 1994), a better understanding of soil redistribution patterns of these ecosystems is necessary to maintain or improve rangeland conditions.

Two general approaches (monitoring and fingerprinting) have been used to identify sediment sources for watersheds. Monitoring of source areas employs erosion pins, runoff plots, and suspended

sediment samples (Slattery et al., 1995; Sutherland and Bryan, 1989). Fingerprinting compares properties of potential sediment sources and suspended sediment using physical, chemical, radiological, and mineralogical properties to determine sediment sources within the watershed (Walling, 2003, 2005; Slattery et al., 1995; Walling and Woodward, 1992).

Physical, chemical, and radiological ( $^{137}\text{Cs}$ ) properties have been widely used for fingerprinting suspended sediment (Smith and Dragovich, 2008; Walling, 2005; Mabit et al., 2008; Walling and Woodward, 1992; Bonniwell et al., 1999; Wallbrink et al., 1999). These properties of potential sources and suspended sediment are used in mixing models (Walling, 2005; Walling and Woodward, 1992; Slattery et al., 1995) to establish the relative contribution of the potential sources to the suspended sediment load.

The objective of this research was to use radioactive fallout  $^{137}\text{Cs}$  distribution patterns to determine soil redistribution and sediment

**Table 1**  
 $^{137}\text{Cs}$  inventories for the reference site and the Lucky Hill and Kendall subwatersheds.

Site	Maximum Bq m <sup>-2</sup>	Minimum Bq m <sup>-2</sup>	Mean Bq m <sup>-2</sup>	Standard deviation Bq m <sup>-2</sup>	Number of profiles
Reference	5086	1245	2200	1100	20
Lucky Hills	3644	0	1200	1000	68
Kendall	4824	390	2300	2000	62

budgets and to combine measurements of  $^{137}\text{Cs}$  with other physical and chemical properties to identify potential sources of suspended sediment in the streams of grass-dominated and shrub-dominated semiarid subwatersheds of the Walnut Gulch Experimental Watershed.

## 2. Materials and methods

### 2.1. Study area

The study area (Fig. 1) is located in the Southeastern Arizona Basin and Range province on the United States Department of Agriculture (USDA), Agriculture Research Service (ARS) Walnut Gulch Experimental Watershed near Tombstone, Arizona USA (31° 43' N. Latitude, 110° 41' W. Longitude). The watershed is approximately 150 km<sup>2</sup> in a high foothill alluvial fan of the San Pedro River Watershed at elevations ranging from 1220 to 1950 m. Mean annual temperature is 18 °C ranging from 1 °C in January to 35 °C in June. Mean annual precipitation in the watershed is 356 mm with annual totals ranging from 250 to 500 mm yr<sup>-1</sup>, with approximately two thirds of the rainfall occurring in the monsoon season (July–August). Most of the surface runoff occurs during the monsoon period. The main branch of Walnut Gulch is dry approximately 99% of the time (Nichols et al., 2002).

Soils in the Walnut Gulch Experimental Watershed are closely related to their parent material (Rhoton et al., 2008, 2006) and have developed on Precambrian to Tertiary-age sandstone, conglomerate, limestone, volcanic, granodiorite, and quartz monzonite materials. Quaternary alluvium from limestone makes up approximately 80% of the watershed surface. The soils formed on this parent material are well-drained, calcareous gravelly loams (Gelderman, 1970). Watershed soils formed in alluvium and colluvium from andesite and basalt, and residuum from granodiorite are generally fine-textured, shallow, and well-drained. Rock contents at the soil surface range from 0 to 70% (Simanton and Toy, 1994).

At lower elevations in the watershed, shrub species of creosote bush [*Larrea tridentata* (DC.) Coville; *Larrea divaricata* Cav.],<sup>1</sup> whitethorn [*Acacia constricta* Benth.], tarbush [*Flourensia cernua* DC.], snakeweed [*Gutierrezia sarothrae* (Pursh) Britton & Rusby], and burroweed [*Isocoma tenuisecta* Greene] dominate the landscape. At higher elevations, grass species of black grama [*Bouteloua eriopoda* (Torr.) Torr.], blue grama [*Bouteloua gracilis* (Kunth) Lag. ex Griffith], sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.], curly mesquite [*Hilaria belangeri* (Steud.) Nash] and bush muhly [*Muhlenbergia porteri* Scribn. Ex Beal] dominate the vegetation (Simanton et al., 1994; Weltz et al., 1994). The Walnut Gulch Experimental Watershed serves as grazing land for cattle and horses. Grazing (3–4 animal units km<sup>-2</sup>) has occurred in the area since the establishment of Spanish ranches in the early 1800s.

#### 2.1.1. Study area – sediment budgets

Sediment budgets were determined for the Lucky Hills and the Kendall subwatersheds (Fig. 1) of the Walnut Gulch Experimental Watershed. The Lucky Hills subwatershed has an area of 3.7 ha and the Kendall subwatershed has an area of 1.9 ha. For the time period of 1963 through 2004, the measured mean annual precipitation measured at Lucky Hills was 292 mm and 315 mm at Kendall (Nichols et al., 2002). Mean hillslope gradients of the Lucky Hills and Kendall subwatersheds are 7.7% and 12.3%, respectively. The Lucky Hills subwatershed is a shrub-dominated semiarid rangeland with approximately 25% canopy cover during the rainy season and a gravelly sandy loam soils with a primary particle size distribution of 52% sand, 26% silt, and 22% clay. The Kendall subwatershed is a grass-dominated semiarid rangeland with approximately 35% canopy cover during the rainy season with a few shrubs and forbs having a gravelly fine sandy loam soils with primary particle size distribution of

55% sand, 20% silt, and 25% clay. The organic carbon contents of the soils from the Lucky Hills and Kendall subwatersheds are approximately 0.8% and 1.1%, respectively. Both subwatersheds were historically used as grazing land; however, the Lucky Hills subwatershed was fenced in 1963 eliminating grazing by domestic livestock. The Kendall subwatershed continues to be grazed at a density of 3–4 animal unit km<sup>-2</sup> (Osborn and Simanton, 1983). These subwatersheds are instrumented with flumes for runoff and suspended sediment measurements (Renard et al., 1993).

#### 2.1.2. Study area – sediment sources

The sediment source research was conducted on subwatersheds 3, 7, 9, 10, 11, and 15 of the Walnut Gulch Experimental Watershed (Fig. 1). Dominant vegetation in subwatersheds 3, 7, and 15 is shrubs while the dominant vegetation in subwatersheds 9, 10, and 11 is grass (Simanton et al., 1994). These subwatersheds, as well as the outlet of the Walnut Gulch Experimental Watershed, are instrumented with supercritical flumes for runoff measurements and suspended sediment collection (Renard et al., 1993).

### 2.2. Field methods

#### 2.2.1. Soil sampling – sediment budget studies

For the sediment budget studies in Lucky Hill (68 soil samples) and Kendall (62 soil samples) subwatersheds, soil samples were collected on a 25-m grid pattern. A differential GPS (Global Positioning System – Trimble Geoexplorer XT<sup>2</sup> – 1 m accuracy) was used to determine the latitude, longitude, and elevation of each sample site. Cover (i.e., vegetation, bare) was noted for the sample sites. Bulk soil samples at each site were collected for the 0–25 cm soil layer at three points within 1 m and composited for analyses.

#### 2.2.2. Soil sampling – sediment source studies

For the sediment source studies, 530 soil samples were collected from transects from the six subwatersheds based on area occupied by different soil mapping units. Transects were delineated so a range of surface geomorphology factors were represented. At each location, soil samples were collected from the surface of 0–5 cm at three points, approximately 10-m apart and perpendicular to the slope, and composited for analyses. This sampling depth generally represents the A-horizon thickness which is most affected by soil erosion processes. Site data were recorded for latitude, longitude, slope position, slope gradient, and slope aspect.

#### 2.2.3. Suspended sediment sampling – sediment source studies

Suspended sediment was collected with vertical samplers mounted on the face of the flumes on each of the six subwatersheds and the outlet flume (Flume 1) of the Walnut Gulch Experimental Watershed. These samples were collected from the flow in 30.5-cm vertical increments above the floor of the flume to a flow depth to 122 cm in 500-mL plastic sample bottles mounted inside the sealed sampler at each depth. Additionally, 2-L sample bottles were attached to the bottom of the samplers to ensure sufficient volumes of suspended sediment was obtained at each 30.5-cm flow depth during low flow events. Suspended sediment samples collected between 1999 and 2003 were composited to provide a sample for each flume for this study (Rhoton et al., 2008).

### 2.3. Laboratory analyses

Soils and suspended sediment samples were air-dried and then oven-dried at 60 °C. All samples were sieved to pass a <2 mm screen. Weights of soil (<2 mm) and rock fragment (>2 mm) fractions were determined. Particle size analyses were determined by standard pipette analysis (USDA-Natural Resources Conservation Service, 1996). Total carbon and nitrogen were determined using a Leco CN-2000 carbon–nitrogen analyzer (Leco Corp., St. Joseph, MI).

The soil and suspended sediment fractions (<2 mm) were placed into counting containers and sealed for analyses of  $^{137}\text{Cs}$  by gamma-ray spectrometry using a Canberra Genie-2000 Spectroscopy System that receives input from three Canberra high purity coaxial germanium crystals (HpC > 30% efficiency) into three 8192-channel analyzers. The system is calibrated and efficiency determined using International Atomic Energy Agency sample (IAEA-327) as a standard. Measurement precision for  $^{137}\text{Cs}$  is  $\pm 4$ –6% (Ritchie, 2000).

### 2.4. Estimation of soil redistribution rates – sediment budget studies

Radioactive  $^{137}\text{Cs}$  was globally distributed by the deposition of radioactive fallout material from atmospheric nuclear weapon tests from the mid 1950s to the mid 1970s, mostly by rainfall (Playford et al., 1993; Cambray et al., 1989; Carter and Moghissi, 1977). While rainfall may be patchy in semiarid and arid landscapes, the

<sup>1</sup> Scientific nomenclature of plant names according to the USDA, ARS, National Genetic Resources Program, Germplasm Resources Information Network – (GRIN) [Online Database], National Germplasm Resources Laboratory, Beltsville, Maryland. URL: <http://www.ars-grin.gov/cgi-bin/npgs/html/taxgenform.pl?language=en> (1 February 2009).

<sup>2</sup> Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the U. S. Department of Agriculture.

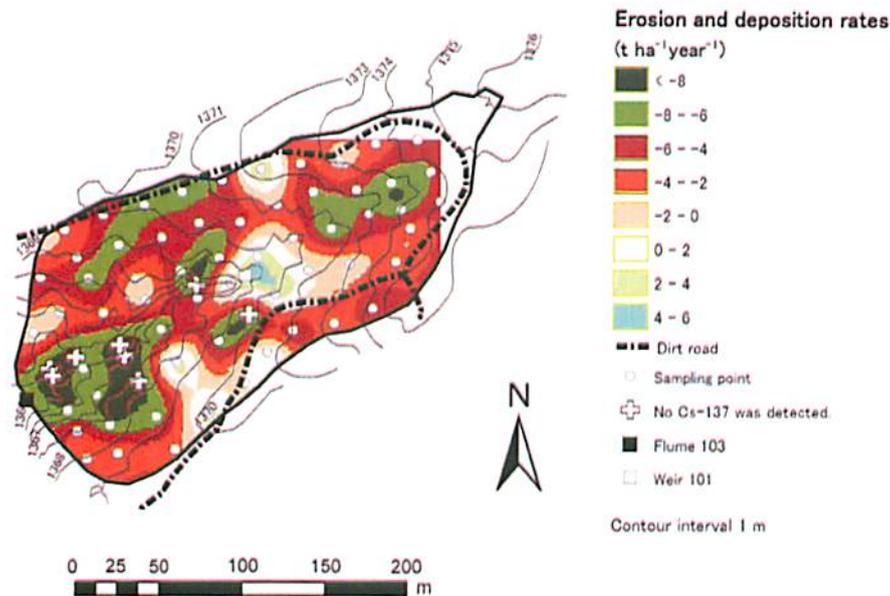


Fig. 2. Soil redistribution patterns in the Lucky Hills subwatershed of the Walnut Gulch Experimental Watershed, Tombstone, Arizona, USA (adapted from Nearing et al., 2005).

assumption is that over the 20-year period of radioactive fallout, all areas would receive approximately equal rain and fallout  $^{137}\text{Cs}$  deposition (Ritchie et al., 2003). Since  $^{137}\text{Cs}$  is quickly adsorbed by clays, any subsequent movement of  $^{137}\text{Cs}$  across the landscape is due to physical processes (i.e., water erosion, wind erosion, tillage erosion). Thus patterns of  $^{137}\text{Cs}$  distribution across the landscape can be used to estimate soil redistribution rates and patterns based on the measurement of  $^{137}\text{Cs}$  inventories in the eroding or depositing sites and comparing them to measurements of  $^{137}\text{Cs}$  inventory at reference sites where soil erosion has not occurred (Mabit et al., 2008; Walling, 2003; Walling and He, 2001, 1999; Ritchie and McHenry, 1990; Zapata, 2002).

The Diffusion and Migration Model for Erosion and Deposition on Undisturbed Soils (Walling and He, 2001, 1999; Zapata, 2002), which accounts the time-dependent behavior of both the  $^{137}\text{Cs}$  fallout input and its subsequent redistribution in the soil profile, was used to convert from  $^{137}\text{Cs}$  inventories to net soil erosion/deposition rates for the Kendall (Nearing et al., 2005) and Lucky Hills (Ritchie et al., 2005) subwatersheds. The net soil redistribution rates were calculated by comparing the  $^{137}\text{Cs}$  inventories of the soil samples collected over the subwatersheds and  $^{137}\text{Cs}$  inventory at nearby reference sites. Negative values represent soil loss and positive values represent soil gains (deposition).

Soil redistribution and sediment budgets were calculated based on contour maps and maps of net soil redistribution produced by using a kriging interpolation method for the Lucky Hills and Kendall subwatersheds. Maps of rock distribution were also developed to compare with the patterns of soil redistribution.

### 2.5. Sediment sources analyses

The relative contribution of suspended sediment from each of the subwatersheds (3, 7, 9, 10, 11, and 15) to the suspended sediment loads measured at the outlet flume (Flume 1) of the Walnut Gulch Experimental Watershed was estimated using the multivariate mixing model methods described in detail by Rhoton et al. (2008) to compare the physical, chemical, and radiological properties measured for the soil and suspended sediment samples. Each property was normalized by its standard deviation. This mixing model allowed the measured properties of suspended sediment at Flume 1 to be expressed in terms of possible contributions of suspended sediment from flumes 3, 7, 9, 10, 11, and 15 and the subwatershed soil samples.

## 3. Results and discussion

### 3.1. Development of sediment budgets

Twenty soil profiles collected at sites near or on the Walnut Gulch Experimental Watershed with little evidence of physical or biological disturbance of the surface were used as reference soil sites for determining  $^{137}\text{Cs}$  input for the area. The mean  $^{137}\text{Cs}$

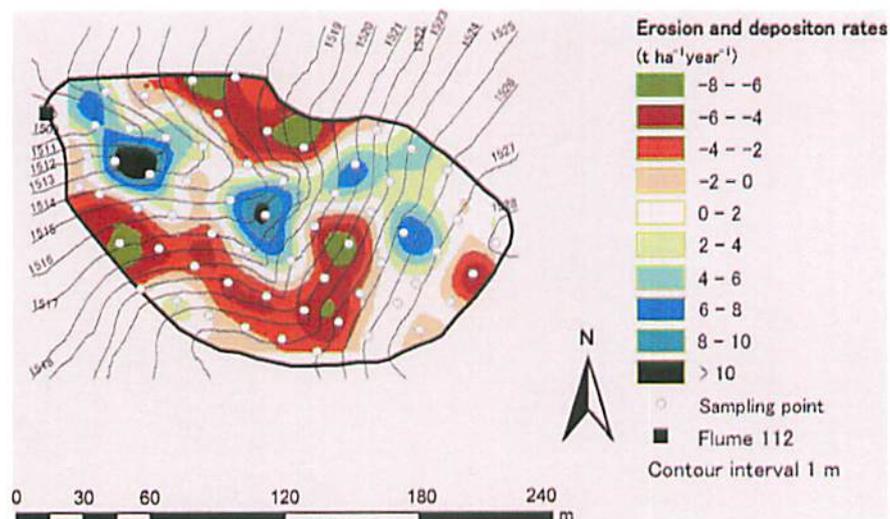


Fig. 3. Soil redistribution patterns in the Kendall subwatershed of the Walnut Gulch Experimental Watershed, Tombstone, Arizona, USA (adapted from Nearing et al., 2005).

inventory in these samples was  $2200 \pm 1100 \text{ Bq m}^{-2}$  (Table 1). This variability in reference samples is similar to the variability measured in other studies (Wallbrink et al., 1994; Sutherland, 1996; Ritchie et al., 2003). We assumed that this  $^{137}\text{Cs}$  inventory ( $2200 \pm 11,400 \text{ Bq m}^{-2}$ ) represented the  $^{137}\text{Cs}$  input to the watershed area and used it as the reference inventory in the Diffusion and Migration Model (Walling and He, 2001, 1999) to calculate soil redistribution rates for the sediment budget studies. The variability of the reference samples was used to calculate the confidence limits for our methodology. To do this, each value of the twenty  $^{137}\text{Cs}$  reference samples was run through the Diffusion and Migration Model (Walling and He, 2001, 1999) to compute 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. The mean reference inventory had a coefficient of variation (CV) of 50% (Table 1). The variation in the reference samples translated to a confidence in the zero value of erosion of  $\pm 1.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ .

The spatial patterns of soil redistribution in the two watersheds are shown in Figs. 2 and 3. Erosion rates were greater in the Lucky Hills subwatershed than in the Kendall subwatershed with eroding sites in Lucky Hills subwatershed averaging  $-5.6 \text{ t ha}^{-1} \text{ yr}^{-1}$  soil loss while the Kendall subwatershed averaged  $-3.2 \text{ t ha}^{-1} \text{ yr}^{-1}$  soil loss. About 85% of the sampling sites in the Lucky Hills subwatershed were eroding compared to 53% of the sites in the Kendall subwatershed. Deposition sites (47% of the sample sites) in the Kendall subwatershed were greater than in the Lucky Hills subwatershed (15% of the sites). The Kendall subwatershed had higher deposition rates within the subwatershed ( $+3.9 \text{ t ha}^{-1} \text{ yr}^{-1}$ ) than the Lucky Hills subwatershed ( $+3.4 \text{ t ha}^{-1} \text{ yr}^{-1}$ ) at the deposition sites.

When the total soil redistribution budgets were calculated based on aerial pattern of soil redistribution, soil loss from the Lucky Hills subwatershed was  $-4.3 \text{ t ha}^{-1} \text{ yr}^{-1}$ , while the calculated soil loss from the Kendall subwatershed was  $-0.1 \text{ t ha}^{-1} \text{ yr}^{-1}$  (which was not statistically significantly different from zero). These rates are similar to soil losses calculated from the suspended sediment loads ( $5.8 \text{ t ha}^{-1} \text{ yr}^{-1}$  and  $0.14 \text{ t ha}^{-1} \text{ yr}^{-1}$  for Lucky Hills and Kendall, respectively) measured at the supercritical flumes on these subwatersheds (Nearing et al., 2005).

Differences in soil loss rates between the two subwatersheds appear to be related to cover and patchiness of the vegetation, while within-watersheds variation in hillslope soil loss rates appeared to be controlled by surface rocks. There was a significant positive linear relationship between soil erosion and percent rock fragments in both Kendall and Lucky Hills (Fig. 4). Less erosion in the areas with more rock fragments may be explained by the reduction of rain drop impact and sediment transport capacity of flow with increasing hydraulic resistance on rocky surfaces and rock fragment armoring (Nearing et al., 1999; Poesen et al., 1999). Contrast in vegetation cover/type between the catchments appears to be related to the patchiness of the vegetation. The vegetation (grass) cover is greater, more uniform, and less patchy in the Kendall subwatershed than that of the Lucky Hills subwatershed, where shrubs were essentially single plants separated by relatively wide inter-plant bare soil spaces. Slope gradient and curvature at the sample site did not have a significant influence on the hillslope erosion rates.

Contrast in the delivery of eroded soil to the outlet of each subwatershed appears to be due to differences in deposition between the two subwatersheds, which were related to differences in the subwatershed and drainage network morphology. The Lucky Hills subwatershed has a strongly incised channel network which facilitated transport of eroded sediments from the subwatershed.

Conversely, the Kendall subwatershed had a swale area which slowed runoff, allowing most of the suspended sediment in the runoff from the hillslopes to be deposited in the swale area before reaching the subwatershed outlet.

An important implication of this study is that sediment yield at the outlet of a watershed may not reflect the actual soil redistribution rates within the watershed (Nearing et al., 2005). The results from this study for the Kendall subwatershed are illustrative of the point. Even though the net soil loss from the subwatershed from the sediment budgets was negligible, and even though past actual measurements show sediment yield rates to be quite small, net soil erosion occurred on more than 50% of the Kendall subwatershed area at rates as high as  $7.9 \text{ t ha}^{-1} \text{ yr}^{-1}$ . Hillslopes at Kendall have been eroding over the past 40 years, even though very little sediment is being exported from the subwatershed at the site of the measuring flume (Nearing et al., 2005).

### 3.2. Identification of sediment sources

Selected physical, chemical, and radiological properties of the soils and suspended sediment (Tables 2 and 3) indicate an enrichment of clay content of the suspended sediment over that of the subwatershed soils ranged from 1.7 in subwatershed 3–1.0 in subwatershed 9 with an average 1.4 for the 6 subwatersheds. Rhoton et al. (2008) concluded that subwatershed 3 had the most erodible soils, and subwatershed 9 had the least erodible soils. Further, suspended sediment was enriched in silt-size material, relative to the clay fractions, in most subwatersheds by a factor of 2–3 times. These differences of particle size were probably due to the selectivity of soil erosion and sediment transport process to detach and move the finer particle sizes.

Organic carbon contents of the suspended sediment averaged 2.1 greater than the subwatershed soils with the suspended sediment averaged 2.4% compared to 1.1% for the subwatershed soils. This difference is probably due to overland flow selectively removing organic matter from the soil surface. Soil organic carbon varied significantly between subwatersheds with subwatershed 15 having twice the concentration of organic carbon as subwatershed 7 soils.

The distribution of radionuclides in the subwatershed soils (Table 3) indicates that the  $^{137}\text{Cs}$  concentrations ranged from  $11.1 \text{ Bq kg}^{-1}$  (subwatershed 11) to  $16.5 \text{ Bq kg}^{-1}$  (subwatershed 10) and averaged  $13.1 \text{ Bq kg}^{-1}$ . The highest  $^{137}\text{Cs}$  concentrations were found in subwatersheds with the highest clay contents. This is as expected since  $^{137}\text{Cs}$  is rapidly and strongly adsorbed by the clay

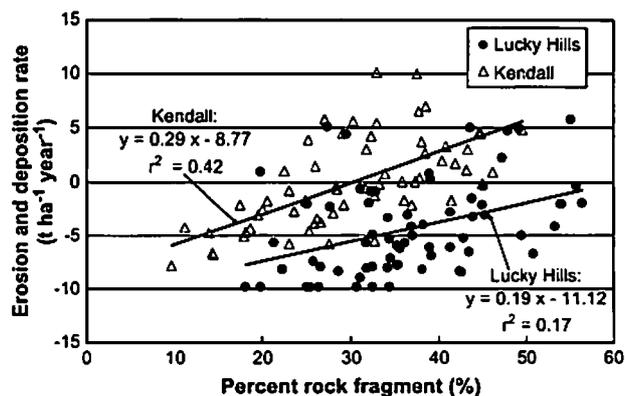


Fig. 4. Relationships between percent rock fragments in the upper 25 cm of the soil profile and calculated erosion and deposition rates in the Lucky Hills and Kendall subwatersheds (adapted from Nearing et al., 2005).

Table 2

Selected physical and chemical properties in soils and suspended sediment by subwatershed. Subwatershed/Flume 1 is the outlet flume of the Walnut Gulch Experiment Watershed. All subwatersheds flow through Flume 1.

Subwatershed/ Flume Cover	Clay (%)		Silt (%)		Organic Carbon (%)	
	Soils	Suspended sediment	Soils	Suspended sediment	Soils	Suspended sediment
1 – Mixed	–	20.7	–	41.3	–	2.31
3 – Shrub	13.3	21.6	14.8	40.9	1.02	3.21
7 – Shrub	11.8	17.6	16.2	32.6	0.85	2.49
15 – Shrub	14.1	18.2	25.1	39.5	1.42	2.60
9 – Grass	16.3	15.7	18.4	33.7	1.21	1.99
10 – Grass	16.0	17.1	14.2	41.0	1.15	1.93
11 – Grass	13.3	16.8	13.6	32.0	1.18	2.16

and organic matter fractions in soils and decreases exponentially with depth (Ritchie and McHenry, 1990; Cremers et al., 1988). The  $^{137}\text{Cs}$  concentrations in the suspended sediment were lower than the  $^{137}\text{Cs}$  concentrations in the subwatersheds surface soils. This suggests that primary sediment sources are not from overland flow erosion but are areas where rills, gullies, and streambanks erosion dominate rather than sheet erosion of the surface soil.

### 3.3. Sediment source estimations

Physical, chemical, and radiological properties of the suspended sediment were used with a mixing model to determine the relative contribution of suspended sediment from each subwatershed to the suspended sediment collected at Flume 1. The shrub-dominated subwatersheds 3, 7, and 15 contributed 46%, 22%, and 18%, respectively while the grass-dominated subwatersheds 9, 10, and 11 contributed only 4%, 6%, and 4%, respectively, of the suspended sediment measured at Flume 1 at the outlet of Walnut Gulch Experimental Watershed (Fig. 1). Thus 86% of the suspended sediment leaving the Walnut Gulch Experimental Watershed originated from the shrub-dominated subwatersheds 3, 7 and 15 with the other 14% coming from the grass-dominated subwatersheds 9, 10, and 11. These shrub-dominated subwatersheds had lower ground cover and lower clay content and are closest to Flume 1 when compared to the grass-dominated subwatershed, thus the suspended sediment contributed by these subwatersheds to the main channel does not undergo as much sorting prior to its delivery at Flume 1.

Stable carbon isotope ( $^{13}\text{C}$ ) data (Rhoton et al., 2006) indicate that 63.8% of the stable carbon isotopes in the suspended sediment at Flume 1 are from C3 plant (shrubs) origin. At the flumes on the shrub-dominated subwatersheds 3, 7, and 15, 68, 65, and 55%, respectively of the stable carbon isotope is from C3 plants. These

Table 3

$^{137}\text{Cs}$  concentrations in soils and suspended sediment by subwatershed. Subwatershed/Flume 1 is the outlet flume of the Walnut Gulch Experiment Watershed. All subwatersheds flow through Flume 1.

Subwatershed/ Flume Cover	$^{137}\text{Cesium}$	
	Soils	Suspended sediment
Bq kg <sup>-1</sup>		
1 – Mixed	–	13.6
3 – Shrub	11.2	9.1
7 – Shrub	12.8	14.2
15 – Shrub	12.8	18.5
9 – Grass	14.2	10.5
10 – Grass	16.5	7.0
11 – Grass	11.1	12.7

data support the mixing model results which indicate sub-watersheds 3, 7, and 15 are contributing most of the suspended sediment at Flume 1, and suggest a strong relationship between stable carbon isotope composition, land cover, and soil erosion.

## 4. Conclusions

Both sediment budget and sediment source analyses indicate that shrub-dominated ecosystems are providing more suspended sediment at the Walnut Gulch Experimental Watershed than the grass-dominated ecosystems. Sediment budgets and sediment source analyses using fallout  $^{137}\text{Cs}$  provided useful data for understanding soil redistribution patterns and sediment sources areas to estimate which portions of the semiarid rangeland watershed are producing the suspended sediment loads in the stream. The sediment budget studies indicate that significant soil redistribution is occurring within the watershed before soil particles reach the watershed outlet, thus sediment yields measured at the outlet of a watershed may be a poor indicator of magnitude of actual soil redistribution occurring within a watershed.

Sediment source studies indicated that most of the suspended sediment measured at the outlet of the watershed were from shrub-dominated subwatersheds. Expanding our sampling areas to include more eroding surfaces (i.e., streambanks, gully faces, etc.) as well as sheet erosion sites would allow inferences to be made about the relative contribution of streambank versus gully versus sheet erosion contributions from the subwatersheds. The ability to identify primary sediment sources in watersheds contributes to a more efficient implementation of management practices to reduce suspended sediment and chemicals load from watersheds. Our studies suggest that management of these semiarid rangelands must consider techniques that will protect grass-dominated areas from shrub invasion to maintain or improve rangeland conditions.

## References

- Boardman, J., Poesen, J. (Eds.), 2007. Soil Erosion in Europe. John Wiley and Sons, Chichester, UK, 878 p.
- Bonniwell, E.G., Matisoff, G., Whiting, P.J., 1999. Determining the times and distances of particle transit in a mountain stream using fallout radionuclides. *Geomorphol* 27, 75–92.
- Cambay, R.S., Playford, K., Lewis, G.N.J., Carpenter, R.C., 1989. Radioactive fallout in air and rain: results to the end of 1988. AERE-R-13575. U.K. Atomic Energy Authority Report, Harwell, UK, 26 p.
- Carter, M.W., Moghissi, A.A., 1977. Three decades of nuclear testing. *Health Phys.* 33, 55–71.
- Cremers, A., Elsen, A., De Preter, P., Maes, A., 1988. Quantitative analysis of radio-caesium retention in soils. *Nature* 335, 247–249.
- de Soyza, A.G., Van Zee, J.W., Whitford, W.G., Neale, A., Tallent-Hallsel, N., Herrick, J.E., Havstad, K.M., 2000. Indicators of Great Basin rangeland health. *J. Arid Environ.* 45, 289–304.
- Gelderman, F.W., 1970. Soil survey: Walnut Gulch Experimental Watershed, Arizona. USDA-SCS Special Report. U.S. Government Printing Office, Washington, DC, USA, 62 p.
- Havstad, K.M., Huenneke, L.F., Schlesinger, W.H. (Eds.), 2006. Structure and Function of a Chihuahuan Desert Ecosystem: The Jornada Basin Long-Term Ecological Research Site. Oxford Press Inc., New York, NY, p. 492.
- Herrick, J.E., Whitford, W.G., 1995. Assessing the quality of rangeland soils: challenges and opportunities. *J. Soil Water Conserv.* 50, 237–242.
- Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V., 1998. The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Ann Arbor Press, Chelsea, Michigan, USA, 128 p.
- Mabit, L., Benmansour, M., Walling, D.E., 2008. Comparative advantages and limitations of the fallout radionuclides  $^{137}\text{Cs}$ ,  $^{210}\text{Pb}$  and  $^7\text{Be}$  for assessing soil erosion and sedimentation. *J. Environ. Radioact.* 99, 1799–1807.
- McCarty, G.W., Ritchie, J.C., 2002. Impact of soil movement on carbon sequestration in agricultural ecosystems. *Environ. Pollut.* 116, 423–430.
- National Research Council, 1994. Rangeland Health: New Methods to Classify, Inventory, and Monitor Rangeland. National Academy Press, Washington, DC, USA, 182 p.
- Nearing, M.A., Kimoto, A., Nichols, M.H., Ritchie, J.C., 2005. Spatial patterns of soil erosion and deposition in two small, semiarid watersheds. *J. Geophys. Res.* 110, F04020. doi:10.1029/2005JF000290.

- Nearing, M.A., Simanton, J.R., Norton, L.D., Bulygin, S.Y., Stone, J., 1999. Soil erosion by surface water flow on a stony, semiarid hillslope. *Earth Surf. Process. Landforms* 24, 677–686.
- Nichols, M.H., Renard, K.G., Osborn, H.B., 2002. Precipitation changes from 1956 to 1996 on the Walnut Gulch Experimental Watershed. *J. Am. Water Resour. Assoc.* 38, 161–172.
- Osborn, H.B., Simanton, J.R., 1983. Runoff estimates for thunderstorm rainfall on small rangeland watersheds. *Hydrol. Water Resour. Arizona Southwest* 13, 9–15.
- Pimentel, D., 2006. Soil erosion: a food and environmental threat. *Environ. Develop. Sustainability* 8, 119–137.
- Pimentel, D.P., Harvey, C., Resosudarmo, K., Sinclair, K., Kurz, D., McNair, S., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., Blair, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267, 1117–1123.
- Playford, K., Toole, J., Idsley, I., 1993. Radioactive Fallout in Air and Rain: Results to the End of 1991. AEA-EE-0498. United Kingdom Atomic Energy Authority, Harwell, UK, 30 pp.
- Poesen, J., De Luna, E., Franca, A., Nachtergaele, J., Govers, G., 1999. Concentrated flow erosion rates as affected by rock fragment cover and initial soil moisture content. *Catena* 36, 315–329.
- Renard, K.G., Lane, L.L., Simanton, J.R., Emmerich, W.E., Stone, J.J., Weltz, M.A., Goodrich, D.C., Yakowitz, D.S., 1993. Agricultural impacts in an arid environment: Walnut Gulch studies. *Hydrol. Sci. Technol.* 9, 145–190.
- Rhoton, F.E., Emmerich, W.E., Goodrich, D.C., Miller, S.N., McChesney, D.S., 2006. Soil geomorphological characteristics of a semiarid watershed: influence of carbon distribution and transport. *Soil Sci. Soc. Am. J.* 70, 1532–1540.
- Rhoton, F.E., Emmerich, W.E., DiCarlo, D.A., McChesney, D.S., Nearing, M.A., Ritchie, J.C., 2008. Identification of suspended sediment sources using soil characteristics in a semiarid watershed. *Soil Sci. Soc. Am. J.* 72, 1102–1112.
- Ritchie, J.C., 2000. Combining <sup>137</sup>Cesium and topographic surveys for measuring soil erosion/deposition patterns in a rapidly accreting area. *Acta Geol. Hisp.* 35, 207–212.
- Ritchie, J.C., Herrick, J.E., Ritchie, C.A., 2003. Variability in soil redistribution in the northern Chihuahuan desert based on <sup>137</sup>Cesium measurements. *J. Arid Environ.* 55, 737–746.
- Ritchie, J.C., McCarty, G.W., 2003. Using <sup>137</sup>Cesium to understand soil carbon redistribution on agricultural watersheds. *Soil Tillage Res.* 69, 45–51.
- Ritchie, J.C., McCarty, G.W., Venteris, E.R., Kaspar, T.C., 2007. Soil and soil organic carbon redistribution on the landscape. *Geomorphol.* 89, 163–171.
- Ritchie, J.C., McHenry, J.R., 1990. Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. *J. Environ. Qual.* 19, 215–233.
- Ritchie, J.C., Nearing, M.A., Nichols, M.H., Ritchie, C.A., 2005. Patterns of soil erosion and redeposition on Lucky Hills Watershed, Walnut Gulch Experimental Watershed, Arizona. *Catena* 61, 122–130.
- Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., Whitford, W.G., 1990. Biological feedbacks in global desertification. *Science* 247, 1043–1048.
- Simanton, J.R., Toy, T.J., 1994. The relation between surface rock-fragment cover and semiarid hillslope profile morphology. *Catena* 23, 213–225.
- Simanton, J.R., Renard, K.G., Christiansen, C.M., Lane, L.J., 1994. Spatial distribution of surface rock fragments along catenas in semiarid Arizona and Nevada, USA. *Catena* 23, 29–42.
- Slattery, M.C., Hurt, T.P., Walden, J., 1995. The application of mineral magnetic measurements to quantify within-storm variations in suspended sediment sources. *Internat. Assoc. Hydrol. Sci. Publ. No. 229*, 143–151.
- Smith, H.G., Dragovich, D., 2008. Improving precision in sediment source and erosion process distinction in an upland catchment, south-eastern Australia. *Catena* 72, 191–203.
- Sutherland, R.A., 1996. Caesium-137 soil sampling and inventory variability in reference samples: literature survey. *Hydrol. Process.* 10, 34–54.
- Sutherland, R.A., Bryan, R.B., 1989. Variability of particle size characteristic of sheetwash sediments and fluvial suspended sediment in a small semiarid catchment, Kenya. *Catena* 16, 189–204.
- Tongway, D.J., Sparrow, A.D., Friedel, M.H., 2003. Degradation and recovery processes in arid grazing lands in central Australia. Part 1: Soil and land resources. *J. Arid Environ.* 55, 310–326.
- USDA-Natural Resources Conservation Service, 1996. Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No.42. U.S. Government Printing Office, Washington, DC, USA, 700 p.
- Van Oost, K., Quine, T.A., Govers, G., De Gryze, S., Six, J., Harden, J.W., Ritchie, J.C., McCarty, G.W., Heckrath, G., Kosmas, K., Giraldez, J.V., Marques da Silva, J.R., Merckx, R., 2007. The impact of agricultural soil erosion on the global carbon cycle. *Science* 318, 626–629.
- Verity, G.E., Anderson, D.W., 1990. Soil erosion effects on soil quality and yield. *Can. J. Soil Sci.* 70, 471–481.
- Wallbrink, P.J., Murray, A.S., Olley, J.M., 1999. Relating suspended sediment to its original soil depth using fallout radionuclides. *Soil Sci. Soc. Am. J.* 63, 369–378.
- Wallbrink, P.J., Olley, J.M., Murray, A.S., 1994. Measuring soil movement using <sup>137</sup>Cs: implications of reference site variability. *Internat. Assoc. Hydrol. Sci. Publ. No. 224*, 95–105.
- Walling, D.E., 2005. Tracing suspended sediment sources in catchments and river systems. *Sci. Total Environ.* 334, 159–184.
- Walling, D.E., 2003. Using environmental radionuclides as tracers in sediment budget investigations. *Internat. Assoc. Hydrol. Sci. Publ. No. 283*, 57–78.
- Walling, D.E., He, Q., 2001. Model for converting <sup>137</sup>Cs measurements to estimates of soil redistribution on cultivated and uncultivated soils, and estimating bomb-derived <sup>137</sup>Cs reference inventory (Including Software for Model Implementation). A contribution to the International Atomic Energy Agency Coordinated Research Programmes on Soil Erosion (D1.50.05) and Sedimentation (F3.10.01), Department of Geography, Exeter, UK, 29 p.
- Walling, D.E., He, Q., 1999. Improved models for estimating soil erosion rates from cesium-137 measurements. *J. Environ. Qual.* 28, 611–622.
- Walling, D.E., Woodward, J.C., 1992. Use of radiometric fingerprints to derive information on suspended sediment source. *Internat. Assoc. Hydrol. Sci. Publ. No. 210*, 153–164.
- Weltz, M.A., Ritchie, J.C., Fox, H.D., 1994. Comparison of laser and field measurements of vegetation heights and canopy cover. *Water Resour. Res.* 30, 1311–1319.
- Whitford, W.G., de Soyza, A.G., Van Zee, J.W., Herrick, J.E., Havstad, K.M., 1998. Vegetation, soil, and animal indicators of rangeland health. *Environ. Monit. Assess.* 51, 179–200.
- Zapata, F. (Ed.), 2002. Handbook for the Assessment of Soil Erosion and Sedimentation Using Environmental Radionuclides. Kluwer Academic Publishers, Dordrecht, The Netherlands, 221 p.