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Soil Geomorphological Characteristics of a Semiarid Watershed: Influence on Carbon Distribution and Transport

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ABSTRACT

In the marginally productive rangelands of the semiarid, southwestern USA, the maintenance of organic C (OC) is essential to the stability of the ecosystem. This study was conducted to identify landscape factors responsible for the distribution of OC in watershed soils, its loss from upland areas and subsequent transport within the stream system of a large semiarid watershed (Walnut Gulch Experimental Watershed [WGEW], Tombstone, AZ). Samples were collected along transects from the surface 5 cm of each major soil mapping unit in six subwatersheds (SW). Data were recorded for slope class, landscape position, and aspect at each of the 435 sampling points. Soil analyses consisted of: total C and OC, particle-size distribution, water dispersible clay, pH, quantitative color, and aggregation index (AI). Sediment samples were collected from flumes at each SW outlet. These 169 bedload and 59 suspended sediment samples were analyzed identically to the soils. Soil data indicated that OC distributions in the SWs were related to parent material with significantly ($p \leq 0.05$) greater contents recorded on the steeper slopes (>9%), and backslope and toeslope positions. Fewer significant correlations were identified for aspect. Soil OC was significantly ($p \leq 0.01$) correlated with silt and clay contents. Organic C contents of the soils and suspended sediments averaged 11.4 and 24.0 g kg^{-1}, respectively, giving an enrichment ratio (ER) for OC in the suspended sediments of 2.13. Bedload sediment was depleted in OC by an average ratio of 0.65 relative to the soils. The results suggest that OC is transported through this watershed predominantly as silt- and clay-size materials in concentrations controlled by the soil AI.

The sustainability of productive rangelands necessarily involves the management of soil erosion and soil OC movement at both field and watershed levels (Whitford et al., 1998; Ritchie and McCarty, 2003). One measure of the stability of semiarid, native rangeland systems is the loss or redistribution of OC and nutrients from a site (Ritchie et al., 2005). Soil C contents vary as a function of soil phase, topography, and land-use (Garten and Ashwood, 2002). Consequently, the distribution of these soil–landscape components must be determined for a comprehensive understanding of ecosystems. The importance of the soil organic matter (SOM) fraction to an ecosystem is its impact on soil behavior. Specifically, this soil fraction is essential to soil fertility through its influence on nutrient cycling and retention, and in the development and maintenance of soil structure (Swift, 2001). From this perspective, the importance of SOM is manifested in the decline of plant nutrient status and soil structure that follow SOM losses and eventually lead to soil erosion losses and degradation (Spain et al., 1983).

Carbon distribution in the landscape is related to several soil properties that are influenced by slope factors. Clay fractions contribute to the retention of C in soils (Monreal et al., 1981), and since clay-sized materials are selectively distributed along hillslopes, clay content and mineralogy gradients can produce differences in nutrient distribution between hillslope positions (Schimel et al., 1985). Considerable research has been conducted to define relationships between topographic parameters and soil properties (Gregorich et al., 1998). Some of the findings indicate OC is correlated with slope gradient and distance from summit positions (Walker and Ruhe, 1968; Kleiss, 1970). In terms of slope position, Norton et al. (2003) indicated that total C concentrations were greatest on backslopes and lowest on summits and toeslopes due to localized accumulations of nutrients from surface runon contributions, whose concentrations gradually decreased downslope. Other researchers (Gregorich and Anderson, 1985) found lower concentrations of SOM in the upper slope positions where erosion was at a maximum, with greater concentrations occurring in depositional areas on lower slope positions. Woods and Schuman (1988) concluded that active SOM concentrations differed less between slope positions than between land-uses or soils. Franzmeier et al. (1969) reported that greater SOM concentrations were found on slopes with north-facing aspects.

Biedenbender et al. (2004) used soil C isotope methodology to trace changes in vegetation as a function of landscape position on the WGEW. Their findings indicated that in the last several decades, grasses on the mid-backslope and summit positions had been replaced by desert shrub vegetation. Additionally, other studies on this watershed (Abrahams et al., 1995) have indicated that the replacement of grassland by shrub vegetation has resulted in decreases in SOM and increased runoff and erosion due to lower infiltration and soil resistance to overland flow.

Soil erosion and organic matter losses are often so closely related that erosion represents the greatest loss of OC from soil surfaces (McCarty and Ritchie, 2002). Harden et al. (1999) attributed 80% of the OC loss on a cultivated site in Mississippi to erosion. Apparently, only small soil losses can result in significant losses of the biologically active SOM fraction most critical to aggregate stabilization that occurs near the soil surface (Gregorich et al., 1998). This fraction is then redistributed on the landscape by water erosion processes through pref-

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Abbreviations: AI, aggregation index; ER, enrichment ratio; OC, organic carbon; SOM, soil organic matter; SWs, subwatersheds; WDC, water dispersible clay.

erential transport of finely divided, less dense OC particles to downslope positions.

The WGEW in southeastern Arizona contains a wide variety of parent materials, soils, vegetation, and a strongly sloping landscape that is occasionally exposed to intense, erosive thunderstorms between July and September. The objectives of the current research were to: (1) assess the distribution of OC as a function of slope factors (i.e., aspect, class, landscape position) in selected SWs; (2) determine the relationship between C distribution and other watershed soil properties; (3) assess C losses from the system; and (4) relate these losses to watershed soil erodibility.

MATERIALS AND METHODS

Watershed Characteristics

The research was conducted on six (3, 7, 9, 10, 11, 15) SWs (Fig. 1) in the 150 km^2 WGEW in southeastern Arizona at Tombstone (31°43′ N. Lat., 110°41′ W. Long.). The watershed is an alluvial basin component of the larger San Pedro River Watershed which lies along a transition zone between the Sonoran and Chihuahuan Deserts (Renard et al., 1993) with elevations ranging from 220 to 1890 m. The mean annual temperature in the watershed is 17.6°C, and the average annual precipitation is 324 mm, which occurs primarily as thunderstorms from July to mid-September (Osborn et al., 1979). The soils were formed predominantly on alluvium composed of Cenozoic age clastic clays and silts. Smaller areas of limestone, basalt, granite, granodiorite, and andesite parent materials occur throughout the watershed. Generally, the soils are well-drained, calcareous, gravelly loams containing large percentages of rocks and gravels at the surface (Breckenfeld et al., 1995). Major vegetation in the watershed includes the shrub species of creosote bush (*Larrea tridentata*), whitethorn (*Acacia* constricta), tarbush (*Flourensia cernua*), snakeweed (*Gutierrezia sarothrae*), and burroweed (*Aplopappus tenuisectus*); and the grass species of black grama (*Bouteloua eriopoda*), blue grama (*Bouteloua gracilis*), sideoats grama (*Bouteloua curtipendula*), and bush muhly (*Muhlenbergia porteri*) (Simanton et al., 1994). Land-use for the entire watershed was rangeland.

Sample Collection

Soil samples were collected for each SW on the basis of relative area occupied by individual soil mapping units as delineated by Breckenfeld et al. (1995) at a scale of 1:5000. This was accomplished by superimposing digitized soil surveys on digital elevation models (DEM) for each SW. Sampling transects of 1000 m were assigned for each 200 ha in a mapping unit, irrespective of its composition. Each transect was delineated on the DEM for each SW, under laboratory conditions. The beginning and ending coordinates of the transects were selected to include as many individual surface morphometry factors (landscape position, slope class, aspect) as possible, based on the definitions of Schoeneberger et al. (2002). These coordinates were entered in a GPS unit used to locate sampling transects in the field. Generally, individual sample collection was dictated by a change in a surface morphometry factor along the transect. An example of this approach with delineated transects and sampling points is shown for SW 15 (Fig. 2). At each sampling location, the surface 5 cm were sampled, in bulk, at three points approximately 10 m apart, perpendicular to the slope. These three individual samples were composited to form a single bulk sample, sieved to <4 mm to reduce sample volume, sealed in a plastic bag, and transported to the laboratory. At each of these sampling locations, data were recorded for latitude-longitude, landscape position, slope class, and aspect.

Each SW was instrumented with a supercritical flume installed near its mouth (Renard et al., 1993) for the collection of sediment samples. Inlet drop boxes with slotted metal plate covers, installed in the floor of the concrete flumes, were used to collect bedload samples during flow events. Bedload is

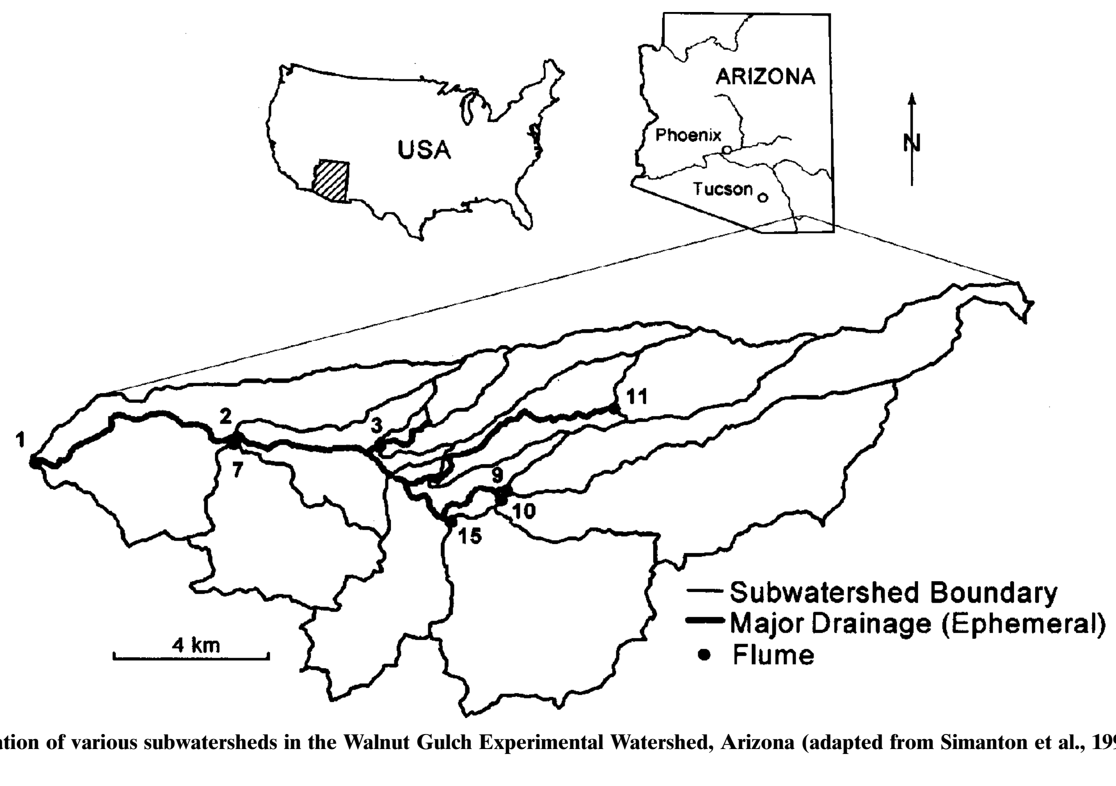

Fig. 1. Location of various subwatersheds in the Walnut Gulch Experimental Watershed, Arizona (adapted from Simanton et al., 1994).

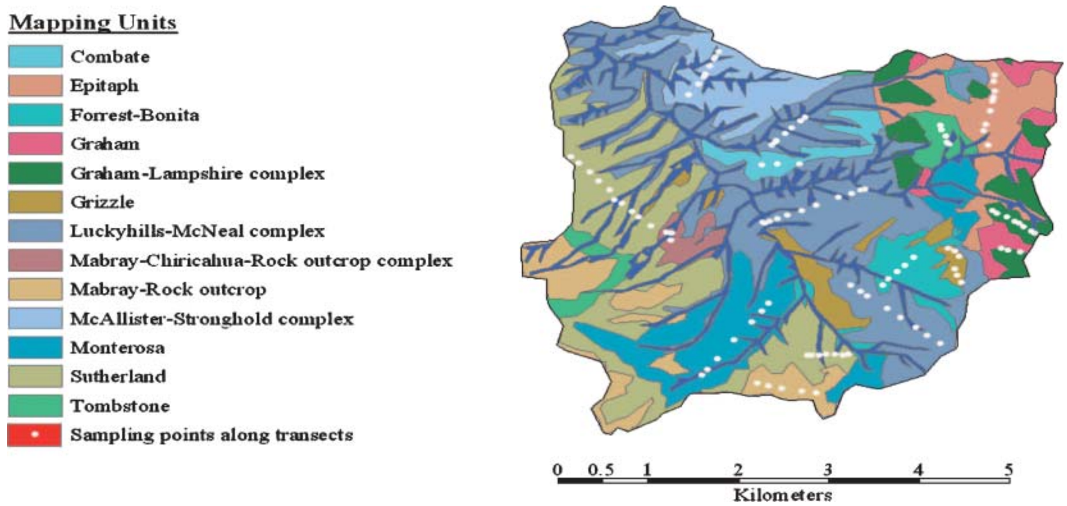

Fig. 2. Watershed soil sampling approach based on relative area of the mapping units, showing sampling points along transects in subwatershed 15.

generally assumed to be equivalent to one-third of the total flow depth, and in this case is defined as that fraction of the bedload washed through the 6.4-mm wide slots in the metal plates mentioned above. Vertical samplers constructed of Al cylinders (10.2 cm i.d. by 137.2 cm in length) mounted on the face of the flumes immediately below the drop boxes were used to collect suspended sediments. These samplers collected sediment through 6.4-mm ports drilled into the Al cylinders in increments of 30.5 cm above the floor of the flume, up to a total flow depth of 122 cm. The ports were connected by plastic tubing to 500-mL plastic sample bottles mounted inside the sealed vertical sampler. An additional 2-L sample bottle was installed at the 30.5-cm flow depth to ensure that adequate sample volumes were obtained for low flow events. Each sample bottle was fitted with a small laboratory-designed float valve inside the lid consisting of plastic tubing connectors containing a free floating plastic bead. As designed, this valve cut off flow and sealed the bottles once they were filled. This prevented continuous flow through the bottles, and allowed for a more accurate estimate of sediment concentrations for a given flow event. All samples were composited to obtain a single sample per flow event by SW occurring between 1999 and 2003. For purposes of this study, the bedload and suspended sediment data were averaged individually at each of the SWs for these 5 yr.

Laboratory Analyses

In the laboratory, soil samples were air-dried. All sediment samples were oven-dried at 70°C. Upon drying, both were sieved to <2 mm. Particle-size distribution of all samples was determined after overnight dispersion in Na hexametaphosphate using standard pipette analysis (Soil Survey Staff, 1984). The water dispersible clay (WDC) content of the total soil clay fraction was also determined by the same pipette method using distilled water as the dispersant. Soil pH was measured in a 1:1 soil/distilled water (w/v) suspension (McLean, 1982). Total C was measured by combusting 0.5-g samples in a LECO CN–2000 carbon-nitrogen analyzer (LECO Corp., St. Joseph, MI). The inorganic fraction of the total C was quantified by treating a separate 1-g sample with 5 *M* HC1 in a sealed decomposition vessel (200 mL) fitted with a rubber septum. Carbon dioxide pressure generated by the acid-decomposition of the sample was measured with a Tensimeter (Soil Measurement Systems, Tucson, AZ) probe inserted through the septum. Pressure readings were converted to C contents using a standard curve, and subtracted from total C to give the OC content. Quantitative soil color was measured with a Minolta Chroma Meter (Minolta Corp., Ramsey, NJ).

The total clay and WDC content data were used to calculate an AI, which is a measure of soil erodibility based on the method of Harris (1971) as follows:

$$\text{AI} = 100\ (1 - \text{WDC/total clay}).$$

All statistical analysis utilized the GLM and CORR procedures of SAS version 8 (SAS Institute, 1999).

RESULTS AND DISCUSSION

Characteristics of Watershed Soils

The taxonomic classification and distribution of the soil mapping units within the WGEW (Breckenfeld et al., 1995) are shown in Tables 1 and 2. The most extensive mapping unit in the watershed is the Luckyhills-McNeal complex, very gravelly sandy loam, which occupies approximately 4300 ha on a whole watershed basis. Other mapping units comprising substantial acreages are the Elgin-Stronghold complex, very gravelly fine sandy loam (1509 ha), McAllister-Stronghold complex, gravelly fine sandy loam (1363 ha), and Tombstone extremely gravelly sandy loam (1280 ha).

Selected soil physical and chemical properties of the six SWs used in the study are shown in Table 3. As previously indicated, these samples were collected at a depth of 0 to 5 cm irrespective of surface horizon thickness. In most cases, however, A-horizon thickness corresponds to our sampling depth according to the field descriptions of Breckenfeld et al. (1995). This sampling depth was assumed to be most affected by erosion processes involving rill formation and infilling. Thus, these data potentially include contributions from both A- and upper B-horizons in various proportions. The data indicate some soil properties reflect the influence of different parent materials between SWs. The greatest differences are between SWs 3 and 7, and the other SWs in terms of total clay, OC, AI, and hue. A large portion of the soils in SW 7 were formed on igneous residuum (i.e., granite, granodiorite) compared with limestone, andesite, and basalt

Table 1. Mapping units in the Walnut Gulch Experimental Watershed with taxonomic classifications.

Soil phase	Taxonomic classification
Baboquivari gravelly coarse sandy loam	Fine-loamy, mixed, superactive, thermic Ustic Haplargids
Bernardino gravelly clay loam	Fine, mixed, superactive, thermic Ustic Calciargids
Blacktail gravelly sandy loam	Fine, mixed, superactive, thermic Calcidic Argiustolls
Bodecker extremely gravelly sandy loam	Sandy-skeletal, mixed, thermic Ustic Torriorthents
Bonita cobbly silty clay	Fine, smectitic, thermic Typic Haplotorrerts
Budlamp very gravelly fine sandy loam	Loamy-skeletal, mixed, superactive thermic Lithic Haplustolls
Chiricahua very cobbly loam	Clayey, mixed, superactive, thermic, shallow Ustic Haplargids
Combate gravelly loamy coarse sand	Coarse-loamy, mixed, superactive non-acid, thermic Ustic Torrifluvents
Elgin very gravelly fine sandy loam	Fine, mixed, superactive thermic Calcic Paleargids
Epitaph very cobbly clay loam	Fine, smectitic, thermic Petrocalcic Calcitorrerts
Forrest loam	Fine, mixed, superactive, thermic Ustic Calciargids
Graham cobbly clay loam	Clayey, smectitic, thermic Lithic Ustic Haplargids
Grizzle coarse sandy loam	Fine loamy, mixed, superactive, thermic Ustic Calciargids
Lampshire very cobbly loam	Loamy-skeletal, mixed, superactive, non-acid, thermic Lithic Ustic Torriorthents
Luckyhills very gravelly sandy loam	Coarse-loamy, mixed, superactive thermic Ustic Haplocalcids
McAllister loam	Fine-loamy, mixed, superactive thermic Ustic Calciargids
McNeal gravelly sandy loam	Fine-loamy, mixed, superactive thermic Ustic Calciargids
Mabray very gravelly loam	Loamy-skeletal, carbonatic, thermic Lithic Ustic Torriorthents
Monterosa very gravelly sandy loam	Loamy-skeletal, mixed, superactive, thermic, shallow Ustic Petrocalcids
Mule very gravelly fine sandy loam	Loamy-skeletal, carbonatic, thermic Ustic Haplocalcids
Schiefflin very stony loamy sand	Mixed, thermic Lithic Torripsamments
Stronghold gravelly fine sandy loam	Coarse-loamy, mixed, superactive thermic Ustic Haplocalcids
Sutherland gravelly fine sandy loam	Loamy-skeletal, carbonatic, thermic, shallow Calcic Petrocalcids
Tombstone extremely gravelly fine sandy loam	Loamy-skeletal, mixed, superactive thermic Ustic Haplocalcids
Woodcutter very gravelly fine sandy loam	Loamy-skeletal, mixed, superactive thermic Lithic Argiustolls

parent materials in the other SWs. This accounts for SW 7 soils having less clay and OC, and a lower AI. The higher Munsell notations in SW 7 are related to the lighter colored, high quartz content, granitic rocks, and lower OC contents. The calcareous alluvium parent materials in SW 3 contributed to similar soil conditions in terms of Munsell notations, a high pH, and low values for OC and AI. By contrast, SW 9 contained substantial acreages of soils formed from fine-grained igneous parent materials (i.e., andesite, basalt) which, on weathering, form soils with finer particle sizes. In fact, the soils in SW 9 had the highest total clay contents and AI, and relatively low average hue and value readings.

Based on the above discussion, it is obvious that the distribution of soil C in the WGEW is closely related to differences in parent material and degree of erosion among SWs. The lowest OC contents occurred on SW 7 where soils developed on coarse-textured igneous residuum (granite, granodiorite) that is resistant to weathering processes under the climatic regimes of southeast Arizona. Consequently, these soils were less well-developed with coarse-textured, droughty profiles that support only a limited number of plant species and growth. Soils in SW 3, containing only slightly higher OC contents, were formed on limestone alluvium and subsequently denuded of their native vegetation in post-settlement

Table 2. The extent of various soil mapping units for the subwatersheds studied in the Walnut Gulch Experimental Watershed.

	Subwatershed					
Soil Phase	WS 3	WS 7	WS 9	WS 10	WS 11	WS 15
	ha					
Baboquivari-Combate complex		19.5	188.7	190.1	6.7	
Blacktail gravelly sandy loam				245.5		
Budlamp-Woodcutter complex				64.6		
Chiricahua very gravelly clay loam		101.3				
Combate loamy sand	3.0	8.2				60.0
Elgin-Stronghold complex	120.2		881.7	283.7	75.3	
Epitaph very cobbly loam			71.9	18.1		152.7
Forrest-Bonita complex			12.6	18.7		103.2
Graham cobbly clay loam			175.7	13.8		66.8
Graham-Lampshire complex			122.1	9.1		113.4
Grizzle coarse sandy loam						81.6
Lampshire-Rock outcrop complex		28.4	52.5			
Luckyhills loamy sand		14.0	7.0			
Luckyhills-McNeal complex	443.4	286.8	44.6	1.1		740.1
Mabray-Chiricahua-Rock outcrop		295.8				36.3
Mabray-Rock outcrop complex		193.4				150.7
McAllister-Stronghold complex	273.0		317.4	229.3	61.4	144.8
Monterosa very gravelly fine sandy	12.7	15.6				248.6
Riverwash-Bodecker complex		8.1		12.6		
Schiefflin very stony loamy sand		190.2				
Stronghold-Bernadino complex	94.9		38.6	178.8	421.1	
Sutherland-Mule complex		65.7				
Sutherland very gravelly fine sandy		141.2				403.9
Tombstone very gravelly fine sandy			486.3	252.0	223.6	73.4
Woodcutter gravelly sandy loam				61.9		
Totals	947.2	1368.1	2398.9	1579.4	788.2	2375.6

Table 3. Selected soil physical and chemical properties of the surface 5 cm averaged for individual subwatersheds.

Subwatershed	n	Particle-size distribution: Sand	Particle-size distribution: Silt	Particle-size distribution: Clay	Water dispersible clay	Aggregation index	Carbon content: Total	Carbon content: Organic	pH	Munsell color: Hue	Munsell color: Value	Munsell color: Chroma
		g kg^{-1}					g kg^{-1}					
3	59	720	148	133	108	18.0†	23.2	10.2	8.6	7.1‡	3.1	2.0
7	49	719	162	118	91	22.8	18.6	8.5	7.9	8.2	3.2	2.0
9	114	653	184	163	111	31.9	19.3	12.1	7.4	6.5	2.9	1.7
10	74	698	142	160	116	28.1	16.4	11.5	6.9	6.4	3.0	1.8
11	47	731	136	134	102	23.9	26.8	11.8	8.5	6.8	3.1	1.5
15	92	608	251	118	98	28.2	29.2	14.2	7.9	6.9	3.1	1.8
Mean		688	171	134	104	25.5	22.3	11.4	7.9	7.0	3.1	1.8

† Aggregation index is equivalent to: 100 (1 − WDC/total clay).
‡ All hues are YR (yellow red).

times resulting in excessive erosion losses and depleted OC reserves. Conversely, the fine-textured, igneous parent rocks (i.e., andesite and basalt) in SW 15 produced soils with higher clay and plant nutrient contents, and a greater water holding capacity which translated into greater OC contents.

When the soil C data were evaluated as a function of slope class (Table 4), maximum OC concentrations were generally observed on the steeper slopes. Specifically, the OC fractions were most concentrated on either D (9–12%), E (13–20%), or F (>20%) slopes. In many cases, the concentrations on these steeper slopes were significantly ($p \leq 0.05$) greater than the other slope classes. The particle-size data (Table 4) indicate that the clay fraction is generally distributed in a manner similar to OC, with the higher contents found on the E and F class slopes. Additionally, the greater AI values were recorded on these slopes, indicating maximum aggregate stability and the least erodible soils.

This seemingly contradictory finding of greater OC contents on steeper slopes may be explained by the distribution of soils as a function of parent material and slope. Specifically, the greater OC contents occurring on the D, E, and F slope classes is related to the fact that the Graham, Graham-Lampshire, and Epitaph soils were mapped on the strongly sloping landscapes. These soils, which were weathered from andesite and basaltic parent

Table 4. Distribution of C and related soil properties by slope class.

Subwatershed	Slope class†	Total C	Organic C	Particle-size distribution: Sand	Particle-size distribution: Silt	Particle-size distribution: Clay	AI
		g kg^{-1}					
3	A	32.1 a‡	14.3 a	621 b	240 a	139 b	21.0 a
	B	18.1 c	9.2 b	722 a	148 b	129 b	16.9 b
	C	23.6 bc	9.5 b	743 a	132 b	124 b	17.1 b
	D	22.5 bc	10.1 b	744 a	127 b	129 b	17.6 b
	E	27.5 ab	14.7 a	692 a	144 b	165 a	20.9 a
	F	–	–	–	–	–	–
7	A	17.5 bc	3.8 d	763 a	149 bc	88 ac	23.3 a
	B	14.8 bc	5.9 cd	724 ab	166 abc	110 abc	22.0 a
	C	10.2 c	4.0 d	769 a	128 c	103 c	22.3 a
	D	21.5 ab	8.9 c	733 ab	141 c	126 c	20.4 a
	E	26.5 a	12.8 b	689 bc	183 ab	128 ab	23.7 a
	F	21.5 ab	17.3 a	644 c	199 a	157 a	27.1 a
9	A	13.7 c	9.4 c	629 a	215 b	156 ab	32.0 b
	B	20.3 ab	10.8 c	698 a	158 c	144 b	29.9 b
	C	15.7 bc	11.0 c	642 a	175 bc	183 a	31.3 b
	D	22.0 a	12.3 c	666 a	168 bc	166 ab	30.2 b
	E	23.0 a	16.5 b	659 a	167 bc	174 ab	34.0 b
	F	25.4 a	21.8 a	488 b	323 a	189 a	46.6 a
10	A	10.4 c	8.6 c	678 a	155 ab	167 ab	30.2 a
	B	16.1 bc	9.7 c	695 a	168 a	137 b	30.0 a
	C	15.2 bc	10.9 bc	748 a	120 c	132 b	25.9 a
	D	25.4 a	13.8 ab	708 a	136 bc	156 ab	26.2 a
	E	20.0 ab	14.7 a	680 a	134 bc	187 a	26.0 a
	F	13.9 bc	13.2 ab	746 a	121 c	132 b	32.0 a
11	A	18.5 d	8.1 c	701 c	165 a	134 ab	18.4 c
	B	20.3 cd	8.8 c	707 bc	150 a	143 a	20.2 bc
	C	32.0 ab	13.2 ab	718 bc	163 a	119 b	24.9 ab
	D	37.4 a	15.1 a	723 abc	150 a	126 ab	26.0 a
	E	26.2 bc	12.1 b	757 a	111 b	132 ab	24.7 ab
	F	28.2 b	13.3 ab	745 ab	111 b	143 a	28.9 a
15	A	25.5 a	14.5 bc	561 bc	285 ab	154 c	28.7 bc
	B	30.6 a	11.4 c	648 bc	230 b	121 c	25.2 c
	C	30.8 a	10.9 c	660 a	209 b	131 c	24.3 c
	D	29.0 a	17.2 b	600 ab	256 ab	143 c	34.1 ab
	E	29.5 a	25.5 a	491 c	318 a	191 b	38.7 a
	F	23.6 a	23.1 a	496 c	276 ab	299 a	36.5 a

† A, 0-2%; B, 3-5%; C, 6-8%; D, 9-12%; E, 13-20%; F, >20%.
‡ Values followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's new multiple range test.

Table 5. Distribution of C and related soil properties by slope position.

Subwatershed	Slope class†	Total C	Organic C	Particle size distribution: Sand	Particle size distribution: Silt	Particle size distribution: Clay	AI
		g kg^{-1}					
3	SU	25.7 ab‡	11.8 b	700 a	165 b	125 b	19.9 ab
	SH	12.7 b	5.2 b	774 a	116 b	111 b	19.6 ab
	BS	22.6 ab	10.0 b	737 a	131 b	131 b	17.5 ab
	FS	16.8 b	10.8 b	742 a	122 b	136 b	15.8 b
	TS	32.8 a	18.2 a	454 b	370 a	177 a	23.0 a
7	SU	15.1 a	1.7 ab	721 b	186 a	93 abc	16.2 c
	SH	15.1 a	7.5 ab	710 b	184 a	106 ab	17.2 c
	BS	20.0 a	9.6 a	705 b	167 a	128 a	22.7 bc
	FS	–	–	–	–	–	–
	TS	16.9 a	3.9 ab	854 a	80 b	66 bc	30.3 b
9	SU	17.5 bc	10.2 ab	645 a	194 a	162 a	32.3 a
	SH	24.6 a	11.7 ab	697 a	155 a	147 a	31.8 a
	BS	20.4 ab	13.4 a	633 a	193 a	175 a	32.4 a
	FS	11.6 cd	9.0 b	699 a	164 a	137 a	28.7 a
	TS	10.1 d	8.9 b	646 a	206 a	148 a	32.4 a
10	SU	14.6 abc	10.8 ab	670 a	146 a	184 a	28.2 ab
	SH	20.9 a	12.2 a	688 a	153 a	159 a	27.0 b
	BS	18.6 ab	12.7 a	707 a	133 a	160 a	26.6 b
	FS	12.4 bc	10.5 ab	677 a	163 a	160 a	31.8 ab
	TS	8.4 c	7.7 b	737 a	153 a	110 b	34.2 a
11	SU	24.9 a	12.1 a	712 a	161 a	128 a	24.5 a
	SH	–	–	–	–	–	–
	BS	29.3 a	12.5 a	741 a	127 a	132 a	25.2 a
	FS	23.3 a	10.6 ab	692 a	164 a	143 a	18.4 b
	TS	12.3 b	7.0 b	695 a	159 a	147 a	16.3 b
15	SU	32.3 a	18.6 a	533 a	327 a	139 a	35.1 a
	SH	28.8 a	17.2 a	601 a	250 a	150 a	33.5 ab
	BS	30.9 a	13.7 ab	622 a	244 a	135 a	26.3 b
	FS	19.1 b	10.1 b	601 a	245 a	154 a	27.8 ab
	TS	24.6 ab	18.5 a	539 a	292 a	169 a	30.1 ab

† SU, summit; SH, shoulder; BS, backslope; FS, footslope; TS, toeslope.
‡ Values followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's new multiple range test.

materials, had redder hues, and higher clay and basic cation contents, particularly K and Mg (individual soil data not shown). Thus, the assumed higher water holding capacity generally associated with higher clay contents coupled with the greater plant nutrient status resulted in the formation of more fertile soils that support a wider variety of grasses and higher levels of organic matter relative to the desert shrub vegetation dominating the other SWs, especially SW 3.

Slope position influences on C distributions in the WGEW (Table 5) are not as evident as slope class. There are no well-defined trends in the data. In two of the SWs (3, 15), OC was greatest on the two most stable landscape positions (summit, toeslope), but these concentrations were generally not significantly different from the other slope positions. In the other four SWs, OC was most concentrated on the backslope positions in all cases, but again there were few significant differences within a SW. Norton et al. (2003) also found the highest OC contents on the backslope positions, which was attributed to slope-wash processes. Similarly, Schimel et al. (1985) reported an increase in C downslope, but higher concentrations in A-horizons on summit positions, which contained the higher clay contents. The current data generally indicate that maximums for OC, clay content, and AI occur on the same landscape position. Apparently, high clay contents are conducive to the accumulation of OC. This is undoubtedly due to a number of interrelated factors. Specifically, the higher clay contents create a less erodible soil surface where OC accumulations, in combination with the clay, further enhances aggregate stability and soil resistance to runoff and erosion losses. Additionally, the higher clay content soils can contribute to increases in OC levels by reducing losses due to oxidation.

Organic C contents recorded as a function of slope aspect (Table 6) indicated that significantly ($p \leq 0.05$)

Table 6. Distribution of C and related soil properties by slope aspect.

				Particle-size distribution			
Subwatershed	Slope aspect†	Total C	Organic C	Sand	Silt	Clay	AI
		g kg^{-1}					
3	N	17.1 b‡	9.2 ab	740 ab	133 ab	126 a	17.2 a
	NE	–	–	–	–	–	–
	E	20.3 ab	9.0 ab	727 ab	135 ab	139 a	17.7 a
	SE	19.4 ab	6.5 b	753 ab	127 ab	121 a	15.3 a
	S	26.7 ab	11.5 ab	685 b	186 a	130 a	19.5 a
	SW	29.3 a	13.7 a	750 ab	123 ab	127 a	20.5 a
	W	23.0 ab	11.6 ab	723 ab	139 ab	138 a	16.6 a
	NW	17.8 b	11.8 ab	781 a	108 b	111 a	15.6 a
7	N	10.1 d	5.1 a	792 a	112 c	96 bc	13.8 c
	NE	15.5 cd	5.8 a	790 a	123 bc	87 c	30.7 a
	E	22.3 abcd	12.7 a	695 a	173 ab	132 ab	20.9 bc
	SE	30.3 a	11.5 a	651 b	215 a	134 ab	27.3 ab
	S	29.4 ab	6.2 a	677 b	218 a	105 abc	21.2 bc
	SW	23.2 abc	9.2 a	715 ab	166 abc	118 abc	21.9 abc
	W	17.1 bcd	11.3 a	669 b	185 a	145 a	24.6 ab
	NW	18.4 abcd	6.9 a	723 ab	164 abc	113 abc	22.2 abc
9	N	20.6 b	18.7 b	473 c	324 a	203 a	38.4 a
	NE	35.5 a	23.3 a	694 ab	145 cd	161 ab	37.5 a
	E	23.9 b	12.4 c	704 a	148 cd	148 b	30.2 bc
	SE	10.9 c	7.5 d	736 a	111 c	153 b	27.7 c
	S	20.3 b	9.7 cd	668 ab	184 bc	148 b	30.6 bc
	SW	19.9 b	11.4 c	680 ab	154 bcd	166 ab	30.4 bc
	W	23.9 b	13.2 c	732 a	129 cd	139 b	35.0 ab
	NW	16.4 bc	12.6 c	609 b	212 b	179 ab	32.1 abc
10	N	27.7 a	18.7 b	473 c	324 a	203 a	38.4 a
	NE	16.7 c	14.2 a	597 b	165 a	238 a	22.4 a
	E	19.4 bc	11.7 ab	711 a	130 a	160 bc	26.9 a
	SE	25.1 ab	14.6 a	690 a	134 a	175 bc	24.5 a
	S	12.8 c	9.8 ab	712 a	138 a	150 bc	27.9 a
	SW	11.8 c	8.8 b	749 a	132 a	119 bc	29.8 a
	W	13.0 c	10.6 ab	740 a	120 a	141 bc	29.0 a
	NW	14.7 c	12.3 ab	655 ab	163 a	183 ab	31.0 a
11	N	14.1 b	7.4 c	606 a	259 a	135 a	25.8 bc
	NE	23.0 ab	10.7 bc	607 a	267 a	126 a	24.7 bc
	E	28.8 a	14.0 ab	555 a	293 a	153 a	29.0 ab
	SE	30.2 a	11.0 abc	621 a	248 a	130 a	20.2 c
	S	22.1 ab	9.8 bc	575 a	279 a	146 a	28.5 ab
	SW	24.3 ab	10.8 bc	642 a	219 a	139 a	33.9 a
	W	27.5 a	14.0 ab	602 a	238 a	160 a	27.4 ab
	NW	33.7 a	15.6 a	620 a	251 a	130 a	29.2 ab
15	N	31.3 abc	12.1 ab	606 a	259 a	135 a	25.8 bc
	NE	35.4 ab	11.3 b	607 a	267 a	106 a	24.7 bc
	E	29.6 bc	12.8 ab	555 a	293 a	153 a	29.0 ab
	SE	38.1 a	12.9 ab	621 a	248 a	130 a	20.2 c
	S	29.6 bc	17.9 a	575 a	279 a	146 a	28.5 ab
	SW	24.5 c	16.2 ab	642 a	219 a	139 a	33.9 a
	W	24.1 c	13.0 ab	602 a	238 a	160 a	27.4 ab
	NW	30.7 abc	15.4 ab	620 a	251 a	130 a	29.2 ab

† N, 338-23°; NE, 23-68°; E, 68-113°; SE, 113-158°; S, 158-203°; SW, 203-248°; W, 248-293°; NW, 293-338°.
‡ Values followed by the same letter are not significantly different at $P \leq 0.05$ according to Duncan's new multiple range test.

Table 7. Correlation coefficients determined for C contents versus watershed soil properties.

Comparison		Subwatershed 3(N = 59)	7(N = 49)	9(N = 114)	10(N = 72)	11(N = 47)	15 (N = 92)	All subwatersheds (N = 433)
Total C vs	Sand	−0.481**	−0.497**	−0.151	−0.039	0.018	−0.295**	−0.248**
	Silt	0.519**	0.556**	0.253*	−0.015	0.109	0.410**	0.360**
	Clay	0.205	0.272*	−0.074	−0.067	−0.195	−0.032	−0.043
	pH	0.039	0.179	0.430**	0.627**	0.259	0.028	0.369**
	AI	0.453**	0.128	0.362**	−0.254**	0.341**	−0.023	0.085
	Hue	0.409**	0.172	0.498**	0.366**	0.704**	0.129	0.274**
	Value	0.530**	0.194	0.195	0.195	0.533**	0.154	0.274**
	Chroma	−0.215	−0.408**	−0.246*	−0.409**	0.082	−0.024	−0.195**
OC vs	Sand	−0.605	−0.545**	−0.573**	−0.349**	−0.016	−0.509**	−0.521**
	Silt	0.600**	0.459**	0.584**	0.028	−0.011	0.442**	0.467**
	Clay	0.409**	0.529**	0.342**	0.486**	0.047	0.471**	0.389**
	pH	−0.007	−0.360**	−0.070	0.312**	0.005	−0.778**	0.196*
	AI	0.453**	0.254	0.643**	−0.214	0.270	0.618**	0.430**
	Hue	0.336**	−0.100	0.352**	0.045	0.455**	0.089	0.032
	Value	0.098	−0.474**	−0.422**	−0.342**	0.040	−05.20**	−0.361**
	Chroma	−0.242	−0.402**	−0.483**	−0.539**	−0.292*	−0.535**	−0.440**

* Indicates significance at the 5% level of significance.
** Indicates significance at the 1% level of significance.

higher concentrations occurred on north-facing slopes (NW, N, NE) for soils in SWs 9, 10, and 11. This is consistent with the findings of other researchers (Franzmeier et al., 1969; Hanna et al., 1982) who attributed higher OC contents on N-facing slopes to cooler temperatures and higher soil water contents, which support greater plant growth. The higher OC contents in SW 3, 7, and 15 occurred on the southwest, east, and southeast facing slopes, respectively. In most cases, there were few significant differences between aspects for these three SWs. The differences in OC distributions between these two groups of SWs as a function of aspect is unclear; however, SWs 3 and 7 are so badly eroded and droughty that much of the landscape will not sustain adequate plant populations needed for higher OC contents, regardless of aspect. However, assessments of vegetation types were not part of this study.

Correlation coefficients (r) determined for C distributions as a function of several soil physical and chemical properties, irrespective of slope factors, indicate that OC was relatively highly correlated with the silt and clay fractions in some SWs (Table 7). Specifically, the significant ($p \leq 0.01$) correlations for SWs 3, 7, 9, and 15 suggest that total C occurs primarily in the silt size range possibly due to the $CaCO_3$ component. Organic C was strongly correlated with the clay-size fractions in SWs 7, 10, and 15, and overall, better correlated with both silt and clay fractions than was total C. This suggests that the size distribution of OC is more evenly distributed between these two size fractions which should have implications relative to the range of flow rates at which it can be transported in the watershed. Correlation coefficients for total C versus pH were not significant in four SWs, suggesting that pH had little influence on total C. Total C versus AI was significant ($p \leq 0.01$) in SWs 3, 9, 10, and 11 probably due to the stabilizing effect of the OC fraction on aggregation. The only significant correlations ($p \leq 0.05$) between OC and pH were in SWs 7, 10, and 15. When all watershed samples were combined, total C was most highly correlated with silt content and pH. Organic C was most highly correlated with silt content, disregarding the negative correlation with sand contents.

Sediment Characteristics

The properties of the suspended and bedload sediments (Table 8) are shown on the basis of each individual SW. Particle-size distributions of suspended sediments were much finer than the watershed surface horizon soils within SWs due to particle-size selectivity created by soil erosion and sediment transport processes. Conversely, the fine earth fraction (<2 mm) of the

Table 8. Chemical and physical properties of the bedload and suspended sediments.

Subwatershed	Sediment source	n	Particle-size distribution: Sand	Silt	Clay	Carbon content: Total	Organic	pH	Munsell color: Hue†	Value	Chroma
			g kg^{-1}								
3	suspended	6	374	410	216	50.3	32.1	7.8	6.7	3.5	2.1
	bedload	26	867	73	60	10.3	4.2	8.0	7.0	3.8	2.2
7	suspended	6	499	326	175	43.1	24.9	7.5	8.6	3.6	2.0
	bedload	15	874	69	57	16.4	6.8	8.0	8.5	3.8	2.0
9	suspended	10	506	337	157	30.8	19.9	7.7	6.8	3.5	1.8
	bedload	24	784	131	85	15.5	8.2	7.8	7.0	3.5	1.7
10	suspended	7	419	410	171	20.8	19.3	7.6	6.6	3.4	1.9
	bedload	14	701	195	105	14.4	9.1	7.3	6.8	3.5	1.9
11	suspended	9	512	321	168	44.8	21.6	7.8	7.0	3.6	1.8
	bedload	31	900	51	49	15.4	4.2	8.0	7.1	3.7	1.7
15	suspended	7	432	395	189	47.8	26.0	7.8	6.8	3.5	1.9
	bedload	27	695	197	108	32.8	12.4	7.9	7.1	3.6	1.9

† All hues are YR (yellow red).

bedload sediment was much coarser than the source area soils. The soils and sediment differed considerably in terms of C contents. Total and OC contents of the suspended sediments averaged 39.5 and 24.0 g kg^{-1}, respectively, compared with 22.3 and 11.4 g kg^{-1} for the watershed soils. The bedload sediments had an average total C content of 17.5 g kg^{-1}, and an OC content of 7.2 g kg^{-1}. These data clearly indicate that the bulk of the OC fraction is being transported in the suspended sediments in the WGEW. The pH of the suspended and bedload sediments was similar within a SW, and slightly lower than their respective soils. Relative to color, the suspended sediment had redder hues, and higher values and chroma than the watershed soils due to higher clay contents in the sediment. Bedload sediments had a slightly greater hue, value, and chroma than the soils probably due to the higher sand contents of which quartz is an important component.

The ratios determined for suspended and bedload sediment versus watershed soil properties (Table 9) indicate that the suspended sediment was more enriched in silt-size material relative to the clay fraction in most SWs, by a factor of 2 to 3 times in some cases. This accounts for the enrichment of OC in the suspended sediment, which averages approximately 2.1 times the amount in the watershed soils. As previously shown in Table 7, OC was better correlated with the silt fraction of the watershed soils relative to the clay-size fractions. The significant ($p \leq 0.01$), negative correlations for C content versus sand also supports this observation. Obviously, very little OC is being transported in the bedload sediments in association with the sand fractions.

The highest ER for OC was recorded for SW 3 (Table 9). Enrichment ratio is defined as the ratio of the OC content in the suspended sediment to that in the watershed soils. This highest ER also coincides with the lowest AI (Table 3). Both of these properties indicate low aggregate stability/high erodibility conditions, therefore, SW 3 would be expected to produce the greatest amounts of C in the runoff on a per unit area basis for a given rainfall event. Following SW 3, the order for ER is: $7 > 15 > 11 > 10 > 9$. The order for AI by SW is: $9 > 15 > 10 > 11 > 7 > 3$. These results may be substantiated by the suspended sediment concentrations measured at each of the flumes. Drought conditions in WGEW for 2002 and 2003 limited the number of suspended sediment samples. Rainfall amounts for 1999–2003 were 305, 420, 279, 232, and 249 mm, respectively. Even though the average number of samples collected over this time span is below five, the relative sediment concentrations are reasonably close to expected values based on ER and AI. Specifically, the order of suspended sediment concentrations were: SW 7 (0.040 g mL^{-1}) > 3 (0.028 g mL^{-1}) > 11 (0.023 g mL^{-1}) > 9 (0.015 g mL^{-1}) > 10 (0.013 g mL^{-1}) > 15 (0.009 g mL^{-1}). Obviously, the relative land areas associated with the various slope factor components in each watershed also have a strong influence on suspended sediment concentrations measured at each flume, but in lieu of such information, the use of soil-sediment factors such as ER and AI appears to be a reasonable approach to estimating which SW is losing the greatest amounts of OC.

CONCLUSIONS

Organic C contents in the surface horizon of WGEW soils are distributed largely on the basis of differences in parent material and degree of erosion among SWs, with the greatest concentrations associated with the soils formed from the weathering of fine-textured, higher base status igneous rocks. Conversely, minimum OC contents were identified in the soils derived from the more acidic, coarser-textured igneous rocks that are relatively resistant to weathering in this climate.

Within this soil-climatic regime, the greater OC contents were found on the steeper slopes of the SWs where the higher clay content soils were capable of supporting greater plant growth. Relative to hillslopes, the greatest soil OC contents were found on the backslope and toeslope positions, reflecting contributions from upslope landscape components. The distribution of OC as a function of slope aspect was largely inconclusive, with the greatest concentrations equally divided between the north- and south-facing slopes.

Soil OC is being transported predominantly as silt-size, and to a lesser extent, clay-size materials in this watershed, and the greatest losses are occurring in those SWs with the lowest average soil aggregation index. This information can be used to identify watersheds losing inordinate amounts of soil OC, essential to the productivity of such rangelands, to runoff and erosion. The data can also aid in the design of sediment retention basins for maximum sediment trapping efficiency. Finally, the

Table 9. Ratio of bedload and suspended sediments to watershed surface horizon soil properties.

		Particle-size distribution			Carbon content			Munsell color		
Subwatershed	Sediment source	Sand	Silt	Clay	Total	Organic	pH	Hue	Value	Chroma
3	suspended	0.50	2.72	1.67	2.07	2.89	0.91	0.94	1.13	1.11
	bedload	1.20	0.49	0.45	0.44	0.41	0.93	0.99	1.23	1.10
7	suspended	0.72	1.83	1.40	2.05	2.59	0.96	1.06	1.13	0.99
	bedload	1.22	0.43	0.48	0.88	0.80	1.01	0.98	1.19	1.00
9	suspended	0.72	2.02	1.03	1.56	1.72	1.04	1.05	1.19	0.99
	bedload	1.20	0.71	0.52	0.80	0.68	1.05	1.08	1.21	1.00
10	suspended	0.58	3.08	1.17	1.74	1.76	1.10	1.03	1.13	1.12
	bedload	1.00	1.37	0.66	0.88	0.79	1.06	1.06	1.17	1.12
11	suspended	0.70	2.36	1.25	1.64	1.81	0.92	1.01	1.16	1.21
	bedload	1.23	0.58	0.37	0.57	0.36	0.95	1.11	1.23	1.00
15	suspended	0.70	1.53	1.36	1.59	2.01	0.98	0.99	1.08	1.00
	bedload	1.14	0.78	1.10	1.12	0.87	1.00	1.03	1.16	1.06

results from this study will aid scientists involved in nutrient transport and C sequestration research related to C balances at watershed scales.

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