Soil Contributions to Sediment Properties in Walnut Gulch Experimental Watershed: Influence of Slope Factors

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Abstract

Variations in soil profile thickness, surface soil properties, erosion rates, runoff, and sediment properties within similar soil types and watersheds can generally be explained by slope factors that influence soil erodibility. This study was conducted to determine the effects of surface morphometry on the distribution of watershed soil properties that control erodibility and sediment properties. Each major soil type in six sub-watersheds in Walnut Gulch Experimental Watershed was sampled intensively along transects positioned to represent the normal landscape features associated with a particular mapping unit. At each sampling point, data were recorded for latitude-longitude, slope gradient, slope position, and slope aspect. Suspended and bedload sediment samples were collected from flumes located at the mouth of each sub-watershed. Clay contents of the soils and sediments ranged from 125.0 to 152.7 g kg^{-1} with averages of 136.8 and 178.1 g kg^{-1}, respectively. Enrichment ratios (ER) calculated for each watershed indicated that suspended sediments were enriched in clay, relative to the soils, by a factor that ranged from 1.02 to 1.68. The aggregation index (AI), a measure of relative erodibility, ranged from 18.0 to 31.9. The correlation coefficient (r) determined for ER vs. AI was - 0.927 ($P \leq 0.05$). The data indicate that watersheds with the lowest AI are producing the greatest amount of suspended sediment. The data also indicate that the highest soil AI values occur on summit, shoulder, footslope and toeslope positions, on slopes steeper than 13%, and on NW-, N-, and NE-facing slopes. These results indicate that this approach could be used to improve our understanding of hillslope erosion processes, and the accuracy of erosion prediction models.

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Introduction

The severity of erosion is largely determined by factors such as rainfall characteristics, topography, and vegetative cover. If these factors remain constant and the soil resource changes, variations in erosion losses can be attributed to variations in soil properties that influence soil erodibility (Bryan 1969). Basically, soil erodibility is determined by aggregate stability by virtue of its control over porosity and infiltration rates. Soil aggregates of low stability are dispersed by relatively low rainfall energies leading to surface sealing, increased runoff, and a high proportion of easily transported fine particles. Generally, the level of aggregate stability depends on the content of bonding agents in the soil such as clay, Fe and Al oxides, and organic C which have the ability to bind soil particles into stable units. Generally, the soil clay fraction serves as the building block for aggregate stability. Thus, the degree to which clay particles in soil aggregates disperse in water can be taken as a measure of aggregate stability.

The distribution of soil properties that influence aggregate stability in the landscape can vary as a function of slope position, slope class, and slope aspect. Franzmeier et al. (1969) found greater organic C contents and darker soil colors on north-facing slopes associated with lower temperatures and higher water contents. They also measured coarser particle size distributions on mid-slope positions, and higher concentrations of basic cations on the lower slope positions. Similarly, Hanna et al. (1982) indicated that north-facing slopes contained 20% more available water relative to south-facing slopes, and that soils on east-facing slopes were the driest. In terms of slope position, soils on backslope and footslope positions contained more available water than summit and shoulder positions. Rhoton et al. (1998) related water dispersible clay contents to the distribution of Fe oxides among soil drainage classes. Water dispersible clay contents and soil erodibility were at a minimum on the lower, wetter slope positions which favored formation of poorly crystalline Fe oxide phases most influential in aggregate stability.

This research was conducted on the basis of these previous findings, which have demonstrated that numerous soil properties that influence soil erodibility vary in magnitude with changes in surface morphometry. Our objectives were to characterize the relationships between soil erodibility and slope factors within a large semiarid watershed.

Methods

Site characteristics

The research was conducted on the Walnut Gulch Experiment Watershed (Figure 1) near the town of Tombstone in southeastern Arizona (31 deg. 43 min. N. Lat., 110 deg. 41 min. W. long). The watershed encompasses 150 km^2 with elevations ranging from 1220 to 1890 m. In terms of geology, the watershed is located primarily in a high foothill alluvial fan portion of the larger San Pedro River Watershed. The alluvium is primarily composed of Cenozoic age clastic clays and silts. The remaining mountainous portion of the watershed consists of limestone, weathered granite, and igneous intrusions ranging in age from pre-Cambrian to Quaternary. The mean annual temperature at Tombstone is 17.6 ^oC, and the average total annual precipitation is 324 mm (Renard et al. 1993).

Study approach

Six sub-watersheds were selected for study within the larger watershed. Each of these sub-watersheds was instrumented with a supercritical flume (Renard et al. 1993) and associated flow measuring equipment. Inlet drop boxes constructed in the floor of the flume were used for the collection of bedload samples once the sediment passed through the 6.4 mm slotted covers. Suspended sediments were collected with vertical samplers mounted on the face of the flume. As with bedload sediment, only the < 6.4 mm fraction was collected.

Watershed soils were sampled on the basis of acreage comprised by individual soil mapping units within a given sub-watershed. Initially, digitized soil surveys were superimposed on digital elevation models of each sub-watershed, then a sampling transect length of 1000 m was chosen for each 200 ha occupied by a given soil mapping unit. Transects were positioned to insure a maximum number of slope factors were represented by the samples. Soil samples were collected along the transects with each change in slope position. At each point, soil samples were collected from the surface 5.0 cm at three locations, perpendicular to the slope, approximately 10 m apart. These were composited to form a single sample, sieved to < 4 mm and sealed in a plastic bag. At each sample point the following data were recorded: latitude – longitude, slope position, slope aspect, and slope gradient.

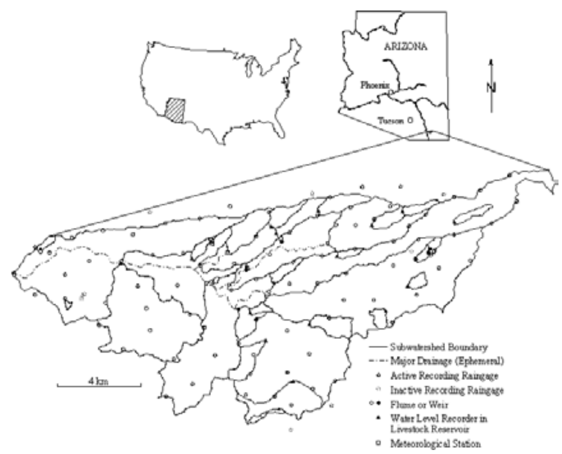

Figure 1. Location of the Walnut Gulch Experimental Watershed.

Laboratory analyses

Prior to analysis, all soil and sediment samples were air-dried and further sieved to < 2 mm. Particle size distribution was determined by standard pipette methods after the samples had been shaken overnight in Na hexametaphosphate (Soil Survey Staff 1984). Water dispersible clay (WDC) was estimated by the same methods, except only distilled water was used during the dispersion phase. Soil pH was measured in a 1:1 soil/distilled water (v-v) suspension (McLean 1982). Total C was determined by combusting a 0.5 g sample in a Leco CN-2000 carbon-nitrogen analyzer. Inorganic C contents were determined by treating a separate 1 g sample with 5N HC1 in a sealed decomposition vessel fitted with a rubber septum. Carbon dioxide pressure generated by the acid-decomposition of the sample was measured with a

Tensi-meter probe inserted through the septum. The pressure readings were converted to C contents and subtracted from the total to give organic C content. Quantitative soil color was measured with a Minolta Chroma Meter. Magnetic susceptibility was determined with a Bartington MS-2 Magnetic Susceptibility Meter. All sediment samples were analyzed identically to the soils.

The data obtained for total clay and WDC contents were used to calculate an aggregation index (AI) for the watershed soils based on the method of Harris (1971) as follows:

$$100\left(1-\frac{\text{WDC}}{\text{total clay}}\right).$$

Results

The data for selected soil properties are shown as an average for the six sub-watersheds (Table 1). Based on these results, some soil property data reflect differences in parent material composition between watersheds. The most obvious differences exist between watershed 7 (W7) and the other watersheds in terms of total clay contents, organic C, AI, and magnetic susceptibility (MS). A significant percentage of the soils in W7 were formed from igneous residuum (i.e., granite, granodiorite), which is more resistant to weathering processes relative to the limestone parent materials in other watersheds. Consequently, W7 soils are expected to have less clay and organic C, and a lower AI value, as is the case. Conversely, W7 soils had the highest MS that probably reflects a higher magnetite content in the igneous parent rocks. The higher overall soil color readings are due to the lighter colored granitic rocks and lower organic C contents. By contrast, W9 had a substantial acreage of soils formed from the weathering of fine grained, igneous rocks (i.e., andesite, basalt) that are composed of more weatherable minerals. Such parent materials should produce soils with finer particle sizes. The soils in W9 had the highest total clay, organic C, and AI, as well as the darker (redder) soil colors (hue, value). Clearly, parent material influenced soil erodibility in the Walnut Gulch Experimental Watershed.

Particle size (clay contents) and organic C data are compared for the watershed soils, suspended sediment, and bedload sediment in Table 2. The watershed soil data represent a weighted average calculated by multiplying the relative acreage occupied by a given soil type in a sub-watershed times the value for a specific soil property. The values were summed for all soil types to give a weighted average for the watershed. Generally, both the total clay and organic C data followed the same relative trend between watersheds as did the simple averages in Table 1. Watersheds 9 and 10 had the highest total clay contents on a weighted average basis followed by W11 and W15 with similar concentrations, while W3 and W7 had the lowest

Table 1. Selected soil physical and chemical properties averaged for individual watersheds.

Sub-watershed	n	Clay content: Total	Clay content: Water dispersible	Carbon content: Total	Carbon content: Organic	Aggregation index	pH	Magnetic suscep.	Munsell color[2]: Hue	Munsell color[2]: Value	Munsell color[2]: Chroma
		gkg^{-1}	gkg^{-1}	gkg^{-1}	gkg^{-1}			10^{-8}m^3 kg^{-1}			
3	81	132.5 b[1]	108.3 abc	23.2 b	10.7 bc	18.0 d	8.6 a	197.9 cd	7.1 b	3.1 b	1.9 b
7	49	118.2 c	91.1 d	18.6 c	8.5 d	22.8 c	7.9 b	799.7 a	8.2 a	3.3 a	2.0 ab
9	115	163.4 a	111.2 ab	19.3 c	12.1 b	31.9 a	7.4 c	294.4 b	6.5 d	2.9 c	1.7 d
10	74	159.6 a	116.2 a	16.4 c	11.5 bc	28.1 b	6.9 d	189.4 d	6.4 d	3.0 c	1.8 cd
11	47	133.6 b	101.7 bcd	26.8 a	11.8 b	23.9 c	8.5 a	264.4 bc	6.8 c	3.1 b	1.5 e
15	92	140.4 b	98.4 cd	29.2 a	14.2 a	28.2 b	7.9 b	216.9 cd	6.9 c	3.1 b	1.8 c

[1] Values followed by same letter are not statistically different at $P < 0.20$ based on Duncan's new multiple range test. [2] All Munsell colors are from wet samples. The hues are YR (yellow red).

concentrations. Organic C contents of the soils were more uniform with the highest contents recorded for W15 (12.9 g kg^{-1}) and the lowest for W7 (9.6 g kg^{-1}). The total clay contents of the suspended and bedload sediments (Table 2) in combination with soil AI were used as an indicator of relative erosion losses from the watersheds. The organic C data are included for purposes of explaining potential differences in AI and suspended sediment concentrations. Relative to the soils, the clay contents of the suspended sediments were enriched by an average factor of 1.38. The greatest enrichment (1.68) occurred in W3, and the smallest (1.02) was in W9. These two watersheds had the highest and lowest AI, respectively (Table 1). The ratios of suspended and bedload sediment clay to soil clay were correlated against the soil AI for individual watersheds. This gave a correlation coefficient (r) of -0.927 ($P \leq 0.05$) for suspended sediment. The only apparent discrepancy in the data is the relatively high enrichment ratio for W15 considering its high AI. Soils in W15 had the highest organic C contents that suggests the sediment is transported in an organic C stabilized, clay aggregate form. Bedload sediment data tends to support this explanation since W15 had the highest clay contents and the highest bedload:soil clay ratio. Apparently, bedload sediment in W15 contains a relatively high proportion of larger, stable clay aggregates. With the exception of W10, the bedload:soil clay ratios were approximately 50% lower than W15. The r value for bedload:soil clay ratios vs.. AI was only 0.51. Obviously, the bulk of the fine sediments leaving the watersheds is in a suspended form.

The organic C contents also indicate that the suspended sediment was enriched and the bedload sediment depleted relative to the watershed soils. The average ratios were 2.13 and 0.66, respectively. The highest suspended sediment concentrations came from the lower AI soils, again with the exception of W15. The r obtained for suspended/soil organic C vs.. AI was -0.866 ($P \leq 0.05$). On the average, the organic C concentrations in suspended sediments are twice that of the watershed soils. The bedload:soil organic C ratios indicate that the highest value (0.96) occurred in W15 and lowest in W3 (0.38) and W11 (0.36). The r value for these ratios vs. AI was 0.61.

Table 2. Total clay and organic C contents of suspended and bedload sediments, and watershed soils.

	Total clay contents					Organic C contents				
Sub-watershed	Watershed soils	Suspended sediment	Bedload	Suspended/ soils	Bedload/ Soils	Watershed soils	Suspended sediment	Bedload	Suspended/ soils	Bedload/ soils
	--------------------gkg^{-1}	----------------				------------------- gkg^{-1}	----------------			
3	129	216	60	1.68	0.46	11.1	32.1	4.2	2.89	0.38
7	125	175	57	1.40	0.46	9.6	24.9	6.8	2.59	0.71
9	153	156	85	1.02	0.56	11.6	19.9	8.2	1.72	0.70
10	146	171	105	1.17	0.72	11.0	19.3	9.1	1.76	0.83
11	134	168	49	1.25	0.37	11.9	21.6	4.2	1.81	0.36
15	134	182	108	1.36	0.81	12.9	26.0	12.4	2.01	0.96

Table 3. Distribution of watershed soil properties as a function of slope position.

Slope Position	Total clay	WDC	Total carbon	Organic carbon	Aggregation index	pH	Magnetic susceptibility	Hue	Value	Chroma
	---------------------- $g kg^{-1}$	-------------------					$10^{-8} m^3 kg^{-1}$			
SU[1]	146 ab[2]	106 ab	21.5 a	11.6 a	26.8 abc	7.8 a	257 abc	6.9 YR a	3.1 a	1.8 b
SH	143 ab	99 b	23.6 a	12.6 a	29.2 a	7.8 a	333 a	7.0 YR a	3.1 ab	1.8 b
UBS	140 ab	110 ab	22.7 a	12.5 a	25.7 cd	7.8 a	284 ab	7.0 YR a	3.1 ab	1.7 b
MBS	138 ab	100 b	23.6 a	11.3 ab	26.3 bcd	7.8 a	337 a	7.1 YR a	3.1 ab	1.8 b
LBS	152 a	116 a	24.1 a	12.5 a	24.2 d	7.8 a	313 a	6.9 YR a	3.1 ab	1.9 ab
FS	146 ab	103 b	14.8 b	9.7 bc	28.5 ab	7.4 b	204 bc	6.4 YR b	3.0 ab	1.9 ab
TS	135 b	99 b	15.4 b	9.4 c	27.2 abc	7.8.b	190 c	6.5 YR b	3.0 b	1.9 a

[1] SU = summit, SH = shoulder, UBS = upper backslope, MBS = mid backslope, LBS = lower backslope, FS = footslope, TS = toeslope

[2] Values followed by same letter are not statistically different at $P \leq 0.20$ based on Duncan's new multiple range test.

The distribution of soil AI as a function of watershed slope factors was determined for the overall watershed using the data from all 457 samples. Additional soil properties were included in these evaluations to assess the dependence of AI on their distribution. The effect of slope position on AI is shown in Table 3. The data indicate that the higher soil AI occurred on the summit (SU), shoulder (SH), footslope (FS), and toeslope (TS) positions. The three backslope positions (UBS, MBS, LBS) had a lower AI although in some cases they were not significantly different ($P \leq 0.20$) from other positions. No clear explanation exists for why the backslope positions have the lowest AI based on this set of soil properties, however, magnetite appears to be accumulating on these slope positions, as indicated by MS. This indicates a coarser particle size distribution as described for mid-slope positions in other studies (Franzmeier et al. 1969). The lower hue and slightly higher chroma values found in the FS and the TS positions may indicate redder soil colors than upslope due to high Fe contents that normally increases the AI.

The distribution of AI as a function of slope class (gradient) indicated that the A, E, and F slopes had significantly ($P \leq 0.20$) greater values than the B, C, and D slopes (Table 4). In this case, the higher AI appears to be due to greater total clay and organic C concentrations. The occurrence of the higher AI on the steeper slopes (E, F) are the result of the Graham/Lampshire mapping units that predominate on the steeper slopes. These soils characteristically are relatively high in clay and organic C.

Table 4. Distribution of watershed soil properties as a function of slope class.

Slope Class	Total clay	WDC	Total carbon	Organic carbon	Aggregation index	pH	Magnetic susceptibility	Hue	Value	Chroma
	---------------- gkg^{-1}	--------------------					$10^{-8}m^3\ kg^{-1}$			
A (0-2%)	148 b[1]	105 bc	18.3 b	10.4 d	27.8 a	7.6 c	239 b	6.7 YR c	3.1 b	1.8 bc
B (3-5%)	130 c	97 c	22.4 a	9.9 d	24.8 c	8.1 a	323 a	6.8 YR c	3.2 a	2.0 a
C (6-8%)	142 b	105 bc	21.3 a	10.2 d	24.9 c	7.8 bc	314 a	6.8 YR c	3.1 b	1.8 b
D (9-12%)	145 b	108 b	24.1 a	12.0 c	24.7 c	7.9 ab	318 a	7.1 YR a	3.1 b	1.8 c
E (13-20%)	167 a	121 a	23.9 a	15.2 b	27.7 b	7.6 c	220 b	6.9 YR bc	2.9 c	1.7 d
F (> 20%)	160 a	104 bc	22.6 a	16.8 a	33.7 a	7.2 d	392 a	7.1 YR ab	2.8 d	1.6 d

[1] Values followed by same letter are not statistically different at $P \leq 0.20$ based on Duncan's new multiple range test.

Table 5. Distribution of watershed soil properties as a function of slope aspect.

Slope Aspect	Total clay	WDC	Total carbon	Organic carbon	Aggregation index	pH	Magnetic susceptibility	Hue	Value	Chroma
	---------------- gkg^{-1}	--------------------					$10^{-8}m^3\ kg^{-1}$			
N (0-45 ^{o})	144 ab[1]	102 ab	241 a	12.5 a	26.5 abcd	7.7 bc	465 a	7.1 YR b	3.0 cd	1.8 b
NE (45-90^o)	139 b	102 ab	243 a	11.2 a	27.7 abc	7.9 b	418 ab	7.5 YR a	3.2 a	1.9 ab
E (90-135 ^{o})	144 ab	110 a	230 ab	10.8 a	23.3 e	8.2 a	189 e	7.0 YR bc	3.2 ab	1.9 a
SE (135-180 ^{o})	149 ab	115 a	232 ab	10.8 a	24.4 de	7.9 b	199 e	6.8 YR cd	3.1 bc	1.8 b
S (180-225 ^{o})	140 b	103 ab	221 ab	11.0 a	25.8 bcde	7.8 bc	250 de	6.7 YR cd	3.1 bc	1.8 b
SW (225-270 ^{o})	138 b	98 b	210 ab	11.9 a	28.8 a	7.6 cd	360 bc	6.9 YR bc	3.1 b	1.8 ab
W (270-315 ^{o})	145 ab	107 ab	218 ab	12.2 a	25.1 cde	7.9 b	267 de	7.1 YR b	3.0 cd	1.8 ab
NW (315-360 ^{o})	158 a	111 a	205 b	12.7 a	28.5 ab	7.4 d	307 cd	6.6 YR d	3.0 d	1.8 b

[1] Values followed by same letter are not statistically different at $P \leq 0.20$ based on Duncan's new multiple range test.

In terms of slope aspect (Table 5), the greatest AI occurred on the N-facing slopes (NW, N, NE) with the exception of the SW-facing slope data. The lower AI was associated with the E-, SE-, S-, and W- facing slopes where average annual temperatures are warmer, and soil water and organic C contents are lowest (Franzmeier et al. 1969, Hanna et al. 1982). The organic C data from this study follows a similar trend, with the lowest concentrations recorded on the E-, SE-, and S- facing slopes. The MS data follow the same general trend as AI. Specifically, the highest readings are on the N-, NE-, and SW- facing slopes, with the lowest on E-, SE-, and S- facing slopes. Apparently, cooler temperatures associated with the N-facing slopes has resulted in less oxidation of the magnetite soil component which is responsible for the magnetic signature in this environment.

Conclusions

This study has shown that a weighted average approach to the characterization of basic watershed soil properties, that influence soil erodibility, has the potential to improve our understanding of hillslope erosion processes in semiarid environments including the composition of sediment in streams draining individual watersheds. The fact that an aggregation index computed for individual soils is highly correlated with suspended sediment properties, and varies as a function of slope position, slope gradient, and slope aspect indicates that soil erodibility zones can be differentiated in watersheds using digital elevation models and digitized soil surveys. The incorporation of this information into soil erosion prediction models has the capability to improve their accuracy at the watershed scale. Additionally, from an environmental science perspective, this approach can provide scientists with a reliable estimate of carbon fluxes, and a means of assessing the movement of chemical contaminants in semiarid watersheds.

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