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The relation between surface rock-fragment cover and semiarid hillslope profile morphology

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Abstract

Rock-fragment covers veneer hillslopes in many parts of the world and influence the operation of hydrologic and geomorphic processes on those surfaces. The purpose of this investigation was to examine the spatial variability of rock-fragment cover on morphological units of hillslopes in southeastern Arizona, U.S.A. Simple statistical models, based upon hillslope gradient as well as a soil-slope factor (SSF) were developed and validated for the estimation of percent rock-fragment covers (RFc) on these units. Although reasonably accurate estimates were made using either hillslope gradient or the SSF, it appears more efficient to utilize hillslope gradient alone. Likewise, reasonably accurate estimates of RFc can be made using either a composite model for the entire hillslope or unit-specific models; however, it appears more efficient to utilize the gradient composite model.

1. Introduction

Recent research demonstrates that rock-fragment cover on hillslope surfaces profoundly influences the operation of hydrologic and geomorphic processes. Poesen et al. (1994) cite the direct effects of such covers as shielding the soil surface from detachment by rainsplash and runoff and entrapping splashed sediment.

1.1. Rock-fragment cover effects on hillslope hydrology and hydraulics

A number of investigations specifically address the relation between infiltration rates and rock-fragment cover. Results reveal both positive and negative associations between the two variables. Dadkhah and Gifford (1980) found, that on uncompacted soil, infiltration increased as rock-fragment cover increased. However, on compacted soil, there was no significant infiltration increase associated with increasing rock-

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fragment cover. Poesen et al. (1990) report that the position of the rock fragments at the soil surface controlled the nature of the relation between infiltration and rock-fragment cover. When the fragments rested on the soil surface the relation was positive and when the fragments were embedded into the soil the relation was negative.

Rock-fragment covers increase hydraulic resistance to overland flow (Shaw, 1929; Abrahams and Parsons, 1991). Poesen et al. (1994) report that with increasing rock-fragment cover, flow resistance and friction factor increase, resulting in an exponential decrease of mean flow velocity; since rock fragments divert and retard overland flow, they also reduce the detaching and transporting capacity of the flow.

Young and Mutchler (1969) concluded that the order of decreasing flow velocities on hillslopes of different morphologies went from convex>straight > concave; resulting in more water and soil loss from hillslopes with the higher flow velocities.

1.2. Rock-fragment cover effects on erosion and sediment yield

Traditionally, rock-fragment covers have been regarded as operating to armor hillslope surfaces against the forces of erosion (Shaw, 1929; Cooke, 1970; Poesen et al., 1994). The energy of raindrop impact is absorbed by the rock fragment and flow velocity is diminished. For southeastern Arizona, Simanton et al. (1984) reported a negative relation between erosion and rock-fragment cover. There have been few studies regarding the influence of hillslope morphology or gradient on the relation between erosion or sediment yield and rock-fragment cover. De Ploey (1981) found a negative relation between sediment yield and rock-fragment cover for a gentle 3.5% (2°) gradient. However, for a steeper 28.7% (16°) gradient, the relation could be either negative or positive.

There is evidence that hillslope gradient influences the characteristics of rock-fragment covers. Parsons and Abrahams (1987) found that the diameter of soil surface particles increased with gradient for Mojave Desert hillslopes. Simanton et al. (1994) concluded that percent rock-fragment cover in southeastern Arizona could be estimated on the basis of either hillslope gradient or gradient plus the rock fragment content of the soil profile.

1.3. Hillslope morphology and erosion processes

Various terms have been used to describe the morphology of hillslope profiles and their parts. In this study we employ the nomenclature proposed by Young (1972). A "segment" is a portion of a hillslope profile through which the gradient remains approximately constant (i.e. straight segment) and an "element" is a portion through which the curvature remains approximately constant; (i.e. convex or concave element). A "hillslope unit" can be either a segment or an element.

The influence of hillslope morphology on the soil erosion process is well substantiated with the sequence from highest to lowest rates going from convex>straight> concave units (Young and Mutchler, 1969; Meyer et al., 1975; Hadley and Toy, 1977).

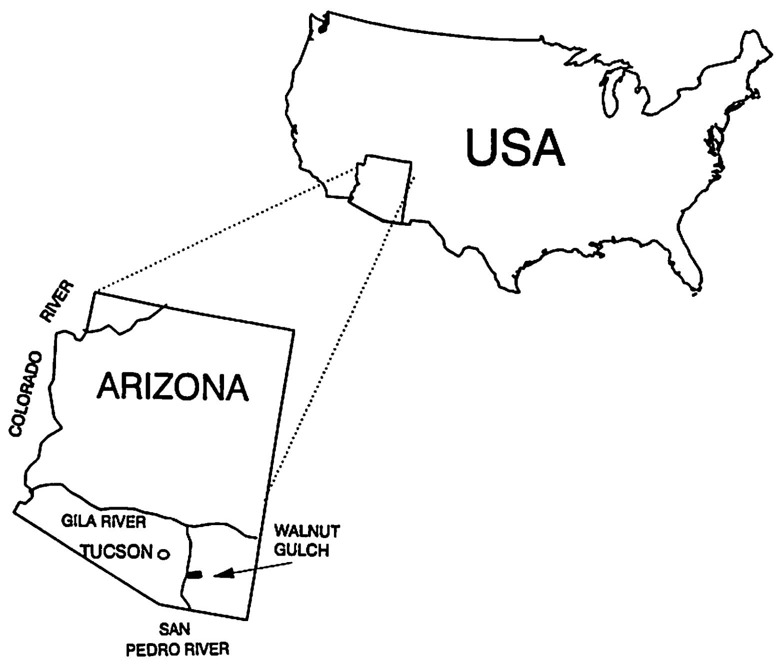

Fig. 1. Location of the Walnut Gulch Experimental Watershed and Tucson foothill location study sites.

1.4. Purpose of research

Rock-fragment covers are products of hydrologic and geomorphic processes operating on hillslopes. These fragments concentrate at the surface as a result of selective removal of fine materials (Cooke, 1970; Cooke and Warren, 1973). Assuming that rock-fragment cover is an erosional product of soils containing rock fragments, and that erosion rates differ among morphological units, it may be inferred that rock-fragment cover varies among morphological units. In the analysis of Simanton et al. (1994) the complex hillslopes were grouped by overall shape (convex, straight, and concave) and results of this general grouping indicated little difference in the relations between percent rock-fragment cover (RFc) and gradient and RFc and the soil-slope factor (SSF). In our extension of Simanton et al. (1994), we examine, on the basis of elements and segments rather than entire hillslopes, the variability of rock-fragment cover of semiarid hillslopes.

2. Study area characteristics

Hillslopes were selected from two general locations: (1) the Walnut Gulch Experimental Watershed in southeastern Arizona, U.S.A. (31°43′ N, 110°41′ W), and (2) the foothills of the mountains near Tucson, Arizona, U.S.A. (32°15′ N, 110°57′ W) (Fig. 1).

These hillslopes are components of alluvial basins within the Basin and Range Physiographic Province of the western U.S.A. (Simanton et al., 1994). The soils are well-drained, calcareous, gravelly loams with rock fragments covering a substantial percentage of the surface. Soil profiles are less than 2 m in depth, with the top 10 cm commonly containing up to 60% rock and gravel. Soils at the sites are classified as thermic *Ustollic Haplargids*; thermic, shallow *Typic Paleorthids*; thermic *Aridic Calciustolls*; *Lithic Torriorthents*; and *Lithic Haplustolls* (Gelderman, 1970; Hendricks, 1985).

Annual precipitation at Walnut Gulch averages about 300 mm (Simanton et al., 1994). Tucson annual precipitation averages about 285 mm with both winter (November to April) and summer (July to mid-September) receiving about half of the annual. Summer thunderstorms at both locations produce nearly all the annual runoff and erosion from the hillslopes used in this study (Osborn et al., 1979).

Vegetation of Walnut Gulch is typical of the Chihuahuan desert (Simanton et al., 1994). The Sonoran desert vegetation in the Tucson area has similar species as those found at Walnut Gulch but also includes paloverde (*Cercidium microphyllum*) and saguaro cactus (*Carnegiea gigantea*).

3. Research methods

3.1. Hillslope selection

Two groups of hillslopes are included in this study. The first consists of 12 hillslopes, within the Walnut Gulch Experimental Watershed, previously examined by Simanton et al. (1994). We graphically reconstructed (from field measurements of hillslope gradient and length) the hillslope profiles and classified them as to convex, straight, and concave units. The data within these groupings were used in the developmental models to be discussed later. The second group consists of 6 additional hillslopes (2 from the Walnut Gulch watershed and 4 from the foothills near Tucson) that were classified in like manner; and used for validation of the developmental models. All hillslopes were rectilinear, valleyside surfaces exhibiting no concentrated flow paths or established rill patterns. They were chosen to represent a range of shapes and gradients characteristic of the study locations.

3.2. Measurements

Once a hillslope was selected, it was divided into morphological units. The mean gradient (%) and field length (m) of each unit was measured with an Abney level and tape from top to the bottom of the unit. Then, the percent rock-fragment cover (RFc) was determined for each unit using the line–point method (Bonham, 1989) at 150 mm intervals along a transect normal to the profile. Rock fragments were defined as particles greater than 5 mm in diameter. This dimension was selected as the lower limit because particles smaller than this can be easily moved from the hillslope by fluvial processes (Poesen, 1987; Parsons et al., 1991). Next, rock fragments were removed from the surface at a representative location near the mid-point of each transect and two soil samples were taken from the top 50 mm of soil. Laboratory sieve analyses were used to determine the percent (by weight) rock fragments (> 5 mm diameter) in the samples.

The soil-slope factor (SSF) for each hillslope unit was calculated using the equation reported by Simanton et al. (1994):

$$SSF = RFp^{SL_d^{0.5}} \quad (1)$$

where SSF = soil-slope factor, RFp = % soil profile rock fragment content > 5 mm, and SL_d = hillslope gradient (decimal or tangent).

3.3. Statistical analyses, model development, and validation

Developmental models for the composite, convex, straight, and concave units were derived using regression techniques that related RFc to both the hillslope gradient and the SSF. Model validation was based on statistical comparison of measured RFc at the 6 validation sites with RFc estimated by the composite and appropriate unit-specific developmental models. For example, the developmental composite model was used to estimate RFc for all validation units regardless of morphology and these estimates were compared to the field measurements by means of regression analysis. To increase the robustness of the RFc predictive models, data from Simanton et al. (1994) and the 6 validation sites were combined to produce final models for composite and specific units.

4. Results and discussion

4.1. Spatial variability of rock-fragment covers

The sample size, mean, standard deviation and range of the hillslope gradient, RFc, and SSF for the developmental, validation, and final (combined) data sets are provided in Table 1. The values for the validation data are generally similar to those for the developmental data. Hence, the size of the validation data sets appears adequate to reproduce the basic statistical characteristics of the developmental data sets and to test the integrity of the developmental models. These data suggest little difference in RFc among the morphological units.

4.2. Developmental models

Models for estimating RFc were developed for the composite hillslope, convex, straight, and concave units. In these regression analyses, hillslope gradient and the SSF served as the independent variables while RFc was the dependent variable.

Table 1
Descriptive statistics: the sample size (*N*); the mean; the standard deviation (STD); and the range for gradient (%), rock-fragment cover (%), and soil-slope factor used in the developmental and final rock-fragment cover models, and of the validation sites

Model/unit	*N*	Slope (%)			Rock fragment (%)			Soil-slope factor		
		Mean	Std	Range	Mean	Std	Range	Mean	Std	Range
Developmental										
Composite	61	21.2	16.2	2-61	46.3	17.1	1-72	5.8	4.2	1-19
Convex	24	17.1	11.6	2-47	48.6	14.7	24-68	4.8	2.6	2-10
Straight	22	25.1	20.6	2-61	48.1	17.6	8-72	7.0	5.6	1-19
Concave	15	21.9	14.4	3-50	40.0	19.4	1-67	5.7	3.8	2-14
Validatation										
Composite	31	19.8	12.3	4-53	47.6	13.2	22-71	5.7	3.7	2-17
Convex	7	23.6	11.4	6-26	49.0	14.3	28-64	4.2	1.6	2-6
Straight	16	20.3	14.6	4-53	47.8	14.2	22-71	6.0	4.5	2-17
Concave	8	15.9	7.1	9-42	46.2	11.4	23-60	6.3	3.3	2-13
Final										
Composite	92	20.7	14.9	2-61	46.7	15.8	1-72	5.8	4.0	1-19
Convex	31	16.6	10.7	2-47	47.9	14.0	24-68	4.7	2.4	2-10
Straight	38	23.0	18.3	2-61	47.9	16.0	8-72	6.6	5.1	1-19
Concave	23	22.4	13.0	3-50	43.1	17.8	1-67	5.9	3.6	2-14

4.2.1. Hillslope gradient

The analyses for RFc estimation based upon hillslope gradient are presented in Fig. 2. In all these models the natural logarithm of gradient provided the most accurate estimations. The model for composite hillslopes (Fig. 2a), with all unit data taken together, had a standard error of estimate (SE) of 8.84% and a coefficient of determination (R^2) of 74%. The model for convex elements alone (Fig. 2b) yielded a slightly lower SE (7.90%) and a slightly lower R^2 (72%) than for the composite model. This indicates little advantage in using a unit-specific equation to estimate RFc of convex hillslope elements. The straight segments model (Fig. 2c) had a SE of 6.35% and a R^2 of 88% indicating some improvement in the accuracy of RFc estimation using the unit-specific model rather than the composite model. The model for concave elements (Fig. 2d) produced a SE of 6.33% and a R^2 of 90%, again indicating a modest increase in the accuracy of RFc estimation by using the unit-specific model rather than the composite model.

4.2.2. Soil-slope factor (SSF)

The analyses for the estimation of RFc based upon the SSF are presented in Fig. 3. For the composite and straight segments, the reciprocal of the SSF provided the most accurate RFc estimations, while for the convex and concave elements, the natural logarithm of SSF provided the most accurate estimations. The composite model (Fig. 3a) had a SE of 7.98% and a R^2 of 79%. The model for convex elements (Fig. 3b) had a SE of 7.19% and a R^2 of 77%. As with the gradient models there is little advantage

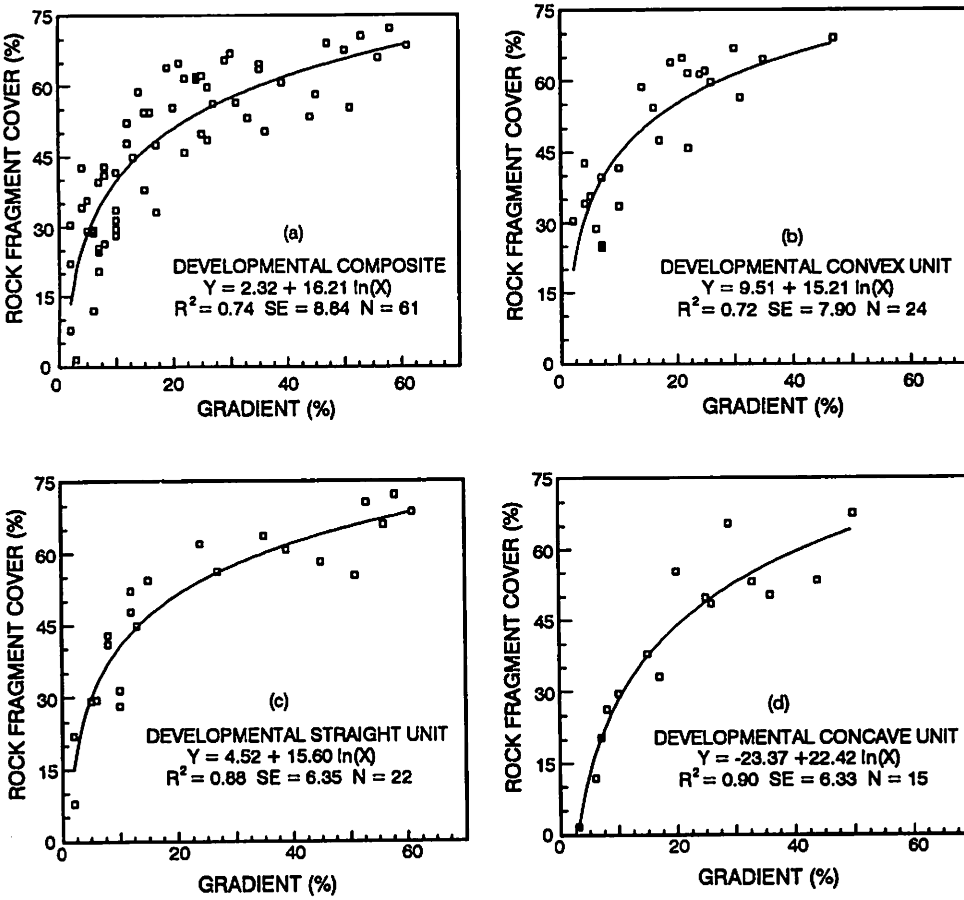

Fig. 2. Relations between hillslope gradient (%) and rock-fragment cover (%) of the composite (a), convex (b), straight (c), and concave (d) units for the developmental models.

in using the unit-specific model to estimate RFc of convex elements. The straight segment model (Fig. 3c) had a SE of 6.30% and a R^2 of 88%. Compared to the composite model, some increase in the accuracy of estimation might be expected based upon this unit-specific model. The model for concave elements (Fig. 3d) produced a SE of 7.04% and a R^2 of 88%. Again, a modest increase in the accuracy of estimation might be expected based upon the unit-specific model rather than the composite model. In both the hillslope gradient and SSF models, the relation between the residuals from regression and the values of the dependent variable suggested random distributions.

4.3. Model validation

Model validation consists of statistical comparisons between field RFc measure-

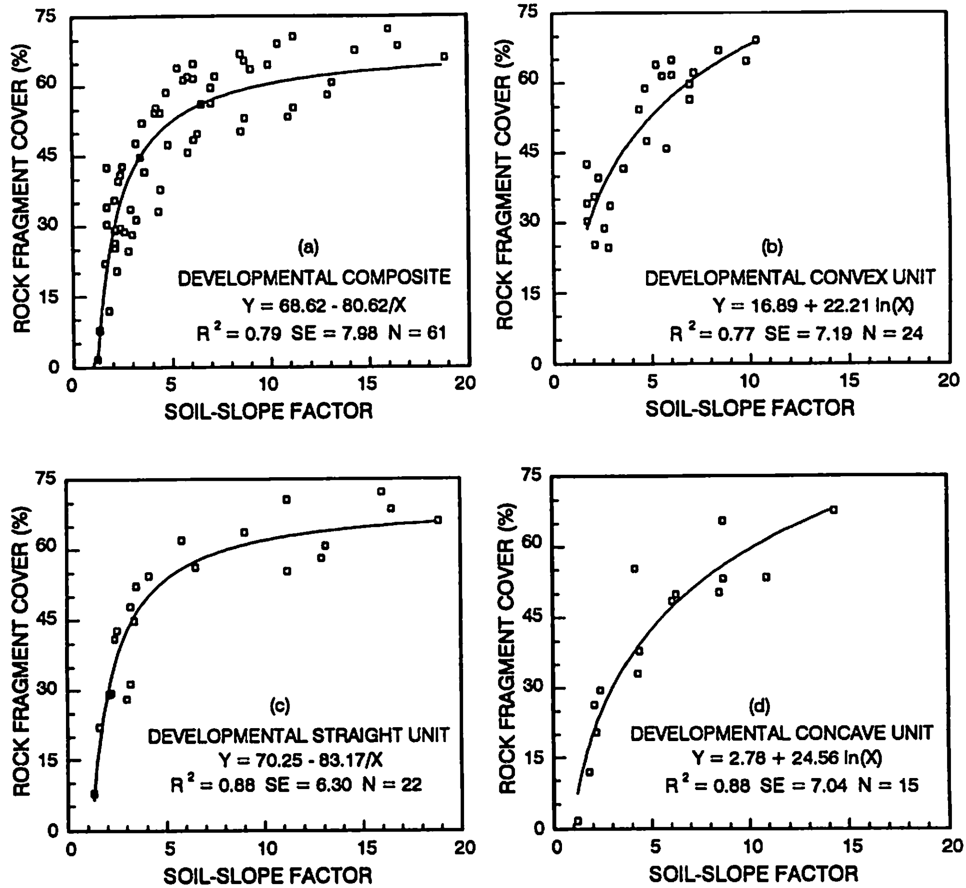

Fig. 3. Relations between the soil-slope factor and rock-fragment cover (%) of the composite (a), convex (b), straight (c), and concave (d) units for the developmental models.

ments at the validation sites and RFc estimates produced by the developmental models based on gradient or the SSF (Fig. 4). Simple regression was used for comparisons; a perfect relation between measured and estimated would result in a R^2 of 100%, a Y-intercept of "0", and a regression coefficient of 1.0 (1 : 1 line in Fig. 4). The gradient composite model (Fig. 2a) was used to estimate RFc for all hillslope segments of the validation sites regardless of hillslope morphology. The results are shown in Fig. 4a including a R^2 of 91% and a regression coefficient of 0.77. The RFc field measurements were compared to estimates based on gradient unit-specific models (Fig. 2b, c, and d) as appropriate (i.e. RFc of convex units were estimated using the convex unit-specific model). The results are shown in Fig. 4b including a R^2 of 89% and a regression coefficient of 0.77.

The validation of the developmental models using the SSF as the independent

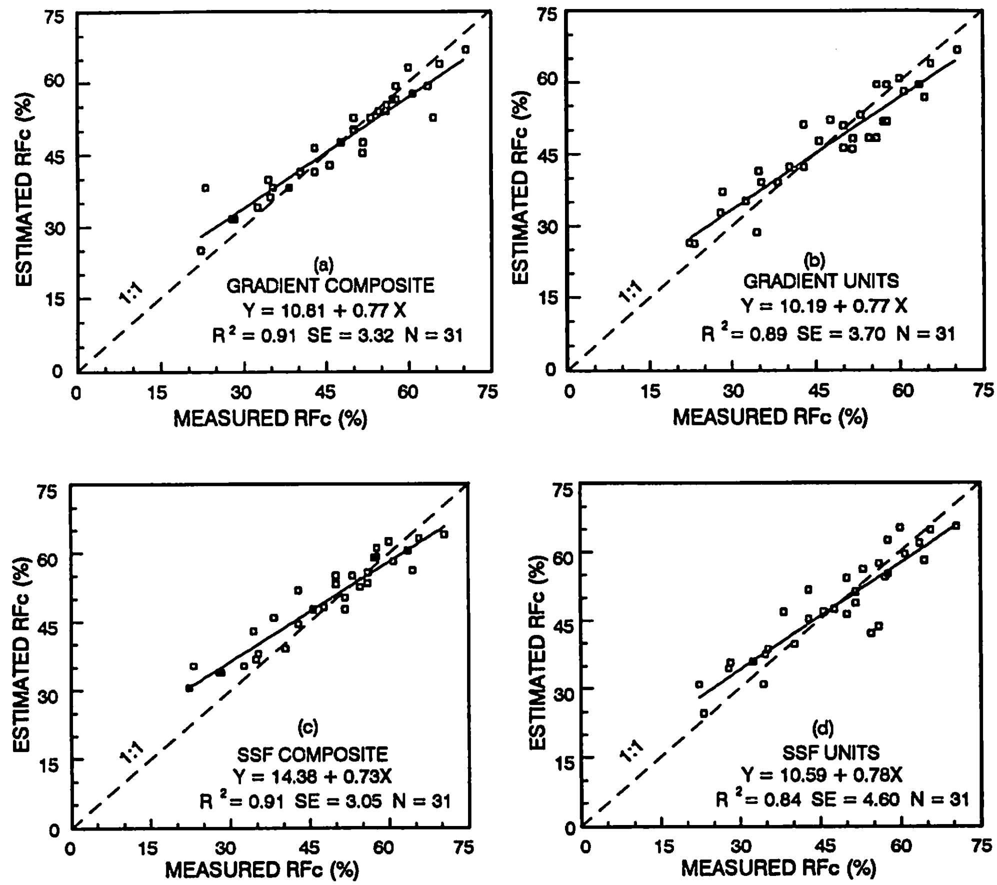

Fig. 4. Measured versus estimated rock-fragment cover based on hillslope gradient for the validation composite (a), units (b); and the soil-slope factor estimated rock-fragment cover for the validation composite (c), and units (d).

variable is also presented in Fig. 4. The comparison of field measurements and RFc estimates based upon the composite model (Fig. 3a) yielded a R^2 of 91% and a regression coefficient of 0.73 (Fig. 4c). The comparison of field measurements and estimates based on the unit-specific models (Figs. 3b, c, d) yielded a R^2 of 84% and regression coefficient of 0.78 (Fig. 4d).

The results of the validation tests indicate that either gradient or the SSF can be used to estimate RFc for the composite or unit-specific components of hillslopes. The SE for the various developmental models differ by only a few percent, although the differences in the R^2 are somewhat larger. The greater than zero regression intercept values (Fig. 4) suggest some measure of bias inherent in the models. We cannot explain this phenomena because the measurements were taken in exactly the same manner for all of the data collected.

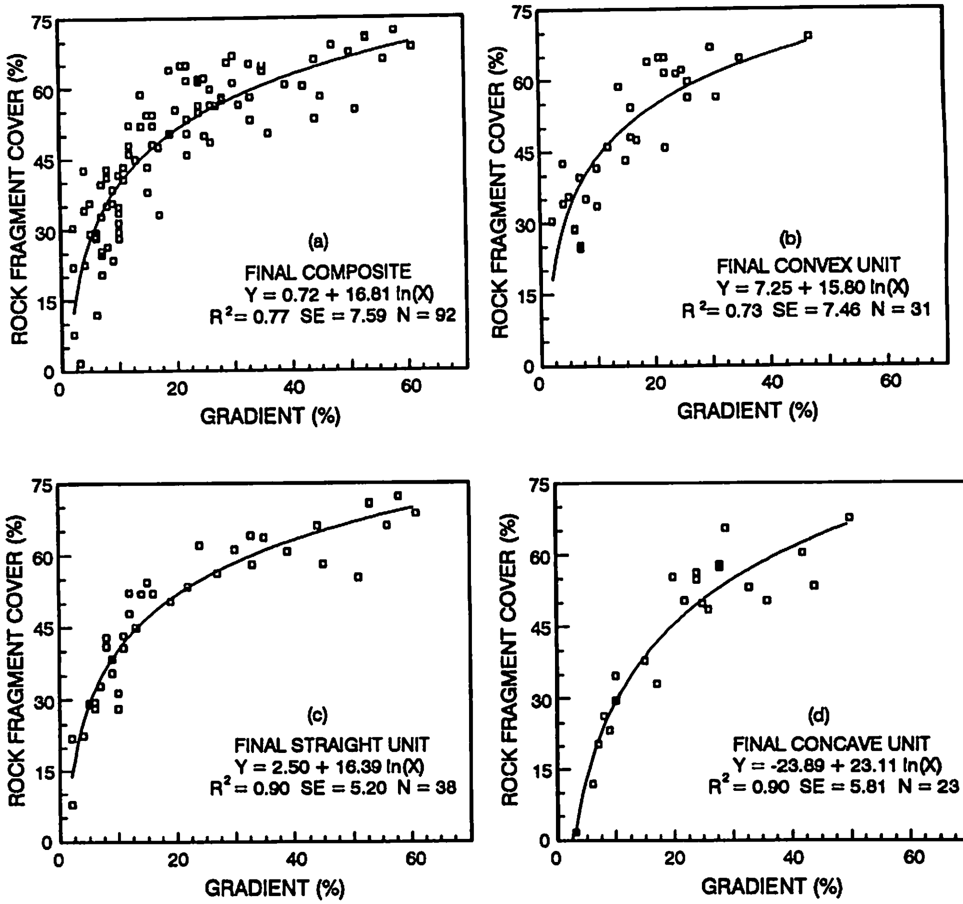

Fig. 5. Relations between hillslope gradient and rock-fragment cover of the composite (a), convex (b), straight (c), and concave (d) units for the final models.

4.4. Final models

The data used for model development and validation were combined to construct the final models depicted in Figs. 5 and 6.

4.4.1. Hillslope gradient

The natural logarithm of the hillslope gradient was the independent variable in each of these final models. The final composite model (Fig. 5a) was developed from data for 92 segments and yielded a SE of 7.59% and a R^2 of 77%. The final model for convex elements (Fig. 5b) has a slightly lower SE (7.46%) and a slightly lower R^2 (73%) than the final composite model (Fig. 5a). The SE (5.20%) of the final model for straight segments (Fig. 5c) was lower and the R^2 (90%) was higher than for the final composite (Fig. 5a). The final model for the concave element (Fig. 5d) had a slightly

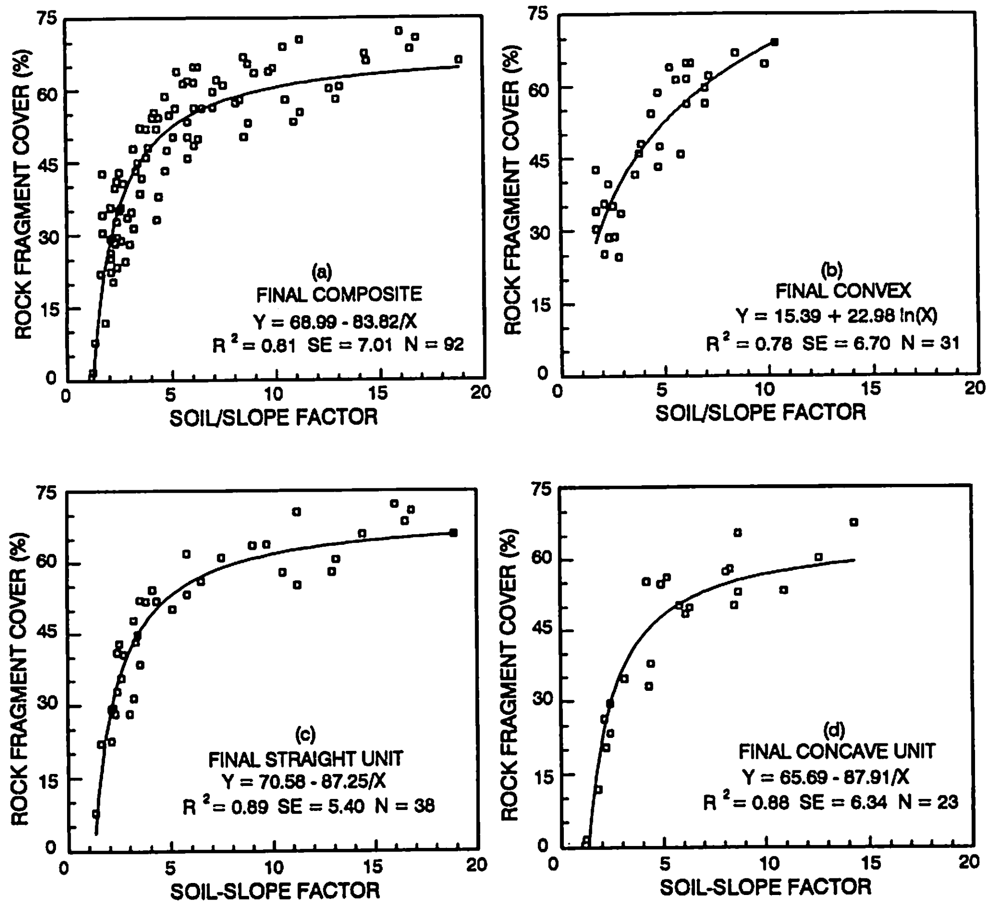

Fig. 6. Relations between the soil-slope factor and rock-fragment cover of the composite (a), convex (b), straight (c), and concave (d) units for the final models.

lower SE (5.81%) than the final composite (Fig. 5a) and the R^2 (90%) was higher than for the final composite model (Fig. 5a).

4.4.2. Soil-slope factor (SSF)

Similar increases and decreases in standard errors of estimates and coefficients of determination were obtained for the SSF final models. However, the final composite, straight, and concave models (Fig. 6a, c, and d) employed the reciprocal of the SSF as the independent variable. The final model for convex elements (Fig. 6b) used the natural logarithm of the SSF as the independent variable and yielded a slightly lower SE (6.70%) and a slightly higher R^2 (78%) than for the final composite (Fig. 6a). Both the final straight and concave models (Fig. 6c and 6d) had lower standard errors of estimates and larger coefficients of determination than for the SSF composite final model (Fig. 6a).

5. Conclusion and observation

The results of the foregoing analyses support the following conclusions and observations:

(1) There is little difference in the RFc on the various morphological units of hillslopes in the environments from which the data were collected. These results, similar to Simanton et al. (1994), indicate that even when morphological units of hillslopes are considered individually that the suite of hydrologic and geomorphic processes operating on hillslopes is likely to be similar in frequency and magnitude, or at least insufficiently different to produce concomitant differences in RFc.

(2) The differences in RFc that exist between morphological units appear to be closely related to differences in hillslope gradient or the SSF. Either of these variables can be used to make reasonable estimates of RFc. Because of the similarity in the estimate errors associated with the use of these two variables, there is little to warrant the additional time and effort necessary to collect and analyze the soil samples as required for the computation of the SSF. Hence, we recommend that estimates of RFc utilize hillslope gradient alone.

(3) There is also similarity in the estimate errors associated with the use of the composite and unit-specific models. Unless a probable reduction in estimate error of very few percent is important for a particular application, we recommend that RFc estimates utilize a composite model. This would conserve time and effort necessary to determine hillslope unit morphology.

(4) Collectively the best choice of models for most purposes is the final composite model presented in figure 5a. Soil erosion models, such as RUSLE (Renard et al., 1991) or WEPP (Lane and Nearing, 1989) that seek to account for the effects of rock-fragment covers on erosion rates may estimate the RFc on the basis of hillslope gradient alone. This model (Fig. 5a) is most appropriate for areas with environmental conditions similar to those from which the data were collected.

(5) Abrahams and Parsons (1992, p. 419) note that "models of hillslope development must recognize the critical role of surface gravel covers in controlling resistance to flow and, hence, the rate of erosion; where gravel size or concentration varies in a systematic manner down a hillslope, form resistance and erosion rate will also vary, and this systematic variation may have a significant effect on the shape of the hillslope as it evolves through time." The results of our study suggest that in these environments, the downslope variation in RFc is largely a function of changes in hillslope gradient. Consequently, systematic changes in one should be linked to systematic changes in the other.

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