A new look at soil erosion processes on hillslopes in highland Ecuador

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Abstract Field research with portable rainfall simulators in the 5186 km^2 Paute River basin in highland Ecuador indicates that footpaths generate runoff more rapidly and more often than adjacent fields and that pasture and abandoned crop lands are frequently important runoff source areas. Differential runoff production allows run-on water to play an important, but previously unexamined role in soil erosion. This research demonstrates that the study of soil erosion on mountain hillsides needs to treat the runoff dynamics of the entire hillside, rather than those of only the cultivated plots.

INTRODUCTION

The assessment, modelling and reduction of soil erosion by rainfall are commonly based on the concept that surface runoff occurs when certain threshold conditions are exceeded. Delineating runoff thresholds for different soil, rainfall, slope, and surface treatment conditions thus helps in predicting and avoiding rainfall erosion losses. In the Ecuadorian Andes, I have been surprised to find evidence of soil erosion in places where it would not have been predicted by conventional methods. One example of such unexpected soil erosion is the presence of rills in cultivated fields following relatively insignificant rainfall events.

The heterogeneity of hillslope surface characteristics and the ensuing variability of surface runoff would appear to be key to the understanding of upland soil erosion. In this paper, the results of field experiments with portable rainfall simulators are presented and discussed in order to address the question: How do the runoff and soil detachment characteristics of different hillslope surfaces affect soil erosion dynamics in the highlands of southern Ecuador?

THE STUDY AREA

This study was conducted in the 5186 km^2 Paute River drainage basin in the Andes Mountains in southern Ecuador (Fig. 1). Elevations range from 4300 a.m.s.l. at the head of the drainage basin, to 1800 a.m.s.l. at the base of the hydroelectric power dam that defines the lower boundary of the study area.

Because of the high elevation and the double rainshadow effect provided by the two cordilleras of the Andes mountains, the climate is driest in the central portion of the drainage basin and is relatively cool for its location at approximately 2 to 3°S. Annual precipitation ranges from 800 mm in the drier central region to 1400 mm in the high paramo and to a maximum of 3500 mm in the vicinity of the dam, where Amazonian air penetrates the eastern Andean cordillera via the Paute River valley (Morris, 1985). The daily mean temperature of 14.6°C at the airport in Cuenca (2527 a.m.s.l.) varies little throughout the year. At the downstream boundary of the drainage basin, the Paute River is a sixth order stream with a mean discharge of 122 $m^3 s^{-1}$. Soils in this area are derived primarily from Tertiary marine sediments (Figueroa, 1987).

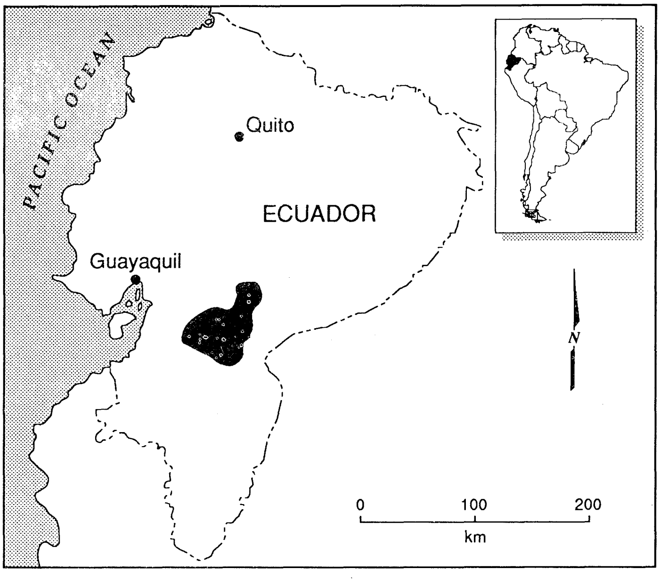

Fig. 1 Location of the River Paute study area.

Approximately 500 000 persons live in the study area, 200 000 of whom live in the provincial capital of Cuenca (UMACPA, 1989). Inhabited mountain environments in Ecuador are characterized by a mosaic of small cultivated plots and pasture lands. In the Paute River basin, the average farm size is 1.1 ha and 91.6% of the farms have <5 ha (Figueroa, 1987).

The landscape of the Paute River basin differs substantially from that of the midwest United States where large numbers of runoff plots have supported the development of empirical soil erosion modelling. In the Paute, farm units are small and frequently on steep (>50%) slopes. The primary crop is corn, often grown in association with beans. Peas are typically rotated with corn so that fields are in use for 12 months. Nearly all agricultural labour is by hand and cattle, sheep and hogs are staked in the fields to graze after the corn is harvested. An extensive network of footpaths links homes, villages, fields, pasture lands, and primary roads. About one-fourth of the Paute drainage basin is in forest or scrub vegetation.

METHODS

Rainfall experiments were conducted using two portable rainfall simulators based on the design of McQueen (1963). These instruments generate a replicable "rain shower" 15.2 cm in diameter into a ring of the same diameter inserted into the soil. A fixed 5.6 mm drop size is calculated to deliver the kinetic energy representative of natural rain having an intensity of 25 mm h^{-1}, and the experimental rainfall intensity is controlled by maintaining a constant hydraulic head in the rainfall simulator. Thus, experimental rain events may be replicated at the same or different sites. Because the apparatus uses only several litres of water per trial, it may be easily transported and set up at many different locations.

The experiments described in this paper involved 30-min simulated rains with a median intensity of 26 mm h^{-1}. This I_{30} has a frequency of 1.2 $year^{-1}$ at Cuenca (Ecuador, 1989). Antecedent soil moisture was standardized in 107 trials, including all trials reported in this paper, by pre-wetting the soil. During each trial, simulated rain that ponded at the surface within the ring was drawn off at 5 minute intervals to measure the volume of "runoff". It was filtered at the site and later dried to determine the oven dry mass of detached sediment. Splashed sediment was washed from the ring and weighed with the entrained sediment. Although the simulators may be used on sloping sites, the small size of the base and the microrelief of the land surface do not allow ponded water to obtain any noticeable downslope velocity within the basal ring.

Experimental sites were chosen to represent the range of soil and land use conditions characteristic of the drainage basin. Because little runoff or soil erosion have been previously shown to occur in the high altitude paramos (Harden, 1988), emphasis was placed on rural lands below the paramo. Land uses investigated included road and trail surfaces; actively farmed crop lands, with standing crops or stalks; abandoned crop lands; recently ploughed crop lands, characterized by large clods; grasslands, with the sod removed for the experiment; and tree cover, with either native *Polylepis* forest or plantations of *Eucalyptus* or *Pinus*. It is common for all of these land uses to occur on the same hillside. All of the experiments reported here involved simulated rain falling onto pre-wetted, unvegetated soil surfaces.

RESULTS

The values of runoff and soil detachment measured in the Paute watershed varied spatially and temporally. Spatially, analysis of variance yields no significant relationship ($p > F = 0.65$) between mapped soil type and runoff volume. Closer examination of runoff volumes and soils within land use groups shows that runoff variations relate to soil type only in recently ploughed fields (significant at the 0.08 level). Runoff volume appears to be more closely related to land use, but its overall relationship to land use is significant at only the 0.19 level. Analysis of variance shows that, within mapped soil units, the relationship between runoff volume and land use is significant at the 0.10 level for three out of nine and at the 0.15 level for five out of nine soil types. Because surface runoff is the primary control of soil erosion in this study and land use appears to be better than soil as a predictor of runoff, results are presented by land use rather than by soil categories.

Variation in runoff volume within land use categories was nonetheless high; in some instances, it was high between adjacent trials in the same field. Table 1 shows the presence and amount of runoff and the quantity of soil detached on bare surfaces in 30-min rainfall simulation experiments. The results shown in Table 1 were obtained from trials involving experimental intensities ranging from the median of 26 mm h^{-1} to the lower and upper quartiles of 19.8 and 32.6 mm h^{-1}, respectively. Because most road and trail surfaces were tested at intensities below, and most tree covered surfaces at intensities above, this range, those three within the range are included in the table for comparison only. The difference between runoff reported in categories of > 0 or > 1 ml represents the occasional presence of a trace of runoff too small (less than 1 ml) to be measured.

Seven road or trail surfaces were tested in the Paute drainage basin, using rainfall intensities ranging from 5.6 to 11.4 mm h^{-1}. In all cases, more than 1 ml of runoff was produced during the 30-min experiment; in almost all cases, runoff began within the first 5 min. Of the two tree covered sites tested in the median intensity range, one yielded runoff and sediment and one did not. This dichotomy was further explored using higher simulated rainfall intensities. Nine experiments were conducted in forests and tree plantations. In the five trials in native forests and high elevation *Pinus* plantations with *Sphagnum* ground cover, no runoff was generated, even at extremely high intensities (I_{30}

Table 1 Runoff and sediment detachment from bare, pre-wetted soil in 30-min rainfall experiments with I_{30} between 19.8 and 32.6.

Use	*N*	% Trials with runoff		Runoff: mean ± std dev.	Sediment detached: mean ± std dev.
		>0	>1 ml	(ml)	(g)
Road/trails[a]	1	100	100	190	2.6
Cropland:					
Abandoned	13	100	85	84 ± 81	5.0 ± 2.2
Active	20	85	65	50 ± 76	5.0 ± 3.9
Recently ploughed	8	75	62	74 ± 95	4.1 ± 4.0
Grassland (sod lifted)	6	100	83	106 ± 117	1.3 ± 0.7
Tree cover	2	50	50	2 ± 3	2.8 ± 4.0

[a]Because all trials on roads and trails yielded runoff at lower intensities, only one was tested in this intensity range.

up to 200 mm h^{-1}). Runoff occurred and sediment was detached in the remaining four trials in *Eucalyptus* plantations. *Eucalyptus* is commonly planted on degraded soils in highland Ecuador, but it is known to contribute little to the improvement of soil infiltration characteristics (Morris, 1985).

The mean time required to initiate runoff on a pre-wetted surface was calculated for each use category by analysing field data taken at 5-min intervals. Time to runoff, shown in Fig. 2, is generally less for roads, trails and many abandoned surfaces, and particularly high (higher than all experimental intensities) in sites with native forest. Pastures and abandoned lands produce runoff more rapidly than most cultivated fields.

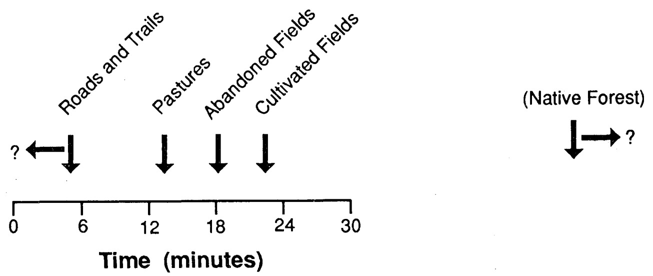

Fig. 2 Mean time thresholds for runoff on various pre-wetted surfaces.

DISCUSSION

Variations in runoff and soil detachment between land use categories demonstrate the importance of land use in determining spatial patterns of soil erosion. These results from Ecuador agree with the work of Dunne in Kenya (Dunne, 1977, 1979) which showed land use to be the dominant control of sediment yield.

The assumption that the erosional behaviour of soil is inherently related to its taxonomic classification is attractive when extrapolating soil erosion rates or determining spatial patterns of soil erosion. This assumption allows models such as the USLE to be used over large areas and often forms the basis for the designation of erosion risk zones in Geographic Information Systems (see, for example, Giordano, 1984). The poor relationship in the Paute River basin between soil and runoff, however, does not support this assumption. Although the distributions of runoff and sediment detachment characteristics had been closely related to the distribution of mapped soil units in a previous study area near Ambato, Ecuador, where soils are derived from volcanic deposits (Harden, 1990), that relationship does not hold for the clay-rich, sediment-derived soils of the Paute River basin.

Spatial variations in runoff and soil detachment at the microscale (within a few square metres) are site-specific and may be due to numerous factors including the presence/absence of macropores, microtopography, compaction by trampling, spatially heterogeneous surface treatments (e.g. furrow construction or mounding at the base of corn stalks), and spatially heterogeneous soil characteristics. Hills (1971) attributed more of the spatial heterogeneity of infiltration to biotic interference, in the form of compaction, than to natural variations among soils. In the inhabited mountain landscape of the Paute River basin, such biotic interference is widespread. Abandoned fields in the Paute, so called because they are no longer being actively farmed, exhibit a wide variety of surface characteristics, and, are thus highly variable in their runoff and erosion behaviour. In practice, these lands are not truly abandoned - cattle, sheep, and hogs graze in them, compacting the soil and limiting the growth of a protective vegetative cover. Vegetation is also slow to re-establish where crop lands were abandoned for reasons of soil degradation. Because grazing is a year-round activity and because the tropical environment of highland Ecuador lacks a freeze-thaw season that would reduce compaction, trampling impacts are cumulative. The high degree of microsite variability evident in this study and the importance of soil compaction to runoff production suggest that the use of generalized rather than site-specific soil parameters in soil erosion studies may be misleading, thus supporting the view of Govers (1989) that soil erodibility is dynamic and strongly influenced by antecedent conditions.

The existence of partial and variable runoff source areas is well-established in the literature of hydrology. Betson (1964) reported storm runoff to occur in only a small part of the watershed area in pasture watersheds in North Carolina; and subsequent papers by Betson & Marius (1969), Dunne & Black (1970), and Hewlett & Troendle (1975) further developed the partial- and variable source area concepts. It is important that this concept be extended to

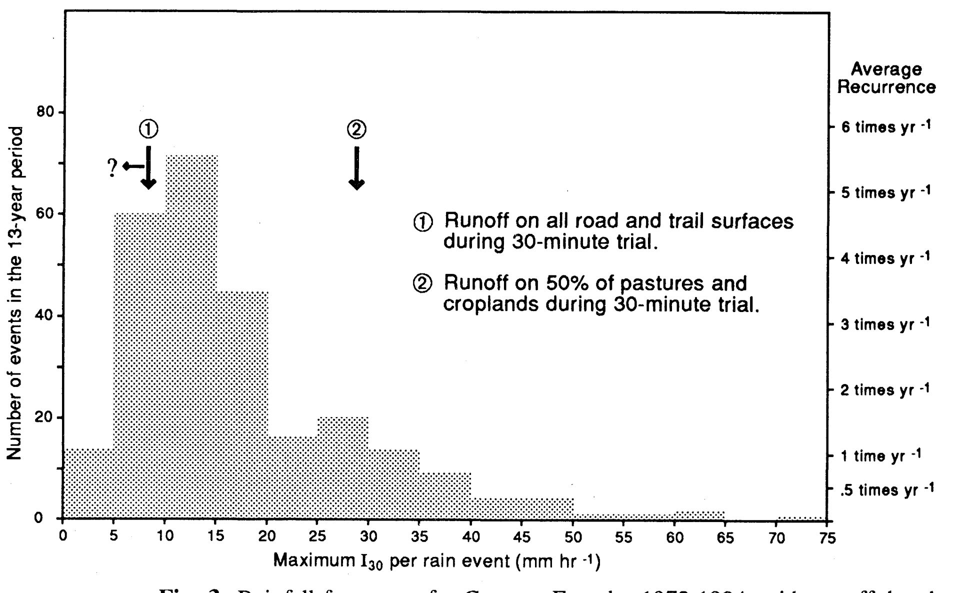

Fig. 3 Rainfall frequency for Cuenca, Ecuador 1972-1984, with runoff thresholds for trails and agricultural lands.

the heterogeneous landscapes of inhabited mountains. Simulated rainfall experiments in the River Paute drainage basin demonstrate that roads and trails play a key role as partial area runoff contributing networks, and that abandoned and pasture lands generate runoff more frequently than actively cultivated and recently ploughed crop lands or forest.

While the spatial heterogeneity of inhabited mountain environments helps to account for the variety of sources of surface runoff, it also provides runoff sinks. These may be high infiltration capacity surfaces, such as recently ploughed fields, or topographic barriers that block runoff and sediment transport and prevent downslope soil losses. The concept of sediment and runoff sinks forms the basis for many conservation practices. Cultivation of the soil may legitimately be the primary cause of soil loss in areas where uncultivated lands have good vegetative cover and high infiltration capacities, but the present study indicates that ploughing the clayey soil of Paute hillslopes improves infiltration and, relative to abandoned and compacted surfaces, retards runoff and sediment transport.

Differences in the time between onset of simulated rainfall and the initiation of surface runoff within a short duration rain event demonstrate an important temporal aspect of partial area runoff. The rapid onset of runoff on roads and trails makes them a primary target for soil loss and (along with muddy feet) helps to explain the greater cumulative losses found from entrenched trails on mountain hillsides compared to adjacent cultivated lands. Although wholesale soil loss in the Andean region is probably rightly attributed post-colonial activities (de Noni *et al.*, 1986), extensive pre-Colombian trail systems may also have played an important runoff contributing role. Temporal differences in rainfall runoff become more noticeable when the soil is not already wet at the onset of rain, since the time needed to generate surface flow is far less on compacted than on uncompacted dry surfaces (Harden, unpublished data).

Differences in time to runoff between land uses appear during single rain events, when trail surfaces begin to initiate runoff prior to crop lands (Fig. 2). These differences in runoff initiation are amplified over the course of a year, since the frequency of rain events exceeding the runoff thresholds of road and trail surfaces is greater than of those yielding runoff on ploughed fields (Fig. 3). Some forest surfaces may never yield surface runoff.

The existence of partial areas of runoff production and sediment transport leads to the presence of run-on water on surfaces that would otherwise not experience runoff. It thus has extremely important implications for the study of soil losses at the hillslope or watershed scale. Particularly in inhabited mountain watersheds, where plots tend to be small and trails tend to be frequent and steep, the study of erosion needs to treat the entire hillside rather than be based on homogenous cultivated plots. "Anomalous" rill erosion that I had observed in highland Ecuador can be explained by looking at site-specific factors, especially the presence of upslope runoff sources. The presence of a trail, pasture, abandoned field, or other low infiltration surface upslope from a cultivated field can (a) cause surface flow to run onto the cultivated field during a rain event that would otherwise not initiate surface flow there and (b) cause surface flow to be present in the field sooner during a rain event, setting the stage for increased erosion. Such interaction of landscape units occurs where barriers are not present and surface flow is able to pass between units.

Dunne & Dietrich (1982) estimated the sediment contributions from roads in densely settled subsistence agricultural areas in both wet and drier regions of Kenya to be 25 to 50% of basin yields. As in Kenyan regions, roads and trails are estimated to occupy about 1% of the area of the Paute River basin in Ecuador. Preliminary observations in the Ecuadorian drainage basin indicate that, although interaction with less efficient transport surfaces leads to generally poor delivery of runoff and sediment from footpaths to stream channels, the interaction itself is an aspect of upland erosion that merits further study. Dunne & Dietrich (1982) did not link road erosion with a lowering of the productivity in agricultural land in Kenya, but the present work in Ecuador suggests that run-on water from road and trail runoff, as well as that from pastures and abandoned lands, may be responsible for a significant portion of annual soil losses from crop lands.

This study demonstrates the need for soil erosion research and models to extend beyond crop lands and to include potential upslope contributing areas. Since the distribution of overland flow-producing areas can be expected to influence the composition of compound overland flow downslope (Hills, 1971), identifying surface runoff patterns on entire hillslopes will contribute to hydrogeochemical modelling. A further implication of this study is that conservation efforts should look beyond the small farmers, whose activities may cause their lands to play greater roles in the upland erosion system as runoff sinks than as sediment sources.

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