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Soil Erosion and Sustainable Mountain Development

Experiments, Observations, and Recommendations from the Ecuadorian Andes

Accelerated soil erosion is a common and environmentally destructive consequence of development, especially in mountain regions. Soil erosion is of special concern in agricultural lands, but agriculture is only one of many development activities that greatly accelerates soil erosion processes. Road building, trail use, excavation, extractive activities, and construction also can cause severe soil erosion. Soil conservation technologies are relatively simple and well known, but often they are not applied where they could be most effective because the connections between different elements of the landscape (eg, roads and cultivated fields) are not well understood. This paper reviews two previous soil erosion research projects in the Ecuadorian Andes involving field observations and small-plot rainfall simulation experiments and provides examples of erosion-related landscape connections at the drainage basin scale. In light of the important influence of roads, trails, and abandoned farmlands on soil erosion processes on Andean slopes, sustainable management of the soil resource requires both looking across and managing across conventionally delineated boundaries in the natural and altered landscapes of mountain regions.

***Keywords**: Soil erosion; roads; abandoned land; hillslope runoff connections; Andes; Ecuador.*

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Introduction

In mountain regions, accelerated soil erosion is a common and environmentally destructive consequence of development. Soil erosion has been extensively studied by agricultural researchers, and reducing soil erosion is widely recognized as a key to sustainable agriculture. Soil loss lowers crop productivity, changes on- and off-site hydrology, and creates off-site deposits that may be damaging (Pimentel et al 1995). Cook (1988) has reported that, in combination, the mechanical, chemical, and biological changes caused by soil loss constitute the greatest drawbacks for cultivation on steep slopes. Many contemporary landscapes, including one third of the Ecuadorian Sierra, have been severely eroded in the past (Gómez 1988; De Noni et al 1992, 1996), and examples of mountain regions with long legacies of soil loss can be found across the globe (eg, McNeill 1992). To maintain the potential for future cultivation and to protect water resources, it is important for any further development in mountain regions to involve dedicated efforts to avoid soil loss.

Much is well known about soil erosion, especially about the general characteristics of soil, rainfall, and topography that favor it (eg, Bennett 1939; FAO 1978). Essentially, soil is vulnerable to erosion where it is exposed to moving water or wind and where conditions of topography or human use, such as steep slopes, compacted surfaces, removal of vegetation, or years of plowing, increase the force of the moving fluid or decrease the cohesion of the soil.

Techniques for minimizing soil erosion in agricultural fields are also well known. The most effective way to control erosion due to rainfall and wind is to ensure that the land is densely vegetated (Sanders 1988). Where that is not feasible, maximizing rainfall infiltration (minimizing runoff) and limiting opportunities for soil to be lost from the field are the two essential components of soil conservation. In much of the Andes, restricted soil moisture is thought to be the most limiting factor in crop production (Vonk 1988); therefore, conserving the infiltration and water-holding capacities of the soil is an important aim of Andean soil conservation. But, although soil conservation practices are well established and generally low tech, they are not implemented everywhere because soil loss is a long-term problem, often overshadowed by short-term problems such as market prices and the costs of fertilizers, transportation, or medical care (Hudson 1981; Stadel 1989). Political, economic, and historic considerations also affect land management practices and programs (Blaikie and Brookfield 1987).

At the broader scale of mountain drainage basins, agricultural lands are only one component of a larger system of runoff and soil movement. To increase the sustainability of development in mountain regions, it is therefore essential to understand these broader patterns and to identify additional factors contributing to soil loss and changes in rainfall runoff beyond the factors in a single plot or property. In this paper, I discuss two themes that emerge from earlier research: (1) the erosional role of roads and trails and (2) the effects of land abandonment on rainfall infiltration and sediment detachment. Considering these themes in the context of the sustainability of development activities in mountain regions, I offer recommendations for soil and water management.

Research methods

Field research for both of these themes used portable rainfall simulator-infiltrometers to investigate site-specific rainfall runoff responses and rates of surface sedi-

FIGURE 1 Design of a hand-portable rainfall simulator-infiltrometer based on McQueen (1963).

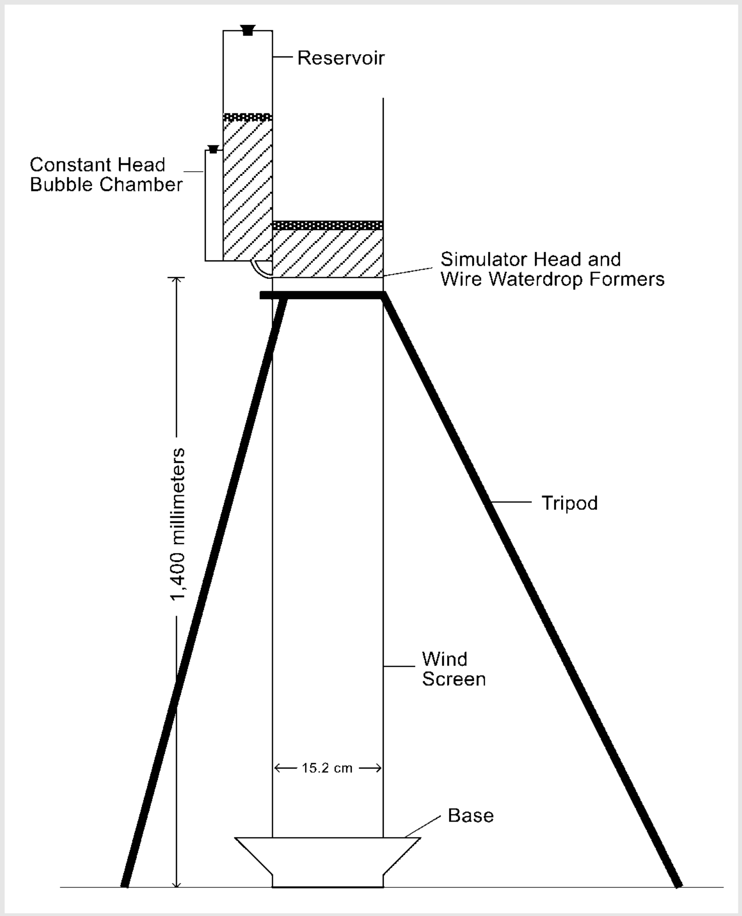


FIGURE 2 Use of a rainfall simulator-infiltrometer on a trail near Quito, Ecuador. (Photo by author)

ment detachment by simulated raindrops. The portable rainfall simulator-infiltrometers, based on McQueen's (1963) design (Figure 1), have small circular plots (182 cm^2) and constant drop size. Pre-wetting the plots controlled antecedent moisture. An infiltration ring with a flared collar was set into the soil directly beneath the simulator-infiltrometer to define the plot area and to prevent any water that did not infiltrate into the soil from leaving the plot. On highly compacted surfaces, we used bentonite clay to seal the ring at the soil surface. Direct observation confirmed that the 15-cm wide flared collar caught most of the soil particles that were detached by the splash of raindrops. At 5-minute intervals during each 30-minute rainfall simulation experiment, the increment of simulated rainfall (rain) input was recorded, and any pooled water (runoff) collected and measured. After the 30-minute experiment, the collected runoff, combined with the particles caught on the flared collar, was filtered and saved to be oven dried and weighed in the laboratory.

This experimental strategy made it possible to repeatedly sample runoff and splash detachment characteristics at multiple sites on different soils under different land uses. The experiments allow comparisons of runoff rates and soil detachment by raindrop impact between sites at which the same experimental procedure was used, thus providing a basis from which to understand spatial patterns of vulnerability to soil erosion over a broad area. In a runoff-generating natural rain, sediment entrainment by the tractive force of water flowing downhill would be able to erode more soil than that dislodged by splash alone. However, splash detachment rates from very small plots can exceed soil erosion rates determined in large, conventional plots for comparable natural rainstorms because conventional measures require entrained particles to be transported to the lower edge of the plot, usually tens of meters, before being trapped and measured. Additional benefits of conducting microplot experiments across a large area were the accompanying opportunities to observe rainfall at many different sites and to consider how those sites fit into the integrated dynamics of the broader drainage area.

Results

The erosional role of roads and trails

Previous experiments with a portable rainfall simulator-infiltrometer in southern Andean Ecuador revealed that differences in runoff and sediment detachment between soil units were very small compared with differences between different land uses (Harden 1991). Although most soil erosion is commonly thought to occur on agricultural lands, rainfall simulator-infiltrometer experiments in recently plowed fields in soils of the Río Paute drainage basin in southern Andean Ecuador absorbed all rainfall at frequently occurring intensities without generating sufficient runoff to erode soil. Later in the growing season, as soil between the plants (primarily maize) became more compacted, soil detachment and rainfall runoff rates in agricultural fields increased, but evidence of soil washed out of a cultivated field by natural rainfall runoff was extremely rare. If agricultural fields were not generating rainfall runoff and agricultural soil was not leaving the fields, what were the sources of rapid runoff and sediment in tributary streams when it rained? In the field, rainfall runoff was observed on the densely compacted surfaces of roads and trails during rainstorms, even when no runoff was evident in fields or pastures.

To investigate the hydrologic and erosional role of roads and trails, I measured time to runoff, runoff volume, and detached sediment at pairs of road/trail and nearby off-trail sites using portable rainfall simulator-infiltrometers. Off-trail sites, typically less than 10 m from the road or trail site, were selected to represent local conditions and to be outside the visible range of compaction by road or trail use. The experiments simulated a replicated 30-minute rain of low to moderate intensity (10–30 mm/h) at 17 sites (8 pairs with 1 additional replication) in the Quito region (Figure 2), 18 sites in the Southern Appalachian region of the United States (Harden 1992), 17 sites at the Jatun Sacha Biological Station on the Napo River in Ecuador, and 31 sites at La Selva Biological Research Station in Costa Rica (Wallin and Harden 1996).

The off- and on-road experiments (Harden 1992; Wallin and Harden 1996) demonstrated that nearly all of the roads and trails generate measurable runoff within the first 5 minutes of most rain events but that, after 30 minutes of simulated rain, only 0–50% of nonpath surfaces generated runoff (Figure 3). Compared with adjacent sites that are cultivated, grassy, or in shrub, the compacted surfaces of paths and roads generate greater runoff volumes, initiate runoff at lower rainfall intensities, and produce runoff sooner during a rain event. More frequent and higher magnitude production of surface runoff on unpaved roads and trails is thus able to cause more frequent erosion of those surfaces and others connected to them. Moreover, many roads and trails on hillslopes can very efficiently convey sediment to stream channels (Figure 4). Other researchers, working in Thailand (Ziegler and Giambelluca 1997) and in the US Virgin Islands (MacDonald et al 1997), have

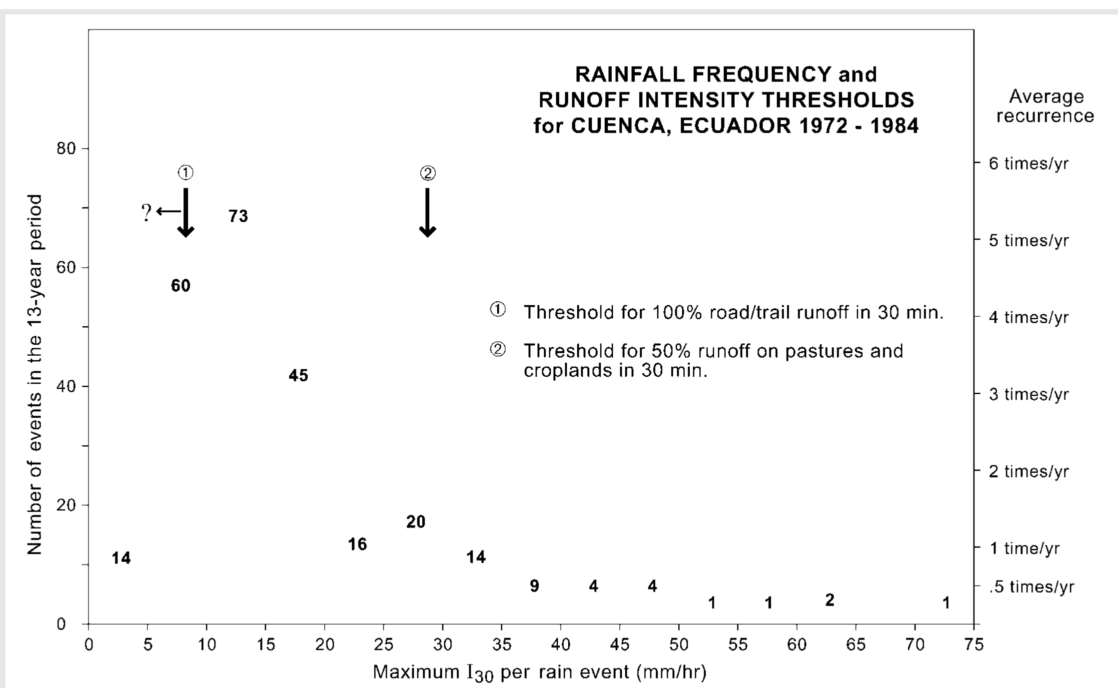


FIGURE 3 Times of appearance of surface runoff in rainfall simulation experiments in the Paute watershed, Ecuador (numbered arrows), compared with the frequency distribution of 30-minute rainfall intensity.

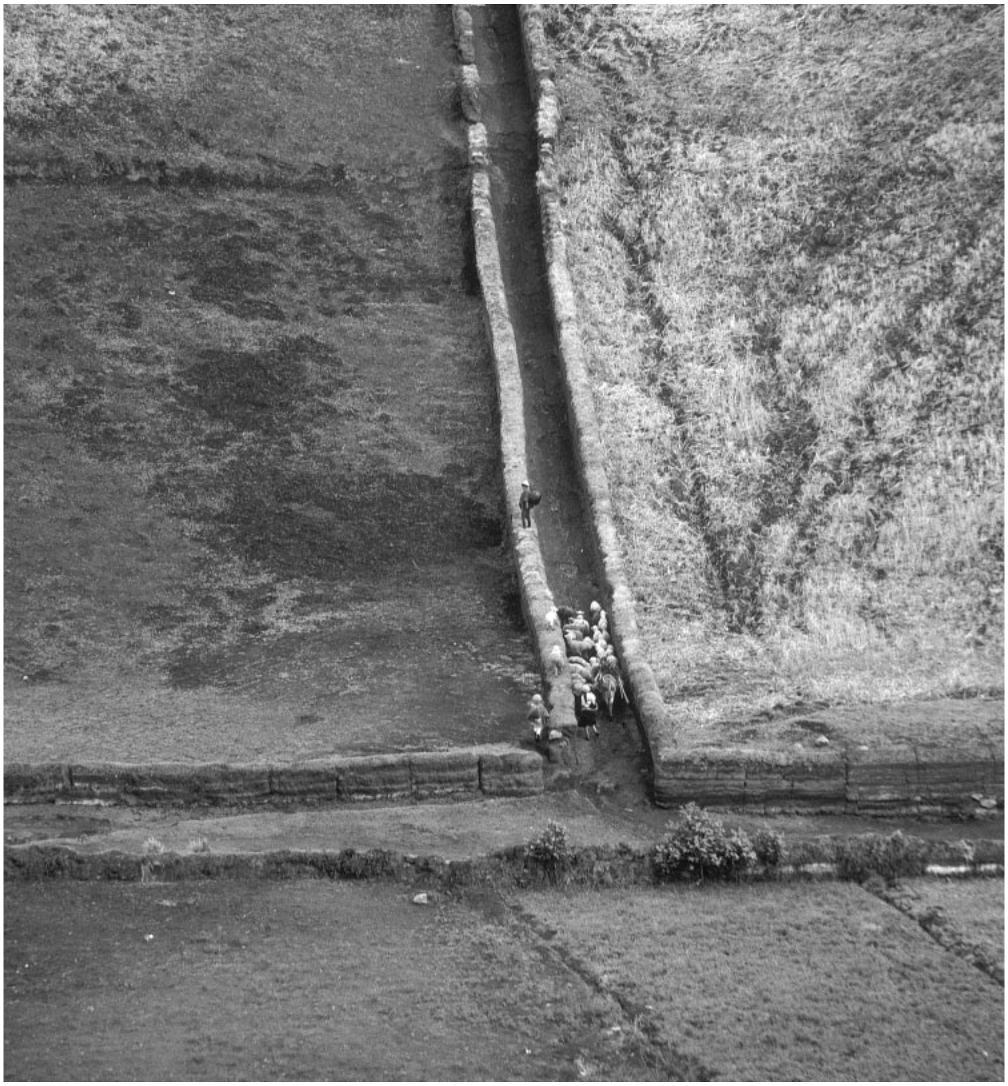


FIGURE 4 Eroded soil from the field at right is trapped by the wall, but runoff and eroded soil from the field at left and from the path between directly flow on to other pathways and into a tributary stream of the Río Ambato. (Photo by author)

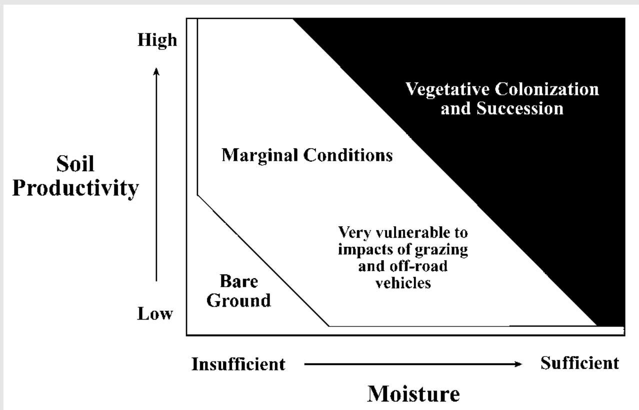
similarly identified rural roads as significant contributors to sediment movement by rainfall runoff.

The very significant differences in rainfall-runoff response between trail versus off-trail sites (Wallin and Harden 1996) are important in explaining patterns of differential runoff generation in drainage basins and in understanding the spatial connections between runoff-generating sites and receiving streams. In the long-term, the greater runoff and erosion rates of roads and trails cause them to become incised into the land surface. Many old Andean pathways, especially those used by cattle, horses, and sheep, are incised 1–2 m. Overland flow with entrained soil particles enters rivers where trails approach or cross them. Off-site consequences of road erosion, then, include changes in aquatic habitats, reduction of the useful capacity of downstream reservoirs, and increased potential for flooding downstream. Furthermore, runoff on trails may spill over and flow on other surfaces, such as agricultural fields. Even in a storm that is not sufficiently intense to initiate runoff on agricultural surfaces, concentrated runoff spilling onto fields from uphill trails or roads frequently causes visible erosion.

Abandoned land (previously cultivated)

An earlier research project involved 108 rainfall simulation experiments on soil surfaces with different land uses in the 5186-km^2 drainage basin of the Río Paute in central Andean Ecuador (Harden 1991). Nearly one quarter of the rainfall simulation experiments were on land that had once been cultivated but which had been abandoned or left in a state of long-term fallow. In ana-

FIGURE 5 Conceptual model of the relationship between soil productivity and moisture status of abandoned lands. The diagonal (white) zone in the center represents the marginal conditions that are especially susceptible to soil erosion.



lyzing the resulting runoff and sediment detachment across different land uses, it soon became apparent that, like roads and trails, abandoned and fallow lands produced a disproportionate share of runoff and mobile sediment.

Despite the variability in runoff generation and sediment detachment with a given land use, runoff coefficients on abandoned and fallow lands (median = 0.35) significantly exceeded those on recently plowed sites (median = 0.08) and in fields with mature corn plants (median = 0.02) (Harden 1996). Higher sediment detachment rates (dry mass/mm rain) by the simulated rain on abandoned and fallow lands demonstrated the potential for higher soil erosion rates on surfaces with only poor vegetative cover to protect them from rainfall (and wind) erosion. The maximum sediment detachment rate measured, 3.7 g/mm, was on abandoned land, while the maximum on a mature corn field was 1.7 g/mm. Laboratory analysis of total percent carbon from 91 sites revealed significantly less organic matter in surface soils on abandoned or fallow fields (median 0.4%) than those on cultivated fields (median 20.9%), hence less capacity to retain moisture and nutrients (Harden 1996).

Contrary to the expectation that vegetative succession on fallow or abandoned land improves soil conditions and decreases erosion, results from the Río Paute drainage basin rainfall simulation experiments are similar to those of Lasanta et al (1995), who found land abandonment in the Pyrenees to often lead to further soil degradation. One of the many reasons for land abandonment is low soil productivity. Two additional factors that have limited vegetative succession in both the Ecuadorian Sierra (Harden 1996) and the Pyrenees (Lasanta et al 1995) are lack of moisture, which hinders the establishment of new plants, and informal grazing on abandoned land, which prevents revegetation from surviving. Based on these earlier results, I offer the conceptual model, shown in Figure 5, for anticipating problems associated with abandoned or fallow land. It indicates that land abandonment would not necessarily promote soil erosion in environments having sufficient moisture and soil quality, and it shows that abandoned soils are especially vulnerable to erosion and further degradation under conditions of lower moisture and soil productivity.

The erosional importance of abandoned and fallow land raises major questions about the implementation of soil conservation programs. It is not always easy to gain the cooperation of farmers in soil conservation efforts, but it is even more difficult to engage the interest and cooperation of off-site landowners and anonymous members of the local community whose animals graze on unused land. Rates of land abandonment and long-term fallow appear to be increasing as the rural population declines in parts of the Ecuadorian Andes. In a 7-canton rural subregion of the southcentral Andean sector of Ecuador, for example, a census undertaken by the University of Cuenca in 1995 found 30.5% of 39,995 homes abandoned (Universidad de Cuenca 1998). Thus, as many occupants of rural mountain lands choose to move to urban areas and foreign countries in search of more comfortable or more promising lifestyles and as others are driven from lands with decreasing productivity, erosional losses of valuable topsoil will accelerate unless measures are taken to allow a good cover of vegetation to protect the soil.

Sustainable use of the soil resource in mountains

Development in mountain regions may involve extending or intensifying agriculture or it may involve other changes in land use. Land uses associated with mountain development include the following:

- Recreation: hotels, cabins, second homes, hiking, skiing, cycling, ecotourism, camping, fishing, swimming, picnicking.
- Microwave towers, communications equipment.
- Resource extraction: mining, lumber, commercial flower cultivation, increased agricultural pressure.
- Industry.
- Additional homes, villages, towns, cities to house increased population.
- Construction and maintenance of infrastructure, such as irrigation canals, roads, pipelines, power lines.

These land uses typically involve building new roads. Higher proportions of impervious surfaces, whether due to roads, parking lots, or trails, speed up rainfall runoff processes, and faster surface runoff provides more energy for soil erosion. Other specific effects of mountain development projects that accelerate soil erosion include:

- Removal of vegetation, exposing soil to forces of erosion.
- Excavation that exposes soil to forces of erosion.
- Spillover effects onto agricultural land.

In all of the land use changes listed above and in the absence of mitigating measures, runoff to rivers will increase, opportunities for soil erosion will increase (dramatically during the construction phase), and less moisture will be stored in hillslope soils. Even ecotourism at a local scale compacts surfaces and can contribute to erosion and increased runoff (Wallin and Harden 1996); it also increases the flow of traffic and the need for infrastructure (Wall 1997).

Because the steep and often long slopes of mountain regions exacerbate the erosional consequences of development activities, soil conservation should be a key component of sustainable development in mountain regions. Writing of rural Mexico, Landa et al (1997) argue that mountain soils should be saved for future agricultural production by the inhabitants of mountainous areas, who are often the rural poor. Although the most effective and cost-effective soil conservation practices are site specific (Sanders 1988), some themes can be generalized across regions. Hudson (1988), for example, notes that cultivation will never be sustainable on extremely steep (>45%) slopes. A second theme that applies across regions is the need to examine the spatial linkages that favor rainfall runoff and soil movement between parcels of land on the same mountainside.

Different land uses on mountain slopes are linked by their uphill–downhill spatial relationships. Because upslope activities such as road construction and land abandonment can generate runoff that flows to and degrades soil on downslope lands, both soil conservation and economic development projects need to assess these linkages. Studying rainfall erosion only in agricultural fields does not yield a complete picture of the erosional consequences of development in mountain regions. From the earlier research projects summarized in this article, it has become apparent that any program of soil (and water) conservation or of sustainable development in mountain environments must address the role of roads and trails in generating runoff and moving sediment and the role of abandoned lands, if present, in leading to further soil degradation. To that end, I offer the following recommendations for both researchers and managers:

1. Approach hillsides and rivers as connected systems, examining entire spatial connections between runoff-generating surfaces, surfaces susceptible to soil erosion, and channels that deliver eroded soil to streams and rivers.
2. Provide drainage and sediment traps for water flowing down roads and paths. Such drains and traps should accommodate used irrigation water as well as rainfall runoff.
3. Coordinate efforts between agencies to avoid practices that degrade soil, such as the use of tractors on steep slopes.
4. Recognize that any bare ground is subject to soil erosion. As shown in earlier work (Harden 1996), fallow and abandoned lands, especially those previously degraded, can have much higher erosion rates than cultivated sites. Reducing erosion on abandoned and fallow lands may necessitate special efforts by family, community members, or agency personnel.

Although the value of basin-scale attention to soil and water conservation may need to be explained to individual mountain farmers (Sanders 1988), insights gained from field-based observations at broader scales can contribute to those from site-specific research to generate more successful strategies to eliminating site-specific soil erosion problems. Seeing the linkages between runoff- and erosion-generating elements of the land surface is essential to conserving soil and increasing the sustainability of development actions.

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REFERENCES

Bennett HH. 1939. *Soil Conservation*. New York: McGraw-Hill.
Blaikie P, Brookfield H. 1987. *Land Degradation and Society*. London: Methuen.
Cook M. 1988. Soil conservation on steep lands in the tropics. *In:* Moldenhauer WC, Hudson NW, editors. *Conservation Farming on Steep Lands*. Ankeny, IA: Soil and Water Conservation Society and World Association of Soil and Water Conservation, pp 18–22.
De Noni G, Viennot M, Trujillo G. 1992. Soil erosion and conservation research in Ecuador. *In:* Hurni H, Tato K, editors. *Erosion, Conservation, and Small-Scale Farming.* Berne: Geographica Bernensia, International Soil Conservation Organisation (ISCO), and World Association of Soil and Water Conservation (WASWC), pp 549–558.
De Noni G, Viennot M, Trujillo G. 1996. Agricultural erosion in the Ecuadorian Andes. A natural and historical phenomenon. *In:* Roose E, editor. *Land Husbandry—Components and Strategy.* FAO Soils Bulletin 70. Rome: Food and Agriculture Organization of the United Nations (FAO), pp 321–329.
FAO (Food and Agriculture Organization of the United Nations). 1984. *El Suelo: Como Conservar el Suelo*. Edición Española. Rome: FAO.
Gómez N. 1988. *Erosión y Conservación de Suelos en Ecuador*. Quito: Surco, Editores Agropecuarios.
Harden C. 1991. Andean soil erosion. *National Geographic Research & Exploration* 7:216–231.
Harden C. 1992. Incorporating roads and footpaths in watershed-scale hydrologic and soil erosion models. *Physical Geography* 13:368–385.
Harden C. 1996. Interrelationships between land abandonment and land degradation: A case from the Ecuadorian Andes. *Mountain Research and Development* 16:274–280.
Hudson NW. 1981. Non technical constraints on soil conservation. *In:* Tingsanchali T and Eggers H, editors. *South-East Asian Regional Symposium on Problems of Soil Erosion and Sedimentation.* Bangkok: Asian Institute of Technology, pp 15–26.
Hudson NW. 1988. Tilting at windmills or fighting real battles. *In:* Moldenhauer WC, Hudson NW, editors. *Conservation Farming on Steep Lands*. Ankeny, IA: Soil and Water Conservation Society and World Association of Soil and Water Conservation, pp 3–8.
Landa R, Meave J, Carabias J. 1997. Environmental deterioration in rural Mexico: An examination of the concept. *Ecological Applications* 7:316–329.
Lasanta T, Pérez-Rontome C, García-Ruiz JM, Jachin J, Navas A. 1995. Hydrological problems resulting from farmland abandonment in semi-arid environments: The Central Ebro Depression. *Physics and Chemistry of the Earth* 20:309–314.
MacDonald LH, Anderson DM, Dietrich WE. 1997. Paradise threatened: Land use and erosion on St. John, US Virgin Islands. *Environmental Management* 21:851–863.
McNeill JR. 1992. *The Mountains of the Mediterranean World: An Environmental History*. Cambridge: Cambridge University Press.
McQueen I. 1963. *Development of a Hand-Portable Rainfall Simulator Infiltrometer.* US Geological Survey Circular 482. Washington, DC: US Geological Survey.
Pimentel D, Harvey C, Resudarmo P, et al. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267:1117–1123.
Sanders DW. 1988. Soil and water conservation on steep lands: A summary of workshop discussions. *In:* Moldenhauer WC, Hudson NW, editors. *Conservation Farming on Steep Lands*. Ankeny, IA: Soil and Water Conservation Society and World Association of Soil and Water Conservation, pp 275–282.
Stadel C. 1989. The perception of stress by campesinos: A profile from the Ecuadorian Andes. *Mountain Research and Development* 9:35–49.
Universidad de Cuenca. 1998. *Censo: Familia, Mujer, Migración Internacional y Actividades Productivas*. Cuenca, Ecuador: Universidad de Cuenca, Instituto de Investigaciones.
Vonk J. 1988. Soil conservation in Peru. *In:* Moldenhauer WC, Hudson NW, editors. *Conservation Farming on Steep Lands*. Ankeny, IA: Soil and Water Conservation Society and World Association of Soil and Water Conservation, pp 242–246.
Wall G. 1997. Is ecotourism sustainable? *Environmental Management* 21:493–491.
Wallin T, Harden C. 1996. Estimating trail-related soil erosion in the humid tropics: Jatun Sacha, Ecuador, and La Selva, Costa Rica. *Ambio* 25:517–522.
Ziegler AD, Giambelluca TW. 1997. Importance of rural roads as source areas for runoff in mountainous areas of Northern Thailand. *Journal of Hydrology* 196:204–229.