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Erosion Processes in High Mountain Agricultural Terraces in Peru

Old developed systems of agricultural terraces are found in settled areas with high relief in different parts of the world. The present trend to abandon many of these terraced areas constitutes a process that increases erosion and sediment yield values following the collapse of supporting walls. This paper addresses the problem of changing human activities in the fragile environment of the historical terraces in the Central Andean mountains of Peru. The study is based on field experiments. Eight small plots were installed in the Santa Eulalia basin at altitudes of 2800 m and up to 3650 m. Annual run-off coefficient values were less than 5% and sediment yield values less than 1 g/m^2 on the experimental plots. Daily rainfall intensity does not exceed 10 mm/d on most rainy days. Simulation of rainstorms by sprinklers was performed on terraces with different physiographic characteristics, lithology, soil, exposure, slope, altitude, degree of abandonment, and vegetation cover. Rainfall simulation tests revealed that run-off is high on steep, nonvegetated slopes and very low on grass-covered, low-angle slope terraces. A morphometric analysis was conducted on about 300 terraces with the same physiographic parameters. The average terrace area was 170 m^2, and most terraces surveyed were in a semiabandoned stage. Terrace degradation was noticeable by wall swelling, collapse, and deterioration of wall and terrace structure. Terrace degradation is a function of physical, economic, and social processes, which are linked and irreversible.

Key words: *soil erosion; agricultural terraces; Peru; plot experiments; rainfall simulation; morphometric analysis.*

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Introduction

Peruvian landscapes are among the settled areas with the highest relief in the world and are characterized by an old system of agricultural terraces (Spencer and Hale 1961). Dry and semiarid habitats at high altitude are the most common in the Andean region, and ecosystems are characterized by intensive erosive processes (Llerena 1987). Agricultural land use is a major factor affecting erosion processes; corn, potatoes, and, recently, alfalfa, the most important crops in Peru, are considered to be soil erosive (Felipe-Morales 1987). The maintenance or abandonment of terraces is a crucial factor in determining the trend of the erosive processes.

Abandonment of agricultural land is widespread in the mountainous areas of Europe. Erosion processes increased due to the abandonment of terrace fields in Spain (Garcia-Ruiz 1989; Cerda-Bolinches 1994), Greece (Lehman 1993), and in old land terrace systems in Israel (Inbar and Zgaier 1996).

No accurate inventory of the total terrace area in Peru exists, but it has been roughly estimated at about 2 million hectares (CEPAL 1989). Denevan (1986) estimates that 62% of the terraces in the Colca Valley are abandoned and 91% are abandoned in the high areas. The main reasons for abandonment are socioeconomic, with a clear tendency of increase of the urban population. According to the 1976 census, 75% of the population lived in the sierra and less than 10% in the cities. By 1995, the urban population had increased to 71% (Yepes 1992; Webb and Fernandez-Baca1995).

Extensive and detailed studies on cultural, economic, and anthropological aspects of the Peruvian agricultural terraces were published by Cook as early as 1916, followed by Donkin (1979), Denevan (1986, 1988), Treacy (1989), and others. Soils in the Colca Valley terraces have been studied by Sandor and Eash (1995). Few attempts have been made to study the water–soil relationship and the geomorphic processes affected by the use and abandonment of terraces (Felipe-Morales 1987). The aim of the present paper is to determine sediment yield quantitatively from abandoned terraced areas and to analyze the erosion processes.

This paper addresses the problem of changing human activities in the fragile environment of the historical agricultural terraces in the Central Andean mountains of Peru. The high degree of connectedness of this coupling is a major threat to one of the oldest achievements of humankind in the development of the Earth's natural resources. For over a millennium, soil accumulated and was retained on man-made terraces, which were the economic basis for a flourishing culture. Abandonment of the terraces leads to an increased rate of soil erosion and sediment yield values (Cotler 1985; Treacy 1989). Like the Himalayas, the Andes mountain ecosystems are sensitive to small disturbances, with consequences that are often irreversible (Ahmad 1993). Land degradation is determined by social change in farming communities and is one of the consequences of the migration of the young rural population to overcrowded urban areas.

The study area

The Santa Eulalia River is an affluent to the Rimac River and forms a large alluvial plain and delta on which the city of Lima has developed. It flows from the divide in the Central Andes, at a height of 5000 m, to a junction with the main branch at 900 m, a distance of 60 km with an average slope of 6.6%. The study sites are near the villages of San Juan de Iris and San Pedro de Casta at altitudes between 2500 and 3700 m (Figure 1).

The Santa Eulalia basin covers an area of 1012 km^2 (Barriga Ruiz 1994). In the upper basin, the main rock types belong to the tertiary volcanic series, while in the lower basin, intrusive rocks belonging to the coastal batholith predominate (ONERN 1982). Loose, recent alluvial material is found in the valleys and on valley slopes. An alluvial terrace150 m above the river channel, probably from Holocene times, indicates a very rapid incision process due to the uplifting of the Andes Mountains. Valley slopes are 1000 m deep and more, with slope angles reaching 50° and 60°. Frequent land-

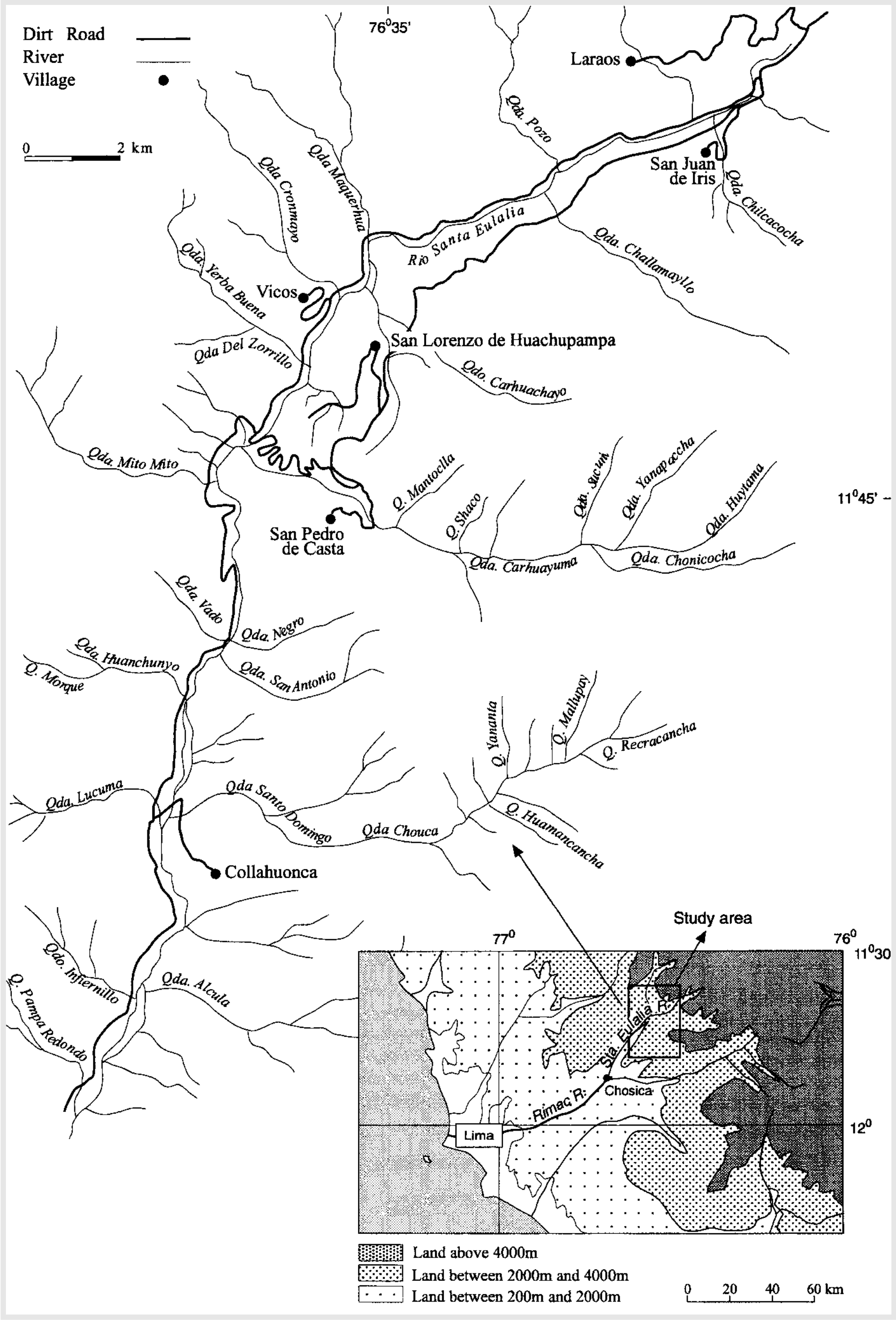

FIGURE 1 Location map of the study area in the upper basin of the Santa Eulalia River.

FIGURE 2 View of the steep slopes in the Santa Eulalia river valley. Paths of frequent debris flows, known locally as *huaycos*, are clear. Terraces are built on slopes steeper than 400°. (Photo by authors)

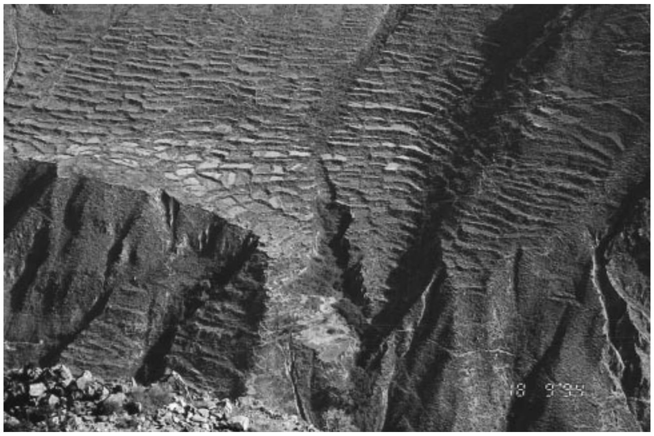

FIGURE 3 View of San Juan de Iris village above the Santa Eulalia River, at an altitude between 3500 and 3800 m. (Photo by authors)

slides, known locally as *huaycos*, left visible paths and alluvial cones (Figure 2). Due to the rapid incision rate, channels are narrow and no floodplain has developed. Due to the rugged landscape, settlements are distributed on the higher flat terrains below available water sources.

The soils, mainly Lithosols, are shallow, with high infiltration rates. Annual rainfall of 350 mm or more makes them fertile and suitable for cultivation of grain (Tosi 1994). Variability of soils and vegetation is in accordance with the ecological altitudinal gradient. Residual soils with varying depths up to 1 m or more are found below 3800 m on the mountain slopes; they are mainly silty and well drained. The terrace soils have been defined as Torroxic Haplustolls, with an anthropic profile overlying the colluvial material. Carbonates are scarce and pH is neutral. Organic matter content is about 2 to 4% in the upper horizon and decreases with depth (Masson 1986). Long-term agricultural practices left higher concentrations of phosphorous, organic carbon, and nitrogen in terrace soils, even in the abandoned ones (Sandor and Eash 1995).

A clear altitudinal gradient of the mean annual precipitation, from 800 mm in the high mountain zone above 4000 m to 100 mm at an elevation of 1000 m, exists down to the coastal zone. Rains are concentrated in the southern hemisphere summer from December to April, but in the high mountains, snow and rain precipitation starts in August. The mean annual precipitation for the Santa Eulalia basin is 436 mm. The maximum river discharge is in March and the minimum is in June. Maximum flood peaks are about 50 m^3/s. In the upper mountains in the divide zone, small lakes are used for hydroelectric water storage and partially for local irrigation. Since the 1960s, most of the water has been diverted to a tunnel and pipe system for hydroelectricity.

Vegetation and soil use is according to the altitudinal gradient. Between 2000 and 2900 m, xerophytic vegetation predominates, but *gramineae* communities are the dominant species after the rainy season, with development of grazing. Most of the shrub vegetation is composed of cactus species, even on terraces that have been abandoned. Between 3000 and 3500 m, a dense cover of perennial vegetation consisting of shrubs, cactus, and grass is found, made up of such species as *Solanum amblophyllum, Jaltomata bicolor, Malva parviflora, Marrobium vulgare, Heliotropium arborescens,* and others. Exotic species such as pines, cypress, and especially eucalyptus were introduced, with eucalyptus being used mainly for charcoal and in construction (Lopez Cornelio 1996).

The community of San Juan de Iris (Figure 3) is a typical small Andean sierra village of about 100 households (families) at an elevation of 3400–3600 m. Each farmer, or *comunero,* has about 10–20 terraces, each covering an area of 70–300 m^2. All active terraces are irrigated, the others having been abandoned. The main crops are potatoes, corn, alfalfa, and beans. Cows are the main livestock for milk production. Each farmer owns about 10 cows; goats, sheep, and pigs are present in smaller quantities. Except for the terraces where alfalfa is grown, there is no grazing of livestock on the terraces. A small number of llamas and horses are used mainly for transport. The trend in recent years has been to grow more alfalfa for livestock production, abandoning the traditional potato and corn crops.

There is no demographic growth despite high birth rates. A large proportion of the young people migrate to the urban areas of Lima and to Chosica, the nearest town. A survey of 20 families showed that all of them have at least one or two children that migrated and settled in Lima or its surroundings.

Methods and results

Experimental plots

Eight experimental plots were installed on abandoned terraces and one control plot on a cultivated terrace in order to measure run-off and sediment yield from ter-

FIGURE 4 Experimental plot for measuring run-off and sediment yield on an abandoned terrace. (Photo by authors)

races after rainstorms. The plot area for each terrace was between 50 and 100 m^2. The plot was bordered by a plastic fence closed at a lower apex, with a plastic tube delivering water and sediment through a pipe to closed containers (Figure 4). Rainfall was measured by a daily rain gauge reading. Water and sediment were collected after each rainfall, and either the total amount or a sample was kept for sediment content and analysis at the laboratory. Data collection was regular, despite the theft of some water containers.

The average annual rainfall for San Juan de Iris village is about 300 mm. The four experimental years, 1993–1997, had average rainfall or were relatively dry, with no major rainstorms recorded (Table 1). The highest rainfall intensity was 16 mm/d (13 March 1995); daily rainfall exceeded 10 mm/d on only a very few days.

Run-off was negligible during most rainstorms and few sediment samples were collected (Table 2). The largest run-off event occurred on plot Marcahuasi 2 after a 16-mm/d rainstorm. The highest measured run-off for the plot for a single storm was a total of 17 L (2.3 L/m^2) and 6.8 g sediment yield (0.9 g/m^2). The annual run-off coefficient for the Marcahuasi 1 plot was 3.3% and 5% for Marcahuasi 2, but run-off coefficient values were less than 5% for most plots during the measuring period. The high run-off discharge and sediment yield for the cultivated control plot is explained by the failure of the irrigation system, when the terrace was flooded and water and sediment flowed out of the terrace. During periods when the cultivated terrace was well maintained, no run-off was detected during the rainy periods.

Rainfall simulation

A portable field rain simulator was used to measure run-off and infiltration rates under different physiographic conditions and terrace land uses, including differences in soil, slope, exposure, stoniness, vegetation cover, cultivated area, and abandoned terraces (Table 3). The equipment was adapted from a model used in Spain (Calvo et al 1988) and consisted of (1) two pressure pumps, giving a constant pressure of 1.7 atm, equivalent to rain intensity of 40 mm/h; (2) an aluminum structure connecting the pipe to a spray nozzle jet at a height of 170 cm above ground; (3) a metallic ring 56 cm in diameter fixed about 5 cm into the ground to limit the run-off of the draining ground area to a collecting tube and can (Figures 5, 6). The simulator produced rainfall with a realistic drop size and was applied until a constant rate of run-off was achieved, usually after 1 hour. If the infiltration rate was very high and no run-off occurred, the simulation was suspended after 2 hours. The simulated rainfall amounts and intensities are considered to be high and of low frequency in this area—the highest intensity of natural rainfall measured during the study period was 16 mm/h. The amount of water for each simulation was about 50 L; in some areas distant from water sources, local llamas were used to transport the water. Water and sediment samples were collected every 3–5 minutes throughout each experiment. Samples were oven dried (1100°C) and weighed, and sediment yield was calculated.

All tests were carried out in the dry season under dry antecedent soil moisture conditions. Infiltration was high on the cultivated and low-gradient terraces. On high, steep slopes, run-off started after 15–20 minutes, and rates of infiltration were 15–20 mm/h. Run-off and sediment yield were high at the steep slope sites and low on the cultivated and low gradient ter-

TABLE 1 Annual rainfall (mm) for 1994–1997/1998 in San Juan de Iris (elevation 3400 m).

Year	November	December	January	February	March	April	Total
1993–1994	0	45.0	59.0	74.0	72.0	61.0	311.0
1994–1995	0	47.0	65.0	22.0	66.0	36.0	236.0
1995–1996	0	0	51.5	126.0	114.0	21.5	313.0
1996–1997	0	0	23.0	82.0	1.5	14.5	121.0
1997–1998 (El Niño)	52.5	113.3	184.0	121.0	197.0	21.0	688.8

TABLE 2 San Juan de Iris experimental plots; run-off and sediment yield for 1994/1995.

Plot	Area (m^2)	Runoff		Sediment yield	
		Total (L)	L/m^2	Total (g)	g/m^2
M1	5.70	43.70	7.60	11.50	2.00
M2	7.50	89.50	11.90	19.24	2.50
C3	25.00	4.80	0.19	46.81	1.87
P4	35.00	7.40	0.21	8.93	0.25

Run-off storm	M1		M2		C3		P4	
	Run-off (L)	Sediment (g)	Run-off (L)	Sediment (g)	Run-off (L)	Sediment (g)	Run-off (L)	Sediment (g)
29 Dec 94	13.00	0.04	12.00	0.24	0	0	2.50	0.02
30 Dec 94	8.00	1.60	16.00	0.80	0.75	23.25	1.00	0.30
8 Jan 95	3.00	0.12	8.00	1.12	0.80	9.36	0.70	5.95
20 Jan 95	2.00	2.58	9.00	1.08	0.30	1.74	0.30	1.26
26 Jan 95	0.90	0.36	13.00	5.20	0.70	1.30	0.50	0.20
6 Feb 95	0.30	0.18	0.50	0.10	0.40	3.56	0.20	0.12
12 Mar 95	13.00	5.20	17.00	6.80	0.90	3.60	2.00	1.00
13 Mar 95	3.00	0.90	11.00	3.30	0.50	2.00	0.10	0.04
16 Mar 95	0.50	0.55	3.00	0.60	0.50	2.00	0.10	0.04
Total	43.70	11.53	89.50	19.24	4.85	46.81	7.40	8.93

TABLE 3 Rainfall simulation field experiments; physiographic and land use characteristics of sites.

Experiment	Site	Elevation (m)	Vegetation		Exposure	Stoniness (%)	Slope (%)	Soil	Land use	Terrace abandonment
			% cover	Type						
1	Upica 1	2600	80	Dry grass	NW	10	15	Silt	Grazing	Semi-abandoned
2	Casta	3150	50	Grass	E	10	14	Clay	Cultivated	Terrace
3	Upica 2	2610	70	Grass	W	30	24	Silt	Cultivated	Terrace
4	Upica, house	2430	100	Grass	NW	20	14	Silt + clay	Grazing	Terrace
5	Upica, slope	2440	30	Dry grass	NW	60	46	Silt	—	No terrace
6	Upica, slope	2450	20	Dry grass	NW	70	51	Silt	—	No terrace
7	Upica, terrace	2600	30	Grass	W	10	15	Silt	Plowed	Cultivated
8	Marcahuasi 2	3540	80	Dry grass	NW	10	15	Silt	Grazing	Abandoned
9	Marcahuasi 1	3550	50	Shrub-cactus	W	50	28	Silt	Grazing	Abandoned
10	Iris, slope	3550	20	Shrub-cactus	NW	50	38	Silt	Grazing	No terrace
11	Iris, irrigated	3230	75	Potato, grass	E	5	15	Silt + clay	Cultivated	Cultivated
12	Iris, eucalyptus	3150	50	Eucalyptus	W	30	46	Silt	Forest	No terrace

FIGURE 5 Schematic drawing of the rain simulator. Constant pressure is obtained by alternating between two 7-L water pumps.

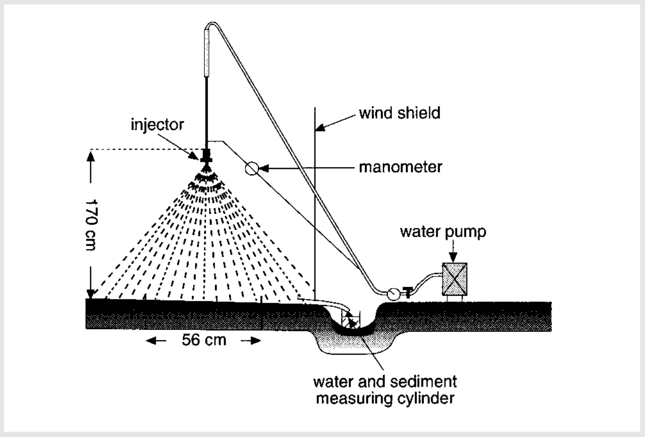

FIGURE 6 Rain simulation on an abandoned terrace in San Juan de Iris. (Photo by authors)

races. A forested site with 10-year-old eucalyptus trees generated more run-off and sediment yield than any other area covered with vegetation. A similar effect with eucalyptus cover has been described in a rainfall simulation experiment in southern Italy (Sorriso-Valvo et al 1995), with rapid run-off generation on leaf litter 1–2 cm thick. Run-off generation was higher in the lower Upica site due to siltier soils and crust formation after rainfall simulation.

Morphometric analysis

A field survey was conducted on 233 terraces on both sides of the upper Santa Eulalia basin in order to assess both their degree of abandonment and physiographic and morphometric characteristics. The following parameters were measured: length, width, area, stoniness, and slope of the terrace and length, height, stone dimensions, and curvature of the terrace wall. Vegetation cover and class were also surveyed for the terrace area and wall.

Three orders of degree of abandonment were determined according to the local condition of the terraces and information obtained from local farmers. Cultivated, active terraces (order 1) constituted 7% of the terraces surveyed, while 93% were abandoned (order 3) or semiabandoned (order 2). Most of the terraces were in order 2. Abandoned terraces are covered by cactus vegetation, their walls are collapsed, and terraces are covered by large stones. The length of time since abandonment is more than 40 years, according to aerial photos and local information, and depends on many factors such as distance from a village, soil and slope conditions, property rights, etc. Most of the active terraces are under irrigation.

The average area was about 170 m^2, but large terraces up to 500 m^2 were found. Walls were built from local stones 20 cm in diameter. Terrace degradation was noticeable in wall swelling, which causes the wall to collapse and the terrace structure to deteriorate further.

Discussion

Sediment yield values measured on the experimental plots in the Santa Eulalia basin were about $1 g/m^2/y$, or equivalent to $1 ton/km^2/y$, which is considered a negligible or very low rate in comparison with average world rates of about $100 tons/km^2/y$ (Young 1969). Large wall failures and considerable erosion from the terraced slopes occur only during high magnitude rainstorms of very low frequency, probably with a return period of 1:50 years, as reported by local villagers. There is no natural vegetation on the terraced slopes, as it was removed in the process of terrace building many years ago. Terraces uncovered by vegetation may be affected by severe erosion during high-magnitude catastrophic processes. The rate of infiltration is high on the cultivated terraces and there should be no erosion, but incorrect irrigation management and poor maintenance may cause large quantities of soil to be washed out by irrigation flood systems.

The terrace wall is the main factor determining terrace stability or degradation. Wall swelling and bulge development are characteristic of many retaining walls prior to failure. Saturated soils and their shearing effect determine pressure and swelling on the walls until failure occurs (Salas Pinto and Vasques Villanueva 1987; Pallares Bou 1994). The wall bulge appears at a point one-third of the way up the wall and divides the wall into two sections. All wall failures checked in the field reached the critical value before the slide process. Maintenance is constant on the cultivated terraces, but a shortage of labor adversely affects proper and constant repair of wall stone slides. A similar process occurs in the Spanish Pyrenees with the abandonment of cultivation on mountain slopes, even if they are terraced (Garcia-Ruiz and Lasanta-Martinez 1990). Cereal production is no longer economical, and even livestock production has declined. New nonrural activities, mainly winter and summer tourism, cause severe problems. Due to the high precipitation in the Pyrenees, the natural forest rehabilitates rapidly, a process that is not likely to occur in the more fragile and populated areas of the Andes.

The degree and type of vegetation cover are the most important factors determining rates of erosion on the terraces, as found in the rain simulation experiments. Vegetative protection of the soil has been indicated as the critical erosion variable in an Andean basin of Ecuador (Harden 1988) and in many other parts of the world, such as in an experimental terrace area in the Mediterranean area of Spain (Cerda-Bolinches 1994). Stoniness is a factor that increases infiltration (Poesen et al 1990) by reducing the impact of rain on the soil and preventing crust formation. Most of the terraces have a high degree of stone cover (Table 2). Planting eucalyptus as an erosion control factor is a controversial issue. Rain simulation experiments indicate that erosion rates under eucalyptus trees were greater than on terrace sites covered with grass but less than on uncovered bare slopes. The massive planting of eucalyptus that took place in the mountainous areas of Peru on 100,000 hectares in 1976 in order to prevent erosion (Millones 1982) may have provided a valuable source of firewood, but it may not be as efficient a tool for preventing erosion as ancient terrace technology.

Terrace abandonment is almost total on nonirrigated terraces. The irregular rainfall regime makes labor and seed investment too risky for the low crop prices obtained, so land use has changed to grazing, which promotes erosion and collapse of walls because of the cattle. San Juan de Iris is still a strong agricultural community, although during the last 10 years, there has been an increasing switch to livestock and alfalfa growing at the expense of traditional crops, with marginal areas being abandoned. A new water reservoir and improvement of the irrigation canals have been factors in the maintenance of terrace cultivation.

Methods for diagnosing erosion are essential in any land planning and natural resources conservation policy (Millones 1982). In the study area, traditional terrace farming practices reduce erosion by using contour furrows for corn or potato planting, by leaving fields fallow and exposing them to natural fertilizers consisting of the manure of cattle and other animals, and especially by maintaining terrace walls. Abandonment of terraces, followed by overgrazing, creates the major risk of massive soil loss (Harden 1996). In many other regions of the world, such as traditionally agricultural areas of China, terracing provides effective protection against severe erosion (Quine et al 1992). Terrace abandonment due to emigration of rural laborers to the oilfields of the Persian Gulf led to accelerated erosion processes and the appearance of barren slopes in the Yemen Arab Republic (Vogel 1988).

Terrace abandonment and degradation are a function of physical, economic, and social factors, such as land use and ownership, distance from a village, community strength, etc. In the Laraos community of the Santa Eulalia valley, most of the terraces were abandoned and the *comuneros*, village farmers, turned to other activities such as collecting and marketing medicinal plants. The links between biophysical land degradation and social decline have their roots in household and social behavior. Soil erosion control by terracing is expensive, owing to the shortage of local labor (Syers et al 1996), and was found to be the most expensive soil conservation technique in the Ecuadorian Andes (Dehn 1995). Contour bunds were suggested as a more efficient method. No contour bunds or infiltration ditches are possible on the very steep slopes in most terraced areas in Peru because terraces are small and narrow and the type of terrace, as well as suitable techniques, must be adapted to local conditions.

Changing land use and changing human behavior are socioeconomic factors now affecting the high Andean mountains. Traditional subsistence agriculture is being replaced by a market-oriented economy of labor and agricultural production. Young people in mountain villages are gravitating toward more diverse job and study opportunities in the coastal cities. This causes a shortage of labor needed for long-term soil conservation practices such as terracing, irrigation, and ditch maintenance. The result is soil erosion on traditional terraces that have been abandoned. No soil will be transported back uphill, and sierra migrants will not go back to the mountain villages. These two gravitational processes, ie, soils flowing down the mountain slopes to the ocean floor and people migrating from the Andean villages to the coastal cities, are linked and irreversible.

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