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Cangahua in Ecuador: Its Strength, Classification and Delineation

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EXECUTIVE SUMMARY

Cangahua, sometimes spelled cangagua, is the name used in Ecuador for indurated, volcanic-ash materials. The name originates from a Quechua word meaning "hard land". Similar materials occur throughout Latin America and in each country, a local folk name, usually of Indian origin, has been applied to the material: it is called tepetate, talpetate, and sillar in Mexico, Nicaragua, and Peru, respectively. The names are used interchangeably in this paper to indicate country of origin.

Prior to intensive agriculture, the porous soil overlying cangahua was productive and absorbed water readily. But serious soil erosion developed when the pre-Hispanic culture switched from nomadic to sedentary with the accompanying cultivation, grazing, irrigation, wood cutting, and other practices. These cultural practices modified the sensitive soil/environment system causing massive soil loss. Once the porous soil was removed, cangahua was exposed, and water, roots, and air could not permeate it. The land became a sterile landscape. Thousands of hectares of barren, exposed cangahua occur throughout Latin America. Lands in this barren condition are national disasters: they are aesthetic eyesores, do not contribute to agricultural productivity and enhance flooding. They need immediate reclamation. We developed this project to assist Latin American nations in the correction of this serious problem.

The objective of this report is to summarize what the authors have learned about cangahua genesis, properties, remote sensing and reclamation.

RESEARCH OBJECTIVES

Objective 1.

Our first objective was to develop a rapid, inexpensive, field technique to measure cangahua strength with a modified auto jack. Scientists throughout Latin America are studying indurated materials in volcanic ash because these lands need to be returned to some semblance of their original productivity and hydrologic potential. They don't have access to sophisticated equipment for the measurement of strength, and they especially need an inexpensive technique that can be used in the field. The equipment we have developed is the only field technique used to determine strength and is being used in the Valley of Mexico and Jalisco State in Mexico in addition to Ecuador.

Objective 2.

Our second objective was to finalize a cangahua taxonomy developed by Ramon Vera and his colleagues. A number of taxonomies have been developed to classify the various types of indurated, volcanic-ash deposits. The one proposed by Vera and Lopez (1986) was specifically designed for cangahua in Ecuador and is more complete than other taxonomies proposed for Mexican indurated, volcanic-ash deposits. We tested the Vera and Lopez model and a revised version was published (Vera and Lopez (1991).

Objective 3.

The third objective was to test whether GIS techniques combined with remote sensing can be used to map cangahua distribution and type. However, cangahua was found to occur at the surface or with any amount of soil occurring on top of the cangahua including very thin soils. Soil depths, active soil surface erosion and green biomass present became important parameters in remotely sensed measurements of cangahua.

BACKGROUND

Distribution

Ecuador has three distinct physiographic zones; the Costa Zone is the western flank of the Andes that borders the Pacific Ocean, the Oriente Zone is the eastern flank of the Andes that forms the headwaters of the Amazon River, and the Sierra Zone is the mountainous spine represented by the Andes Mountains. The Interandean Valley is in the center of the Sierra and runs almost continuously from Peru to Columbia. Much of Ecuador's population and agriculture is concentrated in the Valley because of the mild climate. Approximately 25% of the Sierra is underlain by cangahua and in about 10% of the cangahua area the cangahua has been exposed by soil erosion (del Posso and Bedoya 1989). The Sierra has a long agricultural history and severe erosion problems.

Physical Properties

Some of cangahua's properties have been described briefly but only in Ecuadorian articles.

Cangahua occurs in a variety of colors, as shown in Table 1. Brown to very pale brown (the Munsell system) are the most common. A black indurated material, locally called chocoto, is not considered cangahua by some. Chocoto is weakly indurated volcanic ash that occurs at elevations above 2,800 meters. It slakes in water, has very low strength and is one of the few types of cangahua that is being reclaimed manually. Its black color is apparently not due to organic matter because its organic content is less than other, brown cangahua.

Cangahua has a unique morphology. Its upper boundary, to the overlying porous soil, is abrupt, and its lower boundary is to the next layer of ash. It has two types of structure in the upper part of the section. Polygons of about eight cm in diameter are found in cangahua without carbonates and laminar fractures in the upper few cm of cangahua with carbonates.

There are three types of carbonate accumulation. The most common type is composed of thin, discontinuous coatings similar to Stage I (Harden et al. 1991) that do not cement particles. The second type are horizontal lamellae of a few mm thickness in the upper two decimeters of the section. These lamellae cause horizontal fracturing that overlies cemented cangahua. A less common type features thick (usually less than one cm), vertical carbonate accumulations where water tables are high (seasonally, at least). This type occurs on the flanks of Mount Ilalo and near Montufar.

Cangahua strength is an important parameter because it determines the energy requirements for reclamation of lands where erosion has stripped the porous soil and left cangahua exposed. In some cases, cangahua strength is so low that campesinos reclaim it manually with hoes (Nimlos and Savage 1991). However, in most cases, it can only be reclaimed with tractors.

Soil strength has been characterized by Hillel (1980) as easy to define but difficult to measure; he defines it as the ability of a soil to resist stress without collapsing or deforming. Both tensile and compressive strength are involved when measuring strength for reclamation where rippers are used to break up the cangahua. Part of the matrix is pulled apart by tension and part is compressed.

Farrell et al. (1967) measured tensile and compressive strength in samples of a soil adjusted to various moisture contents. Their data show that both types of strength decline rapidly with increasing moisture and that there is a direct correlation between tensile and compressive strength; over the

Table 1. Some characteristics of the areas studied.

Cangahua Site	Elevation		Climate		See (paper) Vegetation (Holdrige)	Color**	
	Strength (kg/cm ³)	Density	Mean	Mean		Dry	Moist
	(m)	Slopes	Annual Precip. (mm)	Annual Temp (°C)			
	Dry	Saturated					
Montufar 45	3,000 7	25-70% 1.58	850	12.0	---	10YR7/3	10YR4/3
Ilalo 38	2,800 7	25-40% 1.38	850	16.0	Low wet forest	10YR7/3	10YR6/3
Salcedo 30	2,700 8	25-40% 1.58	620	14.0	Mesothermic semihumid equitorial	10YR5/3	10YR3/3

*Weather Stations: Montufar (San Gabriel), Ilalo (Tumbaco), Salcedo (Salcedo).

**All colors according to the Munsell system.

range of moisture contents they were studying (2 and 14%), dividing unconfined compressive strength by 9.8 gives a very close estimate of tensile strength. We elected to measure unconfined compressive strength because measurement is easier, it can be measured in the field, and there are more data on this parameter.

We measured strength on a number of cangahua samples by standard methods developed previously for tepetate (Cook et al. 1992). Blocks shaped as rectangular parallelepipeds (three mutually perpendicular planes) with dimensions of approximately 3x3x7 cm. are cut with saws and formed with sandpaper or a file; the pressure at which they crumble is then measured.

Strength, tensile and compressive, declines with increasing moisture content, especially in the drier range (Farrell et al. 1967, Nimlos 1989 and Nimlos and Hillary 1990). Therefore strength should be measured at a number of moisture contents for complete characterization. Dry strengths vary from 11 to 46 kg/cm² and at least one type of cangahua (black) slakes in water.

Unconfined compressive strength is much less in Ecuadorian cangahua than Mexican tepetate. Nimlos (1989) and Nimlos and Hillary (1990) have shown that the dry strength of tepetate varies from 2 to 210 kg/cm² and that the strength of tepetate with carbonates is much higher than when carbonates are absent.

Whereas unconfined compressive strength is often difficult to measure, especially on weak samples with carbonate lamellae, cangahua bulk density is easy to measure once blocks have been cut, and variability is relatively low (Nimlos 1989). Also, strength and density are positively correlated on samples of Mexican tepetate without carbonates (Nimlos 1989).

The bulk density of the cangahua samples we measured from block samples (Table 1) varies from 1.36 to 1.58 Mg/m³. Luzuriaga (1974) found the bulk density of eight samples of cangahua to be from 1.32-1.57 Mg/m³. The bulk density of most uncemented, porous soils varies from 0.8 to 1.3 Mg/m³, the density of most rocks is about 2.65 Mg/m³, and the densities of duripans in three soils is 1.44 to 1.91 Mg/m³ (Soil Survey Staff 1975). Thus, cangahua has densities intermediate between those of porous, uncemented soil and rock and comparable to some duripans.

Cangahua has a porosity intermediate between normal soils and rocks. Porosity can be calculated from bulk density if particle density is known. The particle density of cangahua, as determined with a pycnometer, was found to be 2.397 gm/cm³ (Personal communication, C.T. Luzuriaga, Central Universidad, Quito, Ecuador). Porosity calculated from all the bulk density data mentioned above shows that it varies from 26-45%. Comparable values for other igneous rocks are nearly zero. The distribution of pore sizes has not been determined, but examination of cangahua samples suggests that the pores are mostly micropores.

The hydraulic conductivity of two cangahua samples was shown to be 1.35 and 4.48 x 10⁻⁶ m/s (Personal communication, C.T. Luzuriaga, Central Universidad, Quito, Ecuador). Mexican tepetate has been shown to have a conductivity of 1.0 to 62.0 x 10⁻⁷ m/s (Nimlos and Hillary 1990). These values indicate that cangahua is a very impermeable material.

The spectral characteristics of cangahua are similar to rock. Plants and organic matter in the soil absorb visible light. Since cangahua contains few plants and little or no soil, it is usually brighter than adjacent areas of soil. In addition, green vegetation reflects highly in the near-infrared wavelengths; thus, cangahua reflects little of it. Cangahua is also droughtier and warmer than adjacent soils. Short-wave infrared and thermal infrared wavelengths are absorbed more with increasing moisture and decreasing temperatures, respectively. Cangahua reflects/emits more short-wave and thermal radiation than soil. The above characteristics may be observed in remotely sensed data (Ringleb and Gonzales 1991, Gonzales and Ringleb 1992).

Chemical and Mineralogical Properties

The pH of a profile of cangahua near the volcano Ilalo, in the community of San Juan de Chuzpiaco, varies from 8.2-8.9 (Personal communication, C.T. Luzuriaga, Central Universidad, Quito, Ecuador).

Luzuriaga (1974) studied the mineralogy of eight samples of cangahua with x-ray diffraction, electron microscope, differential thermal analyses and infrared absorption. Sample site location was not given. He concluded that the dominant clay minerals are amorphous and that there is a small amount of kaolinite and montmorillonite.

He also studied various fine sand and coarse silt fractions, although he did not describe his methods. The heavy minerals constituted about 10% of the fractions and consisted of opaque and transparent types. The opaque fraction contains grains of pyroxenes covered with iron oxides and transparent types of monoclinic pyroxenes.

Luzuriaga concluded from his studies that the dominant cements are silica and iron oxides and that other cements include carbonates, manganese and clay.

Soil Erosion

Soil erosion in the Interandean Valley is massive and widespread. The history of soil erosion in Ecuador was presented by De Noni (1986) and De Noni and Trujillo (1986). They pointed out that Ecuador is a country of great variety and richness of natural resources, but also an environment of great fragility because steep slopes, erodible soils, limited vegetation and "aggressive climate" are common in some areas and especially in the Sierra. The result has been that erosion has affected 50% of the country, primarily because of the imposition of agriculture and the associated irrigation on the fragile environment. The culture changed from a nomadic existence that had little impact on the land to one that was sedentary and involved cultivation, increasing the rate of soil loss. With the sedentary culture came a rapid population increase; the population of the Sierra increased ten fold in 157 years. Also, the agrarian reform program of 1964 encouraged farmers to crop land of steeper slopes.

There are two aspects of the erosion problem as it relates to cangahua: erosion of the porous soil overlying cangahua and erosion of the cangahua itself. The latter type of erosion occurs where cangahua strength is low and it results in deep gulleys.

The porous soil overlying cangahua erodes rapidly when cultivated intensively. Apparently the impermeable cangahua restricts water percolation, and water flows over the surface, carrying away soil particles and leaving a relatively smooth surface of exposed cangahua.

The normal pattern of erosion is not the loss of successive horizons but rather the erosion of the entire profile and the gradual exposure of cangahua as the erosion moves upslope in a U-shaped configuration. This erosion pattern leaves islands of uneroded soil, which we call relicts, of varying size where the erosion has not been complete. At Salcedo all soil has been removed and no relicts exist. At Ilalo about 5% of the land surface retains islands of complete profiles and at Montufar 30% of the land still is covered by a mature soil profile.

Soil Development

Porous soil on cangahua is fairly well developed. We studied soils in the Montufar area intensively because relict islands of soil are much more common there than in other parts of Ecuador. The profile we observed is shown as Figure 1.

Figure 1. The typical soil profile over cangahua at Montufar.

- A fine sandy loam; massive and hard when dry; 10 YR 5/2 moist and 10 YR 6/2 dry.
- Bt clay; 10 YR 2.5/2 moist; very strong blocky structure with thick continuous clay films.
- Ckqm loam; 10 YR 4/3 moist and 10 YR 6/4 dry; black orgillans in cracks; coarse prismatic structure; carbonate lamina

The profile shown in Figure 1 was on a north-facing ridge at 2,630 meters elevation with about 4% slope gradient; it supported Phylodacea spp. and a number of grasses including *Andropogon* spp. We studied the profile over about 100 hectares and found it very uniform over the area.

The A horizon was rarely more than 20 cm thick.

Brown (10YR 4/4) lapilli occurred throughout most profiles. The lapilli are generally round although they are not perfect spheres. They are pitted, have 10YR 5/4 moist internal colors and are less than 1.5 cm in diameter although we found one that was 7 cm in diameter. They contain no carbonates and lack concentric rings in the interior. The volume of lapilli increases with depth: we estimate that the volume of lapilli is 1% in the A, up to 30% in the Bt and up to 50% in the cangahua (Ckqm). In the Bt they are stained black but the black coatings are missing in all lapilli exposed by erosion and laying on the surface of the cangahua. We interpret the distribution of the lapilli to mean that the parent material of the profile was a single material, a hot ash flow, and not air fall ash that was deposited on top of the flow.

We studied the profile in April which is in the rainy season. The moisture content of the Bt was surprisly high. The stucture of the Bt was very strong and clearly visible from quite a distance.

Some authors have suggested that volcanic ash indurates only after it is exposed by erosion. We hold that exposure is not a prerequisite of induration, that exposed cangahua is drier than cangahua covered with porous soil (A and Bt) and therefore harder. To test these conflicting views we collected six samples of cangahua under a soil profile in one of the relict islands and six samples of cangahua exposed by erosion a meter away. The moisture content of the cangahua under the soil averaged 10.97% and 5.60% in the exposed cangahua. Thus exposed cangahua is drier and its strength is therefore greater. We plan to determine the relationship between strength and moisture content in cangahua exposed and covered with soil.

Silica coatings and two forms of carbonate were present in the cangahua: thin threads and coatings and horizontal and vertical lamina less than 1 cm thick. But there were no carbonates in the matrix.

Cracks in the upper part of the cangahua had black organoargillans and many fine roots.

Occasional layers of indurated material of the same color as the lapilli occurred throughout the ash flow and in other flow in other parts of Ecuador. They were about 4 mm thick.

METHODS AND RESULTS

Objective 1. (portable jack).

The field equipment we developed is shown in Figure 2. It consists of a jack modified with a pressure gauge sitting in an iron frame. A parallelepiped sample of indurated material is placed on the piston of the jack and in

Figure 2. A modified auto jack for the field determination of unconfined compressive strength.

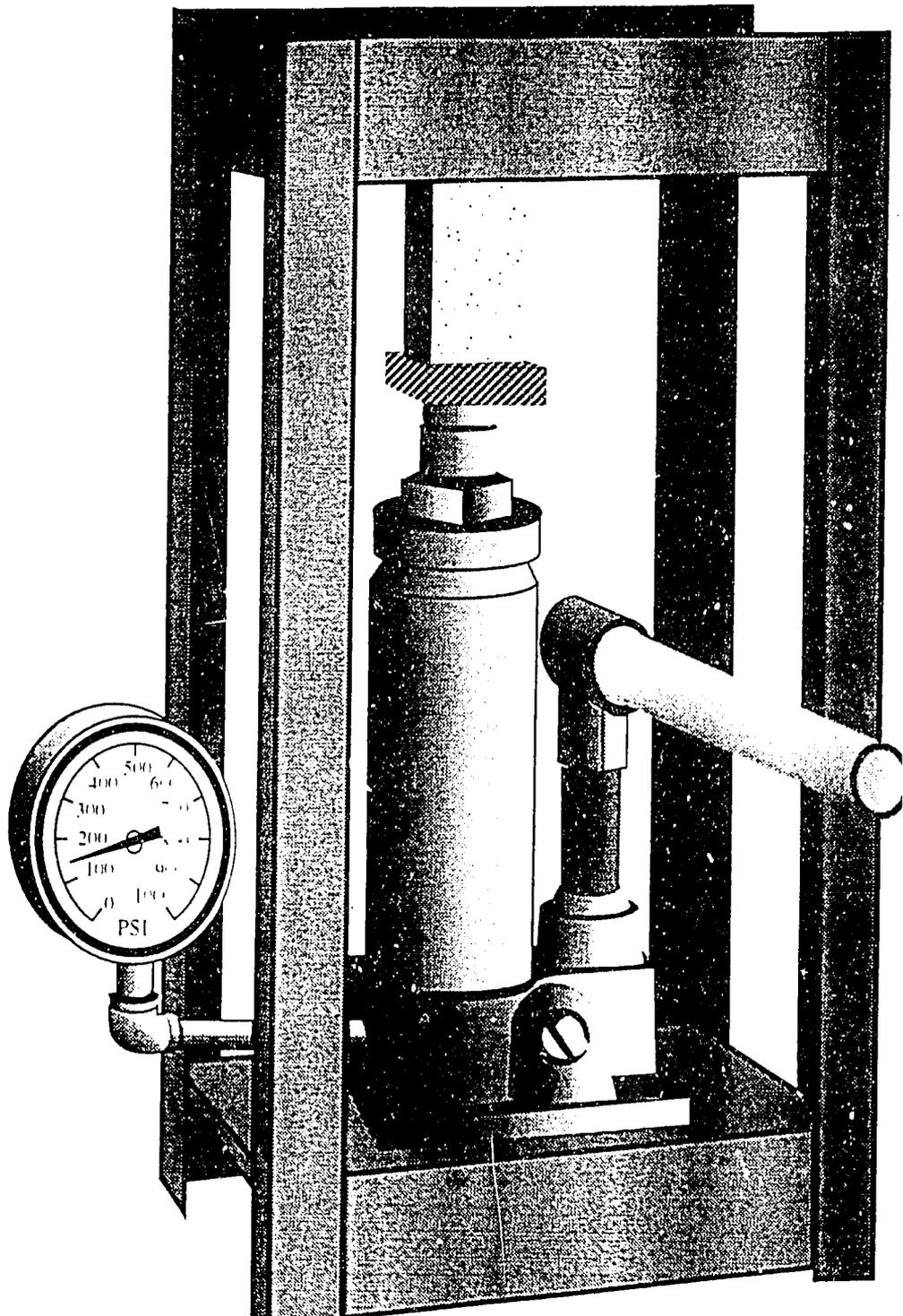


Figure 2. A modified auto jack for the field determination of unconfined compressive strength.

contact with the iron frame and pressure increased in the jack by pumping the handle until the block fails. The jack we used is a heavy duty, 2 ton (1814 Kg) jack that costs less than \$15. The frame is constructed of 3/4 inch angle iron and the pressure gauge has a capacity of 1,000 psi and costs about \$30. Total cost of the equipment and its construction is about \$70.

The most sophisticated equipment for the measurement of unconfined compressive strength is the Tinius Olsen testing machine. We compared the strength of tepetate samples as measured with the jack to the strength of paired samples of tepetate measured with the testing machine. The R-square value was 0.81 with samples of tepetate.

The results of this phase of the project are being summarized by a graduate student as his MS theses and will be published.

Objective 2. (Vera's taxonomy)

Types. Cangahua occurs on three principal types of deposits: 1) airfall ash, 2) pyroclastic flows, and 3) redistributed airfall and flows. An excellent text that presents volcanic processes and deposits, with clear illustrations, is Cas and Wright (1987); in this report we follow their terminology.

1) Airfall ash. Airfall ash is composed of particles of volcanic tephra that were ejected from the volcano and cooled while dropping to the land surface.

The area south and west of Quito is primarily covered with a sequence of several airfall ash layers totalling one to six meters thick. The deposits apparently thicken with increasing elevations to approximately 3600 meters where commonly are draped over pyroclastic flows. Above 3600 meters the ash deposits thin over lava flows and bedrock.

2) Pyroclastic flows are the deposits left by surface flows of pyroclastic debris which travel as a high particle concentration gas-solid dispersion. They are gravity controlled, hot and generally, massive and poorly sorted.

Pyroclastic flows dominate the topography adjacent to the volcanoes of the Interandean Valley. They occur as both long ridges that extend from near the mouth of the volcanos down to the valley floors and as thinner sheets mantling the existing paleo-topography. Higher basins of undulating topography represent numerous flows filling every depression.

Road cuts through mountainous terrain show pyroclastic flows of up to fifty meters thick. Pyroclastic flows are at or near the surface in most areas north and west of Quito.

The more common types of flows in these areas are ignimbrites and block and ash flows.

A) Ignimbrites or pumice flow deposits. These flows are typically poorly sorted and massive and contain various amounts of pumice and lithic materials. They are easily confused with mud flows but can be separated from them by the presence of carbonized wood and occasionally, rounded pumice lapilli. Widespread, massive ignimbrites with few lithic fragments are common north of Ibarra. Surge deposits are found at the base of a few of these flows although a fine-grained basal layer is more common. Many of these deposits contain horizontal, indurated layers ranging up to a meter thick. The presence of carbonised roots and indurated top on this flow suggests they are paleosols. Ignimbrites are most of the mesoscale topography in the Interandean valley.

B) Block and ash flow deposits. These are pyroclastic flows with unsorted to reversely sorted lithics with welded edges. A matrix of coarse ash deposits and large lithic blocks makes this type easy to identify. These flows are flattened on the bottom, with a rounded dome and pinch out to the edges when viewed in cross section. Plinian deposits commonly occur both above and below these flows. They occur regularly adjacent to ignimbrites and make up only a small portion of the total ash flows.

3) Redistributed ash deposits. Ash deposits (airfall or pyroclastic flows) may be redistributed as mudflows, slumps or mixed with alluvium. Mudflows are common and appear to travel larger distances. Topographically controlled, they fill many channels and stream beds, and provide fans at the base of steeper slopes. They commonly contain coarse lithic fragments, are shallow deposits, and are the least indurated. Fine-grained mudflows as massive sheetwash have also been observed, probably due to heavy rains on freshly-deposited ash. They appear as hummocks where depressions or other changes to lesser slopes occur. Slumps or scarps may be seen adjacent to intermittent or continuous streams and alluvium occurs primarily near major river ways.

Following deposition of the various types, pedocementation indurated the materials in addition to the consolidation that occurs during deposition. Silica and carbonates are the common cements, but some authors suggest that clay and iron oxides also play a role (Vera and Lopez 1992). Secondary silica is difficult to identify in the field, and the lower limit of silica cementation is, therefore, not established. Silica apparently weathers out of volcanic glass in the ash, modern dust or both and welds the particles (Harden et al. 1991). By contrast, carbonates are readily identified by their color (white) and their positive reaction to acid.

Microscopic analysis. Numerous thin-sections were developed for both the pyroclastic flows and some other ash deposits.

1) The ashflow types contain a dense matrix of silica with fractures forming layers similar to a chip on an automobile windshield. This glass matrix (welded tuff) contains numerous large and sharply angled particles of glass (shard). Larger, dark particles of obsidian or other mafic minerals are scattered throughout the matrix. This analyses remains conducive to the notion of ignimbrites as the dominant land form in the Ecuadorian highlands.

2) Thin sections of deposits presumed to be airfall ash were collected from horizontally-stratified deposits west of volcanos south of Quito. These reveal a dark, fine-grained matrix of silica and clays where glass shard are uncommon, small and rounded with no large particles of obsidian visible. The clays appear as weathering products of the silica. Some welding is present but this appears as resulting from either hot ash falling on the landscape or from pedogenesis. The fine-grained matrix and rounded shard suggest the material may have been transported by the water to these locations.

Classification and management. Cangahua occurs in all of the types, in pyroclastic flows, block and ash deposits contain welded zones and large lithic blocks and little opportunity for soils management. The common ignimbrites are much more difficult to generalize on. Many of these ash flows contain congahua layers apparently due to hydration and some devitrification of the surface layer being covered by hot ash. Moisture on this exposed surface combined with the heat from the new flow reorganizes the silica into an amorphous glass texture and indurates this surface. In addition, there are zones of welding and possibly, prolonged hydrothermal alterations. In air-fall ash, massive sediments may demonstrate rather strong induration.

This may occur when the sediments are drenched with water, the silicates dissolved by monosilicic acid or some other agent, and redeposited as films on the other minerals in the matrix as it dries. Redistributed ash may be indurated in a similar manner.

Due to the complexity of the processes involved in the distribution and induration of the volcanic materials, classification of the landscape into air-fall ash, pyroclastic flows or redistributed ash offers little in predictability for hardness and reclamation.

Objective 3. (remote sensing)

The results of the study including graphical images were published earlier (Ringleb and Gonzales, 1991, Gonzales and Ringleb, 1992, Ringleb et al., 1993).

Remote sensing of soil properties is normally accomplished by proxy interpretation. Vegetation type and production, terrain features and other information are used to delineate soil characteristics with remote sensing (Siegal and Gotz, 1977). The application of remotely sensed data to detect vegetation production using near infrared (NIR) and red data in a ratioed format has been used successfully for a number of years. Tucker, (1979a, 1979b) found the Normalized Difference Vegetation Index (NDVI) of satellite data could detect several classes of green biomass while Ringleb (1990) used NDVI data to estimate leaf area and net primary productivity classes. More recently, Ringleb and Key (1992) combined short-wave infrared data with a vegetation index to delineate fire severity classes in burned coniferous forests.

Techniques used to compare remotely sensed data with environmental variables included 1) selection of study sites, 2) obtaining and downloading of remotely sensed data, 3) developing imagery for field examinations, 4) conducting an initial review of the imagery/data, 5) field measurements of environmental variables, and 6) accuracy assessments.

Study sites: Three study sites separated spatially (north to south) with different environments were selected. Their location is shown in Figure 3. Each site is nearly 13 km square. The Ibarra study site, named for a city on the northern edge of the study area, is the driest of the sites and has the steepest slopes. The Ilalo study site, named for a mountain in the center of the area, is the wettest of the three sites and has intermediate slope gradients. The Salcedo study site is named for a city on the eastern edge of the area. Precipitation in this site is intermediate and slope gradients are the most gentle.

Remotely Sensed Data: Landsat Thematic Mapper data collected in June of 1990 were selected for analyses. These data were obtained by the Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos (CLIRSEN), Cotopaxi Station, Ecuador. These data were geo-referenced, resampled to 25 meter pixels, and downloaded as 512 by 512 data sets for each study site.

Image Processing: The Landsat data were examined on an ERDAS image processing system at the University of Montana. Each of the seven Thematic Mapper bands were displayed as grey levels and processed by the film recorder. Multi-band images were also processed, including the Normalized Difference Vegetation Index (NDVI), the near-infrared/short-wave infrared ratio (B4/B5), and the Band 5/Band 7 ratio. A special algorithm was developed to combine short-wave infrared data with near infrared and red data. This algorithm - Band 4 times (255 minus Band 5) over Band 3, labeled as B5VI, was designed to include measurements of the moisture associated with a site.

Initial Field Review: A preliminary investigation of the study sites was conducted in 1991 to compare environmental characteristics with the processed data. A portable computer loaded with the satellite data and image processing software, was used for classification development on location. The NDVI, B5VI and B4/B5 data sets were selected for further analyses since they appeared related to important environmental variables.

Ecological information including the distribution of plant species occurring across the study sites and those on disturbed and undisturbed sites, were noted. Soil depths and their relationships with erosion and associated landforms were examined. Green biomass measurements were taken using a .5 meter frame and clippers. The plant material was put in cheese cloth, air dried and weighed.

Field examinations found soils at many depths, from no soil on the exposed cangahua to thin soils barely covering the cangahua, and a variety of other depths. Soil depths depended upon the surface erosion associated with the land use, and landforms. Generally, vegetation production varied due to the amount of soil present, perhaps due to the soil water-holding capacity. The remote detection and measurement of site quality as related to vegetation production and soil depths, became an important directive in this study.

Field Measurements: A second field trip to conduct measurements of variables related to reflectivity was undertaken in January, 1992. Sampling design included development of travel routes across the study sites and measurements of kilometer points on these routes. Random starting points were selected from the numbered kilometer locations and variable length transects were established. Transects were taken in the four cardinal directions to avoid diagonal travel through the geo-referenced pixel data. The five authors worked together to traverse a 100 meter swath using specially designed data sheets. A transect was stopped and restarted when parameters changed as described on the data sheets. See Table 2. Global Positioning System (GPS) technology was used to record the locations of these stop and restart points.

Variable	CLASS			
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Green Biomass ¹	0-200	200-500	500-1500	>1500
Soil Depth (cm)	0-5	5-15	15-40	>40
Surface Erosion ²	1	2	3	4
Slope (%)	0-5	6-15	16-40	>40

¹ = (lbs/acre) ² = erosion class

Table 2. Some environmental categories recorded during a transect. Changes in any one category ends that portion of the transect, the location is recorded and a new form developed prior to continuing.

GIS Analyses: Results of the field transects were compared with the satellite data using the GRASS GIS. Using the programs r.transect and r.profile, raster data were extracted three pixels wide (75 meters) between the start and stop points measured with the GPS during the field analyses. The extracted data were input into statistical software packages for further analyses.

The field reviews found: a) the vegetation indices including the NDVI and the B5VI displayed the eroded areas better than single band images or other multi-band data (Gonzales and Ringleb 1992), b) the Ilalo and Salcedo study areas declined in productivity with little change in species composition as erosion increased, and c) eroded areas at Ibarra converted from grasslands to shrublands following disturbance.

A correlation coefficient table was developed from the GIS analyses (Table 3) to display the relationships between/among the parameters measured in the field and the selected imagery.

	B5VI	NDVI	B4/B5	DEPTH	BIOMASS	EROSION
NDVI		.74				
NIRRED	.20	-.17				
DEPTH	.59	.50	-.22			
BIOMASS	.36	.48	.27	-.44		
EROSION	-.58	-.50	.22	-1.0	.44	
SLOPE	.80	.87	.14	.24	.77	.24

Table 3. Pearson Correlation Matrix (r). Good correlation occurred between both the B5VI and the NDVI with soil depth, soil erosion and slope.

The transect techniques described above appear appropriate for data collection and GIS analyses. However, the correlation matrix provides several surprises. These include:

1) Green biomass and the remotely sensed data were less correlated than expected. We felt this was due to: a) the biomass categories measured in the field were too broad and failed to display the variation detected with the remote sensing, and b) as woody plants increased, including the numerous plantings of Eucalyptis trees, the values of the NDVI and the B5VI increased less than the investigators recorded. It appears the vegetative life forms need to be separated prior to classification to productivity classes.

2) The highest correlations with the B5VI and the NDVI were with slope. Although the farmed areas on steep slopes were seriously eroded in some areas, increased slope gradient meant less farming in much of the area surveyed. Almost no farming occurred on steep slopes in the droughty, Ibarra study site. Increased green biomass was correlated with increased slope for this reason.

Field exams found soil depths varied from exposed cangahua (no soil) to various amounts of soil. Erosion of the soil occurred at the surface and steeper slopes are more sensitive to this erosion. In the more mesic sites of Ilalo and Salcedo, reduced soil depths provided reduced productivity and increased amounts of bare ground. Herbaceous invaders (weeds) common to much of the rest of the world (at least in temperate climates) have not found their way into the Ecuadorian Highlands environment to any great extent. They may establish soon however, and the results may be disastrous to both the farming and the grazing industries.

The B5VI and the NDVI were correlated and demonstrated similar responses to environmental variables. The B5VI appears to respond to increased site moisture slightly more than the NDVI, but the vegetation type and productivity dominates the response of these indices. Vegetation production, at least in the moist Ilalo and Salcedo areas, appears to be the best ecological measure of site quality.

Remote sensing for site quality parameters may contribute significantly to land managers in a GIS format. Its contributions may arise in providing (overlying) vegetation parameters on an abiotic land classification. Scaled landscape units of abiotic limiting factors regarding site quality would put the remotely sensed data in its proper context. An appropriate classification scheme may be:

- Macroscale: Physiographic Zone
- Mesoscale: Effective Precipitation/Landform
- Microscale: Slope Gradient/Land Use

Biotic information gleaned from the satellite data may include both green biomass categories taken from NDVI or B5VI data and woody biomass categories. Woody biomass categories may be taken from supervised classifications or unsupervised categories which include a measure of the albedo or average reflection of these dark and shadowy, woody types.

Conclusions: Cangahua, and similar materials in other Latin American countries, become a land management problem when exposed by soil erosion, because the material is so hard that roots, air and water can not permeate its surface; lands so exposed are barren landscapes. These lands need to be reclaimed for a number of reasons. Ecuador needs to increase agricultural productivity to feed its increasing population, revegetation of these lands will improve the global carbon budget, and improved water infiltration will enhance streamflow characteristics. Although the data on cangahua is not extensive, some characteristics are apparent. It is not as strongly indurated as similar materials in other countries, so the task of reclamation will not be as difficult. The particle size of most cangahua is medium textured, and it will make a good growing medium. Finally, Ecuador has had some experience in reclamation that would provide a basis for operational programs.

The methodologies exist to classify the Inter-Andean valley into appropriate land units for prioritization in both reclamation and erosion control. Remotely sensed data may be used to delineate the areas in need of reclamation and to monitor site quality into the future.

IMPACT, RELEVANCE AND TECHNOLOGY TRANSFER

Ecuadorian natural resource scientists generally agree that lands of exposed cangahua must be reclaimed to return them to some semblance of their original hydrology and productivity. Although there is no national, country-wide reclamation program there are three current or former programs that would provide the experience for building such a national program. One is a sustainable agriculture program in progress that includes the reclamation of exposed cangahua; the other two are discontinued programs that were specifically devoted to cangahua reclamation.

The SULAMAN project is a labor- and extension- intensive, conservation and sustainable agriculture program in eight provinces of the Interandean Valley, from the province of Loja in the south to Imbabura in the north. It is funded by the Ecuadorian Ministry of Agriculture, the U.S. Agency for International Development and CARE (Nimlos and Savage 1991). Included in the program are projects that convert eroded lands of exposed cangahua into productive land by manual reclamation. Cangahua in this part of Ecuador is relatively carbonate-free and of very low strength; reclamation with hoes and shovels is therefore possible.

As of 1991, about 4,000 hectares have been protected by some form of conservation practices including the construction of bench terraces and hillside ditches. Land values where these conservation improvements have been applied have increased about 13-fold.

A second reclamation project was operational near Montufar just south of the Columbian border until approximately 10 years ago. The program was under the direction of INERHI (Instituto Ecuatoriano Nacional de Recursos Hidraulicos). A feasibility study (INERHI 1968) was made of the project and a land class map prepared. The project area is an area of Mollisols overlaying light-colored, carbonate-cemented cangahua that is the most strongly indurated in Ecuador. This area was chosen for the project because potatoes are grown near here year around and sold commercially in Columbia.

There are about 1200 hectares of exposed cangahua in this area. About 160-250 hectares have been treated, mostly by ripping to 80 cm with a D-7 (250 HP) caterpillar tractor followed by disking. The program began in 1975 and was terminated in 1986. There are 1500 fincas (small farms) in the area and the same number of farmers. Farm size varies from 0.11-3.40 hectares and averages 0.95 hectares. Also tried was dynamiting a hole in the cangahua every 50 cm and planting eucalyptus in the loose material.

A third project was a research study at La Tola near Quito that was conducted by Central University. Eighty five hectares have been treated mostly by ripping.

Future research must concentrate on identifying and applying techniques of reclamation including revegetation. Various techniques of land treatment and revegetation have been tried in Mexico (Nimlos and Ortiz 1991) that should be tried in Ecuador. The strength data collected as part of this study will indicate the appropriate equipment and moisture contents for reclaiming the various types of cangahua and the remote sensing techniques we developed will guide the inventory program. CLIRSEN undoubtedly will play a major role in the inventory.

Finally a prototype of the auto jack was left with the Ecuadorian authors to give them the capability to measure strength under field conditions.

Research on soils overlying cangahua can not be high priority because in many areas the soil is completely gone. Research on cangahua types and genesis is also low priority because our work has failed to show a clear relationship between types or genesis and properties important to reclamation and revegetation. However, land classification as it relates to existing and potential site quality is of utmost importance in developing management directions and priorities.

PROJECT ACTIVITIES/OUTPUTS

Meetings attended:

1. Thomas Nimlos, Augusto Gonzales and Ramon Vera gave papers at the First International Symposium on Indurated, Volcanic Soils held at Montecillo, Mexico in October 1991.
2. Richard Ringleb presented a paper at the 27th Pecora Symposium at Sioux Falls, South Dakota in August 1993.

Training:

1. Augusto Gonzales received training in field validation of remotely sensed data.
2. Guillermo del Posso, Augusto Gonzales and Ramon Vera received training in landscape ecology concepts and applications.

Publications:

Cook, B.J., Nimlos, T.J., and Olsen, D.S. (1992): Determining unconfined compressive strength in indurated, volcanic ash. Bulletin of the Association of Engineering Geologists. December.

Gonzales, A. and Ringleb, R. (1992): Características espectrales de la cangahua en el Ecuador. Proc. of the Intern. Confer. on Indurated Soils. Terra 10:120-127, Montecillo, Mexico.

Nimlos, T.J. 1992. Reclamation of indurated, volcanic-ash materials in Latin America. Advances in Soil Science 17:153-170. R. Lal and B.A. Stewart, Eds.

Nimlos, T.J. and C. Zamora J. 1992. Indurated volcanic ash soils in Peru. Proc. of the Intern. Confer. on Indurated Soils. Terra 10: 283-289, Montecillo, Mexico.

Ringleb, R., T. Nimlos, A. Gonzales, G. del Posso, and R. Vera, Assessing Eroded Farmlands and Site Capabilities of Indurated Volcanic-Ash in Ecuador, 1993. Photo. Eng. and Rem. Sens., 27th Pecora Symposium, Souix Falls, SD.

Ringleb, R. and A. Gonzales, 1991. Los Suelos Erosionados, Revista Technica, CLIRSEN, Quito Ecuador.

Vera, R. and Lopez, R. (1992): Tipologia de la cangahua. Proc. of the Intern. Confer. on Indurated Soils. Terra 10:113-119, Montecillo, Mexico.

Patents applied for. None.

PROJECT PRODUCTIVITY

All objectives of this project have been completed.

FUTURE WORK

We are continuing to characterize cangahua strength/moisture relations. We have established the strength/moisture curves for a number of cangahua types and are applying formula to those curves. This will allow the calculation of the strength of indurated materials through a range of moisture contents from a single reading and will greatly simplify the quantification of strength.

We are uncertain regarding this work continuing by any of the Ecuadorian authors of this report. However, the importance of the subject ensures the methodologies developed in this study will contribute to management efforts. Training in concepts of landscape ecology and remote sensing applications should be part of a national environmental direction. Remote sensing for site quality parameters important for management and reclamation should continue.

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