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COOPERATIVE AGREEMENT ON HUMAN SETTLEMENTS AND NATURAL RESOURCE SYSTEMS ANALYSIS

AGRICULTURAL TERRACE CONSTRUCTION: THE VALLES ALTOS PROJECT OF VENEZUELA AS AN EXAMPLE FOR AID

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PREFACE

This report is the first case study conducted under the auspices of the Fragile Lands Initiative (FLI). The initiative began in 1984 as a joint effort combining resources, expertise, and projects of the Latin America and Caribbean (LAC) missions, LAC Bureau, and three offices of the Science and Technology (S&T) Bureau: Agriculture (AGR); Forestry, Environment, and Natural Resources (FENR); and Rural Development (RD). FLI was designed as a ten year program with two broad goals: 1) to slow the degradation of resources on the steep slopes and humid tropical lowlands of the LAC region; and 2) to maintain and improve the agricultural production on these fragile lands.

Representatives of the LAC Bureau and S&T Bureau worked together during 1984 to produce a fragile lands theme paper and a concept paper which was presented to the LAC Agricultural and Rural Development Officers (ARDO) meeting in November. As a result of this meeting, the FLI focused on five priority areas:

1) POLICY: to help mission and host countries develop public and donor awareness of the fragile lands problem;
2) STRATEGY : to assist missions and host countries identify the magnitude and nature of the fragile lands problem in each country, to help select the areas most strategic for intervention, and to suggest appropriate types of interven-

tion;

3) INSTITUTIONAL INFRASTRUCTURE: to help missions and host countries devise appropriate mixes of public and private sector involvement for program/project implementation;

4) TECHNOLOGY INFRASTRUCTURE: to assist host countries and regional research institutions in the selection, adoption, and spread of technology related to the use and protection of fragile lands, to identify technology gaps and assist in development of appropriate technologies to fill those gaps, and to monitor fragile lands technologies for success or failure;

5) FARMER INCENTIVE: to explore the incentive systems that govern farmer behavior in order to help missions and host countries design effective fragile lands programs and projects and to assist in effective policy formulation.

During the first nine months of 1985, the Fragile Lands Working Group (FLWG: composed of representives of S&T and LAC Bureaus) collaborated on the production of a Project Identification Document (PID) and a Project Paper (PP) for the Development Strategies for Fragile Lands (DESFIL) project. DESFIL, is scheduled to begin in late 1986 as the coordinating, catalytic, and synthesizing project for this common theme, ribbon effort, known as FLI. DESFIL will act as the executive arm of FLI and will have five broad functions:

1) BROKERING, COORDINATING, AND SYNTHESIZING: DESFIL will act in a catalytic and synergistic way assisting LAC missions in the utilization of S&T project resources in conducting

studies of feasibility, design, or evaluation; it will coordinate and assist in bringing resources to bear in a timely way and synthesize these efforts over the long-term to improve the process.

2) TECHNOLOGY ASSISTANCE: DESFIL will backstop S&T projects by providing technical assistance to missions when the pertinent S&T projects are unable to do so for any of a variety of reasons.

3) RESEARCH: DESFIL will conduct research on topics of need, especially those focused on incentives.

4) DONOR COORDINATION: DESFIL will initiate and provide support for a series of donor coordinating meetings, at both the technical and policy level, as a distinctive aspect of the Fragile Lands Initiative (FLI).

5) ASSESSMENTS: DESFIL will conduct both country and mission strategic assessments.

In the course of the design of DESFIL, the FLWG sought to initiate a number of the above activities. For example, making use of a number of S&T projects, a brief mission assessment was conducted in Peru and pre-project feasibility studies were carried out in Haiti and Jamaica. The case study presented in the present report was similarly initiated and is an example of the synthesizing function of DESFIL. Case studies which have region-wide relevance and contain significant lessons are to be done by DESFIL and the results widely disseminated in order to advance our knowledge generally and to improve project design specifically.

This case study was chosen as the first one, not because of the breath of its relevance in the LAC region, but rather because of fortuitous circumstances and timing. Its applicability will be limited to areas where terracing is a viable option and most particularly, terracing using rock walls. The research team examined a soil conservation program, focused on terracing and irrigation, in the Trujillo and Merida region of highland Venezuela. To provide some comparability, members of the team made brief visits to a limited number of sites in Peru and Guatemala where the Agency for International Development (AID) missions have terracing projects. To incorporate an even broader perspective, the report discusses examples of other terracing systems, including the Inca and Japanese methods.

The research team wishes to express appreciation for the kind attention of individuals in several agencies in Venezuela, Peru and Guatemala. We are especially indebted to Ing. Ramón Pérez and Ing. Rosalva M. de Rodríguez of CORPOANDES in Escuque, Venezuela for their support of our research. We also wish to thank Ing. Jaime Soriano (now retired from CORPOANDES), and Dr. Luís Aguilar (former Valles Altos project director and currently with the Universidad de los Andes in Mérida) for their support and attention.

In Peru, we are especially indebted to Jeff Vonk and other AID and conservation personnel. In Guatemala we wish to thank George Like and others in AID and DIGESA who supported our work.

Bob J. Walter

READERS GUIDE

The report contains a large amount of material that is technical or descriptive in nature or otherwise relevant only to field application of terrace construction. For quick reading, the following guidelines are recommended:

1) An overview: "Summary of Findings" and "Program Recommendation" sections.

2) Additional detail (by topic for either or both the Valles Altos and AID programs): a) organizational and institutional framework; b) terrace construction; c) social and economic benefits; d) conservation aspects.

3) Background: the remaining sections of the main body of the report.

4) Annex 1: meant for readers with some engineering background or interest; contains the explanation and verification of many points made in the main body of the paper.

5) Annex 2 and Annex 3: meant for technicians engaged in terrace construction or evaluation.

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THE VALLES ALTOS PROJECT OF VENEZUELA AS AN EXAMPLE FOR AID

PURPOSE AND METHOD

The purpose of this Case Study is to examine the methods and the organizational framework of agricultural terrace construction in Venezuela as a potential example for AID sponsored soil conservation programs. Terracing programs in Peru and Guatemala, as well as "Inca" and Japanese terraces, provide comparative models for this study. The aim is to furnish the "Fragile Lands Working Group" and AID country missions with an accurate assessment of actual and potential role of AID sponsorship of terracing projects, and to make recommendations for modifying and expanding these programs. Of specific concern are techniques and methods of terrace construction, the institutional and organizational framework within which the projects are developed, and the social and economic impact of this form of soil conservation.

The first two sections of the paper examine the problems of erosion in hillside agriculture and the potential benefits of, and alternatives to, the construction of agricultural terraces. These sections are based largely on secondary sources. The following two sections are descriptions of the Valles Altos and AID sponsored terracing projects observed by the research team in Venezuela, Peru, and Guatemala. The final two sections of the

paper summarize the findings of the study and present recommendations for AID sponsored terracing projects. Three annexes are included: these supplemental papers deal with 1) theoretical issues related to terrace construction; 2) techniques for rock wall construction; and 3) computer programs and output for examples of terrace dimensions and labor input for terraces as presented in the paper.

Field investigation was conducted in Venezuela, Peru, and Guatemala during a five-week period in August and September of 1985. Most of this effort (19 days) focused on the highland region of Trujillo and Merida in Venezuela. Investigation methods included: 1) in-depth interviews with current and former conservation project directors; 2) visual assessment of twenty-one Valles Altos project sites; 3) in-depth interviews with one or more farmers in about half the sites visited for a total of twenty cases (including 10 who had participated in the terracing project and 10 in project areas that had not participated): 4) informal discussions with a large number of farmers and other individuals in and near project sites; 5) interviews with local conservation and soil specialists; and 6) examination of primary and secondary sources. Moreover, the principal investigator was able to draw on previous experience in the region, as a member of a 1977 research team from the Universidad de los Andes in Merida in a related investigation.

In most cases, responses from both technicians and farmers appeared to be open, frank, and relatively consistent. We have a very high level of confidence that the information gathered in

Venezuela is accurate. Unfortunately (and perhaps inevitably), our recognition of some of the important issues evolved during the period of investigation or during careful analysis of the data after returning from the field. Therefore, supplemental materials are used, including secondary sources and other information not directly related to the conservation projects observed in the field. In addition, the Japanese method of construction and maintenance of agricultural terraces is taken as a comparative example for some of the theoretical work presented in Annexes 1 and 2.

In both Peru and Guatemala, field investigation was brief, with eight days in Peru and four days in Guatemala. The information gathered in these countries is based on: 1) in-depth interviews with AID personnel and project directors; 2) a visual assessment of project sites; 3) informal interviews with local farmers; and 4) secondary sources.

Most of the field time in Guatemala was spent in the Quetzaltenango region where a volcanic eruption around the turn of the century deposited about a meter of fine ash over the area, creating a very distinctive ecological setting. Because there is essentially no surface rock available in this area, the use of rock walls for agricultural terraces is not an option. Of course, elsewhere in Guatemala the amount of rock, and thus the option for rock wall construction, varies from site to site, as it usually does in mountainous regions elsewhere in the world.

In Peru, most of the field time on project sites was spent in the Chincheros Basin area of the Cuzco region. This region of Peru is substantially higher and drier than most of the highlands

of the country. Moreover, southern Peru is an economically depressed area, and the Chincheros communities are among the poorest in that region. Among other limitations, the region is isolated from major urban markets so that the potential for marketable surplus production is severely limited.

Neither the Quetzaltenango nor the Chincheros regions can be considered to be typical of environmental conditions generally in highland Guatemala and Peru. Nevertheless, these two sites did provide an excellent opportunity to observe the AID sponsored agricultural terracing program. In addition, the principal investigator was able to draw on previous work in both regions, including more than two years in the Cuzco region of highland Peru.

SOIL EROSION IN HILLSIDE AGRICULTURE

The critical variables in the soil erosion equation are: 1) aggresiveness of the environment, especially erosivity of rainfall; 2) erodibility of soils; 3) landform factors, especially steepness and length of slope; and 4) soil management practices. Although conditions for each of the above variables are site specific in detail, some general statements can be made with regard to the tropical highlands of Latin America.

Soil erosion may be caused by wind or water. There is no wind erosion when the soil is wet (Greenland, 1977a, p. 4); by extension, wind erosion is a potentially serious problem only in subhumid and arid regions. Subhumid and arid regions in the tropical highlands of Latin America include southern portions of the Altiplano of southern Peru, western Bolivia, and northwestern

Argentina, the western flank of the Andes in Peru and northern Chile, and a few other isolated pockets, especially in northwestern Venezuela and central Mexico. We have been unable to find literature related to wind erosion in these regions; this may suggest that wind erosion does not pose a major threat to the environment or the economies of the tropical highlands of Latin America.

The literature dealing with water erosion in the tropical highlands of Latin America is voluminous (Ahmad, 1984 and Lal, 1977d, provide a review of this literature; also see Bremer, 1984b; Chang-Navarro, 1984; Hoy and Belisle, 1982; and Pla, 1977). Unfortunately, most of this literature is highly generalized and descriptive, and there is relatively little empirical data on erosivity of rainfall, erodibility of soils, impact of slope and management factors, or actual data on soil loss and off-site impacts of erosion. In addition, there is disagreement among experts on several issues that are directly or indirectly concerned with erosion control. The discussion of factors related to erosion in highland Latin America presented below is therefore generalized and cursory.

Erosivity

Soil erosion by water occurs when water flows over the surface and carries with it small soil particles. It involves two factors: first, the detachment of small particles from soil aggregates, mostly under the impact of raindrops on exposed soil; and second, surface runoff, which occurs when the rainfall rate exceeds the infiltration rate. It is only under conditions of

very intensive rainfall that particle detachment of soil aggregates takes place. Careful study has shown that the correlation between soil loss and total rainfall is poor (Lal, 1977a, p. 52). Soil loss in Zimbabwe correlates strongly with the product of the kinetic energy of the storm and the maximum intensity during the first thirty minutes of the storm (Lal, 1977a, pp. 52-3). Kinetic energy is a function of the terminal velocity and size of raindrops. In Zimbabwe it was found that soil loss correlates strongly with rainfall exceeding twenty-five millimeters per hour, and that storms producing less than that amount of rain per hour were not erosive (Lal, 1977a, p. 53). Another study suggests that less than ten millimeters of rain in a single storm cannot induce runoff or erosion, and rainfall intensities of less than 0.18 millimeters per minute (about 11 mm per hour) cannot produce erosion irrespective of rainfall quantity (Georgiev, 1985, pp. 425-6).

The rainfall patterns in Western Europe do not cause serious erosion, so that the relatively conservative farming practices that evolved there were not geared to deal with severe erosion problems (Russell, 1977, p. xi). Likewise, probably ninety to ninety-five percent of all rainfall in most temperate zones is not erosive (Lal, 1977a, p. 49). By contrast, tropical storms have a much greater energy load, and the majority of tropical rain falls in erosive storms (Edwards, 1977, p. 33; Greenland, 1977a, p. 3; Kowal, 1977, p. 57; Lal, 1977a, p. 49). Maximum intensities of forty to two hundred millimeters in fifteen minutes and five hundred to a thousand millimeters in

twenty-four hours are reported in the humid tropics (Lal, 1977a, p. 49-50).

Maximum intensities in the highland areas of the tropics are usually lower, but are nevertheless high in comparison with most temperate regions. In Kenya, maximum intensities for extreme weather events have been estimated to be 130 millimeters per hour at 900 meters of elevation and 110 millimeters per hour at 1,500 meters. The maximum twenty-four storm expected once every two years declines in intensity with elevation (Mombasa, 190 mm; Voi, 152 mm; Kisumu, 132 mm; Kabete 118 mm; and Kitale 95 mm: Ahn, 1977, p. 166). It is reasonable to expect a similar decline in intensity with elevation in Latin America. Data on extreme weather events for the study sites are not available, but during the apparently typical year of 1967, the City of Merida, Venezuela, at 1,641 meters above sea level, received forty-three millimeters of rain in a twenty-four period, and in 1965 there were four months in which the rainfall intensity equaled or exceeded twenty-five millimeters in one hour (CORPOANDES, 1971, pp. 4, 6, & 14).

There is little reason to assume that very intensive storms are absent in other tropical highland areas, or that the probability of occurrence of such storms is substantially lower in those areas with lower rainfall totals. The forty-three millimeter storm in Merida, noted above, occurred in the month of January, which is normally the month with the lowest rainfall. During the two years the principal author lived in the highlands of southern Peru, a region considerably drier than highland Venezuela, major storms were less frequent, but appeared to be

almost equal in intensity to those observed in regions with much higher rainfall totals.

Erodibility

Even in an erosive storm, erosion will occur only when the rainfall rate exceeds the infiltration rate and excess water moves over the surface. It is generally assumed that tropical soils have good permeability, and are therefore structurally very stable. However, recent study suggests that this generalization is much too broad-- that many tropical soils have weak structures which do pose problems of erodibility (Greenland, 1977b, p. 18). When natural vegetation is removed, soils are exposed to direct raindrop impact and are compacted, severely limiting the infiltration rate. Studies suggest that few, if any, soils are able to withstand the compactive forces to which they are exposed (Greenland, 1977b, p. 22). On the other hand, tillage, especially when organic matter is added to the soil, will tend to recreate the structure, and thereby increase the infiltration capacity of the soil (Edwards, 1977, p. 33; Greenland, 1977b, p. 22).

Very little information on other erodibility aspects of soils in the tropical highlands is available (Hudson, 1977, p. 12). Some areas of highland Latin America, especially Central America, have volcanic soils which are unusually stable. Soils weathered from volcanic ash have a high organic matter content compared to most tropical soils, and their relative stability is in part due to this factor (Greenland, 1977b, p. 21). Organic matter supports animals and microorganisms which bind the smaller soil particles into aggregates, hindering their detachment.

Organic matter content, generally low in the tropical lowlands, is usually somewhat higher in the highlands because of lower rates of decomposition due to lower temperatures.

Landform

Potential erosion problems increase exponentially with both the degree and the length of slope. Hudson has found the exponent for degree of slope to be about two; that is, erosion potential increases with the square of the slope angle. He suggests that the impact of slope length is similar (Hudson, 1977, p. 13). On the other hand, Roose found that slope length is much less important than slope angle. He suggests that the exponent for length is less than one, and varies from 0.1 to 0.9 (Roose, 1977, p. 183). Taking the upper end of that range, a ten-fold increase in length would increase erosion potential by about six-fold.

Terrace construction can reduce both the angle and length of the slope. However, the emphasis on angle versus length varies according to terrace design. It is easier to reduce the length of a slope (with a vegetation or rock wall barrier) than it is to reduce the slope angle. Therefore, the question of angle versus length of slope, as a potential erosion problem, is an important issue in terrace construction.

In contrast to the tropical lowlands, the landform factor is a principal component in the erosion equation in the tropical highlands. With the exception of some portions of the Altiplano region in southern Peru and Bolivia, and occasional basins, mesas, and natural terraces, the landforms in the Andes are

characterized by moderate to extreme slopes. Likewise, the tropical highlands of Central America and southern Mexico are generally characterized by very steep slopes. Many of these areas have relatively high, or extremely high, agricultural population densities. Therefore, cultivation of steep slopes is common. In Venezuela we observed cultivation on slopes of from twenty-five to forty percent almost throughout the region, and found cultivation on slopes of from seventy to eighty-five percent in many areas. Lal reported that seventy-five percent of the cultivable area in highland Venezuela is on slopes exceeding twenty-five percent (Lal, 1977d, p. 236)

Management

The final variable in the erosion equation is management. There are two basic ways of approaching erosion control through management: agronomic adjustment of land use on steep slopes to avoid the erosion threat, and engineering efforts to reduce that threat. It is the management factor that has allowed traditional agricultural systems in the tropical highlands of Latin America to survive in spite of the erosivity of rainfall, the erodibility of soils, and the steepness of slopes (Russell, 1977, p. xi). Sound management was achieved in most cases by agronomic adjustment to the environment; however, engineering works designed to change the environment were not uncommon.

Shifting cultivation on steep slopes is one agronomic adjustment to minimize the erosion problem. The pattern of shifting cultivation, in which small plots are cultivated for two or three years and then fallowed for five to twenty years, does

not produce major erosion problems (Olayide and Falusi, 1977, p. 118; Russell, 1977, p. xi). Slope length is relatively modest, and the cultivated plots are surrounded by perennial plants on fallowed land. When abandoned, the small plots are quickly reseeded naturally, so that regrowth of vegetation is vigorous. Shifting cultivation, however, is generally associated with low, or very low, yields, and is not adaptable to sustained rates of increase in production.

Where population densities were higher, as they were in much of Mesoamerica and the Inca region of South America, more intensive agricultural systems were required. The development of "raised field" agriculture in lacustrine basins, deltas, and other poorly drained areas was a major engineering achievement. However, from the point of view of agricultural adjustment to highland regions, the emphasis on poorly drained areas can be considered an agronomic solution to the erosion problem. Intensive cultivation in those areas where erosion problems are minimal allowed for a lower level of land use intensity on steep slopes.

Engineering solutions to erosion problems on steep slopes include relatively simple drainage ditches at the tops of fields to remove excess water during periods of heavy rain. This technique is frequently used today in conjunction with shifting and other cultivation on steep slopes, and may have evolved during pre-Colombian times as a soil conservation practice. The most spectacular engineering solution to erosion on steep slopes, however, was the construction of agricultural terraces.

Agricultural terraces were probably used in many parts of the densely settled highlands of Meso and South America. Indeed, it is argued in this paper that terraces "evolve" naturally in response to cultivation on steep slopes (see Annex 1). However, it was only in the Inca region of South America that agricultural terraces were formalized along the contours of slopes with strong rock retaining walls, and therefore it is only in that region that pre-Colombian terraces survive to the present time.

Terrace construction occurred in Peru at a time when society was predominantly agricultural, and presumably well organized and tightly controlled. It can be assumed that the opportunity cost for labor between agricultural cycles was very low, and hence the real cost to Inca society for terrace construction would have been substantially less than the actual man-hour requirement would suggest. The absence of alternative employment possibilities between crop cycles may be one key to terrace construction and other major engineering efforts to control erosion and improve the agricultural resource base. This is a theme to which we shall return later (see "Window of Opportunity").

The Current Erosion Crisis

The current crisis of soil erosion in Latin America is the result of the rapid pace of change in demand and the frequent failure to adjust imported agricultural systems to the environmental conditions of the tropics and subtropics. Population growth and the desire for marketable surplus income has led to a breakdown in the equilibrium between production and demand. Land previously used under shifting cultivation is being cropped

annually or continuously, and land previously thought to be unsuitable for agricultural use is now being cultivated. The pressure of too many people on too little land is forcing some farmers out of their familiar ecological setting and into new areas where their store of traditional knowledge regarding conservative land management may be inappropriate. Agricultural systems transplanted from temperate lands have not been adequately adjusted for the more aggressive tropical and subtropical environments (Russell, 1977, p. xi; also, with reference to Nigeria, see Olayide and Falusi, 1977, p. 118).

A similar breakdown in the equilibrium between production and demand occurred during the early colonial period when new cultigens and domestic animals were introduced. The catastrophic decline in the Native American population, mostly as a result of imported disease, greatly reduced the demand for traditional subsistence crops, so that much of the land was planted to wheat and other commercial crops or converted to pasture. Much of central and southern Mexico, especially the Oaxaca, Hidalgo, and Tlaxcala regions, was so badly eroded that even today the land has little agricultural value. In this case the introduction of the plow is held responsible (West and Augelli, 1966, p. 280). Native Americans did not have a plow, or domestic animals that could have made a plow useful. The adoption of the oxen-drawn plow system designed for Spain proved disastrous under intensive tropical weather conditions.

In Peru, most of the approximately one million hectares of Inca terraces were abandoned or converted to pasturage for livestock. As a result of lack of maintenance and damage by cattle,

and perhaps other still undiscovered factors, about two-thirds of this valuable agricultural resource is now in ruins (Denevan, 1985). Lal states that in highland Latin America hundreds of thousands of acres of land have lost their capacity for production because of serious soil erosion (Lal, 1977d, p. 231).

The potential for ecological disaster, resulting from the current increase in demand and change in farming method, is at least as great it was during the early colonial period. On the positive side, we are in a better position to predict the consequences of our actions, and development agencies are generally cognizant of the need to follow sound land-management practices. At the same time, there is an immediate pressing need to produce food and fiber for the rapidly growing populations and economies of Latin America. Clearly, the overriding issue in Latin American agriculture today is increased production; the task of the conservationist is to pursue that goal in such a way that the longer-term economic interests of society as a whole are not ignored.

AGRICULTURAL TERRACES: BENEFITS AND ALTERNATIVES

The construction of agricultural terraces is just one of a number of soil conservation practices. The primary purpose is to reduce the length of the slope and to remove water at a velocity that will not cause erosion (Moldenhauer and Onstad, 1977, p. 89). There is no single terrace design that is technically feasible, ecologically sound, and cost-effective under all environmental and social conditions. Important considerations are the amount and erosivity of rainfall, the erodibility of

soils, steepness of slope, crops and farming practices, the presence or absence of rock on the field, and the opportunity cost of labor for terrace construction.

The construction of agricultural terraces has been carried out in many parts of the world from pre-historic times to the present. It might appear that terrace construction is an "obvious" solution to the problems of cultivation on slopes. Actually, terracing has usually occurred under conditions of extremely high agricultural densities and/or very intensive, high value output per unit of land production. Terracing is not the only solution to problems associated with the agricultural use of steep slopes; indeed, it is probably the most radical solution.

Terrace construction is a solution in which the landform is modified to fit the desired farming system, in contrast to the less radical solution of adjusting the farming method to the landform. It is a solution which is very costly-- usually in terms of high inputs of labor. With some exceptions, such as in the case of wet rice cultivation, some or most of the benefits of terracing can be achieved through alternative practices at a much lower cost. Therefore, terrace construction is usually restricted to those cases in which the benefits of controlling problems associated with hillside agriculture are very high; it is therefore a solution which will normally be applied selectively and sparingly. Nevertheless, under appropriate circumstances, terraces can yield important economic and conservation benefits.

Economic versus Conservation Benefits

The distinction between economic and conservation benefits is to some degree arbitrary-- related more to our methods of cost accounting than to some fundamental distinction between the two. The most important economic benefits of terrace construction are those which normally fall under the category of conservation; they include the preservation of the land resources for continued agricultural use in the future and the reduction or elimination of off-site costs associated with erosion.

These benefits are mostly long-term, and difficult or impossible to calculate precisely. When cost accounted, future benefits are generally discounted at some rate to determine their current value; it is, of course, the current "discounted" value that is used to determine whether a given investment is justifiable. If the discount rate is set at ten percent, then a one thousand dollar benefit five years hence has a discounted current value of 621 dollars; the same one thousand dollar benefit ten, fifty, and one hundred years hence has discounted current values of 385, 8.50, and 0.07 dollars, respectively. A well constructed agricultural terrace will continue to provide economic benefits for many generations; likewise, it may result in reduced off-site erosion costs for a similar period. However, beyond a period of twenty years or so, those benefits are given little or no economic "value" in cost-benefit analysis (for a discussion of the pros and cons of discounting future benefits, see: Dickinson, 1978, pp. 89-90; Herrick and Kindleberger, 1983, pp. 291-3; Nafziger, 1984, pp. 285-8).

There are, to be sure, good economic and social arguments in favor of discounting future benefits to ascertain their current value for planning purposes. Individual households and firms attempt to invest their money in such a way as to maximize the rate of return; they would probably consider it uneconomic to invest in a conservation project which is expected to yield a lower rate of return than an alternative investment. Public agencies have similar responsibility to use public funds in a way that maximizes the rate of return on investment.[1]

In addition, the further into the future the analysis is projected, the less certain we can be that forecasted benefits will actually materialize. In the case of agricultural terrace construction, there can be no guarantee that even the best designed system will survive, or be useful for future generations. A terracing system can be destroyed by natural catastrophe or war; it could deteriorate due to lack of maintenance, or be made obsolete by some future change in farming practice or demand.

In short, there are valid arguments in favor of considering

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[1]The current discounted value (DV) of an expected future benefit can be calculated as:

$$DV = V / (1+r)^t$$

where V is the expected benefit in t years and r is the discount rate selected. It should be noted that few planners would argue against the use of a discount rate; it is, rather, the value selected that is in question. Consider, for example, the difference between using discount rates 5 % and 15 % to determine the current value of a 1,000 dollar benefit expected in 30 years. The 5 % rate would depreciate the future 1,000 dollar benefit to to a current value of 230 dollars, and the 15 % rate would depreciate it to only 15 dollars. If the 5 % rate is used, the future benefit may have considerable weight in cost-benefit analysis; by contrast, if the 15 % rate is used, the future benefit would have little or no influence on decision making.

the longer-term, less certain, economic gains as "conservation" benefits, which are separate and distinct from short-term "economic" benefits. It is a simple fact that uncertain benefits accruing to unborn generations have little or no "economic" value when cost accounted against the certain and desperate needs of the present. Thus, if the long-term benefits are not considered separately under the heading of "conservation" they will probably not be considered at all!

One caveat is nonetheless required. Although the desperate current needs of people may outweigh the uncertain benefits that accrue to future generations, immmediate gains in income cannot justify a project which carries a high risk to the lives and/or livelihood of people within the foreseeable future. A statement in a recent Worldwatch Paper on soil erosion suggests that this caveat may be apropos to the subject of agricultural terraces (Brown and Wolf, 1984, p. 9).

> Centuries of laborious effort are embodied in the elaborate systems of terraces in older settled countries. Now the growing competition for cropland in many of these regions is forcing farmers up the slopes at a pace that does not permit the disciplined construction of terraces of the sort their ancestors built . . . Hastily constructed terraces on the upper slopes often begin to give way. These in turn contribute to landslides that sometimes destroy entire villages, exacting a heavy human toll. For many residents of mountainous areas in the Himalayas and the Andes, fear of these landslides has become an integral part of daily life.

The Worldwatch Paper does not provide documentation of specific cases where "hastily built" terraces have contributed to the loss of life and property, and that publication is not one to understate environmental issues. Nevertheless, the disasters

described are not outside the range of possible consequences of poorly designed terrace construction. There are other reports of serious erosion problems resulting from poorly designed and/or constructed terraces and other land shaping methods of erosion control (Greenland and Lal, 1977, p. 262 and Plate 36; Lal, 1977d, Plate 33; Moldenhauer and Onstad, 1977, p. 88).

In terrace construction, as in all development projects, there is an obligation to take reasonable precautions against future hazards to life and property. It would be a false economy indeed to pursue short-term gains in income at the risk of destroying the potentially renewable soil resources and the lives of the people affected.

Potential Economic Benefits

Among the potential immediate economic benefits of constructing agricultural terraces is increased water absorption as a result of the more level surface. In areas of ample rainfall or where sufficient irrigation water is available, the value of increased water absorption probably will not justify terrace construction. Even in regions where potential evaporation exceeds rainfall, or where there is a significant dry season, the use of terracing as a means of increasing water availability will probably be considered a last resort.

The more obvious and certain method of increasing water availability is the installation of irrigation systems. Throughout much of the Andes and elsewhere in Latin America, there is ample potential for building and improving irrigation systems. In some areas little or no attempt has been made to

provide irrigation water. Even in areas where irrigation is practiced, farmers are frequently limited to gravity-flow systems by canal. These canals must follow long circuitous routes along the contours of hillsides with consequent high maintenance costs and loss of water through evaporation and canal failure; some areas cannot be served by the canal system at all. With the use of tubing, irrigation water can be transported across narrow valleys and directly downslope; the use of movable aluminum or plastic pipe and sprinkler systems can make irrigation water available over a wide area from a single supply tube.

The experience in the Valles Altos region of Venezuela shows that farmers can be readily induced to provide necessary labor for installation of mini-irrigation systems, and can manage these systems without outside support after installation. In those cases where market conditions are favorable, farmers will probably be able to repay the costs of small irrigation systems rather quickly. In highland Venezuela the installation of mini-irrigation systems has not yet exhausted the surface water available through gravity flow. These systems have transformed many small valleys into highly productive intensive farming regions which provide a much improved standard of living for the inhabitants.

The construction of terraces solely as a means of increasing water availability is probably appropriate only under extreme and limited circumstances. In those dry regions where irrigation water through gravity flow is unavailable, and the cost of pumping water is prohibitive, and where farmers have no alternative to cultivation of small plots on steep slopes, terrace

construction may be one important way redundant labor can be converted to income producing capital.

Other potential immediate or short-term benefits from terrace construction include: a reduction in the loss of organic matter and nutrients from downslope erosion and surface runoff; land reclamation such as removal of excess rock or filling in poorly drained areas; the creation of a more manageable cultivation surface; and halting obvious on and off-site erosion damage, such as damage to irrigation canals, roads, ponds and reservoirs, and buildings. These conditions are mostly site or circumstance specific, and may make terrace construction applicable locally in a wide variety of environmental and social situations.

The initiation of terrace construction, or any other new farming system that is designed to increase farm income, may require a modest subsidy or incentive payment to farmers. For the most part, however, the role of public agencies should be organizational and educational. Once proved cost-effective and ecologically sustainable, we would expect a terracing system that results in immediate or short-term economic benefits to diffuse from farm to farm and village to village with little or no further public assistance.

Potential Conservation Benefits

The construction of agricultural terraces solely for conservation purposes is also unlikely to be appropriate except in extreme and limited circumstances. The most obvious response to

excessive erosion on steep slopes is to convert the land use pattern to one which does not result in excessive erosion; that is, to adjust the land use to the landform rather than attempt to change the landform to suit the farming system.

Unfortunately, population pressure and land tenure problems throughout much of highland Latin America will not allow for this solution. Even with the most optimistic estimates of rural to urban migration, fertility decline, and land redistribution, many highland regions of Latin America will continue to have large farm populations confined to steep slopes for at least another generation. Under less optimistic, and perhaps more realistic, assumptions, there is no foreseeable end to the cultivation of steep slopes in much of Latin America.

Notwithstanding the impossibility of eliminating cultivation on steep slopes, there are a number of soil conservation measures that are less costly than terracing, and may accomplish some or most of the objectives. A hillside that is contour plowed has, in effect, a large number of small terraces, which will act to reduce erosion and increase water absorption. Drainage ditches can be dug at the tops of fields to channel excess water away from the cultivated area during heavy rain. Vegetation barriers and/or ditches can be build along the contours of the slope at various intervals to break the downslope flow of water. The erosivity of surface flow is a function of both steepness and length of slope; it is much cheaper to create breaks in the length of the slope than it is to change the degree of

steepness.[1]

It is not a foregone conclusion that cultivation of steep slopes will necessarily result in a degree of erosion that will significantly depreciate the agricultural utility of the land or produce major off-site problems. Latin American farmers have cultivated steep slopes for many hundreds of years. It is more than a little presumptuous to conclude that that hillside agriculture per se cannot be sustained for another generation. There is a need to show that slope cultivation does result in substantial on or off-site damage before terracing as a conservation measure would be justifiable. Even in those cases where significant off-site damage of erosion is obvious the problem may not necessarily be tied to erosion from agricultural land. Proper maintenance of road cuts and streams or erosion gullies may yield more off-site benefits than attention to agricultural land.

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[1] It should be noted that contour plowing and ditching may not be an effective control for erosion under extreme weather conditions, and these systems can increase the risk of an erosion disaster when poorly designed, constructed, or maintained. Dr. Aguilar, formerly with the Venezuelan Soil Conservation program noted that ditches along slope contours must be carefully designed to assure sufficient slope to carry off excess water during periods of heavy rain; they must also be well maintained so that the free flow of water is possible (personal interview). In one case in Venezuela, erosion control ditches were poorly designed and maintained. During a heavy rainstorm several of the higher ditches on the slope became clogged and water began to spill over the slope, overloading the ditches below. Within a few hours a large gully had formed and much of the hillside was destroyed. The case was made more embarrassing by the fact that it is clearly visible from the main plaza in Mucuchias, Merida. Dr. Aguilar stated "our conservation medicine was worse than the illness!" A contour-plowed steep slope is potentially subject to the same kind of failure. Similar failures of erosion control systems are reported in Tanzania, including some that were well constructed but based on inadequate design criteria (Greenland and Lal, 1977, pp. 262-3).

In those cases where there is a clear danger that valuable farmland will be destroyed by erosion, or where there are serious off-site problems as a result of erosion, terrace construction is one potential solution. As noted above, terrace construction is not the only method of erosion control, and it is likely to be the most costly method. On the other hand, terracing, if properly constructed and maintained, will probably be the single most effective soil conservation practice. As a soil conservation measure, therefore, terrace construction is probably appropriate when valuable cropland is threatened by erosion and/or when major off-site damage of erosion is clear and apparent.

When terrace construction is pursued for conservation purposes a public subsidy payment is probably appropriate and may be essential. The long-term preservation of soil resources and reduction of off-site costs frequently do not appear in the farmer's cost accounts (Olayide and Falusi, 1977, p. 121). Conservation benefits are frequently greater for society than for individuals because of the different time perspective of their respective plans. The farmer can often reap higher net incomes by exploiting soil resources in a destructive, rather than conservative, way. In some cases the farmer is a sharecropper or squatter with little or no long-term stake in the land (Olayide and Falusi, 1977, p. 121). Even farm owners may not perceive erosion to be a problem on their own land, and may have little concern for off-site damage.

Dual Purpose Terrace Construction

In is likely that in most cases, terrace construction will not be justifiable by either economic or conservation objectives alone. However, some combination of those objectives may make terrace construction a desirable development alternative. Probably most publicly sponsored development programs have dual or multiple objectives, no single one of which would justify the public investment. Terracing, and other erosion control systems, are by no means unique in this respect.

When a development scheme has more than one primary objective, there is a danger that the different objectives are not mutually consistent or even compatible. For example, when erosion control canals are dug along the contours of slopes they are constructed with a slight slope, and maintained free of debris, so that during period of heavy rainfall excess water can be channeled away from the slope. Thus, the primary soil conservation purpose of erosion ditching is to protect the land from erosion during times of very heavy rainfall. If a similar technique is constructed to increase the absorption of water, the ditches are made level and sometimes built into short segments to prevent the flow of water away from the slope. The purpose is therefore to prevent, rather than expedite, the removal of excess water from the land.

There are many good reasons for conserving water with absorption ditches, but decreasing the risk of soil erosion during periods of heavy rain is certainly not one of them. Likewise, level or backsloped absorption terraces are designed to prevent the loss of water, and might be incompatible with conser-

vation objectives where there is a need to assure removal of excess water during periods of heavy rain. It is important to be explicit on this point: **the long-term conservation and short-term economic objectives of terracing are not necessarily, or even usually, in conflict; however, there is a potential for conflict between those objectives.**

When a terracing program is pursued for both short and long-term objectives, it is important that both objectives be given adequate attention. The short-term income objectives of farmers are more easily measured and visible, and the beneficiaries are on site and vocal. It is important to have someone in the project who speaks for the public good as well, especially when public funds are being used to pay part of the costs. It is especially important to be sure that pursuit of immediate increases in income does not carry with it an increased risk to the lives and/or property of the people involved. In short, we must be sure that the "conservation medicine" is not worse than the "erosion disease."

THE "VALLES ALTOS" PROGRAM

Physical Setting

The Valles Altos conservation program focused on small valleys located at elevations ranging from 1,600 to 2,500 meters in the central and western Andes of Venezuela, including the States of Trujillo and Merida where the field investigation was carried out (Aguilar, 1977, p. 17). About half the total area of those states is held in farms, the remainder having environmental

conditions that are too extreme (primarily in terms of elevation and steepness of slope) for agricultural settlement; only about twenty-five percent of the agricultural land is used for crops (CORPOANDES, 1971, pp. 3 & 149). Terrace building under the conservation program affected perhaps one-half of one percent of the land in crops.[1]

As is true generally in the tropical highlands, the range of variation in climate, vegetation, landform, and soil is so great that even chapter-length description is likely to be superficial. The brief treatment here must, of necessity, be confined to the most general features.

Characteristics of the myriad of micro-climates are determined primarily by elevation and slope orientation with respect to moisture bearing winds. Annual mean temperatures range from about twelve to twenty degrees centigrade, depending upon elevation, and there is little variation in temperature from month to month. Killing frosts are rare within the elevation zone. Annual rainfall ranges from 600 to 1,200 millimeters with maximums associated with the passing of the Intertropical Convergence zone (ITC) in the late spring and fall. The driest months are usually December through March. In mid-summer, especially July, rainfall is generally low due to the extreme northern location of the ITC at that time. Locally, slope aspect and rainshadow

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[1]Actual documentation of the area affected by the terracing programs is not available. However, during the middle and late 1960's an annual average of 20 to 30 thousand cubic meters of retaining wall were built (DRNR, 1974); that amount of wall is sufficient for about 50 hectares of land. Thus, during the lifetime of the program the total amount of land affected was probably between 300 and 1000 hectares, with 500 being a reasonable estimate.

effects of mountains can be as or more important than regional factors in determining temperature and rainfall conditions (Aguilar, 1977, p. 17).

Landforms are likewise extremely variable. In general the higher valleys are more narrow and have a higher percentage of very steep slopes. Exceptions are many large natural terraces and mesas with slopes that are relatively modest. Elsewhere, valleys have slopes of from ten to forty percent in the direction of the primary drainage system. The valleys are narrow and enclosed by ridges with much steeper slopes.

Soil characteristics reflect the varied geology and erosional patterns, as well as climatic conditions. The narrow valleys are frequently covered with alluvial materials. In general they range from moderately acid to acid with elevation, reflecting lower evaporation and thus higher positive water balance values. Many of the high valleys have a high percentage of rock material in the soil-- a factor that is critical to retaining wall design in terrace construction. Where rock is slight or absent, alternative soil conservation practices, including earthen-banked terraces were constructed. However, in those cases observed, the earthen terraces have been largely eroded away.

Social and Economic Background

Agricultural terracing has been practiced for many hundreds of years in areas of dense agricultural settlement around the world. Terrace construction, along with the development of irrigation systems and the construction of "raised fields" was one

of the major achievements of the Inca civilization in the Andean Highlands of South America. It is estimated that in Peru there are one million hectares of land in Inca terraces, with about one-third still under cultivation (Denevan, 1985, p. 2).

Highland Venezuela is far removed from the heartland of the former Inca Empire. There is no evidence of agricultural terracing, or indeed of any advanced farming systems, in pre-Colombian Venezuela. The native hunter-gatherers and primitive farmers were absorbed into a mestizo society that, until quite recently, practiced the farming system imported from Medieval Spain. Prior to 1950 the agricultural system in the Highland areas of Trujillo and Merida was largely one in which the more level valleys were used mostly for sugar cane at lower elevations, and coffee or extensive grazing at higher elevations. The vast majority of the population produced subsistence crops on steep slopes (Aguilar, 1977, pp. 9-10; EG, 1976, pp. 2-3 & 6-8).

Beginning in the 1950's, the growth of several cities on the coast and in the northwestern Andes gave rise to a rapid increase in the demand for vegetables. The highland region of Trujillo and Merida States possessed the physical and locational characteristics required to fill that demand. The region is cool enough to allow for the production of high quality vegetables, and yet generally frost-free so that two or three crops can be obtained per year. The high farm population density, small farm size, and high degree of underemployment made intensive horticulture a viable and desirable option.

On the other hand, the region faced a number of serious problems. Although relatively close to the major urban centers

of the country, it was isolated by poor highways and the absence of penetration roads. During much of the year there is insufficient moisture for intensive horticulture, and irrigation systems were generally lacking. Finally, some of the small high valleys were covered with rocks and boulders at a density of ten to forty percent (Photo 1).

Rapid population growth and the incipient growth of demand for marketable surplus production had led to a rapid pace of increase in land use intensity. The fallow period was reduced or eliminated and relatively large fields on steep slopes were permanently cleared of natural vegetation. For many farmers the problem of obtaining subsistence and marketable-surplus production for a meager income became more difficult (Photos 2 & 3). Intensification led to deforestation and loss of pasture land, and lacking replacement fertilizer and organic matter, soil fertility declined rapidly under continuous cultivation. Thus, inadequate infrastructure and environmental difficulties were combined with intense farm poverty and probably a declining resource base due to deforestation and soil erosion.

Organizational and Institutional Framework

It was in this context that the Ministry of Agriculture initiated the Subsidio Conservacionista (Conservation subsidy) in 1961 (Aguilar, 1978, pp. 21-22). In the early stages of this program, the goals were mostly, and in some cases exclusively, long-term soil conservation. An earlier "Emergency Employment" act had made funding available to contract labor for conservation projects (Aguilar and Soriano, personal interviews). The program

was patterned after the Depression era CCC program in the U.S. Indeed, Dr. Luís Aguilar, a former program director, stated that the U.S. Department of Agriculture conservation program was adopted as the model for Venezuela, and that a translated version of a U.S. soil conservation manual (a probable reference to the mimeographed document: PDA-VA, c) was "carried around as if it were the Bible" by Ministry officials in Venezuela.

Soil conservation projects included the construction of bench terraces on steep slopes with bulldozers, digging absorption canals along slope contours, and reforestation (DRNR, 1974; DRNR, 1973; DRNR, 1970). The evidence of many of these works are clearly visible on the landscape today (Photo 4).

The program also included the construction of rock retaining walls along the contours of slopes in the small highland valleys. Prior to 1965, much of the conservation work, including the construction of retaining walls was accomplished with the use of construction crews and heavy machinery, paid for by the government (Aguilar and Soriano, personal interviews). The retaining walls were frequently spaced randomly over the fields, conforming more to property boundaries than to the landform itself.

Agronomist Jaime Soriano, who directed the Ministry conservation program in Trujillo and eastern Merida States, initiated some important changes in the program, which probably contributed to the increased success of the conservation aspects of the program there. The use of hired construction crews was discontinued in favor of working directly with farmers. Retaining

walls were planned to conform to the landform, rather than to property boundaries. The use of heavy machines was minimized. Emphasis was placed on the incorporation of the farmer into the conservation process. The installation of development related works was frequently tied to prior completion of conservation measures, and subsidy payments for conservation were used to pay for irrigation and other infrastructure on individual farms. Soriano insisted that farmers understand, appreciate, and participate in, terrace construction (Aguilar and Soriano, personal interviews). These innovations appear as policy guidelines in a 1975 Ministry publication (DCSA, 1976, pp. 2-8 & p. 32).

Although the emphasis was on conservation during this early stage of the program, the social and economic impact of the program became apparent. Building retaining walls required large amounts of rock, and because the rock was taken from the field, wall construction resulted in reclamation of the land for intensive (or more intensive) cultivation. Once the walls were built, the process of leveling, and hence terrace formation, began; however, it was the removal of the rock, rather than slope leveling, that produced immediate positive implications for land use.

Even more important for land use conversion to horticulture were several other non-conservation projects that were sometimes included as an adjunct to the conservation program. Frequently, access roads were constructed or improved. In some cases, rural electrification was installed. Most important, irrigation systems were frequently built or upgraded. These innovations led to a rapid conversion of the land to intensive vegetable gardening.

In many cases, farmers abandoned subsistence production on steep slopes and took up horticulture in the narrow valleys. The abandoned land on steep slopes was sometimes reforested, but more frequently was simply allowed to recover to brush and natural pasture (Pérez and Rodríguez, personal interviews; and field observation). Thus, the non-conservation elements of the package paid important indirect dividends in soil conservation.

The social and economic impact of the program was far more visible than the conservation impact. Land that had been marginal was converted to a highly productive and valuable resource. The value of land suitable for horticulture was estimated at between 3,500 and 5,800 dollars per hectare in 1977 (Aguilar, 1977, p. 30).[1] Farmers who had previously been among the poorest people in Venezuela achieved major gains in living standards. A farmer with two or three hectares of land in intensive vegetable gardening could achieve a moderately high income; jeeps, TV sets, and improved homes became accessible. Those farmers with more than two hectares usually had insufficient labor to work all the land intensively; frequently, they would allow sharecroppers (medianeros) to work the land in about one-half hectare units, and split the harvest. This process helped to reduce that population that was previously confined to subsistence production on

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[1]These figures must be viewed within the context of extremely high land values throughout Venezuela and most other regions of Latin America. Among the reasons for inflated land values is the tendency to use land investment as a hedge against inflation and a poorly developed real estate market for agricultural land. Throughout the Valles Altos region, one is frequently told that land is not for sale at any price. Although obviously an exaggeration, the view does confirm the general attitude of farmers regarding the value of land resources.

steep slopes.

It is important to note that it was the introduction of irrigation and other innovations, rather than terracing or retaining wall construction per se, that resulted in land conversion to intensive horticulture. The construction of retaining walls did result in the removal of excess rock from the field, but that could be (and in some cases was) accomplished by simply throwing the rock into the nearest erosion gully. It was irrigation systems and access roads that were in demand-- not rock retaining walls.

In 1975 the Subsidio Conservacionista was transferred from the conservation section of the Ministry of Agriculture to the Corporacion de los Andes (CORPOANDES), and the project name was changed to "Valles Altos." CORPOANDES is a nationally funded development and planning agency which operates in several highland states of Venezuela. The soil conservation aspects of the program were presumably retained; however, the clear mandate of the program shifted from conservation to socioeconomic development (PDA-VA, a; PDA-VA, 1976).

Both the Ministry of Agriculture and CORPOANDES recognized the fact that conservation was being sacrificed for development projects that produced immediate returns in the form of social and economic benefits. In 1976, a Ministry of Agriculture publication argued that the conservation program had been converted to one which focused on the social welfare of farm communities, and that conservation had become secondary (DCSA, 1976, p. 2). Likewise, a CORPOANDES statement indicated that the conservation

program had achieved less than was expected because most attention was given to the non-conservation elements of the program (CORPOANDES, 1974, p. 211). Nevertheless, the CORPOANDES statement of purpose for the newly acquired project focuses primarily on the installation of irrigation systems, and gives little attention to soil conservation (PDA-VA, 1976).

To be sure, retaining wall construction may have continued in several areas, and it would be unfair to say the Valles Altos program abandoned the overall objective of soil conservation. Soriano, who took charge of the Valles Altos program in the state of Trujillo,[1] continued to push for the construction of rock retaining walls. However, the installation of irrigation systems led to immediate and dramatic gains in farm income in contrast to the longer-term and less visible benefits of soil conservation. Given limited resources and the extreme conditions of poverty among those farmers that did not have access to water, it was perhaps inevitable that the primary emphasis would shift from soil conservation to the construction of irrigation systems and access roads.

Terrace Construction

Terrace construction was accomplished by controlling the natural process of erosion. Substantial rock retaining walls were constructed along the contours of the slope at intervals of

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[1]Previously Soriano had directed the Ministry program in the Trujillo "region" which included that portion of the State of Merida on the northern and eastern side of the watershed divide. Thus, after 1975 the jurisdiction of several project sites started or completed under Soriano's direction was transferred to the Merida CORPOANDES office.

from ten to forty meters. Thereafter, erosion and downslope plowing provided the fill behind the retaining wall (DRNR, 1973; PDA-VA, b; PDA-VA, c).

The first step was to excavate a foundation trench about one-half meter deep for the retaining wall. This excavation was done to assure a firm foundation for the wall in the subsoil. The material removed from the foundation trench was thrown up-slope. Even this modest effort to move the soil and subsoil was not done primarily to accomplish terrace leveling. The area behind the wall is a convenient place to dump subsoil where it will be covered by topsoil eroding downslope (PDA-VA, c; Soriano, personal interview).[1]

The second step was to move rock to the wall construction site. Most of the rock was moved downslope from the field above. A number of methods were used. Wheelbarrows were quickly ruled out. Ing. Soriano noted that when a man picks up a heavy rock he will tend to hold it chest high, and then drop it from that height (or risk straining his back by bending over with the weight). The wheelbarrow, or at least those available, could not take the weight and pounding for long. One unique method which did prove to be efficient was the use of two-man stretchers. Wooden sleds pulled by oxen were also used. In some cases, bulldozers were used to move large rocks. Smaller rocks were carried by children; in terms of total volume, children probably accomplished most of the effort to move the rock (Aguilar and

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[1] Inasmuch as subsoil must be buried beneath topsoil, the area behind the retaining wall is the only convenient place to deposit material excavated from the foundation trench.

Soriano, personal interviews).

The third step was to build the retaining wall. Because the walls must be free-standing above the surface (until the erosion process fills in behind) double walls were constructed with a strong face on both the uphill and downhill sides. The base of the double wall is 1.2 meters wide, or more in the case of very high walls. Both the uphill and downhill faces of the wall are sloped at between 500 and 1000 percent to the top, where the wall is about eighty centimeters wide.[1] The largest rocks were placed at the bottom, so that the thickness of both the uphill and downhill faces are thirty centimeters or more at the bottom, and decreasing to fifteen or twenty centimeters at the top. The space between the walls is filled with rock debris (Photos 5 & 6).

Cementing material cannot be used to hold the rock in place, since excess water must be allowed to drain through the wall.[2] The rock is not simply stacked or piled; it is fitted together into a strong surface (Annex 2).

There appears to be a great deal of skill involved in rock wall construction. Indeed, some of the walls in the Valles Altos

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[1] Documents actually called for walls to have a slope of from 250 to 300% (PDA-VA, c); in practice they are much steeper. Apparently, documents were translated from U.S.D.A. manuals which presupposed far less expertise in rock wall construction.

[2] Of course drainage can be achieved by installing drainage pipes within a concrete wall. An advantage of that method is that much less skill is required to construct the wall. However, rock wall construction requires only labor whereas the alternative would require substantial cash outlays for cement and pipe. In addition, a properly built rock wall will provide superior drainage and thus reduce the major cause of retaining wall failure-- waterlogging behind the wall.

projects were built by individuals who specialize in that work. Yet, we were told by farmers and program directors that many farmers know how to build strong rock walls (which are also used as foundations for houses and to maintain roads). Soriano stated that most farmers could be trained to build walls within a few days. He noted that it might take a farmer two or three days to build the first cubic meter of wall, but that soon he could build two or three cubic meters of wall per day.

Clearly, not all the walls were constructed with equal skill, and wall failures were seen occasionally (Photo 7). Nevertheless, a certain amount of wall failure can be expected over a period of ten to twenty years in any case, and in general the quality of construction is evident by the longevity of the system. The wall failures noted in the region are more likely to reflect an unwillingness to do normal maintenance than the poor quality of the work.

Once the retaining walls are completed, the process of leveling by erosion will begin. If the walls are constructed so that complete leveling is possible, a decade or two of erosion and downslope plowing is sufficient to do most of the job. A slight slope can be maintained to allow for adequate drainage, or some soil moved downslope to create a backslope.

In actual practice, the retaining walls are usually not designed to allow for complete leveling. The retaining walls are generally only one-half to one-third the height required for complete leveling. It was expected that the height of the wall would increase as erosion exposes additional rock material for continued wall construction. However, leveling cannot be

achieved by simply increasing the height of the retaining walls. In order to achieve a level terrace, half the retaining wall must be below the original surface (see Annex 1).

The problem is not so much preventing soil movement over the top of the wall as it is preventing erosion at the bottom from undermining the foundation. If a wall, which is 1.5 meters high including one-half meter below the original surface, must be twenty centimeters higher to achieve leveling, it must also be seventy centimeters deeper; that is, the 1.2 meters above the original surface must be matched by 1.2 meters below that surface. In the Valles Altos project, even the one-half meter excavated for the retaining wall was meant to assure a firm foundation for the wall in the subsoil rather than to expand the wall face below the original surface (although in effect it does serve that purpose).

The effect of the retaining walls is to reduce, rather than eliminate, the slope of the cultivation surface. The reduction in slope achieved by the retaining walls ranged from ten to twenty-five percent on land which had an original slope of from twenty to forty-five percent (field observation). The problem of erosion undermining the wall is solved by maintaining a steep earthen bank at the back of the terrace in some cases (Photo 8).

Alternatively, a steeper, relatively even, slope can be maintained between retaining walls (Photo 9). In this case, care must be exercised to prevent erosion from undermining the wall above. This can be accomplished by assuring that the soil is covered, either by crops or mulch (during fallow), and by the use

of upslope plowing to counteract the effects of erosion. Venezuelan farmers rarely use mulch on their fields, and usually remove or burn crop residue because it hinders plowing. We did not observe upslope plowing in Venezuela; this technique was observed under similar circumstances in Japan. If Venezuelan farmers with steep "terraced" cultivation surfaces do not use this, or some other appropriate method to counteract erosion, the base of the retaining wall above must eventually be undermined by erosion and the system will fail.

An attempt was made to determine the amount of labor required to build the retaining walls. However, the projects were completed ten to twenty years previous, and memories fade. An estimate of two to three cubic meters of rock wall construction per man-day was relatively consistent, although it was not always clear whether this estimate included excavation and moving rock, as well as building walls. Based on this estimate, the per hectare labor requirement for wall construction, assuming walls two meters high and twenty meters apart, would be about 400 man-days. Assuming farm units (or that portion terraced) to be from one-fourth to one-half hectare, and two or three workers, the job could be completed in about two months.

The retaining walls are generally from 1.5 to two meters high, and from ten to thirty meters apart, largely independent of slope. That is, a steeper slope is more likely to have a steeper final terraced surface than higher, or more closely spaced retaining walls that would allow for additional leveling. To be sure, wall height and spacing may correlate with slope at the extremes; slopes of twenty percent or less usually have walls

from one to 1.5 meters high that are widely spaced and slopes exceeding thirty-five percent sometimes have walls from two to 2.5 meters high, or walls which are spaced more closely together. Nevertheless, there was no systematic attempt to achieve a specific final slope on the cultivation surface by adjusting the height and spacing of the walls. It appears that the height and spacing of the walls is explained mostly by the amount of rock on the surface of the field, and the willingness of the farmer to invest additional labor.

If the height of the wall is taken to be relatively constant, then the labor requirement for construction is inversely proportional to the width of the terrace (that is, the distance between retaining walls). The greater the interval between walls, the less the length of wall required for a given field. Walls two meters high will achieve a twenty percent reduction in slope if they are spaced at ten meter intervals; if the same walls are spaced at twenty meter intervals the slope reduction would be ten percent, and at thirty meter intervals a reduction in slope of only 6.67 percent could be achieved. On the other hand, the amount of work required to build the walls twenty or thirty meters apart is about one-half or one-third, respectively, of that required if they are only ten meters apart (see Annex 1). In effect, there is a strong incentive to space the retaining walls at wide intervals, and sacrifice the benefits of a more leveled surface.

Social and Economic Impact

It appears that the immediate and short-term economic benefits of terracing were minimal or nil in the Valles Altos program. Some program officers did argue that terracing resulted in higher yields and reduced costs for inputs, but we were not able to find evidence to back that position. One study which purported to demonstrate the cost effectiveness of terracing on the basis of production failed to control for the major change to intensive horticulture (Comerma, 1971). This study notes that it may have been the introduction of irrigation, rather than terracing, that led to the massive increase in farm income.

Another study noted that, as a result of the conservation program, land values increased from three to fifteen fold, farmers were introduced to new cultivation methods, and migration of farmers to urban areas was slowed (Velesquez, 1984, p. 24). In this case as well, there is no way of separating the impact of soil conservation from that of irrigation and other changes in technology and market.

A third study shows that in communities strongly impacted by the conservation program, intensive horticulture is widely practiced and traditional crops account for only twenty-two percent of total production. By contrast, in those communities not affected by the program, traditional crops account for ninety-four percent of total production (Aguilar, 1977, p. 45). However, the selection of communities for the project was determined in part by their suitability for conversion to horticulture, and there is no way to know whether that conversion was dependent upon the soil conservation program.

It seems likely that the soil conservation program did have some impact on the transformation from subsistence production to intensive vegetable gardening in the Valles Altos region. Construction of retaining walls did result in some land reclamation. Farmer contact with the agronomists who directed conservation programs may have helped spark many innovations in cultivation techniques. In addition, the soil conservation program did come to many communities as a package that included irrigation and other infrastructure essential to the conversion to intensive horticulture. Nevertheless, it is unlikely that terracing per se had much impact on that change. Intensive horticulture is by no means confined to terraced land.

With few exceptions, farmers reported that reducing the rate of erosion and leveling the land resulted in no increase in yield or decrease in costs. This view was expressed by both those farmers who had terraces, and those that worked steep slopes. We were surprised by this view, and attempted to find evidence to the contrary. We were unable to discover such evidence, although the investigation was admittedly brief.

Absence of Short-Term Benefits

There are several possible explanations for the perception on the part of farmers that terracing does not result in significant benefits. First, a major advantage of a more level cultivation surface is to increase water absorption. In the Valles Altos region, virtually all farmers who practice intensive horticulture have access to irrigation water. Therefore, an increase in water absorption is of little value. Moreover, because the

aspersion method of irrigation is used, the erosive damage of irrigation water flowing over the surface is reduced and the danger of irrigation canal failure on a steep slope, producing erosion below, is eliminated. On steep slopes the farmer can carefully monitor the sprinkler system and turn it off before the water begins to flow over the surface. In fact, the absence of the need to carefully monitor the irrigation process on terraced surfaces was one of the few benefits reported by farmers.

Second, almost all Valles Altos farmers use contour plowing on steep slopes. In addition, farmers usually dig drainage canals around the tops of their fields to channel excess water away from the cultivated surface during heavy rain. These conservation measures reduce somewhat the rate of erosion and thus may reduce the immediate benefits of terracing. Frequent tillage, required in the multicropping system, also increases infiltration of water and thereby reduces runoff, and potential erosion damage.

Third, the loss of plant nutrients through erosion does not appear to be sufficiently serious to merit the farmer's attention. Soil samples taken on terraced and non-terraced land did reveal a significantly greater amount of some nutrients. However, the sample is not large enough to control for other potentially covariant factors. For example, the higher nutrient content may be related to more recent, or greater, fertilizer application on terraced versus non-terrraced land.

Farmers use an enormous amount of organic fertilizer on their fields. Most reported using from three to five metric tons of organic matter every twelve to eighteen months for a field

approximately a quarter hectare in size. Chicken manure, preferred because of the absence of grass seed content, is trucked from Maracaibo for two to three thousand Bolivars (from 110 to 175 U.S.) per load (Photo 10). Goat manure is also trucked in from Falcon state, and cow manure is brought from the Valencia region. Several farmers stated that the cost of organic fertilizer alone was equal to the gross income from the first crop after application. Thereafter, two to four additional crops could be obtained without additional organic matter application. Chemical fertilizer is also heavily used.

We suspect that farmers are over using organic fertilizer, especially on the more leveled terraced surfaces. This view is shared by several agronomists in the area, and documented for the specific case of potatoes (Brito, 1976, p. 9; Norero, Bandes, and Amisial, personal interviews). On the other hand, it has been shown that organic matter is important in providing trace elements not available in chemical fertilizers (Ayala, 1974). It is also difficult to explain why farmers who have been working both steep slopes and the more level terraces insist that the fertilizer requirement is not related to slope; after ten to twenty years of experience, and given the enormous cost involved, one would expect trial and error to have demonstrated the proper level of fertilizer use. The hypothesis that terracing can significantly reduce fertilizer inputs, and hence costs, is therefore unconfirmed-- although certainly not rejected.

Fourth, it is possible that increased insolation on steep slopes compensates in part for other negative features associated with erosion (Norero, personal interview). This factor may be

especially important on east-facing slopes. During the rainy season, the afternoon sky is frequently very cloudy so that plants receive most insolation in the morning. Morning insolation is maximum on relatively steep east facing slopes.

Fifth, almost every farmer interviewed noted that a steep slope is easier to work because less bending over is required. This factor, initially dismissed as minor, looms larger with careful examination of the conditions of farm labor in Venezuela and other Latin American countries. Most Latin American farmers use short-handled hoes. The sharp back-angle of the blade may increase the leverage and make working heavy soils easier. However, the farmer is required to take a full bending position with his hands no more than a few centimeters from the ground. On relatively level land, the work is tiring and painful. By middle-age, a farmer who has spent much of his life using that tool is likely to have a permanent stooped position, and suffer intense back pain. The same short-handled hoe can be used with ease on a steep slope; indeed, it seems to have been designed for steep slopes both in terms of the length of the handle and the angle of the blade. Some other farming operations that are unrelated to the length of the hoe also require bending over. Especially critical are crops that must be harvested periodically throughout the season. Thus, steep slopes are the preferred locations for crops such as strawberries and parsley.

Sixth, it appears that the most damaging aspect of erosion on steep slopes is the major slope failure during extreme weather conditions that occurs at intervals of ten to fifty years, rather

than as a slow continuous process (Norero, personal interview). Incremental erosion, even if relatively rapid, does not seem to have much effect on yields in the short term.

Farmers who work steep slopes are well aware of the danger of total slope failure and consequent loss of crop and soil. When a major slip does occur, sometimes a farmer will simply move downslope with the soil to follow what is in effect a unique form of "shifting" cultivation (Aguilar and Norero, personal interviews). In the event that the land is completely destroyed, the farmer is forced to move to a new location.

Major erosion disasters tend to be viewed as "an act of God," completely outside the farmer's effective control (Norero, personal interview). For the most part, farmers see little connection between their use of steep slopes and major erosion disasters. Moreover, even when such connections are made, there may be little ability, and even some reluctance, to take precautions. From a fatalistic perspective, to prepare for or even discuss a possible accident or natural disaster is to invite the event to occur (or as some would say, "to tempt God"). This fatalistic position in the face of risk and uncertainty may appear to contradict the well known tendency for traditional farmers to take risk avoidance as a prime strategy. However, it must be remembered that risk avoidance in traditional agriculture evolved through trial and error over the centuries; it is not usually a conscious intellectual exercise. Once the farmer leaves the traditional farming methods or familiar ecology, the store of knowledge regarding conservative practices may be of little use, or may be discarded as not relevant to the changed

farming system.

Finally, much of the land is held in other than fee simple ownership. Many farmers in the region are share-croppers and some are squatters. Frequently farm "owners" do not actually have unambiguous legal titles to their land. Lacking secure tenure to the land they work, farm operators are not inclined to give serious attention to soil conservation and other long-term investments in the land.

The Need for Subsidies

Inasmuch as the short and intermediate-term benefits for terrace construction were insufficient to motivate voluntary farmer participation, project directors were forced to find other means to achieve cooperation. In this regard, directors were not always, and in some cases even usually, successful in obtaining farmer participation.

The subsidy payment was one important motivation for terrace construction. Farmers were paid in cash according to the number of cubic meters of wall constructed on their land. The subsidy, initially set at five Bolivars (about 1.10 U.S. at that time) was raised gradually to seventeen Bolivars to reflect inflation and higher farm wages. Even though the amount of the subsidy was generally no more than half that required to pay wages for the work, it was a source of cash needed by the farmers to make the conversion from subsistence to cash cropping. It is almost certain that terrace construction could not have been achieved without the subsidy payment.

Conservation Aspects

Although most of the terraces constructed by the program are not level (near level or backsloped) and cannot be made level without rebuilding the walls, the goals of soil conservation are substantially achieved. With the exception of wall failure, the amount of soil that can erode over or through the retaining walls is insignificant.

A steep slope behind the retaining wall will tend to increase the frequency of wall failure and thus the level of maintenance required. Unfortunately, retaining wall maintenance seems to be given a very low priority at the present time in Venezuela. Notwithstanding, the retaining walls have stood for ten to twenty years and they are mostly sound. There is no reason to believe they will not remain sound for another twenty years even with minimal maintenance. If properly maintained, the terraces can be considered a near-permanent feature on the landscape.

The terraces are generally wide and long enough, and sufficiently stable, to allow for the use of oxen and heavy machinery (Photos 11 - 13). This is essential for the survival of the system. Most farmers are dependent upon the use of oxen and frequently bring jeeps or trucks onto the field to unload fertilizer and other inputs, and remove the harvest. Some farmers use tractors. If narrow terraces had been constructed, or if the retaining walls were fragile, they would have long since fallen down or have been destroyed.

The terracing project affected a rather minor portion of the land in the Andean region of Venezuela. In the area studied

probably no more than one percent of the land where terracing is needed as a soil conservation measure was affected by the program. In addition, the program failed to achieve the crucial educational objective of "eliminating the attitude on the part of the farmer that he is simply a spectator of the forces of erosion that drain away his future income" (DCSA, 1976, pp. 5-6; author's translation from the Spanish original). Even those farmers who have terraced their land are only vaguely aware of the potential benefits of soil conservation over the long-term. For most Venezuelan farmers practicing horticulture in the Valles Altos region, the occurrence of a major destructive storm is something they hope and pray will not happen, rather than something they prepare for in order to reduce or eliminate potential losses.

The construction of rock walls requires a large amount of rock material. A rock wall 1.5 meter high (including foundation) requires approximately 1.5 cubic meters of rock per linear meter of wall using the Valles Altos design. Thus, depending upon the spacing of the retaining walls, from 500 to 1,000 cubic meters of rock material are typically required to terrace a single hectare of land. The cost of transporting this quantity of material to a field would probably be prohibitive (although that has been done in Japan). It appears, therefore, that the Valles Altos system must be limited to those areas where a large amount of rock material is available in the field itself, and when the removal of that rock is desirable in any case as a measure to increase the size and manageability of the cultivation surface.

The construction of permanent rock retaining walls becomes a

viable option when the field has a twenty percent or more coverage of rock material. In such cases, the rock becomes a resource rather than an impediment to cultivation.[1] For example, thirty percent rock coverage reduces the surface area available for cultivation by 3,000 square meters per hectare, whereas the rock walls would reduce the cultivable surface by 250 to 500 square meters, depending upon the spacing of the walls. Throughout much of highland Central and South America, median farm size is less than one hectare. Hence an increase in cultivable surface of twenty to thirty percent can provide a significant incentive for removing rock, and thus the construction of rock retaining walls. Of course, excess rock can also be thrown into a convenient erosion gully, in which case even the 250 to 500 square meter surface at the top of the wall is not lost to cultivation. We observed cases in the Valles Altos region where retaining walls were destroyed in order to achieve this small increase in the cultivation surface.

The Soriano Factor

Agronomist Jaime Soriano, who directed the conservation program in Trujillo and western Merida States, immigrated to Venezuela from Bolivia (after completing his university training

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[1]Rock on the field might serve some useful function such as storing solar energy which is radiated to plants at night. In Japan, strawberries are grown on the face of stone walls which are covered with clear plastic. Sufficient heat is retained to allow for production of berries during the winter season. It is doubtful, however, if uncovered stones on the ground would retain significant heat to substantially reduce the risk of frost in the early morning hours when frost is most likely. Nevertheless, that possibility, or some other beneficial affect of stones on the field, cannot be totally dismissed.

in Brazil). It seems possible that Soriano was the prime agent of diffusion in the construction of "Inca-like" agricultural terraces in Venezuela. This is not to suggest that the Valles Altos program was a one-man-show; many other individuals, notably Luís Aguilar, also made contributions that were perhaps as important as those made by Soriano. Soriano himself stated that many Venezuelan farmers knew how to build rock retaining walls before the program began. Nevertheless, it is significant that most of the construction of rock retaining walls was confined to those areas under Soriano's direction, and that terrace construction essentially ended after he left the agency.

It is possible that Bolivian Soriano was strongly inclined toward the construction of rock walled terraces, and that his unique cultural background was an important factor in the success of this aspect of soil conservation under his direction. Apparently, he pursued the construction of Inca-like stone wall terraces with a missionary zeal. Soriano insisted on farmer participation because he felt that outside intervention would lead to apathy, if not outright hostility, from farm communities and that only those people who actually build the walls would be willing and able to maintain them. He was able to identify and communicate with farmers and was willing to take the time and effort to "do it their way" even at the expense of delay and inefficiency. It is reported that he even turned down a substantial budget increase on grounds that a higher level of public intervention in farm communities would alienate farmers (Aguilar, personal interview).

Under Soriano's direction, strong efforts were made to en-

courage, or in some cases coerce, farmers to build walls. The highly desirable irrigation and road projects were sometimes held up until the retaining walls were completed. In some cases, cooperation with two consenting farmers was delayed until a farmer owning an intervening field agreed to go along. Soriano reported that in some cases there was physical violence as a result of disagreements within the communities on retaining wall projects.

It seems likely that most engineers and agronomists assigned to agricultural development programs will not have the skills and inclination of Jaime Soriano. Indeed, most program directors will probably prefer to work with a construction team than with farmers, and the incentive to pursue unpopular conservation projects is minimal compared to that for other development projects. We must conclude that the degree of success in the construction of agricultural terraces in the Valles Altos project was strongly impacted by, and may have been dependent upon, the personality of a single individual: Ing. Jaime Soriano (Photo 14).

AID SPONSORED PROJECTS IN PERU AND GUATEMALA

Physical Background

As is true in the Venezuelan Andes, the highland regions of Peru and Guatemala are characterized by a degree of environmental diversity that precludes all but the most general statements in a short description. Much of the northern highlands of Peru is similar to Venezuela in temperature and rainfall; the region of southern Peru visited during the field study is significantly

higher and cooler with killing frosts during the low sun period. That region also has a number of basins with poorly drained lacustrine plains. Soils are generally neutral to moderately acid, reflecting the low or negative water balance. As in Venezuela, some areas have soils that have a high content of rock material, and others have little or no rock.

Most of the densely settled areas of the Guatemalan highlands have temperatures similar to those of the Valles Altos region, and somewhat heavier rainfall. With irrigation, multicropping is frequently possible. Lacking access to large amounts of organic fertilizer, farmers frequently deposit leaves (gathered from forest areas) and other vegetation on the fields to increase the amount of organic matter in the soil. In the Quetzaltenango region visited, a volcanic eruption in the early part of this century covered the region with about one meter of sandy material; essentially no rock is available for retaining wall construction. Elsewhere in Guatemala, the degree of rockiness varies from heavy to light both regionally and locally.

Organizational and Institutional Framework

Both the Peru and Guatemala systems were initiated through AID projects under the direction of Jerome Arledge of the U.S. Soil Conservation Service. Although Arledge no longer works in either country, the terracing projects are continuing in both. In the case of Guatemala, the technical and administrative structure in place is sufficient to achieve a substantial impact in several regions of the country. The program in Peru exists as nine pilot projects in separate highland Departments.

The actual operation of the programs is controlled by the Ministries of Agriculture in each country. The organizational framework in the Quetzaltenango region of Guatemala is especially worthy of note. The project director has ten trained conservation officers. Each field officer works directly with five guias agricolas (agricultural guides), each of whom is responsible for three communities. In each community, two groups of about fifteen farmers are organized into conservation teams. This organization makes it theoretically possible to reach 4,500 farmers annually (DIGESA, 1985, pp. 5-6). In practice, the level of funding does not permit operation at that level.

AID plays an indispensable consulting and financial role in both countries. The scope of the programs is dependent in part upon subsidy payments, in cash or kind, made available by AID. Field workers in Guatemala reported that the organization in place is sufficient to substantially expand the program if additional subsidy were allocated. Vehicles and other program infrastructure are also made available by AID. Each country has an AID sponsored conservation officer on loan from the U.S. Soil Conservation Service who monitors and advises the programs. These individuals may be the only qualified conservation personnel in the projects, and the only officials whose attention is focused directly on the long-term conservation aspects of the program.

Terrace Construction

The methods of terrace construction used in the two countries is a "Single-Effort" system in which the landscape is

physically altered into level or backsloped terraces in one massive effort. This method is designed to achieve the immediate benefits of increased water and nutrient retention as a result of slope leveling. Indeed, the system is referred to as terrazas de absorcion (absorption terraces).

The single-effort system calls for removal of topsoil, physical construction of level terrace benches, and replacement of topsoil (Arledge, 1984; PNCSACH, 1984; also see Photo 15). The work can be done by hand with tools and methods that are generally available to local farmers, or that can be obtained or learned easily (Photo 16). The entire operation is usually completed between crop cycles so that cropping the land is not interrupted.

The retaining wall is usually an earthen wall with a protective cover of rye or other grass (Photo 17). Rock is sometimes used to supplement the earthen retaining wall. In those cases observed, the rock is limited to the upper half of the earthen bank (Photo 18).

It was estimated that an average of 742 man-days of labor are required to terrace one hectare of land (Yakya, 1984, p. 101). A separate source provides an estimate of 330 to 500 man-days per hectare for terraces with earthen walls, and between 800 and 1,000 man-days for terraces with rock retaining walls (Sanchez, 1985, p. 9). Without taking into account the dimensions and relative stability of the finished terraces, these estimates have little meaning. In fact, the labor requirement for terrace construction using the Single-Effort method is largely a function of the width (distance between retaining walls) of the finished

terraces.

In contrast to the controlled erosion method used in the Valles Altos program, the work required with the single-effort system increases (rather than decreases) with added terrace width. Most of the work is expended in moving the subsoil into a level position. Because both the amount of subsoil, and the distance it must be moved are directly proportional to terrace width, the work required is proportional to the square of terrace width (Annex 1).

The AID terrace construction manual recommends that terraces be made as wide as possible, but recognizes that the width selection is dependent upon the willingness of the farmer to increase his work effort (Arledge, 1984, p. 3). In effect, there is a powerful incentive to build very narrow terraces. If the terraces are from two to five meters wide, the work required to move the subsoil into a level position is relatively modest, and equal to or less than that required to build double-faced rock retaining walls, as in the Valles Altos method. Beyond about eight meters in width, however, the work required to move subsoil increases very rapidly and becomes the major component of the work whether rock or earthen retaining walls are used (see Fig. 4 in Annex 1).

The terraces constructed in the AID projects are understandably quite narrow. Those observed in the Quetzaltenango region of Guatemala are generally from one to four meters wide (Photo 19). Likewise, in Peru most of the terraces are relatively narrow (Photo 20), although one group of somewhat wider ter-

races were observed (Photo 21). These terraces are also relatively uneven along their length (in the direction of the retaining wall). In some cases, the small semi-terrace benches that evolve naturally as a result of cultivation on steep slopes, are simply formalized into level surfaces (Photo 22: also see Annex 1). In general an individual terrace has a total cultivation area of no more than 100 square meters.

Given the size and fragile nature of the retaining wall, such terraces are usually suitable only for hand labor. Because the program is limited to those farmers who have only tiny plots of land and use only hand labor, the constraint on width and stability does not appear to be a limiting factor at the present time.

The danger of failure of the retaining wall is especially great during the first year or two before the protective cover of grass is well developed (Photo 23). Considerable maintenance during this early stage is to be expected (Arledge, 1984, p. 12). The rapid development of the grass cover on the terrace face is usually hindered by the fact that the lower portion of the retaining wall is made up of subsoil which will probably have very low fertility. In most of those cases observed, part or all of the retaining wall lacked a vegetation cover. In Guatemala some farmers reported that grass "plugs" were not yet available; in Peru, the method of initiating a vegetation cover on hard subsoil banks was not apparent (field observation). Notwithstanding the apparent fragile nature of earthen retaining walls, we did not observe major failures of the terrace systems.

Social and Economic Impact

Cost-benefit analysis reports major gains in cultivable surface area and yields (Chang-Navarro, 1985; USAID, 1985,; Yakya, 1984). Gains in cultivable surface result from the use of both the leveled surface and the earthen retaining wall for cultivation. The report notes that higher yields are attributed mostly to increased absorption of water and retention of organic matter and nutrients on terraces. The sharp contrast with the results of terracing in Venezuela are probably explained mostly by the lower levels of technology used in agriculture in both Guatemala and Peru.

In both cases, farmers achieve relatively low yields in part because of low inputs of organic matters and fertilizer and insufficient moisture. On the terraced land, the reduced loss of nutrients through erosion and the increased water retention should significantly increase output. The availability of irrigation water and ample supplies of organic material and chemical fertilizer may make these potential benefits of terrace construction less important in Venezuela.

It should be noted that the reported gains from terrace construction, both in terms of cultivated area and yield, appear to be exaggerated. For example, the report notes that the total area of terraced fields (leveled surface plus earthen wall) increased by an average of 26.8 percent, with some areas reporting increases of forty to eighty percent (Yakya, 1984, p. 92). Such increases may have been achieved through land reclamation. However, an increase above about seventeen percent cannot be attributed to terracing (see Table 1, Annex 1). Likewise,

increased yields of 100 percent or more (Yakya, 1984, p. 98) seem to be well out of proportion of potential benefits from a more leveled surface, especially since the actual cultivation surface for the primary crop is reduced by from fifteen to forty percent. As in the case of the Valles Altos program, it is important to separate increases in yields resulting from terracing from those increases produced by other changes in inputs and methods that may accompany the terracing program. Yield increases that result from increased use of chemical fertilizers, changes in planting density, and changes in cropping systems can be achieved without constructing terraces.

The data presented in the Yakya paper were collected from small test plots are used to demonstrate the effectiveness of terraces to farmers (PNCSACH, 1984, pp. 3-5). The primary purpose of these plots is to provide a visual demonstration to farmers of the potential benefits of soil conservation; for that purpose, they are unquestionably an excellent technique.

As a method of data collection for a reliable and unbiased comparison, the test plot system is likely to be flawed. Even under strictly controlled laboratory conditions there is always a danger of unconsciously biasing data collection and analysis in favor of the preferred outcome. When data are collected by persons who have had little or no formal training, the probability of bias is far greater, especially if the persons who collect the data (local <u>guias agricolas</u>) perceive their own positions and reputations to be at stake on the result.

In one case observed in Guatemala, the terraced land on the

test site had an obviously healthy stand of corn which contrasted sharply with a wilted and stunted stand on the nearby untreated control plot. However, the terraced field showed clear evidence of recent chemical fertilizer application which was not apparent on the untreated plot. Moreover, other corn fields on steep slopes did not appear to be wilted and stunted, and from appearance alone could not be easily distinguished from that on terraced test plots (of course, the appearance of the corn is not the significant measure of the utility of terracing).

In contrast to the Valles Altos system, the AID sponsored projects in Peru and Guatemala have not necessarily been tied to other changes in the agricultural system. In Peru, the traditional subsistence crops of potatoes and other tubers, corn, and beans continue to be cultivated on newly terraced land. Likewise, most (but not all) newly terraced land in Guatemala remains in corn and beans.

The Subsidy Debate

Subsidies (social or incentive payments) are sometimes used in both Peru and Guatemala to achieve farmer participation. Payments may be made in cash or kind (such as tools or surplus food). Inasmuch as the subsidy payment for terrace construction is generally not sufficient to cover the total labor cost, farmers are voluntarily accepting a substantial cost to achieve terracing. This strongly suggests that farmers do realize immediate or short-term benefits sufficient to offset part of their costs. In both Peru and Guatemala, field directors of projects reported that many farmers have built terraces with no subsidy

payments (although the field team did not have the opportunity to confirm that with a specific example).[1]

Unfortunately, the use of subsidies leads to a major dilemma-- namely, **once it becomes known that subsidy payments are being made for conservation, farmers who might have initiated such works on their own will tend to wait for the subsidy.**

Development officers in AID and national programs are well aware of the dilemma noted above. Accordingly, policy guidelines stress that in the use of subsidies, care should be exercised to avoid the creation of a "paternalistic" relationship with farmers (PNCSACH, 1984, p. 9 & Quinto Cuadernillo). This is as it should be.

It must be noted, however, that farmers are not the only members of society that develop a "paternalistic" attitude in the face of public subsidy, and there is no reason to set farmers aside as the only members of society that must always "pull their own weight." Urban Latin Americans have grown accustomed to receiving substantial public subsidies in many areas of social and economic life, including public transportation, medical and educational services, housing, rent controls, retirement benefits, and others. Frequently, many basic food items are subsi-

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[1] In Guatemala field project directors reported that some farmers were provided with incentive payments for terrace construction only when they terraced an equal amount of land without the payment. Technically, this might be called voluntary (or unsubsidized) terrace construction. However, it could be argued that in effect the incentive payment has simply been reduced to half that provided previously. This would suggest increased interest on the part of farmers, but not necessarily unsubsidized, or voluntary, construction. Nevertheless, voluntary terrace construction is reported under less ambiguous circumstances both in Guatemala and Peru.

dized by farmers as a result of government regulations which fix prices below their market value. If the problems of "paternalism" in Latin American societies is to be seriously addressed, there is little reason to begin with farmers, and no reason at all to begin with soil conservation.

Conservation Aspects

Absorption terraces, when properly built and maintained in an appropriate environmental and agricultural setting, can be as effective for long-term soil conservation as any terracing system and probably far more effective than any non-terrace engineering solution to soil erosion on steep slopes. It is, however, with regard to construction and maintenance, and the appropriateness of some settings, that questions about some of the AID sponsored projects should be raised.

In what is probably an overly critical view, Greenland and Lal argue against engineering control methods of soil conservation generally. They complain that the effects of length and angle of slope have been little studied, and that it is in reference to engineering design criteria that good data on control methods are most lacking. They note that even a well constructed erosion control system based on inadequate design criteria will frequently fail and lead to serious erosion, and therefore, that agronomic adjustment to the landform provides a much safer course (Greenland and Lal, 1977, p. 262 and Plate 36). Likewise, Lal states that ineffective terraces can result in severe erosion and exposure of bedrock (Lal, 1977d, Plate 33).

This view fails to take into account the fact that in many

less developed countries, the cultivation of steep slopes is unavoidable, and the ability of farmers to make agronomic adjustment to the landform is severely limited or lacking altogether. Obviously, converting steep slopes to perennial crops and forest would be the safest method of erosion control. However, farm population densities and land tenure patterns will not allow for that solution. A more realistic evaluation would probably confine the recommendations to those which lie within the range of options open to farmers in less developed countries. In such a case, the question is, given cultivation of steep slopes, are there engineering solutions that will reduce the risk of erosion. Nevertheless, the caution suggested by Greenland and Lal serve to remind us that experts have not necessarily reached concensus on the sustainability of any given terrace design under all environmental situations.

The advisability, and even utility, of backsloped absorption terraces in those areas where rainfall is relatively high, or soil permeability low, has been questioned. Dhruva reported that both contoured and graded terraces are important soil and water conservation measures in areas with up to 600 millimeters of annual precipitation and high infiltration and permeability rates. For areas with more than 600 millimeters of rainfall, graded terraces were judged to be more efficient irrespective of soil texture, because runoff was impounded against banks of level terraces, delaying planting of crops (Dhruva, 1985, p. 4).

Moldenhaver states that where runoff exceeds moisture storage capacity, terraces should be graded sufficiently to prevent ponding of water (Moldenhauer, 1977, p. 89). Marston also

states that level absorption terraces should not be used on soils with low infiltration rates (Marston, 1985, p. 638).

The total rainfall in the Chincheros area of Peru is at or below the 600 millimeter limit suggested by Dhruva. Moreover, the focus on water absorption, rather than removal during periods of heavy rain, may help to reduce a potential danger inherent in some engineering solutions to soil erosion. In that area absorption ditches have also been constructed above the terraced area. These ditches are built level and in short segments so that they do not provide a potential escape for excess water during extreme weather events. On the other hand, they do not pose the threat of failure with severe erosion consequences of the sort noted by Lal, and Greenland and Lal (above), and described by Aguilar in the case of the Mucuchias area (noted on page 23, footnote 1).

The Chincheros project area in Peru is a case where the achievement of significant long-term benefits of conservation is obvious. In conjunction with terrace construction, a very large erosion gully, which drains immediately into the primary reservoir for Cuzco City, has received an impressive amount of conservation engineering as a part of the AID sponsored project. Rock retaining walls were built at five to fifteen meter intervals along the several hundred meter long gorge.

Project director Mario Duenas reported that this work, along with absorption terraces and ditches almost throughout the catchment area of the gully has reduced the level of runoff at the bottom to a trickle even during heavy rain. The rapid pace

of sedimentation in the reservoir, along with the absence of an obvious alternative site for the Cuzco City water supply, makes conservation there considerably more than a long-term concern for the welfare of future generations. If, as seems likely, the gorge, along with erosion in the catchment area of that feature, was a major contributor to reservoir sedimentation, then the Chincheros project may be justifiable on that basis alone.

In the Quetzaltenango area the team observed terraces that had been constructed on a slope of about sixty percent. The terraces were about 1.5 meters in height and width. Corn planted on the leveled surfaces shade the earthen retaining walls so that the grass cover has little opportunity to develop. In effect, the terraces are an enlarged version of the system of cultivation used previously in which the soil is hoed into steeply backsloped contour ridges about twenty to forty centimeters wide (Photo 24).

Both the contoured ridges and the miniature terraces that replace them appear to be extremely fragile. Whether the terraces are an improvement over the previous system, from the point of view of soil conservation, might be questioned. Conceivably, the increased absorption of water on the terraces could contribute to slope failure during a major rainstorm. Annual rainfall in the region is substantially higher than the 600 millimeter limit recommended by Dhruva for absorption terraces. On the other hand, the volcanic soils have exceptionally high infiltration rates which may offset the rainfall factor.

The terrace construction method used in the AID sponsored projects appears to give relatively little attention to protection and maintenance of retaining walls. The construction

manual devotes only a few sentences to planting vegetation on the earthen walls (Arledge, 1984, pp. 10, 19-20). The problem of how to initiate vegetation on a steep subsoil bank is not addressed. A program review reported that twenty-six percent of the terraces had not been protected with a vegetation cover (Yakya, 1984, p. 76). The review noted that grass seed was unavailable or had not germinated, but that "the absence of vegetation was not critical because no major erosion problems had developed" (Yakya, 1984, p. 76: in translation from Spanish original).

The construction manual recommends that earthen retaining walls be as steep as possible, but not vertical (in practice they are about 200 %) and states that they will require very little maintenance once vegetation has been established (Arledge, 1984, p. 3). It is difficult to understand how a 200 percent earthen wall can be largely maintenance free even if completely and continuously covered with vegetation. Earthen retaining walls in Japan are usually sloped at no more than 100 percent, and the environment is much less aggressive than in most tropical and subtropical regions of the world; yet, these retaining walls do require periodic maintenance. It is also difficult to understand why the protection of exposed subsoil from erosion would not be considered "critical".

In Malaysia, where steep slopes are bulldozed into terraces for African Palm plantations, the exposed subsoil retaining walls are grooved and then sprayed under high pressure with a slurry of manure containing grass seed (personal observation). This method is usually (but not always) successful in preventing terrace

failure (it should be noted that the rainfall total and intensity in Malaysia is probably substantially greater than in most parts of the tropical highlands). In Japan, farmers plaster rich mud from paddy fields on subsoil banks to initiate grass on a new earthen retaining walls or to repair those portions of earthen walls that have been damaged by erosion. In some areas, subsoil banks are covered with a fine-meshed net so that new soil is held into place long enough for vegetation to take a firm hold.

When rock is available, it is sometimes incorporated into the earthen retaining wall. In those cases observed (in Peru), the rock is restricted to the upper half of the retaining wall (above the original surface of the field: see Photos 18 and 21).[1] Superficially, this design is similar to the Valles Altos system in which a steep earthen bank is used to supplement the rock retaining wall (compare previous Photos with Photos 8 and 12). Actually, there are important differences that make the Valles Altos method a better design for conservation purposes.

In the Valles Altos method, the rock wall rests on a firm foundation in the subsoil; the pace of erosion of soil and subsoil away from the base of the wall is not rapid enough to produce an exposed subsoil bank, so that a protective cover of vegetation is continuous. In the AID sponsored design, the rock barrier is at best a wall seated just below the topsoil and, more frequently, a stack or pile of rocks placed directly over the

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[1] Photo 22 is an example where the rock wall extends to the base of the retaining wall. However, in this case an old semi-terrace which was leveled over the years in response to cultivation is formalized into a terrace with very little need to excavate subsoil(see pata-pata fields in Annex 1).

topsoil. In addition, the steep subsoil bank below the rock will not support an initial vegetation cover so that it remains exposed to weathering. Unless something is done to cover the subsoil bank with soil and initiate a cover of vegetation, soil forming on the bank will probably erode as rapidly as it is formed and within a few years, the rock wall will be threatened.

It appears that a simple solution to the problem could be to use the rock to protect the subsoil bank, and use vegetation to cover the upper half of the retaining wall. The material above the original surface is subsoil and soil fill from upslope; with no additional effort the upper portion of the retaining wall could be covered with soil so that vegetation growth would be rapid and vigorous (although the slope would probably have to be reduced to no more than 100 %). Because approximately half the retaining wall is above, and half is below, the original surface, the rock placed at the top is sufficient to cover the lower portion. In this case, the rock would be seated on a firm foundation in the subsoil. It is essential that the rock be fitted together into a strong wall, regardless of whether it is to sustain compact subsoil or fill from upslope.

Our brief field excursion in Peru and Guatemala is not an adequate basis for evaluating the conservation (or for that matter, the economic) benefits of AID sponsored terrace construction. It is most unfortunate that we missed the opportunity to visit the Cajamarca area of Peru (because of a cancelled flight) and were confined mostly to one rather unique example in Guatemala. The examples observed in both countries were not necessarily representative of the projects as a whole.

We are not able to determine whether absorption terraces in the Quetzaltenango project do pose a serious risk of failure, or whether the absence of a vegetation cover on portions of earthen retaining walls will significantly reduce the sustainability of those projects. Soil conservation personnel in project countries are in a better position to judge the relevance of Greenland's admonition on engineering design criteria, to the use of the absorption terrace design under local environmental conditions. We do believe that in those cases where there is uncertainty about the risk factor, any potential risk should weigh heavily in the selection of terrace design, even if the immediate gains from water absorption are reduced.

Rehabilitation of Inca Terraces

The Technical Manual used in Peru also calls for rehabilitation of Inca terraces (Arledge, 1984, pp. 15-17). The reconstruction and maintenance of rock walls is not mentioned. Rather, the authors suggest that attention should focus on leveling the terraces, or building in a backslope of from ten to twenty-five percent. There is a danger here that the potential immediate benefits of water absorption is being emphasized at the expense of sound soil conservation. Waterlogging during periods of excessive rainfall is the prime cause for terrace failure, and a backsloped surface, especially if combined with little or no retaining wall maintenance, may increase that danger.

Empirical studies are needed to show that Inca terraces can support this sort of modification, and whether it would be sustainable under the variety of environmental conditions in

which abandoned terraces are found. If such studies have not been conducted, and unless the reconstruction and maintenance of retaining walls is included within the package, this aspect of the program should be delayed. There are a number of experts in Peru who are currently working directly or indirectly in Inca terrace rehabilitation (Denevan; Masson; Ramos; and Sanchez). The advice of these people, or others who have studied pre-Colombian terraces, should be considered essential before modification of pre-Colombian works is attempted.

SUMMARY OF FINDINGS

Project Design, Application and Impact: Valles Altos versus AID

Both the Valles Altos and the AID sponsored terracing are dual purpose projects with both short-term economic and long-term conservation objectives. However, the two projects incorporate very different terrace designs, and the focus on long versus short-term goals varies accordingly. The Valles Altos project used the controlled erosion method of leveling the land; thus, the prime emphasis was on building durable retaining walls along the contours of slopes. The AID sponsored design is a single-effort method in which the primary emphasis is on moving the subsoil into a leveled or backsloped position.

The differences in terrace design appear to reflect the differences in site, farming method and crop, and and economic circumstances between the Valles Altos region of Venezuela and the areas where AID projects are being implemented in Peru and Guatemala. Certainly, the single-effort design would not have

been a viable alternative in those project sites in Venezuela where the controlled erosion method was used. Likewise, the controlled erosion method probably would not accomplish the short-term economic goals in the Peru and Guatemala project sites as well as the single-effort design.

Nevertheless, it could be argued that terrace design in both cases was partly or mostly a result of chance or project director preference, and failure to consider alternatives to the design initially selected. That is, terrace design is matched with project site conditions because the preselected design determines the set of environmental and social conditions in which the project is applied (rather than the other way about in which case the terrace design would be selected to suit the social and environmental conditions in a particular region). Thus, in the Valles Altos region terracing was mostly confined to those areas where the controlled erosion method was appropriate. Likewise, in Peru and Guatemala, the AID sponsored terracing projects are limited to those areas where the single-effort method is suitable.

The Valles Altos Design and Impact

Terracing in Venezuela was initiated as a conservation measure at a time when a large amount of public capital was available for development schemes and the government was looking for labor-intensive projects that would reduce rural unemployment. Government investment in the scheme was not necessarily tied to achievement of immediate economic returns. These extremely favorable conditions for publicly sponsored soil conservation

must be considered very fortuitous, if not unique to that particular country and period. During the middle and late 1970's, when public funds became more scarce, terracing and other soil conservation aspects of the Valles Altos program were phased down in favor projects that could yield a more visible and immediate economic return on investment.

The selection of the controlled erosion method of terrace construction appears to have resulted from the diffusion of ideas from the U.S. Soil Conservation Service (SCS) and Inca terraces. A translated version of a SCS manual was apparently used as a model for the construction of rock barriers along the contours of hillsides. It appears from the manual that the barriers were originally envisaged as little more than stacks of rock that would break the downslope flow of water. However, when combined with expert rock-wall building techniques and the experience of persons familiar with Inca terraces, these barriers became strong rock walls with a firm foundation in the subsoil which could retain soil that eroded, or was deliberately plowed, downslope. The result was the evolution of terraces over a period of a decade or two.

The controlled erosion method of terrace construction will encourage building relatively wide cultivation surfaces because labor costs are inversely proportional to terrace width. Because rock retaining walls must be free-standing while soil fills in by erosion, they must be strong and well constructed. The result is a relatively wide and stable cultivation surface. The wide and stable design was essential in the Valles Altos project sites.

Most farmers use oxen to cultivate their land, and some use tractors. Heavy trucks and jeeps are brought onto the field to offload organic fertilizer and remove the harvest. If the terrace design had been other than one which would produce a wide and stable cultivation surface, it would not have been suitable in those areas where terraces were constructed; that is, an alternative terrace design would probably have resulted in the selection of a different set of environmental and social conditions for project sites.

The controlled erosion method does not produce a level surface immediately. Leveling takes place over a period of one or more decades, and in most cases a final leveled or backsloped cultivation surface cannot be achieved unless a second effort at retaining wall construction is made. A potential return to investment in terms of higher yields or lower costs through increased water absorption or reduced loss of soil nutrients is postponed.

Because almost all the terraces are irrigated, and organic as well as chemical fertilizer is heavily used, the absorption of water and retention of nutrients that could be achieved by slope leveling was not essential. Again, it may appear that the terraces were designed to accomodate the environmental and social conditions of the region; however, it is more likely that site selection for project application was determined by terrace design.

The Valles Altos terracing program in Venezuela was coincident with other infrastructural changes that led to an almost total transformation of the region from a poverty zone of semi-

subsistence farmers to a highly productive horticulture region. The soil conservation initiative brought trained agronomists into the region who probably sparked many innovations in land use, and the program led directly to one which focused on the provision of irrigation systems and penetration roads. Thus, the indirect effect of the conservation program on the agricultural econo.' was enormous. However, the construction of agricultural terraces had very little direct impact on this transformation. In some cases the removal of rock from the field, the filling in of poorly drained areas, and the creation of a more manageable cultivation surface, produced some immediate economic benefits to the farmer.

Terrace construction is not essential for short-term maintenance of soil stability. Most steep slopes used for horticulture in the region are not terraced, and terrace construction is no longer an important part of the Valles Altos program. Indeed, intensive horticulture on steep slopes has proven to be very successful and farmers are loath to take time away from their profitable activities to construct terraces. Soil conservation measures which take little time away from cultivation and which contribute to immediate gains in income appear to reduce the erosion problem to an acceptable level during normal weather conditions.

Farmers dig drainage canals around the tops of their fields to remove excess rainfall and they carefully monitor their aspersion irrigation systems and turn them off before the water begins to move across the surface. The application of huge quantities

of organic matter to the fields, along with frequent tillage, increases soil permeability and helps to prevent soil aggregates from being broken down by the force of raindrops into small particles that would tend to be highly erodible.

Steep slopes are actually prefered by many farmers because they are easier to work. Slopes of up to seventy percent are plowed by oxen (by extending the length of the yoke to two or three times that of the yoke used for more level land). On steep slopes there is less need to bend over to weed or harvest crops, and the short-handled hoes used in the region appear to be specifically designed for use on slopes rather than level land. A favored location is a steep slope just below a road, where organic fertilizer can be dumped directly from the truck onto the top portion of the field and gravity along with a minor effort with a shovel and normal plowing will carry it to be remainder of the field. With heavy application of organic fertilizer and careful use a field of this sort can be very productive for five to ten years, and with luck it may be usable even longer.

It is most unlikely that large areas on steep slopes where perennial plants have been removed will remain suitable for cultivation over the long-term. Even in the absence of a major storm, a pace of erosion in which the tops of the fields falls by as much as ten centimeters annually cannot be sustained. However, a large share of the farmers are sharecroppers with no long-term stake in the land, and even landowners appear to be unwilling to consider the consequences of a major storm. In view of the current economic needs of the region, and the spectacular immediate impact of irrigation systems, the question of sustain-

ability of intensive horticulture on steep slopes, is one that most farmers and officials are now apparently prepared to ignore.

The Valles Altos terracing system is clearly effective for erosion control and can probably survive most severe weather events. If maintained, the rock-walled terraces can be considered an almost permanent feature on the landscape. The success of the program is diminished, however, by the failure to achieve the educational objective of modifying the fatalistic outlook of most farmers with respect to erosion hazards, and by the fact that the program was terminated after affecting only a small portion of the land where terracing is needed as a soil conservation measure.

AID Project Design and Impact

The terrace design applied in AID sponsored projects in Peru and Guatemala is a single-effort method in which most of the effort is expended in removing the topsoil, physically leveling the subsoil, and replacing the topsoil over the level or backsloped surface. In contrast to the controlled erosion method, relatively little emphasis is placed on building strong retaining walls. In most cases observed, terraces are retained by earthen banks which frequently do not have a complete vegetation cover. Rock is sometimes used to supplement the earthen bank but relatively little attention is given to building a strong wall with a firm foundation in the subsoil.

Because the work requirement for leveling the subsoil is proportional to both the amount of material to be moved and the distance it must be displaced, both of which are a function of

terrace width, the work is proportional to the square of terrace width. Therefore, there is a strong disincentive against building wide terraces. If terrace width is limited to about four meters or less, the work requirement is relatively modest. For wider terraces, however, leveling the subsoil requires a substantial increase in labor so that, depending upon local environmental and labor conditions, a terrace width exceeding six to ten meters will probably be prohibitive.

The combination of narrow width and relatively fragile retaining walls will tend to preclude the use of oxen or machines on the field. Because the project is generally applied only in those cases were tiny plots of land are worked by hand, this constraint is not critical.

In contrast to the Valles Altos project, the AID sponsored terraces appear to lead to significant immediate increases in yields and hence farm income. Yield increases result mostly from increased water absorption and perhaps retention of nutrients because of the reduction or absence of surface runoff. The achievement of significant economic benefits is essential for the success of the AID sponsored projects. Economic benefits are a prime source of farmer motivation for project participation, and they are the primary measure of success or failure in AID cost-accounting.

As in the case of the Valles Altos project, it might appear that the terracing project has been designed to accomodate the local environmental and social situation. However, it is perhaps more reasonable to agrue that the terrace design precludes the

application of the project to those settings where wider and more stable terraces are required, or where water retention is not the overriding goal.

Limitations and Advantages of the Controlled Erosion System

The controlled erosion method of terrace construction will tend to be cost-effective only in those cases where relatively wide terraces are possible. Based on estimates used Annex 1, terraces must be at least eight meters wide on steep slopes and fifteen meters or more wide on gentle slopes if the controlled erosion method is to achieve a reduction in labor requirement over the single-effort method. If terraces are relatively wide, they must either have proportionally higher retaining walls or forego the possibility of achieving a level surface. For example, if a level terrace is to be eight meters wide on a forty-five percent slope, the retaining walls must be 3.6 meters high. With rare exceptions the building and maintenance costs for retaining walls that high would be prohibitive.

As a result, there is a limit on the amount of slope reduction possible, beyond which the costs of excavation for wall foundation and building of a double free-standing rock wall for the controlled erosion method will exceed the cost of moving the subsoil into a level position and building a single-faced retaining wall or an earthen bank terrace. If the maximum wall height is 2.5 meters, and the minimum terrace width is ten meters, then the maximum reduction in the slope percent is twenty-five. That is, on a forty percent slope, a terraced surface would retain a fifteen percent slope after leveling is

completed by erosion.

If a reduction in the percentage of slope exceeding about twenty-five is required, then retaining walls must be spaced closer together, and terraces constructed by the controlled erosion method will require as much or more labor than those constructed by the single-effort method. In such a case, the single-effort method offers the advantage of achieving a level cultivation surface immediately, rather than over a period of a decade or more.

The controlled erosion method can be used in conjunction with a vegetation barrier rather than a rock wall. This allows the controlled erosion method to be used in areas where rock is not available on the field, and where the costs of building rock walls are prohibitive.

The research team did not observe controlled erosion terraces with a vegetation barrier, other than small informal semi-terraces that evolve naturally with the cultivation of steep slopes (see pata-pata fields in Annex 1). However, controlled erosion terraces with a vegetation barrier are reported in Peru and Honduras.[1] This method of terrace construction has been documented in Africa where leucaena leucocephala is planted in contour hedgerows, and indirect terraces are formed as eroded soil collects behind the hedges. The leucaena leucocephala is able to survive the dry season because it has a deep taproot, and prunings from this plant, placed over the soil also provide mulch

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[1]Personal communication with Jeff Vonk, U.S. Soil Conservation Service Adviser to AID-Peru, and Joshua Dickinson III, participant in AID workshop in Washington D.C. in March of 1986.

to prevent sheet erosion (Lundgren, 1985, p. 709). Likewise, contour bunds along slope contours are expected to develop into graded terraces in the course of several decades (Hurni, 1985, p. 765).

There are many good reasons for recommending the controlled erosion method of terrace construction. The land need not be leveled to achieve the conservation benefits of terracing. The controlled erosion method will encourage the construction of wide terraces that can accomodate oxen and machinery, or allow for a future conversion to a system that does require the use of animals and machines. The labor requirement for this method of terrace construction is substantially lower than for the single-effort method when relatively wide terraces are built. If the controlled erosion method is used in conjunction with a vegetation barrier, the labor requirement is much lower than for any other method examined.

Limitations and Advantages of the Single-Effort Method

The single-effort method of terrace construction will tend to be the more cost-effective design in those areas where relatively narrow terraces are suitable and increased water absorption can result in significantly higher yields. With the single-effort method of terrace construction surface leveling is achieved immediately, rather than over a period of one or more decades. A level or backsloped surface can result in significant increases in yields when an increase in water retention is needed for crop growth. Thus, in subhumid areas and areas with a dry season which would otherwise be suitable for cultivation, the

single-effort method of terrace construction can provide an immediate return on the investment. If irrigation water is available, the potential advantage of increased water absorption is reduced or eliminated.

Because the single-effort method will normally result in very narrow terraces, that design is generally suitable only when very small plots are worked by hand. Inasmuch as the size of the cultivation surface precludes the use of oxen or machines, there may be little incentive to build strong and durable retaining walls. As a result, the long-term soil conservation benefits are potentially diminished.

Once installed, the small, relatively fragile, terraces may tend to preclude the conversion of the land to an alternative use which would require larger and more stable cultivation surfaces. A potential decrease in the farm population as a result of rural to urban migration and/or lower fertility, or an increase in median farm size as a result of land redistribution, raises the possibility that small terrace benches would be unsuitable at some future point in time.

There are a number of advantages in the single-effort method of terrace construction currently in use in Peru and Guatemala. First, the system appears to lead directly to significant and immediate gains in productivity and farm income. Therefore, the major problem of farmer motivation, along with the required subsidy payment, is greatly diminished. Second, the construction of small terrace benches is relatively easy to accomplish, and the operation can be completed with unskilled labor and tools

that are generally available. Third, the system appeals to farmers who have only tiny plots of land and use hand labor--thus, it is aimed at those farmers that are poorest and most in need of development assistance.

Although the total area in Latin America where the single-effort design is cost-effective may be relatively modest, the total number of farm families within that category is very large. In fact, a substantial share of the farm families who practice semi-subsistence cultivation on steep slopes in the Andean, Central American, and Antillian countries probably falls into that category. In addition, where market conditions are favorable, small plots are frequently worked by hand for the production of vegetables for urban markets.

It could be argued that small hillside plots that are isolated from a potential water supply have little long-term value for agricultural use other than that of providing a semi-subsistence income for the farmers currently living there. In that case there may be little reason to build a system that could accommodate future conversion to commercial farming, and the immediate income gains with the single-effort system may outweigh any potential advantage of an alternative terrace design.

Potential Conflict Between Short and Long-term Goals

It is probable that most terracing projects will be dual purpose-- designed to accomplish both economic and conservation goals. Indeed, when properly designed, constructed, and maintained, terracing will usually eliminate or minimize the risk of excessive erosion, thereby accomplishing the long-term objective

of preserving a scarce resource, and they may lead to significant short-term increases in farm income. It is, therefore, quite natural to design and evaluate terraces in terms of a dual purpose project.

Unfortunately, the terrace design best suited to accomplish short-term economic goals will not necessarily be coincident with the design best suited to accomplish long-term conservation goals. The immediate benefits of creating level cultivation surfaces, for the purpose of water absorption, may mitigate against the longer-term benefits of constructing wider and more stable terraces over a period of years with the controlled erosion method. Likewise, in the case of terraces designed to achieve long-term soil conservation, there may be an incentive to forego the immediate benefits of increased water absorption in favor of construction of a system that is more likely to survive extreme weather events and accommodate machine traction now, or at some future point in time.

In some cases the design of a terrace constructed for water absorption conflicts directly with the design meant to achieve long-term conservation. An absorption terrace is most effective if it is flat or backsloped, with no provision for drainage; the primary goal is to prevent the loss of water from the terrace. Long-term conservation may suggest the need to design terraces such that drainage away from the cultivation surface is facilitated rather than hindered, so that the risk of failure of the system is reduced during periods of very heavy rainfall.

Complicating the potential conflict between immediate economic and long-term conservation benefits is the fact that pro-

jects sponsored by public agencies must be justified by cost-benefit analysis. In such evaluations income gained is more easily calculated than losses prevented, and immediate returns to investment are more visible than long-term maintenance of resources. In short, there will be a strong tendency to justify expenditures in terms of short-term economic returns, and to fall back on the less visible conservation justification as little as possible. Moreover, the constituency for short-term economic benefits are the farmers themselves. With the exception of the project conservation officer, there may be no one to speak for, or even appreciate, the long-term public good.

Rock Wall Construction is Not A Lost Art

The use of rock retaining walls for agricultural terrace construction is sometimes dismissed as extravagant or even impossible in this era of bulldozers and backhoes. Surprisingly, that view is strongly held even in Peru, where the substitution of machinery for hand labor has hardly begun, and where the existence of Inca terraces would seem to make the appropriate response to high farm density and resource scarcity rather obvious. There is a tendency to view the cultural accomplishments of the Inca (or Aztec, Maya, etc.) Civilization, including the construction of agricultural terraces, as the result of an almost magical quality or knowledge that has since been lost.

To be sure, the techniques and methods used in many of the spectacular monuments of pre-Colombian civilizations are not known. On the other hand, some interpretations of pre-Colombian

civilizations appear to take a romantic view that ancient methods cannot, or perhaps should not, be known. In Peru, farmers and agricultural technicians will sometimes dismiss any suggestion that Inca terraces be rehabilitated or sources of irrigation water be rediscovered with irrational views which hold that the Inca people could make water run uphill or that the required tools and techniques no longer exist.[1]

The construction of Inca-like retaining walls in Venezuela is proof that many farmers do know how to build strong rock walls, and most others can be trained to build walls in a few days. In Japan rock wall construction, both for agricultural terraces and for other erosion control situations, is widely practiced. Most farmers use rock or earthen walls to protect their fields and most communities have individuals who specialize in major rock-wall construction works. Rock wall design in Japan has been studied and modified by soil engineers, so that walls are likely to be distinctly superior to those built by the Inca (see Annex 2).

The potential application of rock retaining walls to agricultural terrace construction should not be dismissed on grounds that it is an extravagant effort for aesthetic purposes. For the most part, the labor requirement for a well-built wall is no greater than for a poorly designed wall. Rocks can be stacked

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[1]These observations are based on interviews and discussions with agricultural technicians and farmers over a period of several years while working in Peru. Specifically, field research was conducted in highland Peru in 1970 when State organized cooperatives were headed by agricultural technicians. The author discussed the rehabilitation of Inca agricultural works with several technicians and many farmers.

properly, in which case they will probably stand for a generation or more, or they can be stacked improperly, in which case they will soon fall down. A well-built rock wall is not simply an object of beauty; it has great and lasting economic utility.

A Window of Opportunity

An examination of the terracing programs in Venezuela, Peru, and Guatemala leads to the strong hypothesis that soil conservation programs are made more difficult as farm incomes rise. That is, soil conservation generally and agricultural terrace construction specifically can be accomplished more easily when farm incomes are very low. This hypothesis reverses the normal assumptions regarding the relationship between programs to improve environmental quality and societal wealth. The view that poor societies must sacrifice environmental quality for development with the hope of a future clean-up after achieving higher income levels is held almost universally within poor countries and is frequently accepted, if grudgingly, by development specialists. Notwithstanding, we suggest that the case of soil conservation is quite distinct.

The costs of agricultural terrace construction are almost totally in the form of labor. It follows that when labor is cheap, the cost is low. In poor countries, agricultural labor is frequently under or unemployed between crop cycles; in such cases the opportunity costs of labor for terrace construction is essentially zero. Farmers in the less developed regions can be motivated to construct terraces more easily. The more marginal the agricultural system (the lower the yield, the lower the fer-

tilizer and other inputs, and the more precarious the system) the greater the short-term impact of agricultural terracing on yields. A more level slope will produce a marginal increase in water retention; this can be extremely important for farmers who do not have access to irrigation water but insignificant for those who do have such access. A terrace will reduce the loss of soil nutrients by erosion; this can be significant for those farmers who have very little organic and chemical fertilizer available for use on their fields.

The small sample in this investigation may be a dubious basis for so radical a hypothesis as that presented above. Clearly, additional theoretical and field investigation will be required to prove or disprove the hypothesis. However, the implications are so far reaching that it is prudent to accept the hypothesis as true and move with haste in the area of soil conservation in poor countries. The experience of Peru and Guatemala proves that the construction of agricultural terraces is at least possible in those countries at the present time. If the hypothesis is correct, we may be seeing a small window of opportunity for soil conservation in those countries currently receiving AID assistance.

PROGRAM RECOMMENDATIONS

1. Research is needed to determine the range of environmental and agricultural conditions in which the single-effort absorption terrace design is the most cost-effective option available for soil conservation. Project literature appears to

suggest that this terrace design is the best (or only) option available anywhere agriculture is practiced on steep slopes. In fact, the range of conditions under which the absorption terraces (of the type described in the AID construction manual and observed in Peru and Guatemala) are appropriate conservation and/or economic investments may be somewhat restricted.

The utility of the absorption may be limited to subhumid areas where irrigation water is unavailable or inadequate and where farmers have no alternative to the cultivation of steep slopes with hand labor. Under other conditions, there may be other methods of terrace construction, or other soil conservation practices, that would achieve similar or greater benefits at a reduced cost.

It is unlikely that adequate documentation of the economic and conservation benefits of absorption terraces can be generated by local Ministry of Agriculture personnel or by project participants, based on small test plots. These individuals may not have been trained to collect unbiased data, and they may not be aware of alternative methods of terracing or other soil conservation practices. Moreover, such persons may perceive their own reputations and positions to be at stake on the results of the study.

It is probably unnecessary to attempt a research design based on long-term observation of test and control plots. Absorption terraces have now been in place in several environmental zones long enough to allow for direct analysis of their utility and cost effectiveness. A small research team that is experienced in field collection of data in rural Latin America, working in conjunction with the U.S. Soil Conservation Service

officer in each country, could determine the economic and conservation merits of absorption terraces under the various environmental conditions where they have been constructed.

2. Under certain circumstances, the controlled erosion method of terrace construction should be substituted for the single-effort method. The only apparent advantage of the single-effort method is that the potential benefits of increased water absorption can be achieved immediately rather than over a period of years as the land is leveled by erosion. The major disadvantage of the single-effort method is that unless the farmer is willing to invest a massive amount of labor for moving the soil and subsoil into a level position, he will be forced to build very narrow terraces that are usually suitable only for hand labor.

Among those conditions in which the controlled erosion method will probably be advantageous are: 1) when irrigation water is available, or can be made available at a lower cost than that required for the single-effort construction method; 2) when terraces must be wide and stable enough to accommodate oxen or machine traction; 3) when the controlled erosion method makes it possible to affect a substantially larger amount of land, within the time and labor constraints existing in the region.

3. AID sponsorship of terrace construction and other soil conservation measures should be expanded in Peru and Guatemala, and initiated in other countries of Latin America receiving AID support. In many relatively dry regions where farmers are confined to tiny plots on steep slopes, absorption terraces can be

one important way redundant labor can be converted to income producing capital. Elsewhere, absorption or graded terraces may achieve important conservation benefits and result in increased yields and farm incomes.

The inclusion of alternative terrace designs, such as controlled erosion terraces using either rock or vegetation retaining walls, can make terrace construction a cost-effective development project under a variety of environmental and agricultural conditions.

4. Increased attention to design and viability of retaining walls is recommended. When rock is sufficient in quantity on the field, it should be used to build strong and durable retaining walls. If the quantity of rock is sufficient for only a portion of the wall, it should be used to protect subsoil banks where a protective cover of vegetation is more difficult to establish. All earthen walls, including subsoil banks, should be protected with a vegetation cover as quickly as possible.

The views that rock wall construction is a "lost art", that it is inconsistent with the current social and economic reality of Latin America, or that it is an extravagant effort for aesthetic purposes, are incorrect. The art of building rock walls is widely known in Latin America and can be acquired by other farmers after a few days of instruction. The agricultural density in many highland regions is currently as great as it was during the pre-Colombian period when agricultural terrace construction was commonplace. The replacement of human labor with machine power has been slight, and the real wage for most farmers is only a little above subsistence. The opportunity cost for

labor between crop cycles is probably little if any higher now than it was during the pre-Colombian period. Well-built rock retaining walls are not simply objects of beauty; they are a time-tested and proven effective method of stablizing the soil on steep slopes for sustained intensive agricultural use.

It is especially essential to be sure the terrace design does not pose a risk to the lives and property of the people affected by the program. An effort should be made to determine whether poorly designed or constructed terraces have led to earth and mud flows in the Andes and elsewhere as reported (see, Brown and Wolf, 1984, p. 9). If these reports are correct, it is important to know what the environmental and/or design problems were, so that the problems can be avoided in the future.

5. A Soil Conservation Training Program is advisable as an additional AID sponsored effort to deal with problem of fragile lands in highland Latin America. Such a program should not be cost accounted in terms of immediate economic benefits to participating farmers. Rather, the goals should be the dissemination of sound soil management techniques and methods.

Those areas where soil erosion is clearly evident, and where on-site and/or off-site erosion damage is substantial, should receive priority. In general, erosion problems are likely to occur in those areas where an increase in the agricultural density or access to commercial markets has led to a rapid conversion from traditional to more intensive farming practices In most cases, such areas are likely to be relatively close to urban centers, so that land values may be increasing rapidly and the

potential for off-site damage of erosion is great. Under these circumstances, farmers may perceive a need to protect their land resources, but have inadequate knowledge on how that can be accomplished. Likewise, the increased potential for off-site erosion damage in densely settled areas makes public investment in the training program more vital.

Ideally, a Conservation Training Program would complement the agricultural extension programs already in place in the various countries. However, it should be noted that extension stations and experimental farms are frequently located on choice sites where erosion problems are absent or minimal. To be effective, a Conservation Training Program must operate in those areas which pose severe environmental difficulties and potential erosion problems.

A Conservation Training Program should attempt to disseminate a wide variety of conservation practices focusing on those which pose the greatest problems locally and those which can accomplish the greatest benefit at the lowest cost. The Valles Altos program of Venezuela provides two techniques that are potentially useful elsewhere in highland regions for soil conservation. These are rock wall construction, and the use of the natural process of erosion to the farmers' advantage in creating more level surfaces.

In many, perhaps most, rural communities in highland Latin America, there are persons who know how to build strong rock walls, and most other farmers can be trained to build them with a few days of instruction. Rock retaining walls can be useful in protecting irrigation canals and other structures from erosion

damage, in repairing erosion gullies, in protecting road cuts, and for the construction of foundations for houses and other buildings. When built across the contours of the slope they can be among the most effective soil conservation techniques, and a method of using the natural process of erosion to the best advantage. Rock wall construction requires only labor, and the wall is a method of making rock a resource, rather than an impediment, to cultivation.

In many ways, terracing is an "appropriate technology." It is labor-intensive and requires no imported capital. It is easily learned (if not previously known), and once in place it provides a visual demonstration of a self-reliant development alternative for farmers.

The AID programs in Peru and Guatemala stand apart from the vast majority of assistance programs in Latin America today as concerted efforts to conserve natural resources. As such, their value may lie more in the demonstration effect than in the actual physical impact on the landscape. It is important, therefore, to be sure that the demonstration effect is a positive one; farmers and technicians alike should understand that the long-term goal of environmental preservation can be and should be pursued, and that the AID programs are a first step in that direction.

PLATE 1

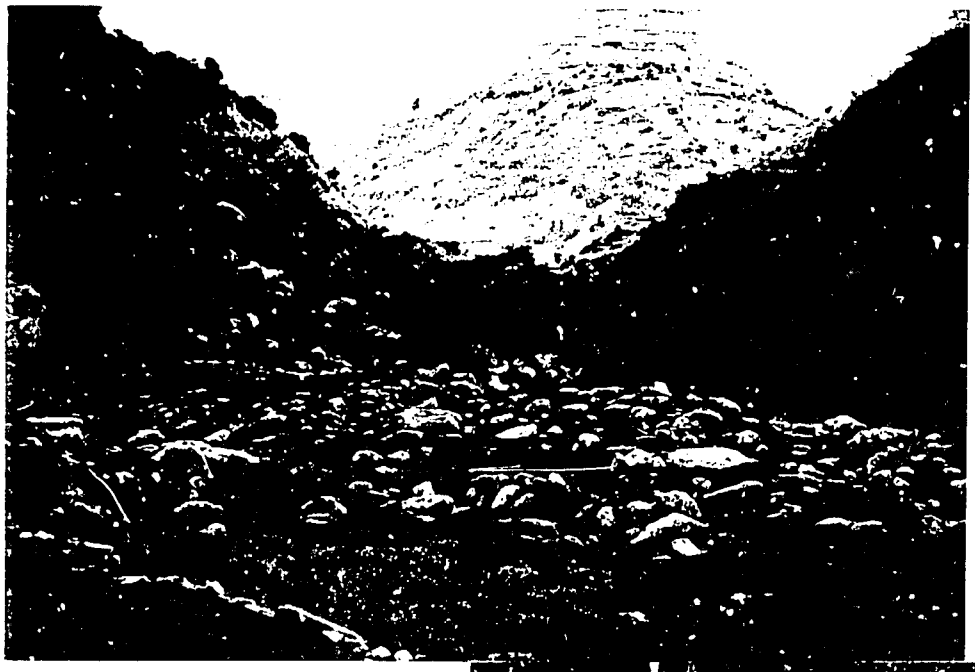

Photo 1. Rock covered "high valley" in Venezuela.

Photo 2. Coffee trees and rock remain in one section of a terraced field. The farmer stated he left this area to "remind me of what it used to look like."

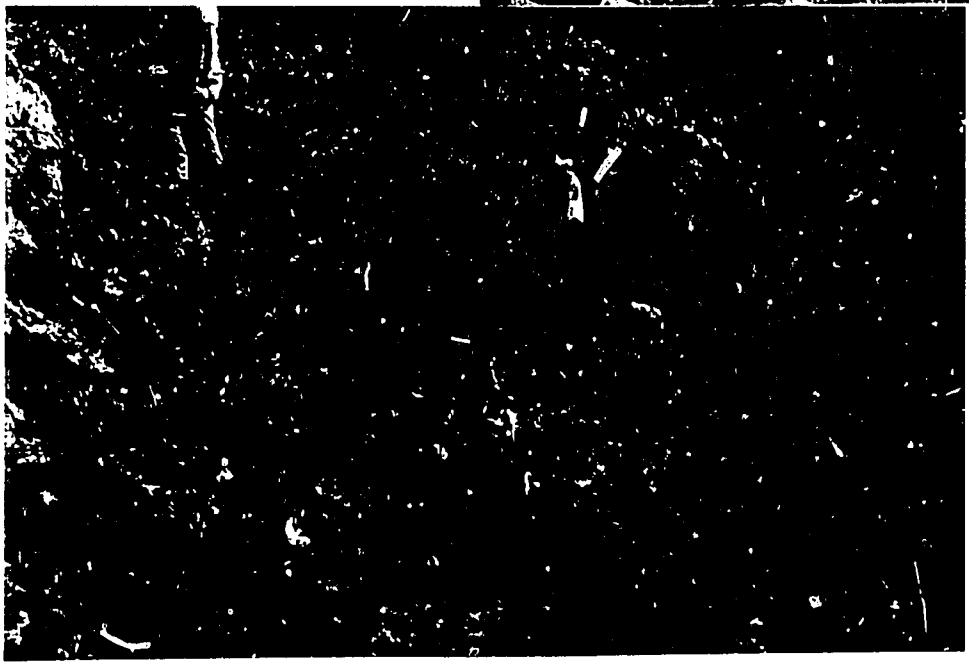

Photo 3. Farmers plant subsistence crops on an 85% slope. Slopes of as much as 70% are irrigated by aspersion and used for intensive horticulture.

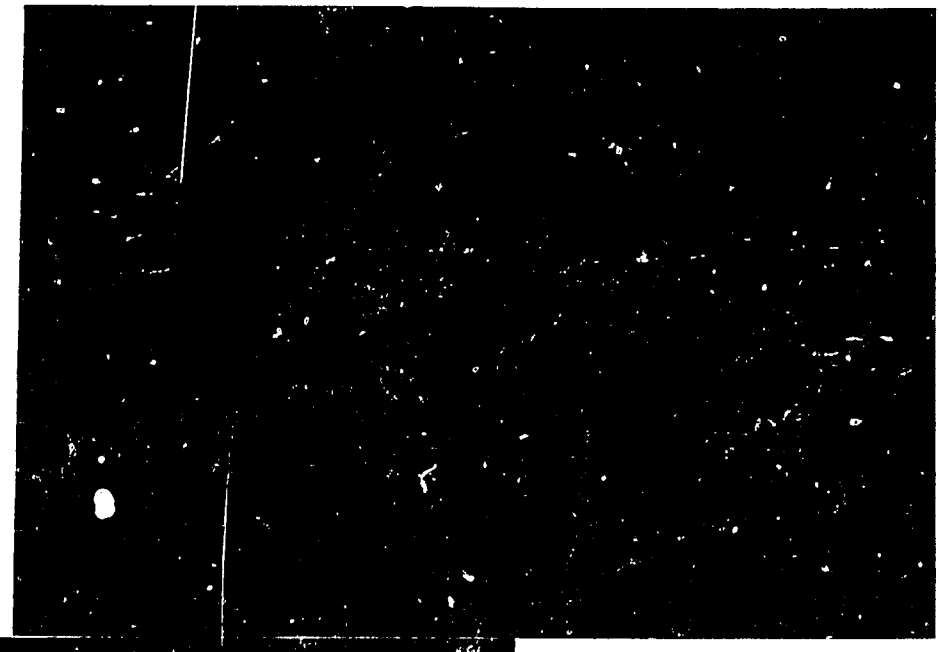

Photo 4. Soil Conservation works in Venezuela. Note infiltration canals along contour of slope. Considerable reforestation was also carried out.

Photo 5. Example of double wall in the Valles Altos region in Venezuela. Note the slight horizontal arch built into the wall which increases wall stability (see Annex 3).

Photo 6. Additional example of double wall in Venezuela. Rock downslope is unearthed by erosion. Note the relative absence of rock above the wall where it is covered by erosion.

PLATE 3

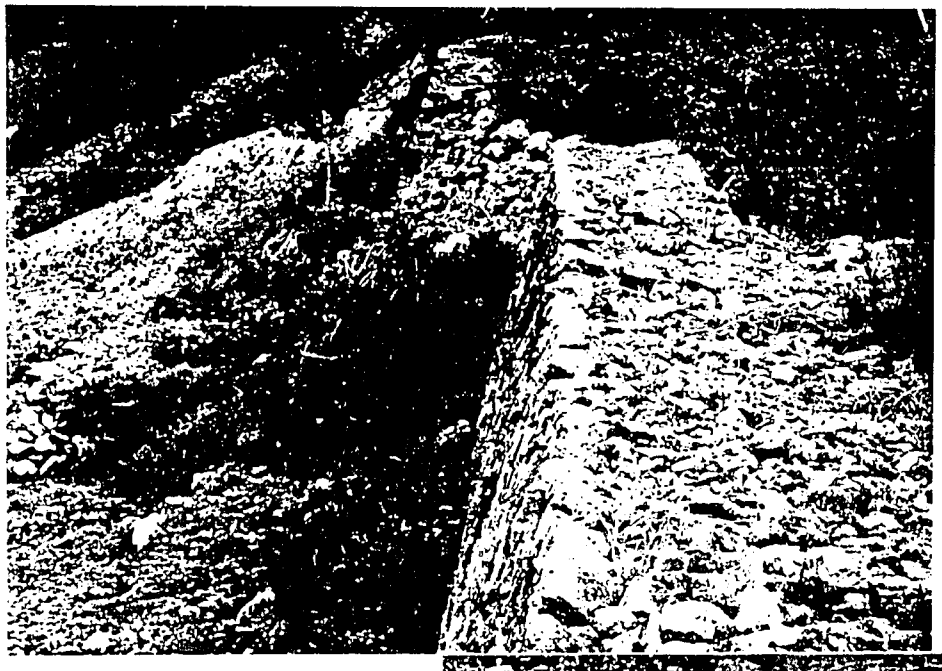

Photo 7. Example of wall failure in the Valles Altos region of Venezuela. Note that failure occurred in area of downslope bend in wall.

Photo 8. Terrace in the Valles Altos region of Venezuela. Note steep earthen bank at the below terrace wall in Venezuela.

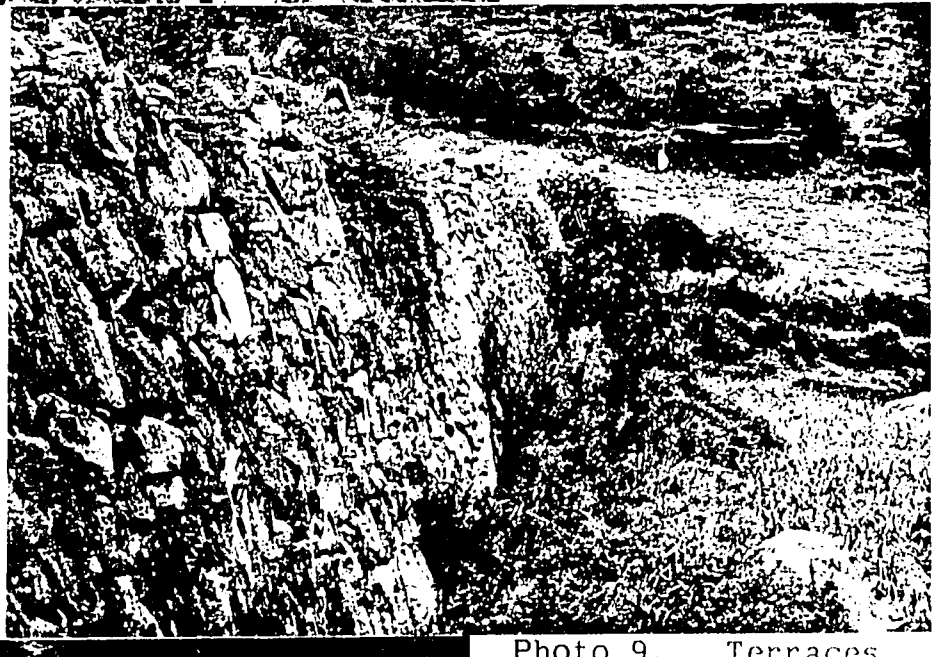

Photo 9. Terraces built on steep slopes with the controlled erosion method. The 1.5 to 2 m high walls have reduced the slope by about 15% (from about 35% to about 20%).

PLATE 4

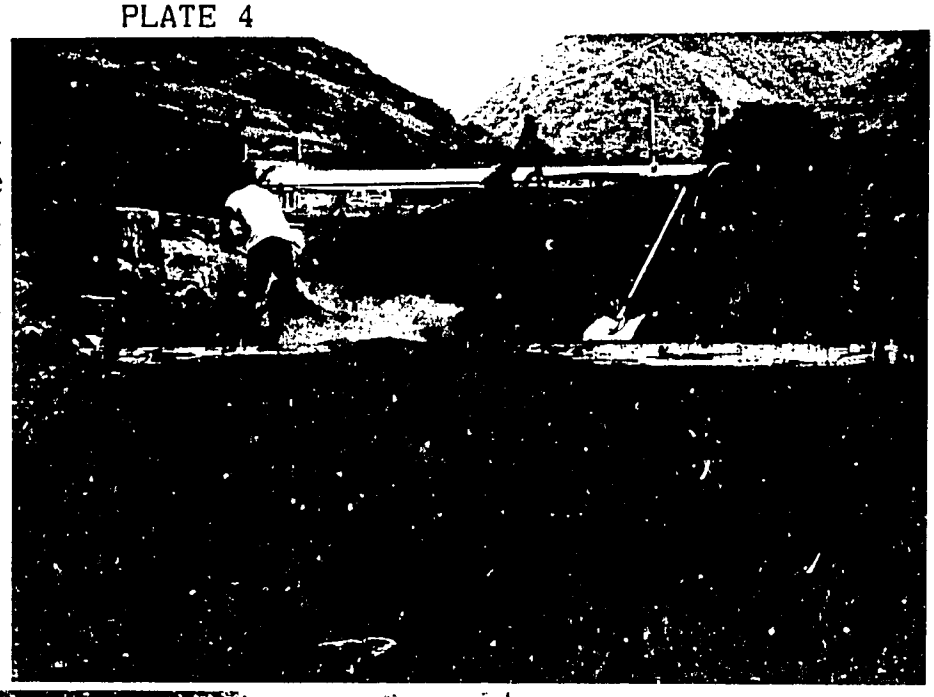

Photo 10. Unloading fertilizer in the Valles Altos region of Venezuela. This 1/4th ha. plot receives a similar truck load every 16 months.

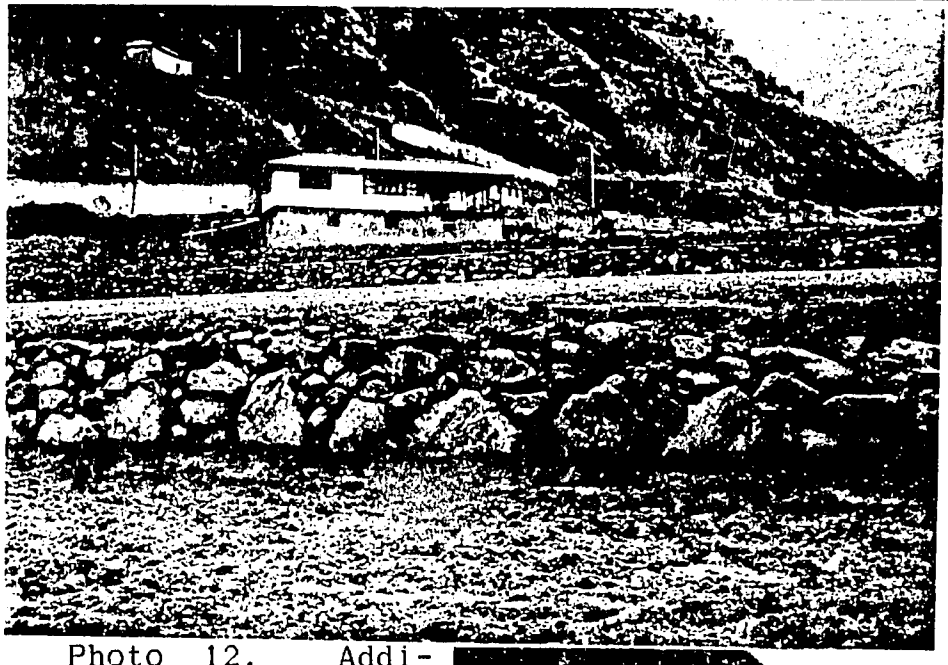

Photo 11. Terraces build by controlled erosion in the Mucuchias region of Merida, Venezuela. This exceptionally wide example has a 10% slope and is worked by tractor.

Photo 12. Additional example of the Valles Altos design. Pictured are team member Bob Walter and Ing. Rosalba Rodríguez of CORPOANDES.

PLATE 5

Photo 13. Note that fill by erosion has reached the top of this approx. 2.5 m wall. A short backslope allows for drainage about 6 m behind wall; from there the final slope is about 20% up to the wall above.

Photo 14. Ing. Jaime Soriano. Former director of the Valles Altos soil conservation program in the Trujillo region under the Ministry of Agriculture, and in the State of Trujillo under CORPOANDES.

Photo 15. Single-effort terrace construction in the Cuzco region of Peru.

PLATE 6

Photo 16. A-frame leveling device built in a few minutes by Guatemalan farmer.

Photo 17. Earthen retaining walls with grass cover in the Quetzaltenango region of Guatemala.

Photo 18. Rock supplement for earthen retaining wall in the Cuzco region of Peru. Note location of former surface below rock wall.

PLATE 7

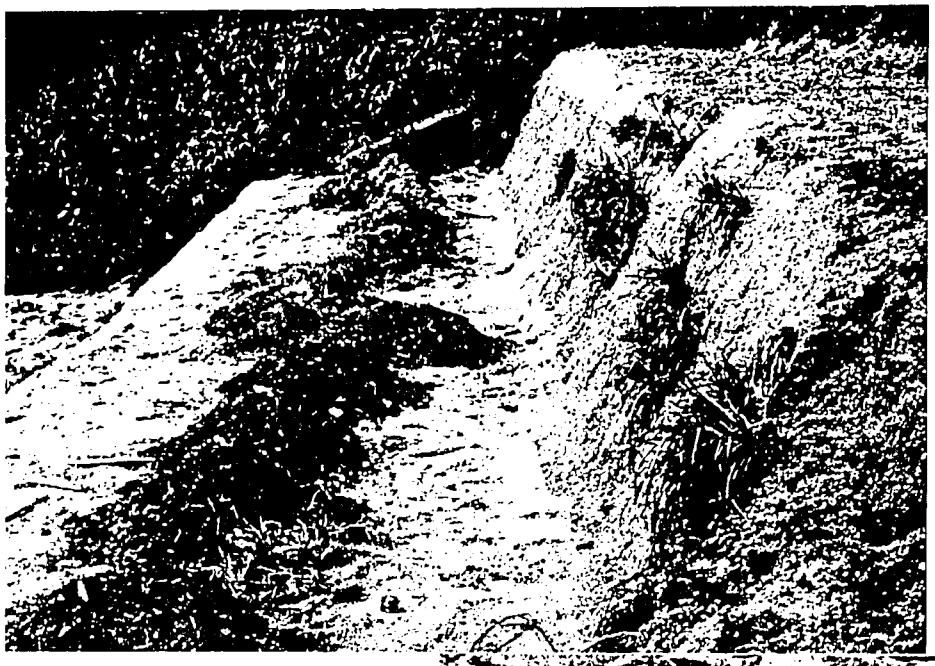

Photo 19. Earthen bank terraces in Guatemala. The material on the surface of the terrace is organic material gathered from the forest.

Photo 20. Example of AID sponsored single-effort terrace design in the Cuzco region of Peru.

Photo 21. Example of an exceptionally wide terrace in the Peru project.

PLATE 8

Photo 22. Old semi-terrace (or pata-pata field) that has been formalized in Peru project.

Photo 23. Earthen bank terraces in Guatemala. Note wall failure and relative lack of protective grass on earthen bank.

Photo 24. Corn field on steep slope using traditional contour plowing system. Photo of terrace system that replaces this traditional method is not available.

ANNEX 1

TERRACE CONSTRUCTION IN THEORY AND PRACTICE

Terrace Dimensions

The critical dimensions in terrace construction are (Fig. 1): 1) initial slope of land; 2) terrace width (distance between retaining walls); 3) height of retaining wall; 4) total length of retaining wall (or walls) per unit of land terraced; 5) total square meters (height X length) of retaining wall per unit of land terraced; and 6) area of cultivation surface after terracing, compared to the area of the original slope. If the final terrace is to have an approximately level surface, and the terrace wall is vertical (constraints that, as we shall see later, do not necessarily hold[1]) then the relationships between the six variables are straight forward.

If we let S be the slope (tangent of upslope angle), then the width (W) of terraces (distance between retaining walls) and

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[1] Retaining walls are usually not vertical. Likewise, terraces usually retain sufficient slope to allow for normal drainage, depending upon the soil texture and crop. The desired slope of the final terrace can be subtracted from (or added to, in the case of a backslope) the actual slope of the field to determine terrace dimensions. If the desired final slope is say 10%, then a field with a 20% slope can be treated as a 10% slope for purposes of calculating wall height and terrace width. If a backslope is used for drainage, the 20% slope must be treated as if it were 30%.

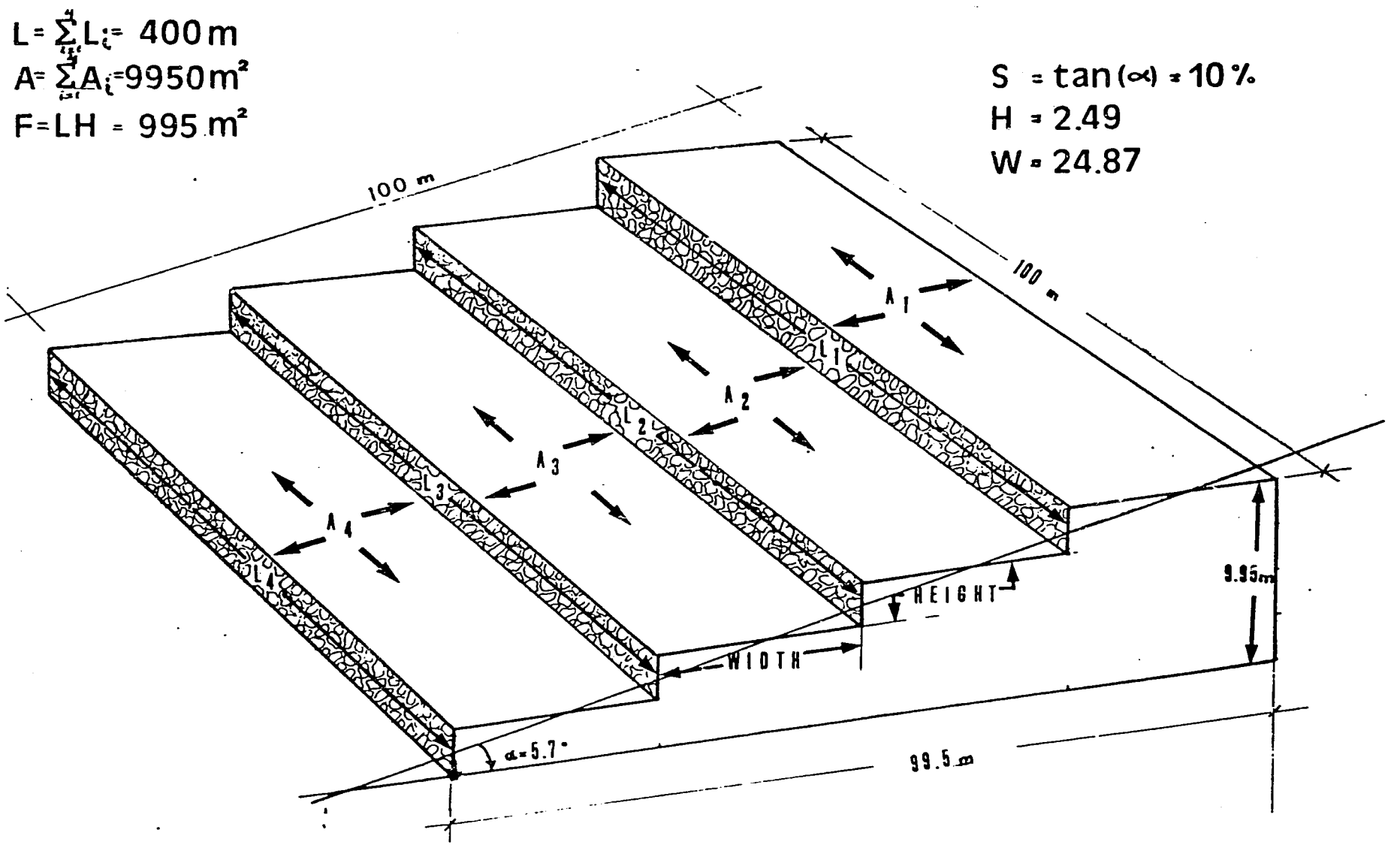

Fig. 1.— Terrace Dimensions.

height (H) of retaining walls are interrelated with the slope as follows:

$$H = WS \quad \text{and} \quad W = H / S \qquad (1 \ \& \ 2)$$

The height is equal to the product of width and slope. For any given slope, the height of the retaining wall can only be reduced by building a larger number of more narrow terraces. Therefore, the total length (L) of retaining walls that must be constructed on a given area of land (A) is inversely proportional to terrace width: $L = A / W$ (3)

where, A is measured in square meters.

The total vertical surface, or "face" of retaining wall (F) per unit of area is proportional to the slope:

$$F = AS \qquad (4)$$

where both F and A are measured in square meters. On a ten percent slope, level terraces require 1,000 square meters of retaining wall per hectare; a field that is 100 meters by 100 meters can be terraced with ten 100 meter long walls that are one meter high, or five 100 meter long walls that are two meters high. In either case, 1,000 square meters of retaining wall is required.

A logarithmic transformation of all variables will facilitate graphic representation (Fig. 2). With the percent of slope measured along the horizontal axis and terrace height measured along the vertical axis, the relationship between the two will yield both terrace width and retaining wall length per hectare. Note that the model assumes the terrace surface will be level (see footnote 1 on page 103). In practice, a terraced surface may retain some forward slope, or may be backsloped.

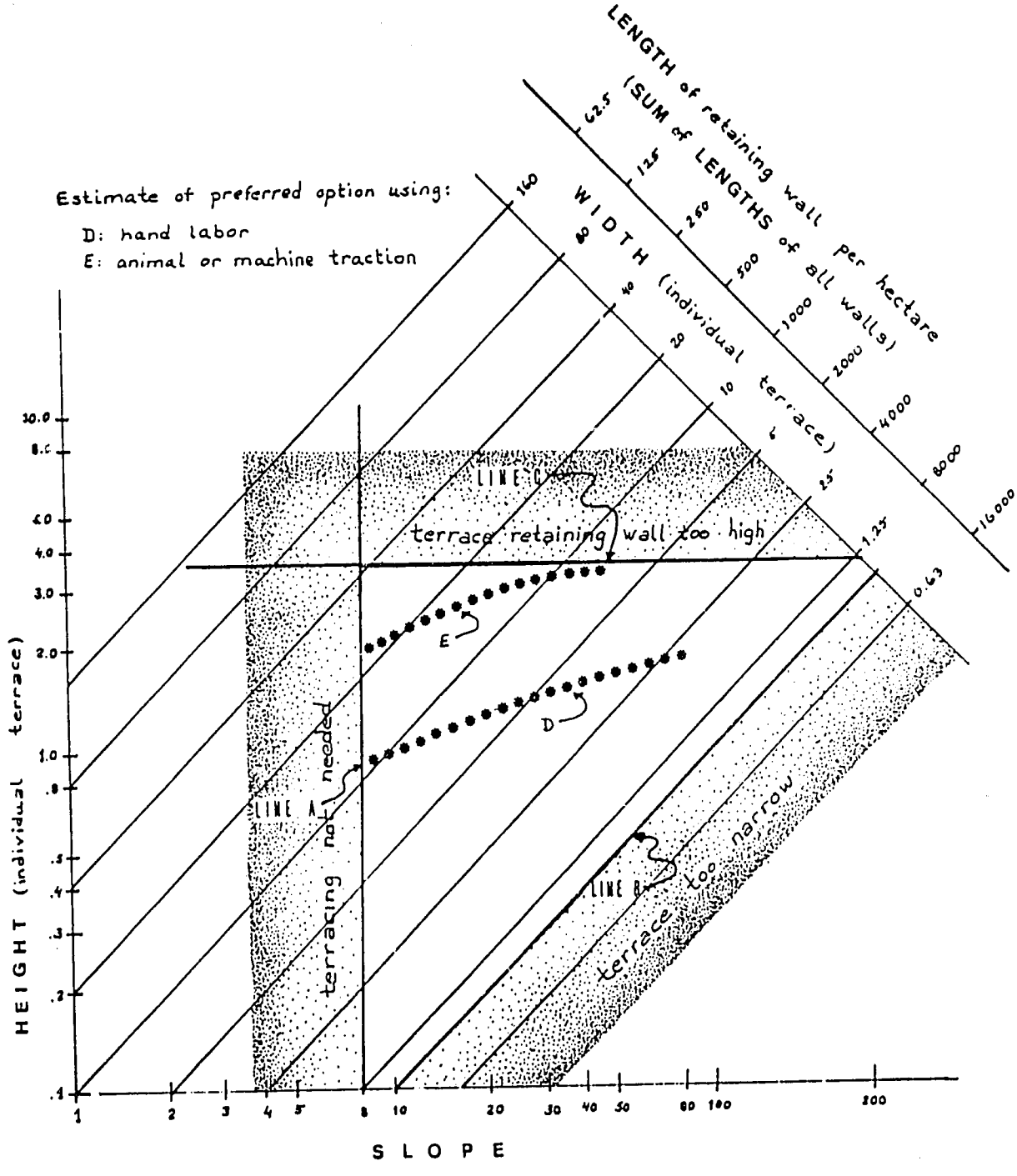

Fig. 2.— Terrace Height and Width Relationships According to Slope.

It can be assumed that there is some minimal slope (8 % is arbitrarily selected here) which renders terracing unnecessary as a soil conservation measure (see line A in Fig. 2). Line B delimits cases in which a terrace would have a width of less than one meter, and hence would probably be too narrow for agricultural use. We can also assume that there is some maximum height for terrace retaining wall, beyond which construction and maintenance costs become prohibitive; a height of 3.5 meters (line C) is arbitrarily selected here. Thus, the rough triangle formed by lines A, B, and C denotes the potential range of options for terracing. In this case, it includes slopes of eight percent or more, with maximum terrace height of 3.5 meters, and a minimum width of one meter. These limits can probably be taken as a liberal estimate of the current options available in the three countries examined in the case study.

Obviously, the actual limits suggested by lines A, B, and C would vary between regions and should be determined empirically. Such variables as method of cultivation, crop, erodibility of soil, labor costs, and scarcity of land resources would determine the critical limits in terrace parameters. Lines D and E are estimates of preferred options under conditions of hand and animal or machine traction, respectively. The basis for these estimates will be discussed later in this paper.

The leveled surface of a terrace is necessarily smaller than the area of the original slope. In effect, the leveled surface is the side, compared to the hypotenuse, of a right triangle. If we let A' and A be the original and terraced surfaces, respec-

tively, and α be the upslope angle of the slope, then:

$$A = \cos(\alpha)A' \qquad (5)$$

where both A and A' are measured in square meters.

If the retaining wall is not vertical, then the leveled surface is further reduced. Also, exposed rock at the top of a rock retaining wall, or the delicate nature of the top edge of an earthen bank, will produce additional reductions in the cultivation surface. Inasmuch as the construction of agricultural terraces is usually undertaken only in cases of extremely high land pressure, the reduction in field surface is a significant negative consequence of terracing.

The reduction in area for three types of terraces is presented in Table 1. A theoretical system which assumes vertical retaining walls is provided solely for comparative purposes. The second example is patterned after the controlled erosion design used in the Valles Altos region, in which rock retaining walls are very steep (between 500 and 1000%). The third example is patterned after the AID sponsored single-effort terrace design observed in Peru and Guatemala in which part or all of the retaining wall is earthen and the slope of the wall is about 200 percent. In this case, the earthen wall surface can be used for a supplemental fodder crop.

If the retaining walls are vertical the surface of the terraced field is reduced by the cosine of the upslope angle of the original surface; that is, it is proportional to the side, as opposed to the hypotenuse, of a right triangle. With the vertical retaining wall, the surface area reduction is relatively modest; for example, on a forty percent slope a one hectare area

TABLE 1.-- CULTIVATION SURFACE BY SLOPE AND TYPE OF RETAINING WALL (in sq.m per hectare of land terraced)

	ROCK WALL DESIGN				EARTHEN WALL DESIGN			
	VERTICAL WALL		750% WALL		200% WALL			
% S.	SURFACE	%CHG	SURFACE	%CHG	SURFACE	%CHG	RET.WALL	TOTAL
10	9950	-0.5	9818	-1.8	9453	-5.5	1112	10565
20	9806	-1.9	9544	-4.6	8825	-11.7	2193	11018
30	9578	-4.2	9195	-8.0	8142	-18.6	3213	11354
40	9285	-7.2	8790	-12.1	7428	-25.7	4152	11580
50	8944	-10.6	8348	-16.5	6708	-32.9	5000	11708
60	8575	-14.3	7889	-21.1	6002	-40.0	5752	11755
70	8192	-18.1	7428	-25.7	5325	-46.7	6412	11737
80	7809	-21.9	6976	-30.2	4685	-53.1	6984	11670
90	7433	-25.7	6541	-34.6	4088	-59.1	7479	11567
100	7071	-29.3	6128	-38.7	3536	-64.6	7906	11441
110	6727	-32.7	5740	-42.6	3027	-69.7	8273	11300
120	6402	-36.0	5378	-46.2	2561	-74.4	8589	11150

field would be reduced by only 715 square meters (Table 1). If the retaining wall is not vertical the terraced surface is further reduced. The additional surface reduction for the Valles Altos design is modest because the retaining walls are very steep. In the case of the AID sponsored terraces observed in Peru and Guatemala, the approximately 200 percent walls result in a substantial reduction in the level surface, in comparison with the original slope. For example, on a forty percent slope the leveled surface is about twenty-five percent smaller in area than the original slope (Table 1).

On the other hand, when earthen walls are used, a supplemental fodder crop can be grown on part or all of the retaining wall. In the case of a forty percent slope the total area of earthen wall for one hectare of land is more than four thousand square meters-- substantially greater than the approximately 2,500 square meters lost on the leveled surface (just as the sum of the two sides of a right triangle is greater than the hypotenuse). Thus, the total planting surface can be as much as seventeen percent greater on the terraced land. Productivity on the earthen bank may be hindered by the steepness of the slope, low fertility (especially on the lower half of the bank), and shading from the main crop. Nevertheless, the supplemental crop will compensate, at least in part, for the loss of area on the primary cultivation surface. In the case of the method used in the Valles Altos region, the loss of area on the terraced surface is much less, but the rock retaining wall eliminates the supplemental fodder crop.

Not taken into account in Table 1 is the loss in cultivation area as a result of exposed rock at the top of the retaining wall or, in the case of an earthen wall, the loss resulting from the fragile nature of the top edge of the terrace. In the case of the Valles Altos design, the exposed rock at the top of the wall is about eighty centimeters wide; assuming 300 to 400 linear meters of rock wall per hectare, the total loss will be from 240 to 320 square meters. As was noted in the paper, this factor has led to the destruction of some retaining walls. The loss related to the fragile top edge of the earthen terrace would be less (perhaps 100 to 200 m^2 per ha.).

Construction Costs

The costs of terrace construction in all three of the regions studied are mostly in the form of labor. By examining each of the various stages of terrace construction, we can estimate the relative amount of work required for terrace construction according to the amount of slope reduction achieved, and determine how the work requirement varies with terrace dimensions. The analysis is helpful in determining the relative merit of alternative methods of terrace construction, such as those used in the Valles Altos program in Venezuela.

For purposes of illustration, we assume the construction of terraces on a uniform slope with rock retaining walls. The time and effort required for each step in terrace construction is taken to be proportional to the weight (product of volume and density) of the material displaced, plus the product of that

weight and some function of the distance it must be moved.[1] Units of work are expressed in thousands of metric ton-meter equivalents.

Rock, assumed to be evenly scattered over the surface of the field, is moved downslope to provide material to build the wall below (Fig. 3). The topsoil is removed and the subsoil in the upper half of the field is moved downslope to provide fill for the lower half. The work required to build the wall is taken to be the product of the weight of the rock used and a constant which expresses the work required to build a rock wall relative to the simple displacement the material used.

The steps in terrace construction are:

1. remove (and replace) topsoil;
2. move rock from field to wall location;
3. build retaining wall;
4. move subsoil into level position.

If earthen, rather than rock retaining walls are used, steps two and three are eliminated, and some additional work is required to plant vegetation on the face of the retaining wall. If leveling is achieved by erosion over a period of years, steps one and four are eliminated, but an additional step of excavating

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[1] Work is usually measured as weight (product of mass and gravity) times distance displaced. However, when hand labor is used it might be more realistic to view the lifting and moving of material as separate operations. If the material is moved only a convenient shovelling distance the work required is approximately equal to the weight. For longer distances, the material would normally be lifted first and placed into a container (say a bucket or wheelbarrow), and then moved. Thus, the work required to move material 20 m would be greater, but not twice that required to move it 10 m. This assumes a fixed cost (initial lifting or loading), and an additional moving cost which is proportional to distance.

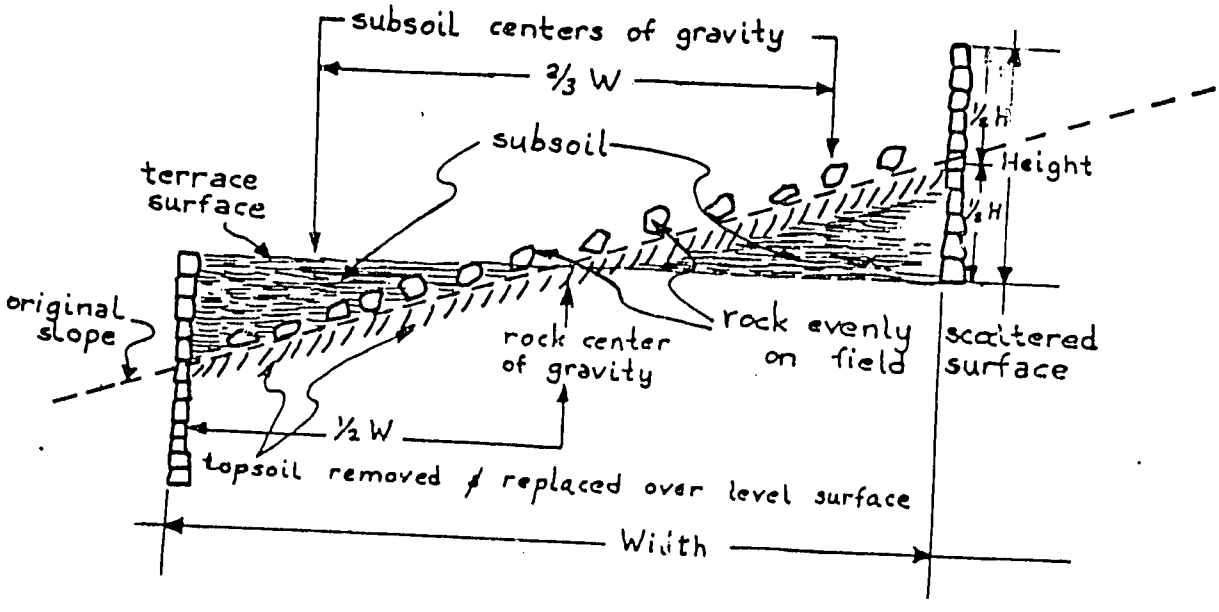

Fig. 3.-- Terrace Profile.

the foundation for the retaining wall is added. Moreover, the erosion method requires a free-standing wall that must have a strong face on the uphill, as well as downhill, side. These alternatives are considered later.

Among the determinants of the work required in the construction of agricultural terraces are a number of constants; that is, factors that are set by soil conditions and the level of technology available. These constants include:

1) the densities of the topsoil (d_1), subsoil (d_2), and rock (d_3), in the area to be terraced;

2) the depth of the topsoil (k_1), the degree of compactness of the subsoil (k_2), and the required thickness of a single-faced retaining wall(k_3);

3) the work required to move material over the surface of the field (f_1: per linear m), and the work required to build the retaining wall (f_2: per m^3).

For purposes of estimation in this paper, the density values are set at 1.25 (d_1), 1.75 (d_2), and 2.75 (d_3), for the topsoil, subsoil, and rock respectively. It is assumed that density variations reflect variations in porosity and organic content of the material. The depth of the topsoil (k_1) is set at .3 meters. It can be assumed that the topsoil is sufficiently loose that the work required to move it is roughly equal to the weight of the material. By contrast, the subsoil is likely to be more compact, so that moving it will require additional work. Ideally, the value set for subsoil compactness would measure the work required to move the more compact material in comparison to loose topsoil.

In the absence of some empirical basis for estimating this value, it is ignored here (that is, k_2 is set at 1.0, or equal topsoil). This variable is included in the equations to alert the reader that in those operations which require the movement or excavation of subsoil the amount of work calculated will be understated. The required thickness of the retaining wall (k_3) is set at .3 meters, based on methods used in Japan.

The work required to move material over the surface of the field (f_1) is measured per linear meter, relative to the work required to simply lift the material (the weight). This value is a function of friction, and hence the method used to move the material. It is assumed here that all material would be moved with hand tools, so the value of f_1 is set relatively high at 0.2; that is, the work required to move material five meters is assumed to be equal to that required for the initial lifting. Because most of the material would be moved downslope, there is a reduction in friction which is measured as the cosine of the upslope angle. However, because all movement is measured in terms of the finished terrace surface rather than the original slope, that factor can be ignored here. The width of the finished terrace is equal to the width of the original surface as modified by the cosine of the upslope angle.

The work required to build the rock retaining wall is dependent upon the skill of the builder and the type of rock available. Clearly, it would greatly exceed the work required to simply lift the rock. In the absence of an empirical basis for estimating this value, it is set arbitrarily at 2.0; that is, the work required to build one cubic meter of rock wall is set at two

times the work required to lift the rock.

Units of work are expressed throughout this paper as thousands of metric ton-meter equivalents. The minimum displacement distance is assumed to be one meter; that is, the work required to load 1,000 tons into a container, or move it a convenient shovelling distance, is equal to one unit (1,000 ton-meters) of work. Likewise, the work required to move 1,000 tons five meters (after it is loaded into a container of some sort) is equal to one unit of work (given $f_1 = 0.2$). All values are expressed in terms of work required to terrace one hectare of land.

The number of man-days of labor per unit of work will depend upon the methods used. Based on minimal empirical observation, one unit of work as measured here can be estimated to be between thirty and sixty man-days under conditions in the three countries observed. It should be noted that a farm family would normally terrace only a portion of one hectare in a given season, and would probably make use of several workers.

The values set for the constants noted above will determine the absolute value obtained for work required for terrace construction. However, the relative differences in effort required for the various stages remains about the same for any reasonable estimates of these constants. Therefore, the validity of the model is not dependent upon the estimates selected.

Several variables also determine the amount of work required for agricultural terrace construction. These include:

1) the amount of land to be terraced or area (A);
2) the slope (or desired reduction in slope) of the land (S);

3) the width of the terrace (W) and height of the retaining wall (H).

A farmer may decide to terrace all, some portion, or none of the land he controls. The slope of his land is, of course, given; however, he may choose to retain a substantial slope on the finished terrace or make it level or backsloped. For comparative purposes, we will assume the construction of level terraces; in actual practice the percent slope on the finished terrace is subtracted from (or added to, in the case of a backslope) the slope of the land to determine the work requirement. The farmer may also choose the width of the terrace (distance between retaining walls) and having done so, will have determined the height of the retaining wall required. Of course, there are absolute limits on retaining wall height (determined by the availability of rock and the skill of the builder) which will constrain the selection of terrace width.

Step 1: Removal (and replacement) of Topsoil (TS)

$$TS = a_1 A \qquad (6)$$

where, a_1 is $(k_1 d_1)$.

The work required to remove (and replace) the topsoil can be considered to be approximately proportional to the total weight of the material because it would be moved only a convenient shovelling distance from one section of the field to a nearby previously leveled section, as in the AID terracing projects (Arledge, 1984). The work required is not related to terrace

width or to the slope of the field.[1] On gentle slopes with relatively narrow terraces, moving topsoil is a major share of the total work required (Fig. 4).[2] On steeper slopes, and for wider terraces, the work required to remove and replace the topsoil is minor in comparison to the total work effort.

Step 2: Move Rock from the field to the Wall construction site

$$\text{Weight of Rock} = a_2AS \qquad (7)$$

where, a_2 is (k_3d_3).

The volume of rock required is a function of slope. If the wall is thirty centimeters thick, a ten percent slope would require 300 cubic meters of rock; if the slope is twenty percent or thirty percent, the required volume of rock is 600 cubic meters and 900 cubic meters, respectively. The rock requirement does not depend upon terrace width; a wider terrace must have a higher wall, but the length of the wall or walls for a given area of land is reduced proportionally (see equations 2, 3, and 4).

$$\text{Move Rock} = a_2AS + b_1ASW \qquad (8)$$

where, a_2 is as defined previously, and b_1 is $(.5k_3d_3f_1)$.

Notice that the average distance the rock must be moved is one-half the width of the terrace, and that the work required to

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[1]The actual surface area of the original slope exceeds that of the leveled terrace surface, so that a 30 cm deep topsoil on the leveled terrace would require the removal of a topsoil cover less than 30 cm deep from a larger original surface.

[2]Computer programming used to calculate data for Fig. 4 is provided in Annex 3, along with print-outs for the examples used. If the values for constants and variables is set according to conditions at a specific project site, the program can be useful in estimating the labor requirement according to terrace design.

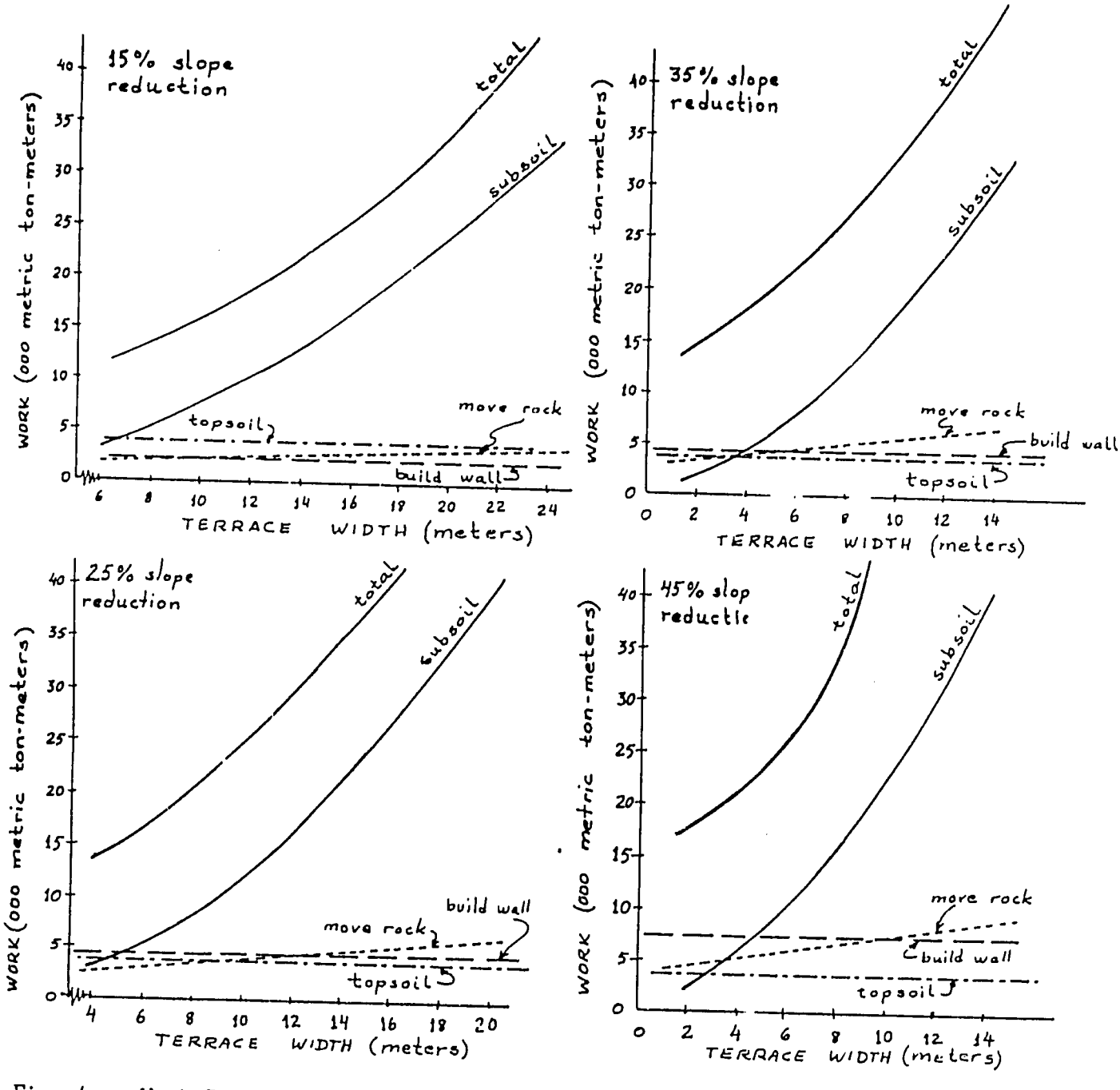

Fig. 4.-- Work Requirements by Width and Slope

move it is assumed to be equal to the weight of the material plus the product of the weight and a function of the distance it is moved.

The work required to move the rock is proportional to both the slope and the width of the terrace. An increase in the slope will increase the volume of material that must be moved, and an increase in the width of the terrace will increase the distance it must be moved (Fig. 4). On gentle slopes the work required to move rock is roughly equal to that required to move the topsoil. In the case of wide terraces on steeper slopes, the work of moving rock will be two to three times more than that required to move the topsoil.

Step 3. Build Retaining Wall

$$\text{Build Wall} = a_3AS \qquad (9)$$

where, a_3 is equal to $(k_3d_3f_2)$.

The work required to build the wall is proportional to the quantity of material used and hence the slope; however it is independent of terrace width.[1]

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[1]The wider the terrace, other things being equal, the higher the retaining wall must be. Of course, for any given area a higher wall will result in a reduction in the length of the wall, so that the total volume of wall will remain constant. It is possible that the increase in work effort required for the higher wall will exceed the reduction in work effort resulting for the shorter length of the wall. Higher walls are probably more prone to failure as well, and may carry higher maintenance costs. The model presented here assumes work is strictly a function of the total volume of wall constructed; the model does not take into account the possibility that the higher walls might require an increase in labor notwithstanding the proportional reduction in length.

Step 4. Level Subsoil

$$\text{Weight of Subsoil} = .5\ (d_2)(.5W)(.5H)(A)\ /\ (W)$$

and, substituting from equation (1)

$$= .5\ (d_2)(.5W)(.5WS)(A)\ /(W)$$

$$= a_4ASW \qquad (10)$$

where, a_4 is $(.125\ d_2)$. Therefore, the volume of subsoil that must be moved is proportional to both slope and terrace width.

$$\text{Move Subsoil} = a_4ASW + b_2ASW^2 \qquad (11)$$

where, a_4 is as defined above and b_2 is $(0.083\ k_2d_2f_1)$.

The average distance the subsoil must be moved is equal to two-thirds the terrace width (that is, 0.125 X 0.667 = 0.083: see Fig. 3). Both the volume of subsoil, and the distance it must be moved are proportional to terrace width; therefore, the work required to move the subsoil is proportional to <u>the square of terrace width</u>.

The absolute limit on height of retaining wall (assumed to be two meters for earthen and three meters for rock retaining walls) will eliminate the option for very wide terraces on steep slopes. For example, if level terraces are ten meters wide, the maximum slope reduction is twenty percent for a two meter high wall, and thirty percent for a wall three meters high (see equations 1 & 2). If a greater reduction in slope is required, the terraces will have to be more narrow, and hence the labor requirement for moving subsoil will be much lower. Likewise, if narrow terraces are selected for the more gentle slopes, the work required to move the subsoil will be relatively low in comparison with the total. However, the rapid increase in the work required to move the subsoil with increasing width will be

a powerful disincentive for wide terraces. It is important to note that the disincentive for wide terraces exists even on gentle slopes, and that leveling the subsoil is the only step which strongly discourages increased width.

Width Selection is the Critical Decision

The selection of terrace width is the critical element in decision-making for agricultural terraces. If the farmer decides to build wide terraces the work effort required will increase substantially. Said another way, the selection of a wider terrace will reduce the amount of land the farmer can terrace over a given period of time. If a farmer has sufficient labor to construct one-half hectare of two meter wide terraces, he would be able to terrace only about one-fourth a hectare if they are to be eight meters wide, and one-tenth of a hectare if they were to be thirty meters wide (given the values selected for constants here: see Fig. 4). The penalty for increased width increases with slope and is greater when earthen, rather than rock, walls are used. On a thirty-five percent slope, the work required for eight and thirty meter wide terraces, using earthen walls, is three and twenty times, respectively, that required for two meter wide terraces.

The decision a farmer makes will depend largely upon the marginal costs and benefits of added terrace width. The marginal costs of added width will necessarily increase rapidly. Marginal benefits, however, depend mostly on whether the land is to be worked by hand or with animal or machine traction. If farmers behave rationally, they will prefer to minimize the work and

maximize the area affected.[1] Therefore, unless some method of terrace construction is used which does not require the subsoil to be physically leveled we would expect to find a major difference in terrace width, depending upon the method used to work the land.

A terrace width of less than x (Fig. 5) is defined as being too narrow for agricultural use. The actual value of x would vary widely between regions, depending upon crop and cultivation method. That value might be ten meters or more in areas where machines are used to cultivate the soil, and as little as one or two meters for some tree crops or where the soil is cultivated by hand. The marginal utility of width will tend to decline as the width increases from x to y. If the land is worked by hand, rather than with oxen or tractors, the marginal utility of added width is low, so that the utility curve would drop sharply with increased width.

There is also a minimum retaining wall height, below which construction costs increase (designated as x' on Fig. 5). For a given area, the length of the wall is inversely proportional to the height; on a ten percent slope, a one-half meter high wall will necessitate 2,000 linear meters of retaining wall per hectare terraced, compared to 1,000 meters for a one meter high wall (see equation 3). Even though the total cubic meters of

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[1]The validity of this assumption is not dependent upon the technology available or the labor system. Rational behavior assumes work is minimized whether it is accomplished with a shovel or a bulldozer and whether by family, wage, or conscripted labor. Of course, there may be motives for building wider or more narrow terraces that are unrelated to the method used to cultivate the soil.

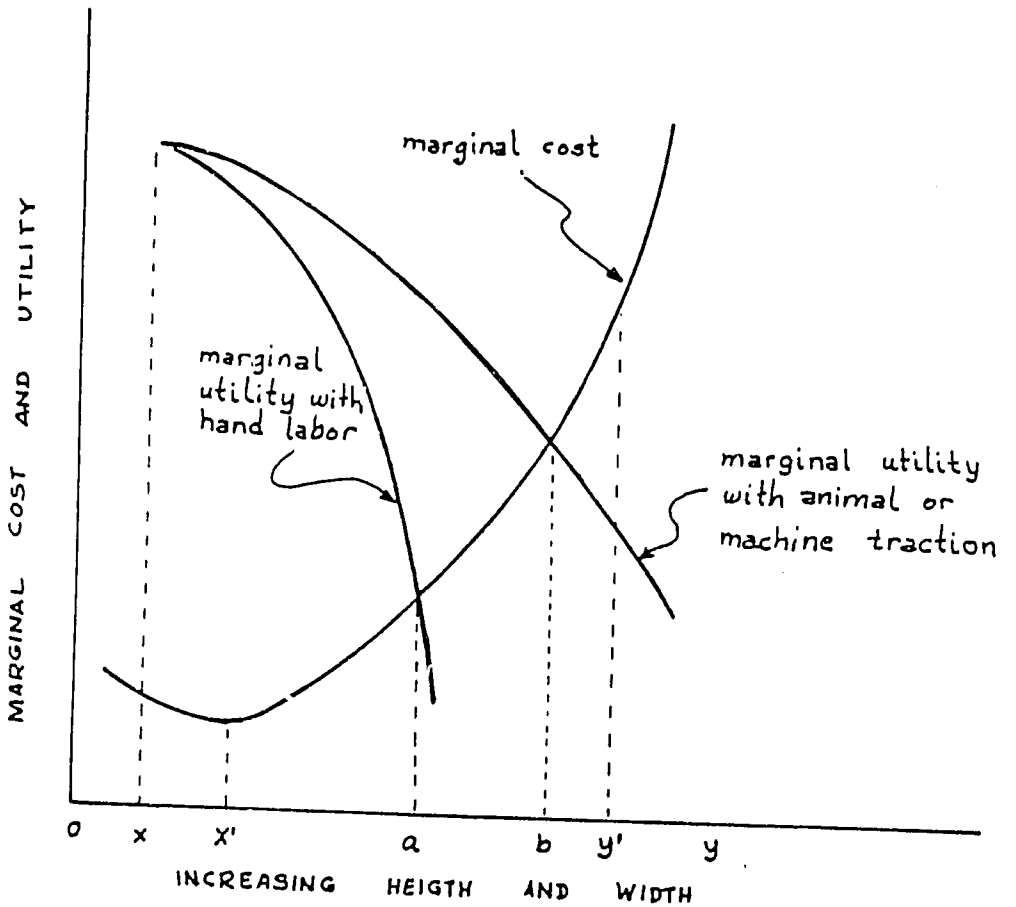

Fig. 5.-- Marginal Cost and Utility of Added Width.

retaining wall is constant (see equation 4), there are fixed costs associated with wall length that can make higher (up to about 1 m) but shorter walls less costly. A wall must have a firm foundation in the subsoil; if a firm foundation is reached at say one-half meter below the surface, then a wall less than one meter high (one-half m above and below the original surface) will have some portion of the wall that is functional only as a foundation and will remain buried after leveling.

The marginal cost of increased width will increase rapidly beyond point x'. Most of this increase reflects the rapid increase in work required to move an increasing volume of subsoil a greater distance (see equation 12). The increased cost of moving a constant volume of rock a greater distance will contribute only slightly to the sharp increase in the marginal cost. Beyond point y' additional width will require retaining wall height to exceed the engineering and construction skills of the builders. Thus, increased building and maintenance costs for higher walls make wider terraces prohibitive.

The range of viable options for width and height are confined to values between x' and y'. Farmers using animal or machine traction for cultivation would tend to select the height and width values at point b. Those using hand labor, with lower marginal utility for added width, would tend to build more narrow terraces with width and height dimensions at point a.

Estimates of terrace width and height selections for farmers using hand, versus animal or machine, labor are provided on Fig. 2 as lines D and E, respectively. It should be noted that Fig. 2

assumes terraces are flat and retaining walls are vertical. In practice the slope of the finished terraces and slope of the retaining wall will modify the design. For example, a 2.5 meter wide terrace would have a leveled cultivation surface of only about 1.5 meters if a two meter high earthen retaining wall with a 200 percent slope is used. It would also have a little more than a two meters wide area on the earthen bank where a supplemental fodder crop could be grown.

The Evolutionary Approach to Terrace Construction

The Valles Altos program demonstrates that terraces can be constructed without physically moving the subsoil. The problem of erosion can be solved with the construction of retaining walls along the contours of the slope; indeed, it is the retaining wall, rather than the level surface of the terrace, that will accomplish the goals of soil conservation. The leveling of the surface can be achieved over a period of years by erosion from the back, and accumulation at the front, of the terrace. Downslope plowing can be used to speed the process where desirable.

The Valles Altos design was dependent upon the existence of a large amount of rock on the surface of the field. If sufficient rock is not available on the field or nearby, the work required to bring rock to the construction site will probably eliminate the option for rock retaining walls. In those cases observed, the use of the erosion method with a vegetation barrier (rather than rock) resulted only in small, randomly spaced, semi-terraces (described below). However, the use of the controlled

erosion method with a vegetation barrier has been reported in several area (see Summary of Findings in main body of the paper).

The process of terrace evolution will frequently begin with the cultivation of steep slopes, whether or not the farmer is a willing participant. When an isolated plot on a steep slope is cultivated, the cultivated soil will tend to erode more rapidly than that above and below, which is held more firmly by permanent vegetation. In Venezuela, we observed soil erosion on steep slopes sufficient to cause the top of the field to drop by about ten centimeters annually. After a few years of cultivation, a steep bank a meter or more high will exist at the top of the field (Photo 25). The soil moving downslope will tend to be impeded at some point by a natural rock outcropping or vegetation barrier; thus a second earthen bank will begin to form at the bottom of the field, and the slope of the cultivated surface will begin to diminish (Photo 26). The earthen bank below becomes a convenient place to dump excess rock, unearthed during cultivation, and can thereby be reinforced to some degree.

In Peru, the small semi-terraces that evolve as a result of cultivation on steep slopes are called Pata-Pata fields (meaning foot-foot, in reference to the staircase appearance: Photo 27). In some cases this evolutionary process may produce a relatively level terrace bench with little or no overt effort on the part of the farmer (Photo 28).

Informal terraces can be easily and quickly converted into formal terraces -- albeit, terraces that are small and irregularily spaced over the slope. In the Cuzco region of Peru, a conservation field officer stated that old Pata-Pata fields are a

favorite target for AID sponsored terraces (Photo 29).[1]

Informal terraces are necessarily spread randomly across slopes, and they are generally very small both in width and length. An exception can occur when irrigation water is obtained from canals that must follow the contours of the slope. In such cases, canal maintenance will encourage formalizing the bank or wall above the canal, and continued erosion will tend to produce terraces that are relatively level along their length (Photo 30). Nevertheless, they tend to be irregular in both width and length, and to be plagued by frequent failure (Photo 31).

Unless direct and purposeful action is taken, the soil conservation benefits of informal terraces are probably minor and temporary. Farmers usually dig drainage canals around the tops of these semi-terraces (and other fields on steep slopes) to channel excess water to the sides during periods of heavy rain. Typically, an erosion gully will form on either side, which if unchecked, will slowly erode into the cultivated area. In the absence of a strong retaining wall, increased water absorption on the more level surfaces of semi-terraces may lead to total failure during an extraordinarily heavy rainstorm. The existence of a few randomly spaced terraces on a steep slope is likely to be inconsequential to the overall process of slope erosion.

The Valles Altos program can be viewed as a method of controlling the natural evolutionary process of terrace formation. It is a method of constructing terraces with minimum overt effort

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[1]Personal interview with Mario Dueñas, soil conservation officer in Cuzco (Sept. 15, 1985).

and maximum use of natural processes to the farmer's advantage. Moreover, the terraces produced in this way are likely to be wider, more stable, and have a longer life expectancy than those produced in a single massive effort to alter the landscape into level terraces.

Construction Costs Using the Erosion Method

The controlled erosion method of terrace construction requires the following steps:

1) excavate the foundation trench for the retaining wall;
2) move rock from the field to the wall location;
3) build retaining wall.

In the construction of retaining walls along the contours of the slope, it is not necessary to assure that the height and spacing of the walls will allow for a finished level (near level or backsloped) surface. Indeed, the initial construction effort using the erosion method will almost certainly not produce a finished level surface. Except for very narrow terraces (which for reasons explained later are unlikely to be built with the erosion method), the engineering skill required to calculate the height and width for finished level terraces on an uneven hillside is formidable. If made, such a calculation would reveal that one-half the height of the wall must be below the original surface; thus, the farmer would be faced with the arduous task of excavating a deep trench and the added difficulty of building a strong wall well below the surface. In the Valles Altos project retaining walls are generally from 1.5 to 2.5 meters high, but only about one-half meter of that was built below the surface of

the original slope.

The farmer is forced to excavate one-half meter or so in order to achieve a stable foundation for the wall. Because the upper portion of the wall will be free-standing (until soil is filled in behind by erosion) he must build a double wall. However, the height of the wall above the original surface is largely a function of the availability of excess rock on the surface of the field, and would usually not exceed from 1.5 to 2.5 meters in any case.

As was noted in the main body of the paper, wall height in the Valles Altos projects does correlate with slope in extreme cases. Gentle slopes never have walls above 1.5 meters and steep slopes sometimes have higher walls. Nevertheless, the wall height is largely a function of the amount of rock available and the willingness of the farmer to do additional work. In the erosion method of terrace construction, it is not the slope of the land, but rather the amount of reduction in slope that is desired, that is important.

In most cases the dimensions of the foundation trench and the retaining wall can be considered constants. Based on the Valles Altos design, the dimension of the foundation trench (k_4) is set at .6 cubic meters per linear meter of wall (.5 m deep and 1.2 m wide). The volume of rock in the retaining wall (k_5) is set at two cubic meters per linear meter (assuming .5 m below and 1.5 m above the surface and an average thickness of 1 m). All other constants and variables are the same as those used previously.

The work required for the three steps can be calculated as:

$$\text{Excavation} = a_5 A / W \tag{13}$$

where, a_5 is $(k_2 k_4 d_2)$;

$$\text{Move Rock} = a_6 A / W + b_3 A \tag{14}$$

where, a_6 is $(k_5 d_3)$ and b_3 is $(.5\ k_5 d_3 f_1)$.

$$\text{Build Wall} = a_7 A / W \tag{15}$$

where, a_7 is $(k_5 f_2 d_3)$.

The work required for each stage of the construction effort, and thus the total work required, is inversely related to terrace width (Fig. 6). That is, the work is directly proportional to the total length of retaining walls in a given area, and length is equal to Area / Width (see equation 3). If relatively wide terraces are constructed, the work required is greatly reduced. By contrast, if the terraces are narrow, the additional work required for excavation and building a double wall makes the total work required for the erosion method much higher than for the single-effort method.

Based on the values set for the constants in the model presented, if a twenty-five percent or more slope reduction is desired, the cost of the erosion method is equal to or greater than that of the Single-Effort method (the data are contained in Annex 3). For a twenty-five percent reduction in slope a labor savings could be achieved by the erosion method only if the terraces ten meters or more wide, requiring retaining walls to be over 2.5 meters high. This was the approximate limit on wall height (wall plus earthen bank supplement) and width in the Valles Altos program.

If the slope reduction is only five percent, the terraces

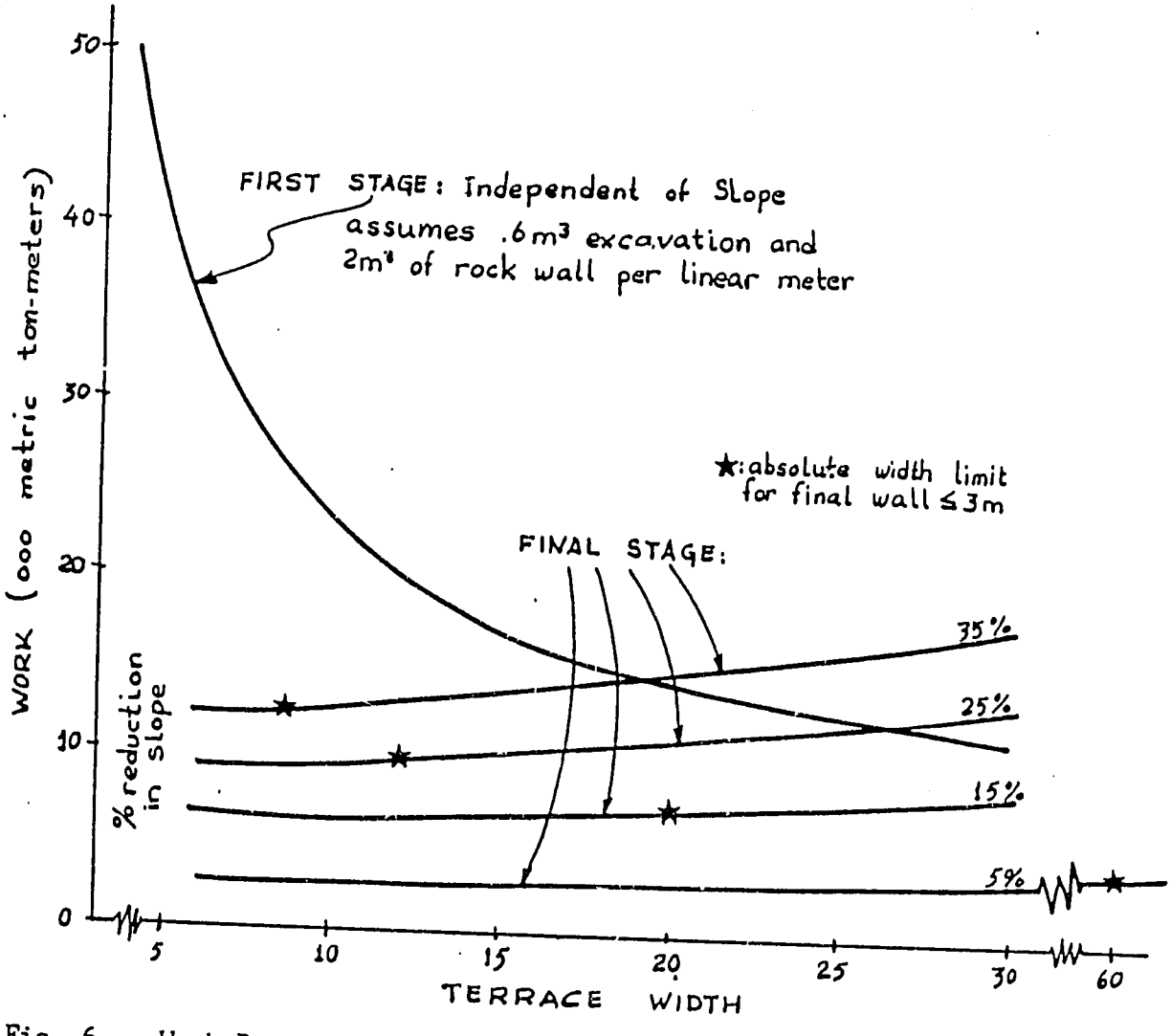

Fig. 6.-- Work Requirement Using Controlled Erosion.

would have to be at least twenty-five meters wide to achieve a labor savings through the erosion method. In this case an even greater savings could be achieved by building the terraces fifty meters wide. In the Valles Altos program the slope reductions achieved were generally from ten to twenty percent, on slopes of from fifteen to forty percent. Based on the estimates used for constants in this paper, and assuming terraces from ten to twenty-five meters wide, the work effort would have been about half that required if the Single-Effort design had been used (see data in Annex 3).

It should be noted that the advantage of initiating wide terraces will exist whether the land is worked by hand or with animal or machine traction. The fact that Inca terraces are frequently quite wide (Sánchez, 1985, & personal observation), even though the Inca used only hand labor for cultivation, strongly suggests that the stage and erosion method was used (Photos 32 & 33).

Once retaining walls are built along the contours of the slope, the process of leveling will begin (Fig. 7). The resulting terrace may take one of several possible forms. An additional reduction in slope can be achieved with a steep earthen bank as a supplement to the retaining wall behind (Photo 34). The slope of the terrace may be greater, but relatively even between the two walls (Photo 35). With the use of up-slope plowing (a common practice on relatively steep "terrace" surfaces in Japan: Photo 36) the system may be maintained almost indefinitely with proper wall maintenance.

Alternatively, an additional construction effort, twenty or

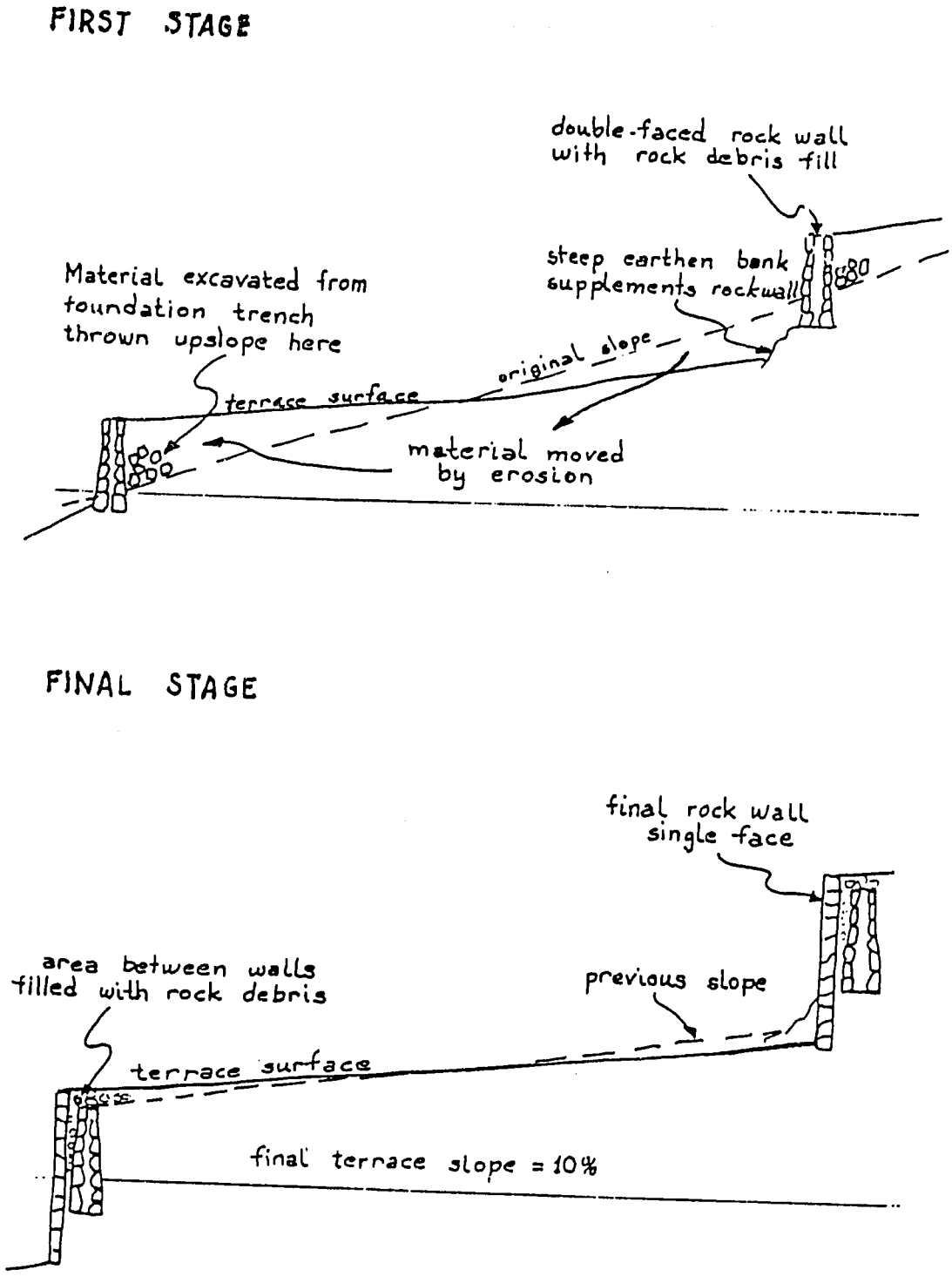

Fig. 7.-- Controlled Erosion Terrace System (First Stage is Valles Altos Design; Final Stage is Hypothetical).

thirty years hence, can reduce the slope to that required for normal drainage (Fig 7). The new wall will have to be only a little higher, but much deeper, to allow for continued leveling by erosion. If excess rock is available on the field or exposed by erosion over the years, there will be a strong incentive to build a new wall in front of the old one because less excavation would be required. Smaller buried walls have been discovered behind current retaining walls on Inca terraces.[1] Otherwise, the original wall can be replaced by a new wall.

The final wall will probably be a single, rather than double, wall because the effort to fill subsoil behind the top of the wall (probably from the excavation trench) would be less than that required to construct a double free-standing wall. The work required to complete the second stage of construction, so that a near level terrace could be achieved, would include additional excavation, moving rock, and wall building. In contrast to the initial stage, the work required for the final stage will increase with terrace width and slope (Fig. 6). That increase is however, rather modest, and in any case postponed by those who make the decision on width to the next generation of farmers.

Construction Costs with Earthen Retaining Walls

In those cases where rock is absent or insufficient in quantity to build rock retaining walls, the use of earthen banks is the only reasonable alternative for terrace construction. The elimination of the need to move rock and build rock walls will

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[1]Personal communication with William Denevan, project director for "The Rio Colca Abandoned Terrace Project, Peru."

reduce the labor requirement for terrace construction. However, the more fragile nature of the retaining wall will usually increase maintenance costs and the danger of total failure during periods of extreme weather conditions.

It is possible to use a vegetation barrier in conjunction with the erosion method of terrace construction. Controlled erosion terraces with vegetation retaining walls have been reported in the Cajamarca region of Peru, and in Honduras.[1] The advantages of using vegetation rather than rock are obvious. The work requirement for planting vegetation along the contours of slopes would be minimal in comparison to moving rock and building rock walls. Moreover, the use of a vegetation barrier would allow for the use of the controlled erosion method in those areas where rock is not available on the field-- thereby eliminating the arduous task of leveling the subsoil.

The use of some material that is transported to the field (including rock) is probably not cost effective for terraces designed for agricultural use. Temporary materials can be, and sometimes are used (Photos 37 & 38). However, if the terrace is to be permanent, the temporary materials must be replaced by a permanent rock or vegetation barrier.

The AID project observed in Guatemala, and to some degree in Peru, can be taken as examples of terrace construction with earthen retaining walls. The work required is similar to that presented in Fig. 4 but reduced by rock and building components.

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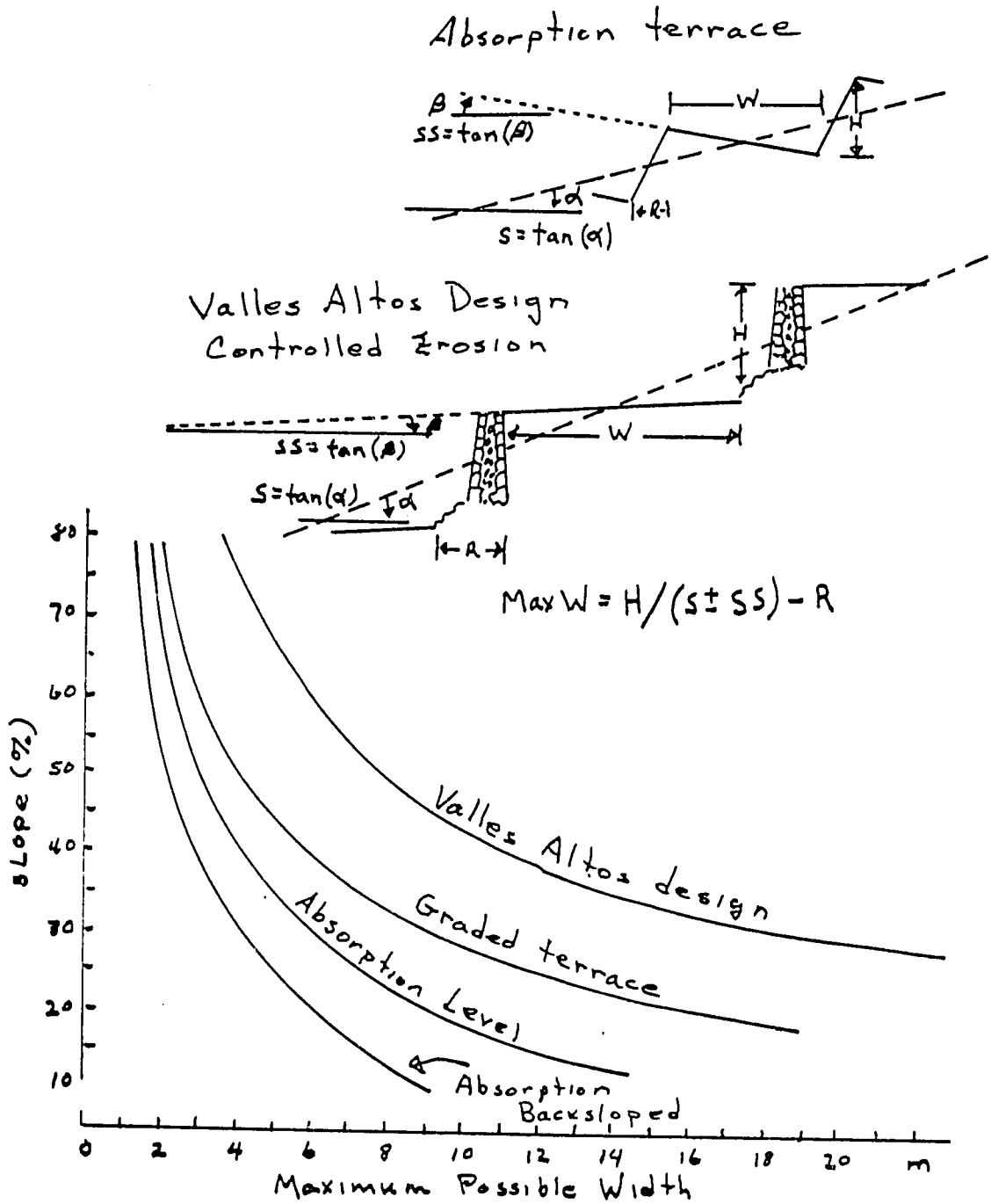
[1]Personal communication with Jeff Vonk, U.S. Soil Conservation officer in Peru, and Joshua Dickinson III who has recently examined agricultural projects in Honduras.

Some additional work is required to plant vegetation on the earthen wall. Because the lower portion of the earthen bank will be exposed subsoil, it will be difficult to initiate the vegetation cover. If this is not done, however, the steep bank will almost certainly erode away leading to terrace failure.

In the AID projects the maximum height of the earthen retaining wall is recommended to be two meters (Arledge, 1984, p. 2). The design does not specify the slope of the retaining wall, except to recommend that it be as steep as possible but not vertical (Arledge, 1984, p. 3). In practice, the slopes of the retaining walls appear to be about 200 percent. The design also calls for a backslope with provision for drainage at the back of the terrace. These constraints set limits on terrace width quite apart from the labor requirement.

Because terrace width is equal to height of wall divided by slope (see equation 1), the maximum terrace width with two meters high retaining walls can be easily calculated (Fig. 8). Line a is the normal AID design observed in Peru and Guatemala, and assumes two meter high walls with a 200 percent slope and a ten percent backslope on the terrace surface. Within the range of slopes where soil conservation is relevant, the maximum widths range from six meters on twenty percent slopes to about one meter on steep slopes. Terraces observed in Guatemala generally fit this pattern.

On relatively gentle slopes a somewhat wider terrace can be achieved by adopting a level terrace surface (with drainage achieved with raised beds) or a forward slope of ten percent, as



a) earthen wall height = 2m; wall slope = 200%; backslope = 10%
b) earthen wall height = 2m; wall slope = 200%; flat surface
c) earthen wall height = 2m; wall slope = 200%; forward slope = 10%
d) combination 2m rock wall and 1m earthen bank; forward slope = 15%

Fig. 8.-- Maximum Width According to Terrace Design

illustrated by lines b and c, respectively. The Valles Altos design is provided for comparative purposes; in this case, the two meter high rock wall is combined with a one meter high earthen bank, and the final slope is fifteen percent. It should be clear that the two systems are not directly comparable. The Valles Altos method is probably superior from the point of view of long-term soil conservation, but it does not provide for an immediate and dramatic increase in water retention and thus potential gains in yields as does the AID method used in Peru and Guatemala (backsloped or flat).

Conclusion

Under certain circumstances, the controlled erosion method of terrace construction used in the Valles Altos region of Venezuela has a number of advantages over the single-effort method used in the AID projects in Peru and Guatemala. In general, the advantages of the controlled erosion method exists in those areas where: 1) there is a relatively large amount of rock on the surface of the field; 2) the removal of the rock from the field is desirable as a means of increasing the cultivation surface and/or manageability of the field; and 3) the desired reduction in slope is relatively modest.[1]

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[1] The break-even point for labor requirement between the controlled erosion and single-effort methods, based on values selected for soil and labor conditions used in this paper, is about 25 %. That is, if a final level terrace is desired, a slope of more than 25 % could be terraced with less labor using the single-effort method. If a final slope on the terraced surface of 10 % is desired, then the advantages of reduced labor for the controlled erosion method would be limited to slopes of less than 35 %. The break-even point for labor requirement is, of course, dependent upon local soil and labor conditions.

In those cases where the three conditions are met, the controlled erosion method can be used to construct terraces that are wider and more stable, and can thereby better accommodate the use of animal or machine traction. If strong rock walls are incorporated into the design, as they were in the Valles Altos project, the system can be expected to survive most extreme environmental events; if properly maintained, the terraces can be considered an almost permanent feature on the landscape. Moreover, terraces can be constructed using the controlled erosion method with less labor.

The controlled erosion method of terrace construction will not produce an immediate major decrease in slope. In most cases, controlled erosion will not produce a level surface at all unless a second stage effort is undertaken at some future date. Nevertheless, the land need not be level to achieve adequate control of erosion. The amount of soil that can erode over or through a well-build and maintained retaining wall is insignificant.

The amount of labor required to build terraces that are sufficiently wide and stable to accommodate animal or machine traction will be extremely high or even prohibitive if the single-effort method of construction is used. Under such circumstances the controlled erosion method may be the only viable option for terrace construction. Even in those areas where hand labor is used to cultivate the soil, the construction of wider and more stable cultivation surfaces with the controlled erosion method may pay important conservation dividends. Conservation requires the preservation of soil resources for the use of future generations of farmers. The system should therefore be

prepared to accommodate the farming methods a future generation is likely to use. Any terracing system that does not meet the needs of farmers in the future is not likely to survive. A future reduction in the farm population or land redistribution could substantially increase the median farm size in most Latin American countries. This could make small terraces suitable only for hand labor obsolete.

The controlled erosion method will not result in an immediate major reduction in slope, and hence will not provide the immediate benefits of a leveled surface (such as increased absorption of water). In those cases where physically leveling the land is cost-effective in terms of higher yields, the economic benefits of the single-effort system may outweigh the longer-term conservation advantages of the controlled erosion method, even if the final terrace is too small and fragile to accommodate a future change in the farming system. However, it should be clear that programs aimed at leveling the land, as opposed to building retaining walls, should be justified primarily on the grounds of productivity and income gains, not soil conservation.

Lynden S. Williams

PLATE 9

Photo 25. Farmer points to the top of his field 10 years previous about 1.5 m above the present cultivation surface in the Valles Altos region of Venezuela.

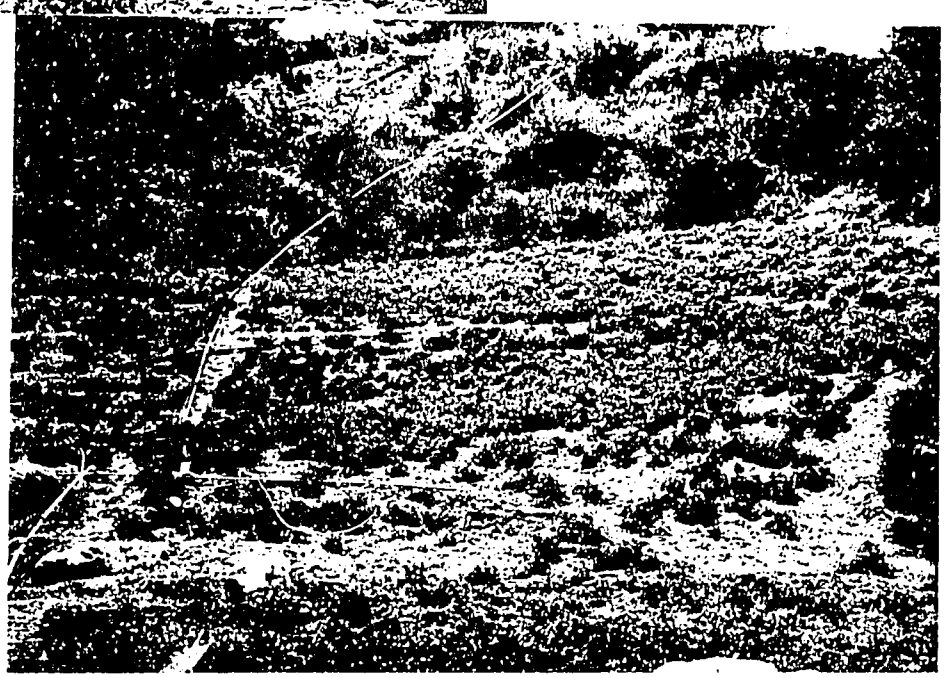


Photo 26. Field pictured in photo above. Note two terraces beginning to form.

Photo 27. Semi-terraces that have evolved in response to cultivation on steep slopes called pata-pata fields in Peru.

Photo 28. A near level terrace that has evolved in response to cultivation on steep slopes.

Photo 29. Old *pata-pata* field in Peru that has been formalized into terrace. Pictured is Ing. Mario Dueñas of the Cuzco field office.

Photo 30. Informal terraces in Peru that have been partially formalized because of canal irrigation. Pictured is team member Dr. Bob J. Walter (canal is to his left).

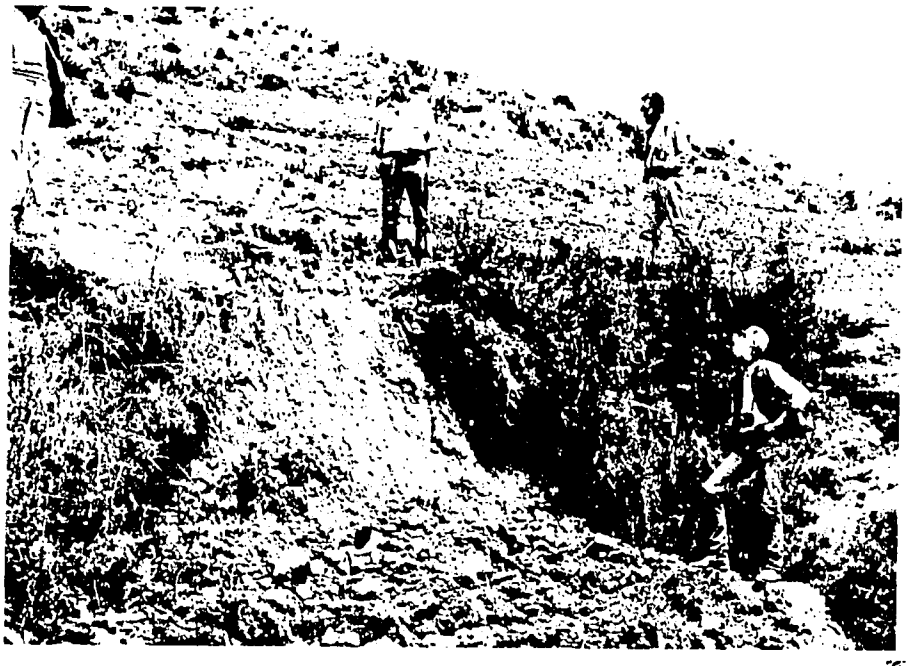


Photo 31. Failure of earthen wall on informal terrace in Peru.

Photo 32. Example of an Inca retaining wall in the Calca valley region of Peru. This example is exceptionally high and approximately vertical.

Photo 33. Additional example of Inca terraces near Zurite (Anta Valley, Cuzco). Note the deterioration of rock retaining walls. These terraces are irrigated by canal and worked with oxen.

PLATE 12

Photo 34. Example of earthen wall supplement at the bottom of the rock retaining wall. Pictured are Ing. Ramón Pérez and Ing. Rosalba Rodríguez of the Valles Altos Program.

Photo 35. Example of maintaining relatively steep slope between retaining walls in Venezuela. Note jeep on terraced field. Team member Leslie Cooperband interviews a farmer.

Photo 36. Example of maintaining a steep slope behind retaining wall by upslope (hand) plowing. Note that the field is covered with crop residue for protection against sheet erosion (during winter fallow), in Shikoku, Japan.

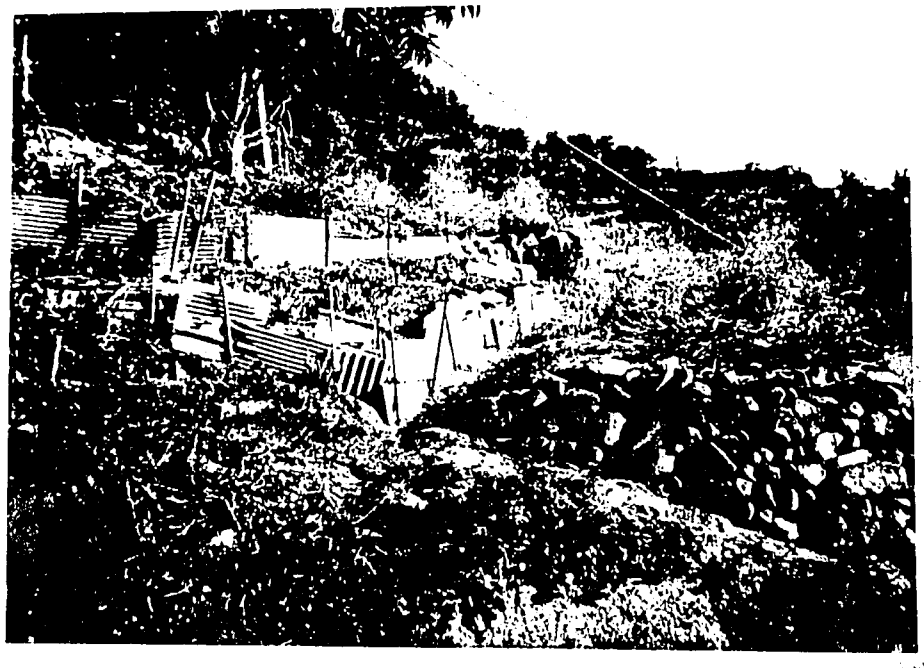


Photo 37. Example of the use of temporary materials for retaining wall in Ogijima, Japan.

Photo 38. Example of the use of temporary materials for retaining wall in the Quetzaltenango region of Guatemala.

ANNEX 2

Terrace Retaining Wall Construction

The Art of Building Rock Walls

The construction of rock retaining walls for agricultural terraces is not a "lost art." Terrace construction is relatively rare in Latin America today, but it is by no means unknown. The research team observed the construction of agricultural terraces in Peru just a few kilometers from Lima (Photo 39). In this case there were no subsidy payments or participation by public authorities. The high value of the land for intensive horticulture, because of the accessibility to the Lima market, and the extreme slope conditions, were sufficient motivation for agricultural terrace construction. The tradition of wall construction has also survived in the form of building foundations for houses and other buildings and for erosion control in connection with road maintenance.

The Valles Altos project in Venezuela is proof that some farmers know how to build strong rock retaining walls, and proof that most other farmers can be trained to build them if properly instructed and motivated. Agricultural terraces have already survived for ten to twenty years in that project, and they appear to be viable for many decades to come.

If not a "lost art," rock wall construction definitely is an

art. It is a skill acquired through trial and error over the years, or one that is learned under the direction of a maestro or expert. It is most unlikely that AID or local university trained Ministry of Agriculture personnel will know the art of rock wall construction, and they may not even appreciate the importance of technique and design for long-term stability of retaining walls. When rock walls are a part of terrace construction, project officials should retain the services of a local expert to act as an advisor and teacher in the project area.

The local expert is preferable for several reasons. First, a local person is more likely to be cognizant of rock and subsoil conditions in the area, and be aware of the potential impact of infrequent major storms. Second, he is more likely to share the language and cultural characteristics of the people he will work with, and thereby be better able to communicate with them. Third, the services of a local builder can usually be obtained at minimum cost; for the most part such persons are farmers like their neighbors who command little additional remuneration beyond the standard rural wage for their work.

The material presented below is not intended as a substitute for the knowledge and instruction of a local rock wall expert. It can, however, be used as a general framework within which retaining walls can be evaluated. In addition, some of the techniques noted may not be known to local builders. For example, the arch was unknown in pre-Colombian America, and is rarely used by traditional farmers today.

Pressure on Retaining Wall

The force, or pressure, on the retaining wall is a function of the weight of the material behind the wall (per unit of area) and inversely proportional to the relative horizontal friction of that material. The weight of the material increases with depth so that pressure would tend to be maximum at the base of the wall and would be directly related to wall height. Waterlogging would increase the weight, and therefore increases the danger of failure. When relatively large textured material is retained, the increased porosity, along with high porosity of the retaining wall in which no cementing materials is used, would tend to reduce that danger. By contrast, silt and clay are less porous and may tend to clog the spaces between rocks in the retaining wall.

However, porosity is not the only, and maybe not the most important, advantage of large textured materials behind the wall. The increased texture increases the internal friction of the material, which shifts pressure downward, rather than horizontally toward the retaining wall. If the friction is minimum, as it would be if the retained material is in a liquid state, the horizontal pressure is equal to the downward pressure (pressure in a liquid is equal in all directions). If the friction is maximum, as in the case of solid rock, all pressure is downward (and, of course, no retaining wall is required). In the case of soil, friction increases from clay to silt to sand to gravel to large rocks.

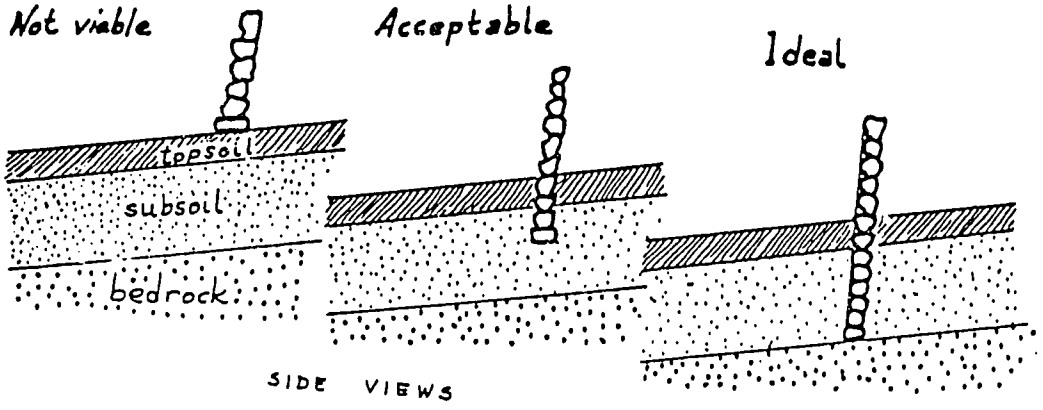
Because the lower one-third to one-half of the retaining wall will probably be backed by subsoil, which will tend to be

made up of relatively larger textured materials, the maximum pressure will probably not be at the base of the wall (as it would be if the material were homogeneous). The danger point is more likely to be near the mid-point from the base to the top of the wall. At or near the mid-point of the wall there will be a substantial weight of material being retained, and the relatively finer texture of the material is likely to result in decreased friction, and hence increased horizontal pressure on the wall.

Wall Foundation

A stable rock wall must have a firm foundation on bedrock or at least deep in the subsoil. The excavation of a foundation trench well below the topsoil is essential. Even a well built wall can only be as strong as the material it rests on.

The required depth of a foundation trench will vary with subsoil conditions. The depth required to reach the subsoil is the absolute minimum; in no case could a wall built over topsoil be expected to support the weight of a substantial amount of fill for more than a few years (Fig. 9). In the Valles Altos design, a foundation trench one-half meter below the surface appears to have been sufficient under conditions in that region. In the single-effort design, one-half meter or more of subsoil is removed from the front of each wall location to provide fill behind the wall below. Thus, no additional excavation for a foundation would be required.



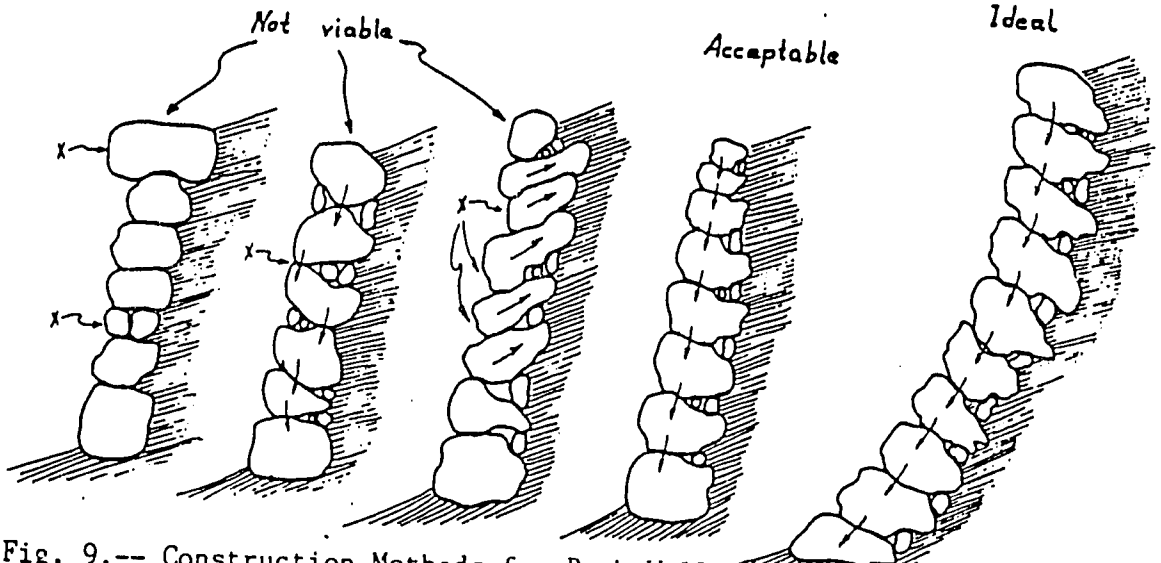


Fig. 9.-- Construction Methods for Rock Walls (side view).

Placement of Rock in Wall

A number of similarities in the method of building walls can be noted between walls built in Venezuela, Inca walls, and walls built in Japan. Similarities between Inca and Venezuela systems might be explained by diffusion. The fact that many of the same techniques are used in Japan (and probably in many other regions of the world) suggests, however, that trial and error has led many people to similar conclusions regarding the best method. In the case of Japan, wall design has been studied by soil engineers and thereby refined and improved. Most of the material presented below is based on the Japanese method.

When possible rock size should be uniform throughout the wall. If rock size varies, it should be graduated from larger to smaller with height in the wall; very large rocks should always be placed at the base of the wall. Rocks should be placed with a smooth face toward the outside, and angled down, into the slope (Fig. 9). Perhaps the most difficult aspect of wall construction is maintaining the proper point of contact between rocks within the wall. Rocks should be placed so that the plane of contact is even throughout the wall. Small rocks can be used to hold those rocks making up the main wall in place.

A maximum of large textured material should be placed behind the wall. Rock and gravel, when available, or at least sandy material, will increase the porosity behind the wall and tend to shift the force of the weight downward and away from the retaining wall. Material excavated from the foundation trench should be thrown upslope. The location behind the wall is the only convenient place to bury subsoil, and the subsoil is more

likely to be made up of rocky material.

The wall itself should be arched vertically (Photo 40). At the bottom, the wall should be angled into the slope at from fifty to 100 percent; the slope of the wall should increase with height to the top where it is approximately vertical. The arched design will shift the pressure from the middle portion of the wall, where it will tend to be greatest, downward throughout the remainder of the wall (just as an arched bridge will shift the weight horizontally throughout the arch). This technique was apparently unknown to Inca stone masons and was not observed in the Valles Altos project. However, the arched wall is common practice in Japan. The technique requires some skill, but little or no additional work; the result is a substantially stronger wall.

When possible, the wall should also be arched horizontally as well (Photo 41). This design is the easiest and most obvious model for the interior of small valleys. Along more even slopes a slight horizontal arch is advisable for added strength. However, the advantage of a straight wall, and hence a more uniform cultivation surface, may outweigh the advantage of added strength. Over the crown of a small ridge or hill, the farmer is forced to accept a wall curved outward (Photo 42). The result is a distinctly inferior wall. An effort should be made to compensate somewhat by increasing the degree of vertical arch in the wall, the size of the rocks, and the porosity of the material behind the wall. The farmer should also be aware that additional maintenance will probably be required in such cases.

Rocks should not be stacked up into a series of side-by-side columns (Fig. 10). Each rock should be placed so that it is centered over the seam of two rocks below it. In Japan, when rock size and uniformity permits, rocks are laid in alternating rows angled first left and then right (Fig. 10: also see Photo 43). This method is almost always used when river rock (rounded rocks) are used to build the wall.

If the erosion method is used to fill behind retaining walls, they will have to be free-standing for a period of time. Therefore, it will be necessary to build a double wall with a strong face on the uphill, as well as downhill, side. The Valles Altos design has been described previously. A similar double wall is used in Japan in cases where it is expected to be free-standing (Photo 44). The area between the inner and outer walls is filled with rock debris. Apparently, there is no attempt to tie the two walls together (by lacing long rocks between the walls as in the construction of a double brick wall). Builders in both Venezuela and Japan suggested that double walls should not be tied by interlacing. One suggested reason was that the independent walls are more flexible during earthquake.

Wall Maintenance

No terrace system is maintenance free. Therefore, provision for terrace maintenance should be build into the project from the outset. The amount and frequency of maintenance is, of course, dependent upon the quality of the work, and on the height of the retaining walls and environmental conditions. Some well-built Inca stone walls have stood from 600 to 1,000 years, and in some

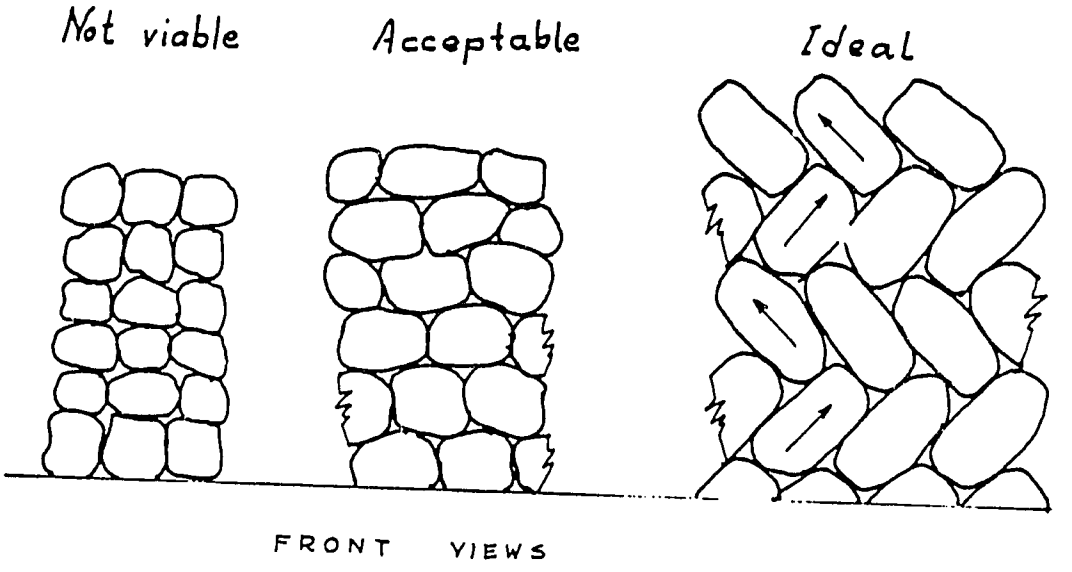


Fig. 10.-- Construction Methods for Rock Walls (front view).

cases they appear to receive very little maintenance (see for example Photo 32). When walls are poorly constructed, or constructed with inadequate materials, minor maintenance is usually needed annually and major repairs are frequently required.

There is an obvious trade-off between building and maintenance costs. The better the job is done in the first place, the less labor will be required for maintenance later. The decision to invest more (or less) labor in construction in hopes of reducing (or willingness to accept higher) maintenance costs must be based on local social and environmental conditions. In Ogijima, Japan, rock suitable for wall construction is not available on the fields. Therefore, farmers are forced to either bring rock in from other areas with consequent higher costs, or make use of small, inadequate rocks and rebuild the walls periodically (Photo 45 & 46). In the Yawatahama region of Shikoku the high price of citrus in the late 1950's led many farmers to bulldoze terraces into steep slopes. Most have since been replaced by rock retaining walls, but those earthen walls that remain are badly eroded so that production is low and some trees have been lost (Photo 47). The result of the farmer's decision on investment in construction versus investment in maintenance can be summed up by the old adage "you can pay me now, or pay me later."

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PLATE 14

Photo 39. Terraces built near Lima without public support or direction are used for intensive horticulture.

Photo 40. Rock retaining walls in Shikoku, Japan are about 3 m high and arched both vertically and horizontally; they require little maintenance. Note stone stairway built into wall.

Photo 41. Note the horizontal arch built into the design: Shikoku, Japan.

Photo 42. Walls are arched down, rather than upslope on a small ridge; additional wall maintenance and failure is expected here.

Photo 43. Note the sequential reversal of rock angle and decreasing size from bottom to top: example from Shikoku, Japan.

Photo 44. Free-standing double rock wall in Megijima, Japan. Note the use of rock debris fill between the two walls as in the Valles Altos project. This example is a sea wall.

PLATE 16

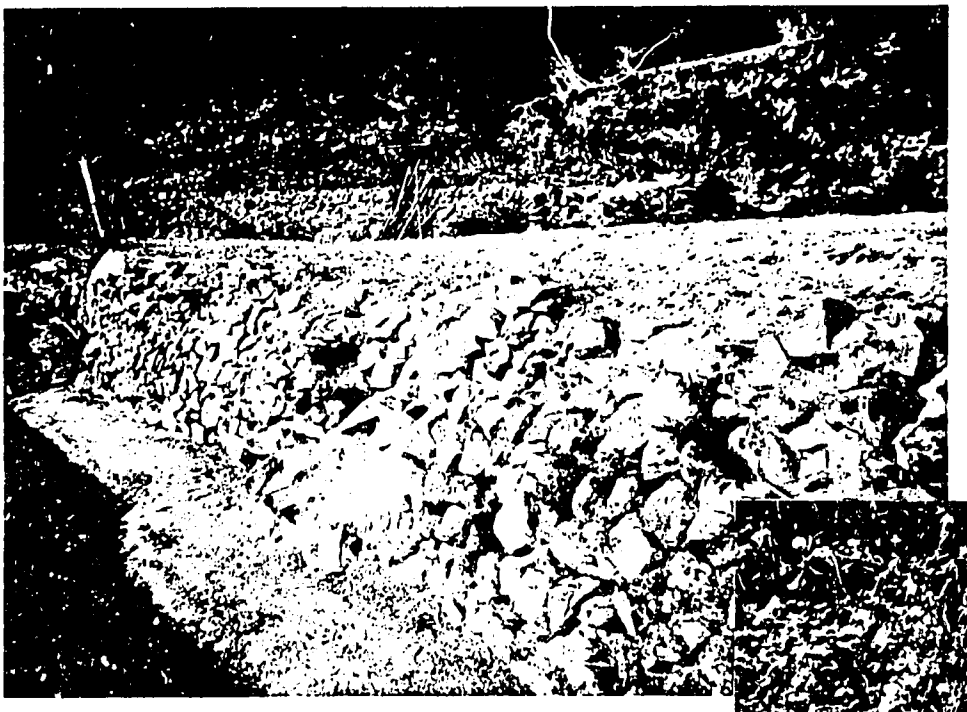

Photo 45. Ogijima, Japan: with little suitable rock in the soil, farmers must either bring rock from great distances or use small stones and make periodic repairs (as in this case).

Photo 46. Note erosion at base is beginning to undermine the wall: Ogijima, Japan. These terraces are used for intensive horticulture.

Photo 47. Earthen-walled terraces were bulldozed into slopes. Most have now been rebuilt with rock. Most others are now badly eroded, as in this case.

ANNEX 3

Programming for Terrace Dimenisions and Construction

All programming was done in Basic (NEC N-88) and can be used, or easily adapted, for any computer system, including most hand-held models. The user should set the values for constants and other constraints according to empirical observation in specific field sites. With minor modifications. the program for work requirement can be adjusted to local conditions and provide estimates in terms of man-days of labor.

Program 1: Terrace surface and retaining wall dimenisions (output from program shown in Table 1).

Program 2: Work requirement according to terrace design and slope (as shown in Figs. 4 and 6).

1) Tables 2 - 5: Output from Program 2 with data presented in Fig. 4.
2) Tables 6 - 9: Output from Program 2 with data presented in Fig. 6.

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Program 1.— Calculates Cultivation Surface According to Slope and Type of Retaining Wall.

```
10 REM program determines surface area of terrace according to slope and retaini
ng wall design.
20 REM set slope of wall type 1 and type 2 in percent
30 WW1=200:WW2=750
40 WW1=1/(WW1/100):WW2=1/(WW2/100)
50 LPRINT "          TABLE 1.-- CULTIVATION SURFACE BY SLOPE AND TYPE OF RETAINING
                         WALL (in sq.M. per hectare of land terraced)
60 LPRINT
70 LPRINT
80 LPRINT "                        ROCK WALL DESIGN                    EARTHEN WALL DESIG
N"
90 LPRINT "                VERTICAL WALL       750% WALL                    200% WALL "
100 LPRINT
110 LPRINT "         % S.  SURFACE  %CHG    SURFACE  %CHG    SURFACE  %CHG    RET. WALL
  TOTAL"
120 LPRINT
130 S = 0
140 S = S + .1
150 REM set value for maximum slope in table as a percent
160 IF S > (130/100) THEN END
170 X=1/S:B=10000*COS(ATN(S))
180 A=B/X
190 BASE = B:WALL = A:TOT = (A+B)
200 DIF= BASE/100 -100
210 B1=B-WW1*A:A1=SQR((WW1*A)^2+A^2)
220 B2=B-WW2*A:A2=SQR((WW2*A)^2+A^2)
230 BASE1 = B1:WALL1=A1
240 DIF1=BASE1/100-100
250 BASE2 = B2:WALL2=A2
260 DIF2=BASE2/100-100
270 AREA = BASE + WALL :AREA1 = BASE1 + WALL1
280 AREA2 = BASE2 + WALL2
290 LPRINT USING "##########    ####  ###.#     ####  ###.#     ####  ###.#
####    #####";S*100,BASE,DIF,BASE2,DIF2,BASE1,DIF1,WALL1,AREA1
300 LPRINT
310 GOTO 140
320 END
```

Program 2.-- Calculates Work Requirement According to Terrace Design

```
10 REM set density values
20 D1=1.25:D2=1.75:D3=2.75
30 REM set subsoil depth, compactness, single wall width, volume of foundation t
rench and double wall per m
40 K1= .3:K2=1:K3=.3:K4=.6:K5=2
50 REM set work ratio for moving material and building wall, and total area in s
q. m
60 F1=.2:F2=2:A=10000
70 REM set absolute height limites for earthen wall and rock wall
80 H1=2:H2=3!
90 REM input slope as a percent
100 INPUT "SLOPE =  ";S:S=S/100
110 REM input slope desired on final terrace; use negative values for backslope
120 INPUT "DESIRED TERRACE SLOPE =  ";Z:Z=Z/100
130 S=S-Z
140 REM input minimum terrace width
150 W= 2
155  LPRINT "        OUTPUT FROM PROGRAM 2":LPRINT
160  LPRINT "     Original slope of the land is "(S+Z)*100"%.  Final terrace slo
pe is "Z*100"%.":LPRINT
170 LPRINT "            Reduction in slope achieved by terrac  is "(S)*100"%."
180  LPRINT:LPRINT:LPRINT
190  LPRINT "          Single-Effort Method      Cont. Eros. method          Tota
ls "
200 LPRINT
210  LPRINT "     width soil rock  build subs.  exc.  rock  build     # 1     #
2     # 3"
220 LPRINT
230 TS=(K1*D1*A)/1000:MR=(K3*D3*A*S+.5*K3*D3*F1*A*S*W)/1000
240 B=(K3*D3*F2*A*S)/1000
250 MS=(.125*D2*A*S*W+.083375*K2*D2*F1*A*S*W^2)/1000
260 EX=(K2*K4*D2*A/W)/1000:RR=(K5*D3*A/W)/1000
270 MM=(K5*D3*A/W+.5*K5*D3*F1*A)/1000:BB=(K5*D3*F2*A/W)/1000
280 T=TS+MR+MS+B:TT=EX+MM+BB:TA=TS+MS
290 H=W*S:IF H < H1 THEN 350
300 IF H < H2 THEN 330
310 LPRINT USING "      ### ###.# ###.# ###.# ###.# ###.#  ###.#  ###.#  ####.#&
&###.#& &###.#& &";W,TS,MR,B,MS,EX,MM,BB,T"*",TT"*",TA"*"
320 GOTO 360
330 LPRINT USING "      ### ###.# ###.# ###.# ###.# ###.#  ###.#  ###.#  ####.#
 ###.#   ###.#& &";W,TS,MR,B,MS,EX,MM,BB,T,TT,TA"*"
340 GOTO 360
350 LPRINT USING "      ### ###.# ###.# ###.# ###.# ###.#  ###.#  ###.#  ####.#
 ###.#   ###.# ";W,TS,MR,B,MS,EX,MM,BB,T,TT,TA
360 LPRINT
370 W = W + 1
380 REM set maximum terrace width
390 IF W > 15  THEN 410
400 GOTO 230
410 LPRINT
420 LPRINT "NOTES: System #1 is the single-effort method with rock retaining wal
ls;"
430 LPRINT "        System #2 is the controlled erosion method;"
440 LPRINT "        System #3 is the single-effort with earthen retaining walls m
ethod."
450 LPRINT "       Asterisks (*) indicates design exceeds the absolute limits on
terrace"
455 LPRINT "              height, assumed to be"H1"m for earthen, and"H2"m for ro
ck walls."
460 END
```

Table 2.-- Labor requirement (in ton-meters) to remove and replace topsoil (soil), move rock to wall site (rock), build wall (build), level subsoil (subs.), and excavate foundation trench for the wall (exc.), by terrace width, according to the method used in construction (15% example in Fig. 4, calculated with program 2).

Original slope of the land is 15 %. Final terrace slope is 0 %.

Reduction in slope achieved by terrace is 15 %.

	Single-Effort Method				Cont. Eros. method			Totals		
width	soil	rock	build	subs.	exc.	rock	build	# 1	# 2	# 3
2	3.8	1.5	2.5	0.8	5.3	33.0	55.0	8.5	93.3	4.6
4	3.8	1.7	2.5	2.0	2.6	19.3	27.5	10.0	49.4	5.8
6	3.8	2.0	2.5	3.5	1.8	14.7	18.3	11.7	34.8	7.3
8	3.8	2.2	2.5	5.4	1.3	12.4	13.8	13.9	27.4	9.2
10	3.8	2.5	2.5	7.7	1.1	11.0	11.0	16.4	23.1	11.4
12	3.8	2.7	2.5	10.2	0.9	10.1	9.2	19.2	20.1	14.0
14	3.8	3.0	2.5	13.2	0.8	9.4	7.9	22.4	18.0	16.9*
16	3.8	3.2	2.5	16.5	0.7	8.9	6.9	25.9	16.5	20.2*
18	3.8	3.5	2.5	20.1	0.6	8.6	6.1	29.8	15.3	23.8*
20	3.8	3.7	2.5	24.1	0.5	8.3	5.5	34.0	14.3	27.8*
22	3.8	4.0	2.5	28.4	0.5	8.0	5.0	38.6*	13.5*	32.2*
24	3.8	4.2	2.5	33.1	0.4	7.8	4.6	43.5*	12.8*	36.8*
26	3.8	4.5	2.5	38.1	0.4	7.6	4.2	48.8*	12.3*	41.9*
28	3.8	4.7	2.5	43.5	0.4	7.5	3.9	54.4*	11.8*	47.3*
30	3.8	5.0	2.5	49.2	0.4	7.3	3.7	60.4*	11.4*	53.0*

NOTES: System #1 is the single-effort method with rock retaining walls;
System #2 is the controlled erosion method;
System #3 is the single-effort with earthen retaining walls.
Asterisks (*) indicates design exceeds the absolute limits on wall height, assumed to be 2 m for earthen, and 3 m for rock walls.

Table 3.-- Labor requirement (in ton-meters) to remove and replace topsoil (soil), move rock to wall site (rock), build wall (build), level subsoil (subs.), and excavate foundation trench for the wall (exc.), by terrace width, according to the method used in construction (25% example in Fig. 4, calculated with program 2).

Original slope of the land is 25 %. Final terrace slope is 0 %.

Reduction in slope achieved by terrace is 25 %.

	Single-Effort Method				Cont. Eros. method			Totals		
width	soil	rock	build	subs.	exc.	rock	build	# 1	# 2	# 3
2	3.8	2.5	4.1	1.4	5.3	33.0	55.0	11.7	93.3	5.1
4	3.8	2.9	4.1	3.4	2.6	19.3	27.5	14.1	49.4	7.1
6	3.8	3.3	4.1	5.9	1.8	14.7	18.3	17.1	34.8	9.7
8	3.8	3.7	4.1	9.0	1.3	12.4	13.8	20.6	27.4	12.6
10	3.8	4.1	4.1	12.6	1.1	11.0	11.0	24.8	23.1	16.5*
12	3.8	4.5	4.1	17.1	0.9	10.1	9.2	29.5	20.1	21.8*
14	3.8	5.0	4.1	22.0	0.8	9.4	7.9	34.8*	18.0*	25.7*
16	3.8	5.4	4.1	27.4	0.7	8.9	6.9	40.7*	16.5*	31.2*
18	3.9	5.8	4.1	33.5	0.6	8.6	6.1	47.1*	15.3*	37.2*
20	3.8	6.2	4.1	40.1	0.5	8.3	5.5	54.2*	14.3*	43.4*
22	3.8	6.6	4.1	47.3	0.5	8.0	5.0	61.8*	13.5*	51.1*
24	3.8	7.0	4.1	55.1	0.4	7.8	4.6	70.0*	12.8*	58.9*
26	3.8	7.4	4.1	63.5	0.4	7.6	4.2	78.8*	12.3*	67.3*
28	3.8	7.8	4.1	72.5	0.4	7.5	3.9	88.2*	11.8*	75.3*
30	3.8	8.3	4.1	82.1	0.4	7.3	3.7	98.2*	11.4*	85.8*

NOTES: System #1 is the single-effort method with rock retaining walls;
System #2 is the controlled erosion method;
System #3 is the single-effort with earthen retaining walls.
Asterisks (*) indicates design exceeds the absolute limits on wall height, assumed to be 2 m for earthen, and 3 m for rock walls.

Table 4.-- Labor requirement (in ton-meters) to remove and replace topsoil (soil), move rock to wall site (rock), build wall (build), level subsoil (subs.), and excavate foundation trench for the wall (exc.), by terrace width, according to the method used in construction (35% example in Fig. 4, calculated with program 2).

Original slope of the land is 35 %. Final terrace slope is 0 %.

Reduction in slope achieved by terrace is 35 %.

	Single-Effort Method				Cont. Eros. method			Totals		
width	soil	rock	build	subs.	exc.	rock	build	# 1	# 2	# 3
2	3.8	3.5	5.8	1.9	5.3	33.0	55.0	14.9	93.3	5.7
4	3.8	4.0	5.8	4.7	2.6	19.3	27.5	18.3	49.4	8.4
6	3.8	4.6	5.8	8.3	1.8	14.7	18.3	22.4	34.8	12.0*
8	3.8	5.2	5.8	12.7	1.3	12.4	13.8	27.4	27.4	16.4*
10	3.8	5.8	5.8	17.9	1.1	11.0	11.0	33.2*	23.1*	21.6*
12	3.8	6.4	5.8	23.9	0.9	10.1	9.2	39.8*	20.1*	27.6*
14	3.8	6.9	5.8	30.7	0.8	9.4	7.9	47.2*	18.0*	34.5*
16	3.8	7.5	5.8	38.4	0.7	8.9	6.9	55.4*	16.5*	42.1*
18	3.8	8.1	5.8	46.9	0.6	8.6	6.1	64.5*	15.3*	50.6*
20	3.8	8.7	5.8	56.2	0.5	8.3	5.5	74.4*	14.3*	59.9*
22	3.8	9.2	5.8	66.3	0.5	8.0	5.0	85.0*	13.5*	70.0*
24	3.8	9.8	5.8	77.2	0.4	7.8	4.6	96.5*	12.8*	81.0*
26	3.8	10.4	5.8	88.9	0.4	7.6	4.2	108.9*	12.3*	92.7*
28	3.8	11.0	5.8	101.5	0.4	7.5	3.9	122.0*	11.8*	105.3*
30	3.8	11.6	5.8	114.9	0.4	7.3	3.7	136.0*	11.4*	118.6*

NOTES: System #1 is the single-effort method with rock retaining walls;
System #2 is the controlled erosion method;
System #3 is the single-effort with earthen retaining walls.
Asterisks (*) indicates design exceeds the absolute limits on wall height, assumed to be 2 m for earthen, and 3 m for rock walls.

Table 5.-- Labor requirement (in ton-meters) to remove and replace topsoil (soil), move rock to wall site (rock), build wall (build), level subsoil (subs.), and excavate foundation trench for the wall (exc.), by terrace width, according to the method used in construction (45% example in Fig. 4, calculated with program 2).

Original slope of the land is 45 %. Final terrace slope is 0 %.

Reduction in slope achieved by terrace is 45 %.

	Single-Effort Method				Cont. Eros. method			Totals		
width	soil	rock	build	subs.	exc.	rock	build	# 1	# 2	# 3
2	3.8	4.5	7.4	2.5	5.3	33.0	55.0	18.1	93.3	5.2
4	3.8	5.2	7.4	6.0	2.6	19.3	27.5	22.4	49.4	9.8
6	3.8	5.9	7.4	10.6	1.8	14.7	18.3	27.7	34.8	14.4*
8	3.8	6.7	7.4	16.3	1.3	12.4	13.8	34.1*	27.4*	20.0*
10	3.8	7.4	7.4	23.0	1.1	11.0	11.0	41.6*	23.1*	26.7*
12	3.8	8.2	7.4	30.7	0.9	10.1	9.2	50.1*	20.1*	34.5*
14	3.8	8.9	7.4	39.5	0.8	9.4	7.9	59.6*	18.0*	43.3*
16	3.8	9.7	7.4	49.4	0.7	8.9	6.9	70.2*	16.5*	53.1*
18	3.8	10.4	7.4	60.3	0.6	8.6	6.1	81.8*	15.3*	64.0*
20	3.8	11.1	7.4	72.2	0.5	8.3	5.5	94.5*	14.3*	76.0*
22	3.8	11.9	7.4	85.2	0.5	8.0	5.0	108.3*	13.5*	89.0*
24	3.8	12.6	7.4	99.3	0.4	7.8	4.6	123.1*	12.8*	103.0*
26	3.8	13.4	7.4	114.4	0.4	7.6	4.2	138.9*	12.3*	118.1*
28	3.8	14.1	7.4	130.5	0.4	7.5	3.9	159.8*	11.8*	134.3*
30	3.8	14.9	7.4	147.7	0.4	7.3	3.7	173.7*	11.4*	151.5*

NOTES: System #1 is the single-effort method with rock retaining walls;
System #2 is the controlled erosion method;
System #3 is the single-effort with earthen retaining walls.
Asterisks (*) indicates design exceeds the absolute limits on wall height, assumed to be 2 m for earthen, and 3 m for rock walls.

Table 6.-- Labor requirement (in ton-meters) to remove and replace topsoil (soil), move rock to wall site (rock), build wall (build), level subsoil (subs.), and excavate foundation trench for the wall (exc.), by terrace width, according to the method used in construction (5% slope reduction example in Fig. 6).

Original slope of the land is 25 %. Final terrace slope is 20 %.

Reduction in slope achieved by terrace is 5 %.

	Single-Effort Method				Cont. Eros. method			Totals		
width	soil	rock	build	subs.	exc.	rock	build	# 1	# 2	# 3
10	3.8	0.8	0.8	2.6	1.1	11.0	11.0	8.0	23.1	6.3
15	3.8	1.0	0.8	4.9	0.7	9.2	7.3	10.5	17.2	8.7
20	3.8	1.2	0.8	8.0	0.5	8.3	5.5	13.8	14.3	11.8
25	3.8	1.4	0.8	11.9	0.4	7.7	4.4	17.9	12.5	15.6
30	3.8	1.7	0.8	16.4	0.4	7.3	3.7	22.6	11.4	20.2
35	3.8	1.9	0.8	21.7	0.3	7.1	3.1	28.1	10.5	25.5
40	3.8	2.1	0.8	27.7	0.3	6.9	2.8	34.4	9.9	31.5
45	3.8	2.3	0.8	34.5	0.2	6.7	2.4	41.3	9.4	38.2*
50	3.8	2.5	0.8	41.9	0.2	6.6	2.2	49.0	9.0	45.7*
55	3.8	2.7	0.8	50.2	0.2	6.5	2.0	57.4	8.7	53.9*
60	3.8	2.9	0.8	59.1	0.2	6.4	1.8	66.6	8.4	62.8*
65	3.8	3.1	0.8	68.8	0.2	6.3	1.7	76.4*	8.2*	72.5*
70	3.8	3.3	0.8	79.2	0.2	6.3	1.6	87.0*	8.0*	82.9*
75	3.8	3.5	0.8	90.3	0.1	6.2	1.5	98.4*	7.8*	94.0*
80	3.8	3.7	0.8	102.1	0.1	6.2	1.4	110.4*	7.7*	105.9*

NOTES: System #1 is the single-effort method with rock retaining walls;
System #2 is the controlled erosion method;
System #3 is the single-effort with earthen retaining walls.
Asterisks (*) indicates design exceeds the absolute limits on wall height, assumed to be 2 m for earthen, and 3 m for rock walls.

Table 7.-- Labor requirement (in ton-meters) to remove and replace topsoil (soil), move rock to wall site (rock), build wall (build), level subsoil (subs.), and excavate foundation trench for the wall (exc.), by terrace width, according to the method used in construction (15% slope reduction example in Fig. 6).

Original slope of the land is 25 %. Final terrace slope is 10 %.

Reduction in slope achieved by terrace is 15 %.

	Single-Effort Method				Cont. Eros. method			Totals		
width	soil	rock	build	subs.	exc.	rock	build	# 1	# 2	# 3
2	3.8	1.5	2.5	0.8	5.3	33.0	55.0	8.5	93.3	4.6
4	3.8	1.7	2.5	2.0	2.6	19.3	27.5	10.0	49.4	5.8
6	3.8	2.0	2.5	3.5	1.8	14.7	18.3	11.7	34.8	7.3
8	3.8	2.2	2.5	5.4	1.3	12.4	13.8	13.9	27.4	9.2
10	3.8	2.5	2.5	7.7	1.1	11.0	11.0	16.4	23.1	11.4
12	3.8	2.7	2.5	10.2	0.9	10.1	9.2	19.2	20.1	14.0
14	3.8	3.0	2.5	13.2	0.8	9.4	7.9	22.4	18.0	16.9*
16	3.8	3.2	2.5	16.5	0.7	8.9	6.9	25.9	16.5	20.2*
18	3.8	3.5	2.5	20.1	0.6	8.6	6.1	29.8	15.3	23.8*
20	3.8	3.7	2.5	24.1	0.5	8.3	5.5	34.0	14.3	27.8*
22	3.8	4.0	2.5	28.4	0.5	8.0	5.0	38.6*	13.5*	32.2*
24	3.8	4.2	2.5	33.1	0.4	7.8	4.6	43.5*	12.8*	36.8*
26	3.8	4.5	2.5	38.1	0.4	7.6	4.2	48.8*	12.3*	41.9*
28	3.8	4.7	2.5	43.5	0.4	7.5	3.9	54.4*	11.8*	47.3*
30	3.8	5.0	2.5	49.2	0.4	7.3	3.7	60.4*	11.4*	53.0*

NOTES: System #1 is the single-effort method with rock retaining walls;
System #2 is the controlled erosion method;
System #3 is the single-effort with earthen retaining walls.
Asterisks (*) indicates design exceeds the absolute limits on wall height, assumed to be 2 m for earthen, and 3 m for rock walls.

Table 8.-- Labor requirement (in ton-meters) to remove and replace topsoil (soil), move rock to wall site (rock), build wall (build), level subsoil (subs.), and excavate foundation trench for the wall (exc.), by terrace width, according to the method used in construction (25% slope reduction example in Fig. 6).

Original slope of the land is 25 %. Final terrace slope is 0 %.

Reduction in slope achieved by terrace is 25 %.

	Single-Effort Method				Cont. Eros. method			Totals		
width	soil	rock	build	subs.	exc.	rock	build	# 1	# 2	# 3
1	3.8	2.3	4.1	0.6	10.5	60.5	110.0	10.8	181.0	4.4
2	3.8	2.5	4.1	1.4	5.3	33.0	55.0	11.7	93.3	5.1
3	3.8	2.7	4.1	2.3	3.5	23.8	36.7	12.9	64.0	6.0
4	3.8	2.9	4.1	3.4	2.6	19.3	27.5	14.1	49.4	7.1
5	3.8	3.1	4.1	4.6	2.1	16.5	22.0	15.5	40.6	8.3
6	3.8	3.3	4.1	5.9	1.8	14.7	18.3	17.1	34.8	9.7
7	3.8	3.5	4.1	7.4	1.5	13.4	15.7	18.8	30.6	11.2
8	3.8	3.7	4.1	9.0	1.3	12.4	13.8	20.6	27.4	12.8
9	3.8	3.9	4.1	10.8	1.2	11.6	12.2	22.6	25.0	14.6*
10	3.8	4.1	4.1	12.8	1.1	11.0	11.0	24.8	23.1	16.5*
11	3.8	4.3	4.1	14.8	1.0	10.5	10.0	27.0	21.5	18.6*
12	3.8	4.5	4.1	17.1	0.9	10.1	9.2	29.5	20.1	20.8*
13	3.8	4.7	4.1	19.4	0.8	9.7	8.5	32.1*	19.0*	23.2*
14	3.8	5.0	4.1	22.0	0.8	9.4	7.9	34.8*	18.0*	25.7*
15	3.8	5.2	4.1	24.6	0.7	9.2	7.3	37.6*	17.2*	28.4*

NOTES: System #1 is the single-effort method with rock retaining walls;
System #2 is the controlled erosion method;
System #3 is the single-effort with earthen retaining walls.
Asterisks (*) indicates design exceeds the absolute limits on wall height, assumed to be 2 m for earthen, and 3 m for rock walls.

Table 9.-- Labor requirement (in ton-meters) to remove and replace topsoil (soil), move rock to wall site (rock), build wall (build), level subsoil (subs.), and excavate foundation trench for the wall (exc.), by terrace width, according to the method used in construction (35% slope reduction example in Fig. 6).

Original slope of the land is 40 %. Final terrace slope is 5 %.

Reduction in slope achieved by terrace is 35 %.

	Single-Effort Method				Cont. Eros. method			Totals		
width	soil	rock	build	subs.	exc.	rock	build	# 1	# 2	# 3
1	3.8	3.2	5.8	0.9	10.5	60.5	110.0	13.6	181.0	4.6
2	3.8	3.5	5.8	1.9	5.3	33.0	55.0	14.9	93.3	5.7
3	3.8	3.8	5.8	3.2	3.5	23.8	36.7	16.5	64.0	7.0
4	3.8	4.0	5.8	4.7	2.6	19.3	27.5	18.3	49.4	8.4
5	3.8	4.3	5.8	6.4	2.1	16.5	22.0	20.2	40.6	10.1
6	3.8	4.6	5.8	8.3	1.8	14.7	18.3	22.4	34.8	12.0*
7	3.8	4.9	5.8	10.4	1.5	13.4	15.7	24.8	30.6	14.1*
8	3.8	5.2	5.8	12.7	1.3	12.4	13.8	27.4	27.4	16.4*
9	3.8	5.5	5.8	15.2	1.2	11.6	12.2	30.2*	25.0*	18.9*
10	3.8	5.8	5.8	17.9	1.1	11.0	11.0	33.2*	23.1*	21.6*
11	3.8	6.1	5.8	20.8	1.0	10.5	10.0	36.4*	21.5*	24.5*
12	3.8	6.4	5.8	23.9	0.9	10.1	9.2	39.8*	20.1*	27.6*
13	3.8	6.6	5.8	27.2	0.8	9.7	8.5	43.4*	19.0*	31.0*
14	3.8	6.9	5.8	30.7	0.8	9.4	7.9	47.2*	18.0*	34.5*
15	3.8	7.2	5.8	34.5	0.7	9.2	7.3	51.2*	17.2*	38.2*

NOTES: System #1 is the single-effort method with rock retaining walls;
System #2 is the controlled erosion method;
System #3 is the single-effort with earthen retaining walls.
Asterisks (*) indicates design exceeds the absolute limits on wall height, assumed to be 2 m for earthen, and 3 m for rock walls.

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