Hedgerows and Their Effects on Crop Productivity and Soil Loss Induced by Water and Tillage Erosion on Small Runoff Plots in the El Pital Watershed, Nicaragua

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Cover Photos:

1) Dr. Larry Wilding (center) teaches a soil management workshop at La Lucha.

2) Don Felix prunes the hedgerows at La Lucha.

Hedgerows and Their Effects on Crop Productivity and Soil Loss Induced by Water and Tillage Erosion on Small Runoff Plots in the El Pital Watershed, Nicaragua

Preface

The effect of water-induced soil erosion on the steep slopes of Nicaragua's El Pital Watershed has been studied for several years. In 1994, CARE (Cooperative for Assistance and Relief Everywhere, Inc.) and UNA (Universidad Nacional Agraria) began a 3-year collaborative study to evaluate the sustainability of corn and bean production on the steeplands. Researchers focused on conservation tillage, mulching, fertilizer, and seeds. They established several soil management systems on small runoff plots. All plots were equipped with instruments to measure surface runoff water and soil removed in the runoff water (water-induced soil erosion). No attempt was made to evaluate the movement of soil downslope caused by tillage.

The CARE-UNA collaborative project terminated in 1997, but the runoff plots were maintained. In 1998, the Steeplands component of the U.S. Agency for International Development-sponsored Soil Management Collaborative Research Support Program (CRSP), in cooperation with research faculty at UNA, began a new project to evaluate soil erosion at several scales. A portion of this research, the "small plot" scale research, was conducted on the refurbished runoff plots in the El Pital Watershed. This bulletin summarizes most of the information generated on the small runoff plots from 1998 through 2000 as well as the runoff and soil loss data collected from 1995 through 1997.

Objectives

This cooperative study was designed to evaluate water-induced soil erosion, tillage-induced soil erosion, and some of their impacts on crop production on steepland or hillside soils developed from volcanic parent material in the El Pital Watershed in Nicaragua. Small plots similar to those used to develop the Universal Soil Loss Equation (USLE) were used. Specific research objectives were to evaluate:

(a) the effect of conservation tillage, including the use of *Gliricidia sepium* and *Cajanus cajan* hedgerows and commercial fertilizer on corn (*Zea mays*) and bean (*Phaseolus* spp.) production,

(b) the effect of *Gliricidia sepium* and *Cajanus cajan* hedgerows on water-induced erosion on cultivated hillside soils,

(c) the effect of manual tillage on soil translocation, soil flux, and tillage-induced soil erosion, and

(d) the effect of manual tillage and landscape position on infiltration.

Introduction and Overview

Soil erosion in the humid tropics is often severe, especially on tilled hillsides or steepland soils. Surface water runoff and tillage operations cause soil to be transported downslope on sloping lands. Both forms of erosion degrade soil quality and, in some cases, destroy the soil to such a degree that it can no longer be farmed. In Nicaragua, the sustainability of tilled soils on farmed hillsides is a major concern. The terms "hillside" and "steepland" are used interchangeably in this publication. Land on hillsides with slopes greater than 20%—which includes about 44% of the Nicaraguan land—is exposed to potentially erosive tropical climatic conditions for 6 months each year (Barreto, 1996). The importance of these cultivated Nicaraguan hillside soils cannot be overstated because they produce 79% of the country's corn and nearly 100% of its beans and coffee. In addition to crop production, hillsides also have important uses for forestry, animal production, and water resource management.

Young volcanic soils in the Pacific region of Nicaragua are highly productive and intensely cultivated. As a result, the local population has increased dramatically over the past several decades. About 50 years ago, the development of large farms on nearly level land at low elevations resulted in the displacement of farmers to the hillside and steepland areas. The displaced farmers transferred with them the farming methods developed for the soils on flat land. These methods include the use of fire to burn crop residues; the use of oxen-pulled plows for tillage, often plowing up and down slope; and the limited use of pesticides. These newly arrived hillside farmers had no idea of the possible negative effects that some of these management practices might have on the physical and chemical properties of soils on sloping lands. Compared to soils on level land, sloping soils subjected to high intensity rainfall face greater erosion risk. The shallower the soil, the greater the risk for soil degradation due to erosion.

Virtually all soil properties, i.e., physical, chemical, mineralogical, and biological, play an important role in the development and variation in soil productivity. Some soil properties are more susceptible to short-term changes than others. For example, on hillside soils the thickness of topsoil and its soil structure—both important factors affecting root growth—can degrade dramatically in only a few years. This degradation reduces soil productivity.

Soil loss or degradation is usually reflected in lower yields or, if compensating measures are taken, in higher costs for a given yield. In severe cases the ability to grow crops (technically, economically, or both) on a degrading soil can be lost completely. Soil loss rates often are compared against the soil loss tolerance value (T), which is an estimate of the maximum rate of soil erosion that would still allow high crop productivity to be sustained economically and indefinitely (Wischmeier and Smith, 1978). Another approach to evaluating soil degradation is to calculate the cost of replacing nutrients for crop use that have been lost from the soil. Soil productivity indices are usually related to an agricultural (ecological) function of the soil, whereas the concept of "sustainability" takes into account other soil functions (Blum and Santelises, 1994).

Rainfall in the humid tropics often is perceived to be less effective for plant growth than rainfall in temperate regions because tropical rains often are so intense that they give rise to appreciable surface water runoff. Rainfall intensities of up to 150 to 200 mm hr^{-1} have been reported in the humid tropics for durations of 5 to 10 minutes (Hudson, 1971). Water losses by evaporation and transpiration can be high due to high temperatures. Because of favorable day and night temperatures, plant growth rates are generally high, leading to high water consumption. These factors, coupled with shallow plant rooting depths due to shallow soils or adverse subsoil conditions, can lead to droughty conditions within only a few days after a heavy rainfall. Adverse soil conditions often occur due to nutrient deficiencies, toxicities, or inadequate water retention (Vine et al., 1981; Babalola and Lal, 1997).

When Hurricane Mitch devastated large areas of Central America in 1998, the hillsides of Nicaragua lost about 33% of their agricultural soils (MAGFOR, 1999). The El Pital Watershed was moderately affected by the hurricane and received between 600 and 700 mm of rain over 3 days. However, the crop loss was nearly 100% due to excessively wet soil conditions, high humidity, low evapotranspiration rates, and low temperatures following the hurricane.

Traditional farming systems and soil productivity

The traditional agricultural system in Nicaragua's subhumid tropics is subsistence farming. When adequate land is available shifting cultivation or bush-fallow rotations are used, which require few external resources such as pesticides and fertilizers. In some regions, especially on marginal land or steeplands with high population densities, traditional "slash and burn" farming is practiced, which is destructive and promotes soil and environmental degradation. Even periodic cultivation reduces topsoil depth, decreases organic matter content, and causes an accompanying loss in cation exchange capacity and water retention.

The rate of decline in crop yield on soil under traditional farming depends on many factors, e.g., soil properties, crop species, climate, and soil management. Traditionally, when land was plentiful and population was low, farmers reduced land use intensity when crop yields became too low due to pests (weeds, insects, diseases, etc.) or soil degradation (compaction, erosion, loss of fertility). For soils of low inherent fertility, such as those in Nicaragua, yields declined 1 to 2 years after traditional farming began. The traditional system is ecologically stable and works as long as the farmers are willing to remain at the subsistence level. However, a better system is needed both to improve the quality of life of the farmer and to increase food production as the population increases.

Cropping systems

In the El Pital Watershed, grain crops are the primary source of income for small farmers. Livestock production is primarily for milk production. Cattle are fed grass supplemented by roughage from rental pasture or given free access to pasture on nearby fallow land owned by other individuals. Oxen are used for land preparation where possible, and vegetation is cleared using manual labor, herbicides, or fire. Unfortunately, much of the plowing is up and down hill rather than on the contour. Cropping systems are corn (*Zea mays* L.) -bean (*Phaseolus* spp.), corn-bean-cassava (*Manitot esculenta* Crantz), or corn-bean-rice (*Oryza sativa* L.). The corn-bean system is dominant in the El Pital Watershed (Somarriba-Chang et al., 1999).

Land in the hillside area is prepared for corn and bean production in late April and early May. Crops are planted when the *primera* (first rainy season) begins in mid-May. Corn rows are typically spaced 80 cm apart, and two seeds are planted at 30-cm intervals in the row. The rate and timing of fertilization and pesticide application depend on the perceived need and the availability of cash. Weeds are controlled by hoe or with herbicides. Corn is harvested during the *canicula*, the short dry season in mid-July through mid-August. Corn stalks are removed from the field in an attempt to reduce the risk of pest infestations. The stalks are either chopped for livestock feed or piled and burned. After the stalks are removed, the field is plowed and bean is planted at the onset of the *postreron* (second rainy season) in late September or early October. Adjacent bean rows are spaced 40 cm apart, and a hill of two seeds is planted at 30-cm intervals in the row. In some cases an alternate row system is used in which bean and corn rows spaced 80 cm apart alternate. For this system two corn seeds are planted at 30-cm intervals and beans are placed at 20-cm intervals in the row.

Corn yields less than 1,000 kg ha^{-1} are common due to low soil fertility, especially nitrogen deficiency (Talavera, 1989). Low P (phosphorus) availability is often a problem on volcanic soils. If P is low, it can lead to a low response to N fertilization or to no response at all. For N-fixing legumes, P is probably the most important fertilizer nutrient required. In Nicaragua, common bean (*Phaseolus vulgaris*) responds to fertilizer N if it is applied in combination with P fertilizer (Talavera, 1989).

Water-induced soil erosion

Water-induced soil erosion is a fluvial process. The soil transport rate due to surface water runoff is a function of erosivity (the energy of the water) and soil erodibility (physical characteristics, type of slope gradient and slope length, land use, and type of vegetation) (Smith and Wischmeier, 1957). Research in the United States beginning in the 1930s led to the development of the USLE for estimating long-term average water-induced soil losses for different soils subjected to various land uses and soil management levels (Wischmeier and Smith, 1978). The runoff plots were only about 3 m wide, but were assumed to be wide enough to minimize edge or border effects and to include downslope rills (Mutchler et al., 1994).

Runoff plots have been constructed at several hundred locations throughout the world, and the experimental techniques are well standardized. However, most of the research has been carried out in temperate regions rather than subtropical or tropical climates. Legitimate use of the USLE requires knowledge about rainfall, length and steepness of slope, soil erodibility, soil management, and the use of soil conservation practices. Additional research on water-induced soil erosion led to the development and adoption of the Revised Universal Soil Loss Equation (RUSLE). Even with the additional refinements to the equation, one still must exercise judgment in using it. Neither equation works well in subhumid and humid tropical regions where rainfall characteristics are considerably different from the range of conditions under which the equations were developed.

Some steepland soils, especially those of volcanic origin, have high infiltration rates, which reduce the potential for surface water runoff and water-induced erosion, and are therefore more compatible for agricultural use than others (Lal, 1990). However, even these soils may have cemented layers (duripans) that restrict water infiltration and percolation, or light-colored, coarse-textured pumicitic layers that promote rapid interflow (lateral flow), which increases the risk of landslides. For example, the village of El Porvenir in Nicaragua was destroyed by a landslide on El Casita volcano that stemmed from excessive rainfall from Hurricane Mitch in 1998. The risk for landslides increases further when trees are cut and their roots decompose rather than help to stabilize the slope.

Tillage-induced soil erosion

During the past two decades tillage-induced soil erosion has been recognized as an important factor in soil degradation in many locations of the world. Tillage is a dynamic process used for various purposes such as preparing the soil for seeding, incorporation of lime and fertilizer, and weed control. Tillage detaches, breaks, and displaces soil aggregates and clods and, on sloping surfaces, moves soil to lower elevations (Powell and Herndon, 1987). Although first recognized by Mech and Free (1942) 60 years ago, tillage-induced soil erosion was largely ignored until the late 1980s. Intense study of this process began during this past decade. Recent advances in tillage erosion research were summarized by various authors in the special publication, volume 51, of the *Journal of Soil and Tillage Research* (1999).

The movement or translocation of soil downslope by tillage and its ultimate loss from the field has only recently been considered a major factor contributing to the overall soil degradation process. According to Veseth and Wysocki (1986), moldboard plowing on sloping soils is responsible for a significant reduction of topsoil depth and exposure of subsoil. In tilled steepland soils in the subhumid and humid tropics, terrace development occurs rapidly, usually within a couple of years after contour hedgerows are planted (Agus et al., 1997). During terrace development, soil surface material in the *alleys* (the area between two adjacent barrier strips) is translocated downslope from the upper part of the alley to the lower portion, where it accumulates. This translocation process results in gradients in topsoil thickness and in soil physical and chemical properties between the upper and lower elevation in a given alley (Agus et al., 1997; Thapa, 1997; Thapa et al., 2001; and Turkelboom et al., 1997). The topsoil is thicker and the soil properties are more favorable for crop production in the lower portion of the alley. Soil displacement and soil transport rates on hillsides depend primarily on the slope gradient (Kachanoski and Carter, 1999; Lobb et al., 1999). Dabney et al. (1999) suggested that tillage erosion accounted for a significant amount of soil movement in a 3-year experiment with adjacent grass hedgerows in Mississippi. They reasoned that tillage erosion caused 30 to 60% of the soil movement and landscape benching (leveling of alleys due to formation of terraces) observed between the hedgerows at the site, which had a tilled, fallow silt loam and 7% slope.

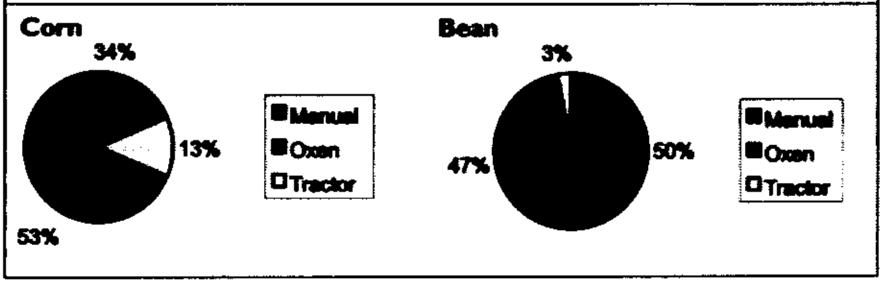
Tillage-induced soil erosion can influence the soil's sensitivity to water-induced soil erosion. Tillage increases soil roughness, breaks crusted soil surfaces, enhances water infiltration, and increases macroporosity, thus reducing surface runoff. In addition, tillage may also decrease the soil's resistance to the detachment caused by raindrop impact or flowing water (Govers et al., 1999). However, when rainfall exceeds the surface depression storage, the soil loosened by tillage is more easily transported (Turkelboom et al., 1997).

Tillage of hillsides in the Nicaraguan Pacific region is commonly performed using an *egipcio* (an oxen-pulled plow) and by manual tillage using hoes and picks. The *egipcio* is used for tillage before planting. Picks are used to break up the soil after the dry season, and hoes are used to break up clods before planting and to control weeds by cultivation after planting. Manual tillage using picks and hoes may be the only tillage method available for some subsistence farmers. For the nation as a whole, oxen-powered tillage was used for 34% of the corn production and 47% of the bean production in the 1999-2000 agricultural cycle (Figure 1). During this cycle 95% of the bean crop and 75% of the corn crop were produced on cultivated hillsides.

Hedgerows

Contour hedgerows were introduced in hillsides in the El Pital Watershed through the CARE-UNA project a decade ago. Hedgerows are narrow strips of dense perennial, or in some cases annual, vegetation that provide numerous benefits. When planted on the contour, hedgerows create barriers that serve as guides for contour cultivation, retard and gradually disperse surface water runoff, enhance on-site deposition of sediment and the development of terraces, and reduce ephemeral gully development (Dabney et al., 1999). In addition, hedgerows improve soil physical conditions (Lal, 1987) and soil fertility due to deeper and/or denser rooting patterns; conserve soil when the vegetation is used as mulch to cover the soil surface, build aggregates, and increase water infiltration; reduce water runoff (Lal, 1987); fracture compacted or indurated layers with their roots (Young, 1989); control weeds, thereby saving labor; and reduce water-induced soil erosion (Paningbatan et al., 1995).

Figure 1. Method of corn and bean production in Nicaragua during the 1999-2000 cropping cycle (from MAGFOR, 2001).



But contour hedgerows have disadvantages, too. They require significant increases in labor to establish and maintain the vegetation and to repair any broken terraces; the vegetation must be protected from grazing animals; and insects, birds, rats, and weeds often use the permanent vegetation as habitat. The main disadvantage is probably the fact that crop yields in the alleys between adjacent hedgerow strips are lower, especially if the adjacent hedgerows are close together on hillsides (Garrity, 1996). This loss in crop productivity remains a dominant issue in the hesitancy of small farmers to adopt contour hedgerows.

The leguminous tree, *Gliricidia sepium* (Jacq.), and the leguminous shrub, *Cajanus cajan*, were used in the hedgerows of the El Pital Watershed. *Gliricidia sepium*, called Madero negro, Madriago, and Madre cacao in Nicaragua, Honduras, and El Salvador, respectively, is a perennial tree native to Central America and Mexico (Salas, 1993). *Gliricidia* is used to provide shade in coffee production systems, but its role as a source of green manure is also important. In Nicaragua, *Gliricidia* species are used for shelterbelts, fodder, wooden poles, pasture, alley cropping, living fences, rat poison, and architectural support for pithaya (*Hylocereur* spp.) and vine food crop plants such as chayote (*Sechium edule* [Jacq.]) or granadilla (*Passiflora liqularis* [Juss.]) (Füssel, 1990).

Cajanus cajan, the shrub, grows 2 to 4 m tall and was introduced to Nicaragua in the early 1980s. The bean produced is used for human consumption (soup, flour, salad, etc.) and as an additive in animal food concentrates. The fodder is eaten by livestock, pigs, and poultry (Binder, 1997). When used in hedgerows, the fast-growing *Cajanus* must be pruned back to 0.8 to 1 m twice a year in order to prevent excess shading of the row crop and to stimulate seed and biomass production. *Cajanus* also provides byproducts like fuel wood, medicine, and honey.

Forty percent of farmers in the El Pital Watershed had adopted hedgerows 2 years after the CARE-UNA project had terminated (Somarriba-Chang et al., 1999). Farmers based their selection of hedgerow species on several aspects. *Gliricidia* was more likely to be adopted at the higher elevations. Farmers said they chose *Gliricidia* because of its excellent adaptability to soils, the production of byproducts (firewood and poles), reduction in soil erosion, support for pepper vines, and production of green manure (*Gliricidia* leaves) for mulching the soil. *Cajanas* was more likely to be adopted at the middle elevations because it was easy to establish, controlled water-induced soil erosion, and generated beans.

Infiltration

Infiltration is the process by which water enters the soil. This complex process is governed by the condition of the soil surface, i.e., soil structure and surface cover; the rate of downward movement or percolation of water once it enters the soil profile; and the flow, if any, through deep cracks in the profile (Campbell, 1985). Volcanic soils have highly variable infiltration rates resulting from their wide range of volcanic ejecta parent material, illuviation, cementation, and soil management. Infiltrating water encounters a distinct impermeable or nearly impermeable soil layer due to textural changes of the volcanic material or to cementation. Tillage increases macroporosity and soil roughness, thus creating a short-term increase in the infiltration rate and the amount of water entering the soil, especially for crusted soils.

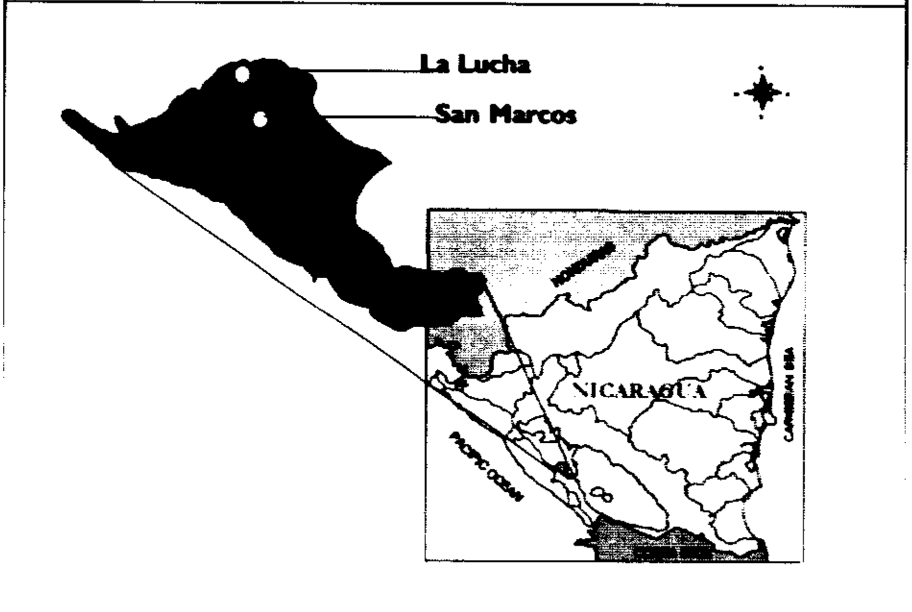
Although infiltration rates are closely related to soil erosion, it is perplexing that infiltration rate data for volcanic-derived soil are unavailable in the literature. Knowledge of the infiltration rate and its variability in volcanic-derived hillside soils might provide insight into how soil management could be improved to minimize water runoff. In the El Pital Watershed a material called *talpetate* (palagonitized tuff) exists in the soil (Prat, 1991). Sometimes this layer is referred to as a duripan. The material typically is formed from loamy material, has a bulk density between 0.8 and 1.0 g cm^{-3}, has a water retention value > 0.5 cm^3 cm^{-3}, is fragile, and can be broken during tillage when it is exposed at or near the soil surface. Pumice is another material commonly found in volcanic soils in the El Pital Watershed, and it is highly variable. Pumice bulk density ranges from 0.1 to 0.5 g cm^{-3}, and its large pores retain little water for plant use.

Soil erosion on steepland soils has been commonly measured at between 100 and 200 tons ha^{-1} yr^{-1} (Pimental et al., 1995). For volcanic soils in Nicaragua, soil erosion rates oscillate between 50 and 100 tons ha^{-1} yr^{-1} when soils are tilled up and down slope (Rivas, 1993). Mendoza (1994, 1997) states that these rates can be reduced to 2 to 12 tons ha^{-1} yr^{-1} by contour tillage.

Characteristics of the El Pital Watershed

Some of the material in this section was extracted from the publication *Soil erosion and conservation as affected by land use and land tenure, El Pital Watershed, Nicaragua* by Somarriba-Chang et al. (1999). The El Pital Watershed is located in the Pacific region of Nicaragua between 11°42'48" and 11°54'47" north latitude and between 85°55'12" and 86°09'12" west longitude in the southern part of the Department of Masaya about 100 kilometers southeast of Managua (Figure 2). The El Pital Watershed borders the northwestern shore of Lake Nicaragua, and it encompasses six subbasins, including Mombacho with 77 km^2 and Diriomo with 88 km^2 of land area.

Figure 2. Location of the experimental sites in the El Pital Watershed, Nicaragua.



Climate

The watershed has a seasonally dry tropical climate, as characterized by the Koeppen Climatic Classification (Critchfield, 1983). Mean annual precipitation is approximately 1,500 mm. Elevation varies from 160 to 1,100 meters above mean sea level. Elevation has a great influence on the mean daily air temperature, which varies from 13°C in December to 25°C in April at the highest elevation, and from 26°C in December to 32°C in April at the lowest elevation. In this watershed, the *primera* occurs from May 1 to mid-July, the *canicula* from mid-July through mid-August, the *postrera* from mid-August to November, and the *postreron* from early September to January.

Hillside grain production

For the typical corn-bean rotation, corn is grown in the *primera* and bean in the *postrera*. Crops are planted in rows made by oxen-pulled *egipcio* or in holes dug manually with a digging stick (*espeque*). Corn and bean are intercropped in some fields using either an "alternate row" or a "randomized" system. In the alternate row system, adjacent rows are spaced 80 cm apart, corn plants are spaced 30 cm apart in the rows, and bean plants are spaced 20 cm apart. No particular planting pattern is used for the random scheme.

Geology and soil

The El Pital Watershed is part of the southwest Nicaraguan depression flank. The geomorphology of soil in the watershed is diverse, with 10 soil series represented from the valley to the mountains. The basin has mainly moderately well to well-drained soils. The soil parent material includes basaltic rock, volcanic ash, alluvial sediment, and limestone. The topsoil depth ranges from deep (> 80 cm) in lowlands and on well-vegetated hillsides to shallow (< 30 cm) on intensively farmed steeplands. The two dominant soil surface textures are sandy loam and clay loam. The organic matter content ranges from 3 to 9%, indicating stable soil structure.

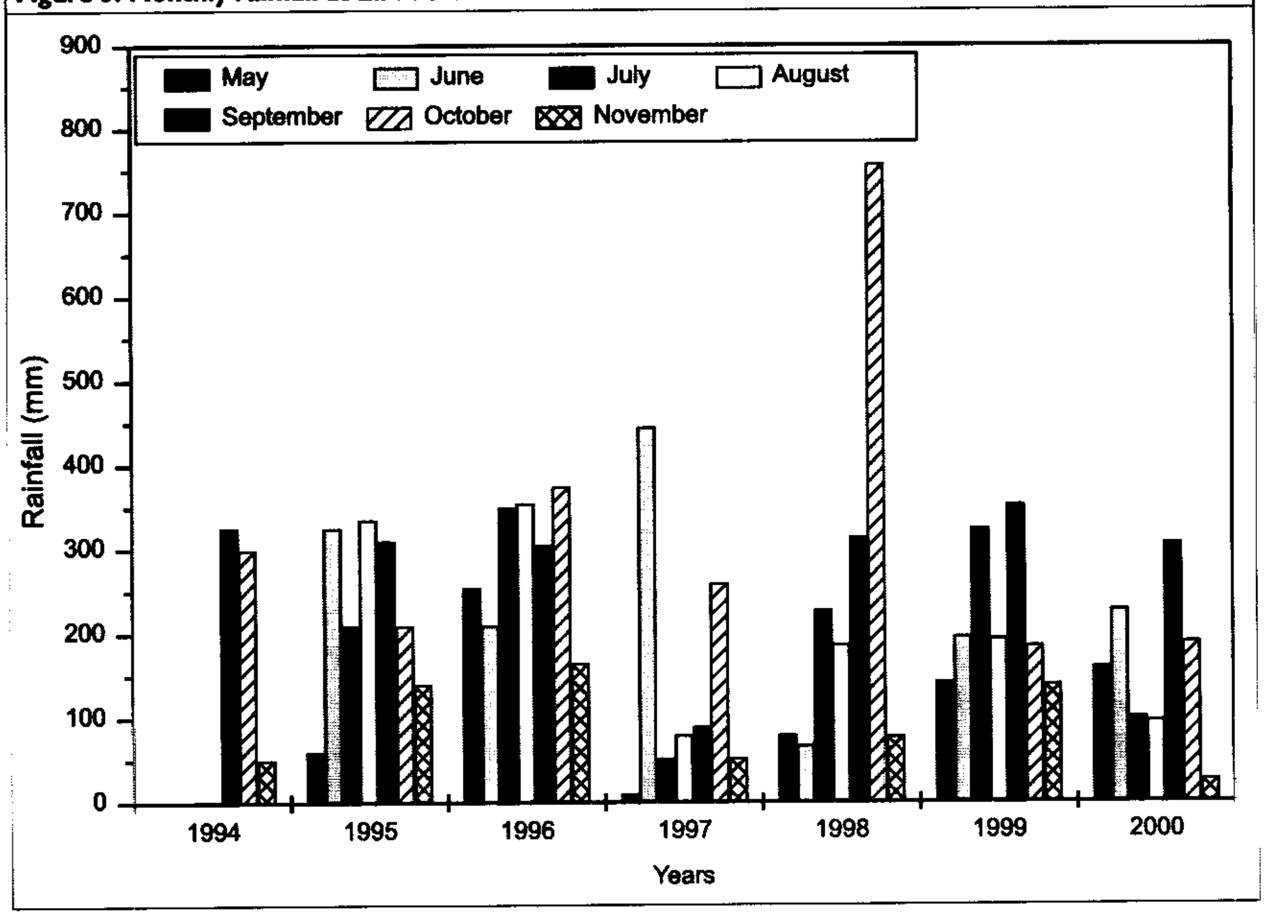
Small plot methodology

The field experiment was conducted on farms at two sites in the El Pital Watershed. Hereafter these sites will be referred to as *La Lucha* and *San Marcos*, the two villages where the farms are located. The owners of the farms performed many of the field operations under the guidance of UNA personnel and with their assistance.

Site 1, La Lucha farm. This experimental site, located at 11°53'55" north latitude, 86°05'10" west longitude, has a nominal elevation of 450 m and its slope ranges from 30 to 55%. Mean annual rainfall (1970-1998) is 1,500 mm, with nearly all of it occurring from May through October. Figure 3 shows the variability of monthly rainfall at La Lucha between 1994 and 2000. Potential evaporation (1,931 mm) exceeds rainfall during the remainder of the year. Average wind velocity is 5 to 10 km hr $^{-1}$ in the rainy season and 10 to 13 km hr $^{-1}$ in the dry season.

This study incorporated eight runoff plots, initially constructed in 1994 for the CARE-UNA project and refurbished in 1998, that were 3 m wide and 20 m long. The disadvantage of using runoff

Figure 3. Monthly rainfall at La Lucha farm from 1994-2000.

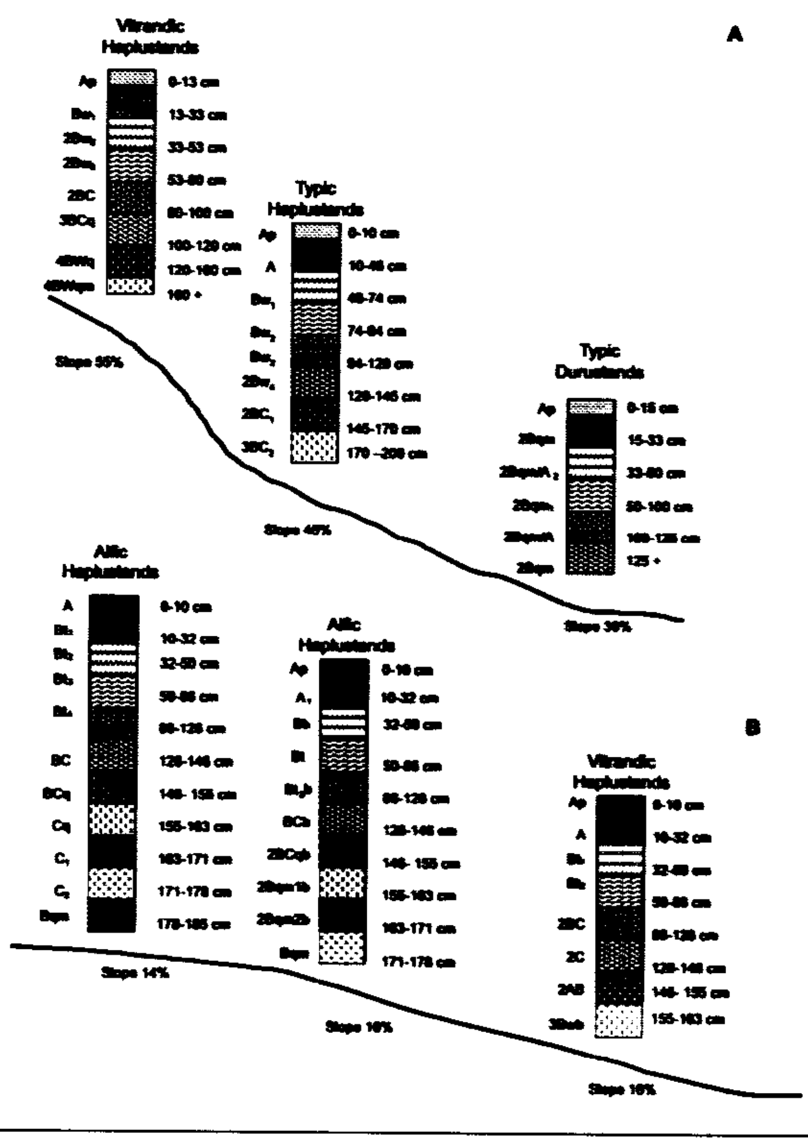


plots is that they must be replicated, they are labor intensive, and they are expensive to operate. It is also difficult to use oxen-powered tillage in such small plots due to their short width. This did not create a problem for the present study, though, as all soil management systems utilized manual tillage. The advantage of these plots is that the methodologies used to monitor runoff water and soil losses are straightforward. The water, soil, and crop production data can be used to estimate economic implications.

Three pits were dug along a toposequence adjacent to the boundary of plot 8, and detailed descriptions of the soil were made under the guidance of Dr. Larry Wilding, Texas A&M University (Figure 4A). The parent materials were of volcanic origin, much of which came from volcano Mombacho. The parent materials vary from ultra-fine dusts to pumice and volcanic bombs ejected by explosive eruptions.

The soil at the upper elevation at the La Lucha site is classified as Vitrandic Haplustands and has 80 cm of soil material overlying a dense, nearly massive

Figure 4. Soil profiles along toposequence adjacent to the runoff plots at (A) La Lucha and (B) San Marcos.



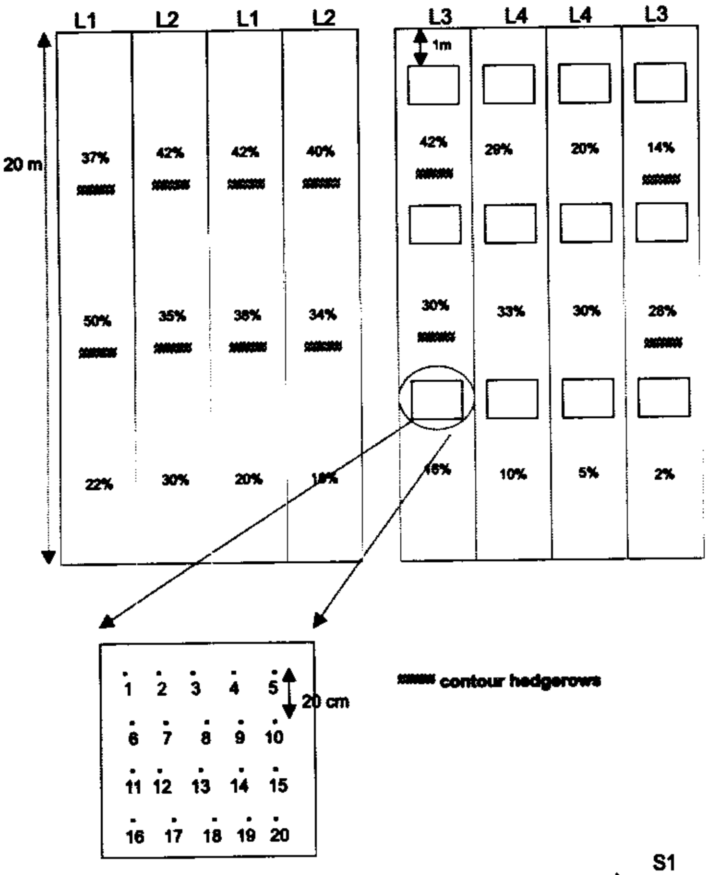


Figure 5A. Schematic diagram of soil erosion plots at La Lucha showing locations of contour hedgerows and mean percent slope for various sections of each plot. The squares show locations where tillage erosion markers were installed. Treatments are identified as L1, L2, L3, and L4.

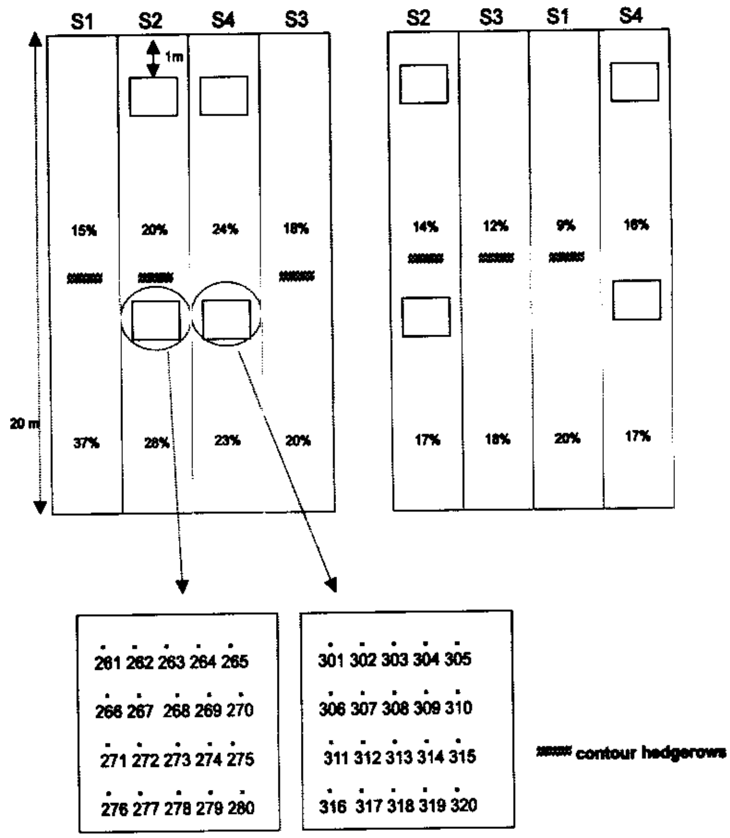


Figure 5B. Schematic diagram of soil erosion plots at San Marcos showing locations of contour hedgerows and mean percent slope for various sections of each plot. The squares show locations where tillage erosion markers were installed. Treatments are identified as S1, S2, S3, and S4.

layer of cemented duripan (containing many glass chards and fragments of pumice) at the 80- to 160-cm depth. This material is underlain by loamy, cemented scoria. Laboratory analysis of the Ap horizon indicates that it contains 1.53% organic matter, 22% clay, 20% silt, 58% sand, 2.08 ppm P, and 0.58 meq $(100g)^{-1}$ K.

The soil at the middle elevation, classified as Typic Haplustands, has 145 cm of soil material overlying a thick cemented duripan that extends below 200 cm. At the lower elevation, the soil has a 15-cm thick clay loam textured Ap horizon and is classified as a Vitrandic Durustands. Laboratory analysis of the Ap horizon indicates that it has 3.0% organic matter, 36% clay, 20% silt, 43% sand, 13 ppm P, and 0.90 meq $(100g)^{-1}$ K. A layer of cemented volcanic tuff (*piedra cantera*) more than 15 cm thick occurred in the profile with some cracks.

Each runoff plot was dedicated to one soil management system (treatment). The four soil management treatments were replicated twice. Corn was planted in the *primera* and bean (*Phaseolus vulgaris*) in the *postreron*. Details for each soil management system at La Lucha follow:

*1. **Treatment L1.*** Two contour hedgerows of *Gliricidia sepium* (Jacq.) were planted in 1994. One hedgerow was established 6.5 m up slope from the base of the plot, and the second was located 12.5 m from the base of the plot (Figure 5A). The *Gliricidia* trees were pruned every 4 months to minimize shading of the row crop. The pruned leaves were applied uniformly to the soil surface to serve as mulch and green manure. The thickest branch-like *Gliricidia* stems were placed on the soil surface on the up hill side of the contour hedgerows to help strengthen the terraces. Slender wood poles (*Gliricidia* tree trunks) were harvested as wood byproducts every 2 years.

*2. **Treatment L2.*** This treatment used hedgerows of *Gliricidia* similar to those used in Treatment 1, but fertilizer was applied to the food crop and not to the hedgerow. The fertilizer rate was based on the crop, soil test analysis, and efficiency of the fertilizer. Initially, 91 kg ha^{-1} of NPK (18-46-0) were applied to corn at planting. An additional 91 kg ha^{-1} of urea (46% N) were applied 21 days after planting. The bean crop received 91 kg ha^{-1} of fertilizer (18-46-0) at planting.

*3. **Treatment L3.*** This treatment was similar to Treatment L1, but the *Gliricidia* hedgerows were pruned twice rather than three times annually. The pruned material was spread on the soil surface as in Treatment L1.

*4. **Treatment L4.*** This control treatment had no hedgerow vegetation, but corn and bean were planted on the contour.

The plots were cultivated and tilled with pick and hoe. Shortly after the *primera* began and about 1 to 2 weeks before corn was planted, the soil was tilled with a pick to a nominal depth of 10 cm. The vegetation on the plots was very dry at this time. The resulting cloddy soil was tilled again with a hoe at planting. Fertilizer was applied to Treatment L2 according to the protocol described above. Corn variety NB-6 was planted on the contour in rows spaced 80 cm apart. The plots were weeded once with a hoe approximately 3 weeks after planting. Dates of cultural operations are presented in Table 1. Plant height and plant stem diameters were measured for each row of corn in each treatment three times during the growing season. Corn was hand harvested by row and allowed to air dry. Stover was cut by machete. The number of ears, the air-dried grain weight, and the weight of stover in each plot row were recorded. The NB-6 corn variety, which was developed in Nicaragua, produces white grain, grows 235 cm tall, flowers in 56 days, and matures in 115 days (INTA, 1995). Its yield potential on intensively farmed land is 3,800 kg ha^{-1} and performs best at pH between 5.5 and 7 (LaMotte, 1994).

Table 1. Manual tillage operations in 1999 for corn and bean crops at La Lucha and San Marcos.

Date	Operation
January 1999	Installed soil erosion markers (pick)
March 30	Prepared land for corn (pick)
June 5	Tilled with hoe and planted corn (hoe)
July 10	Cultivated interrow corn (hoe)
September 25	Prepared land for bean (pick)
October 6	Planted bean (hoe)
October 30	Cultivated interrow bean (hoe)
May 2000	Excavated soil erosion markers

After the *canicula* the soil was tilled (Table 1) and bean was planted in contour rows 40 cm apart. Seeds were placed 20 cm apart in the row. Field-dried bean for each row or pair of rows was manually harvested and weighed. Plant height and stem diameter were measured for each row of bean in each treatment twice during the growing season. The common kidney-shaped bean came from Mexico, is red, flowers in 30 days, and matures in 65 days. Its genetic potential on hillside soils is 645 kg ha^{-1}. It is adapted to low fertility soils with low pH and low P (Tapia and Camacho, 1988).

Site 2, San Marcos farm. The San Marcos site, located at 11°51'43" north latitude, 86°04'43" west longitude, has a nominal elevation of 340 m and its slope ranges from 14 to 20%. Mean annual rainfall (1970-1998) is 1,400 mm, with nearly all of it occurring from May through October. Mean potential evaporation exceeds rainfall during the remainder of the year. Mean wind velocity is similar to that at La Lucha, 5 to 10 km hr^{-1} in the rainy season and 10 to 13 km hr^{-1} in the dry season.

The experimental design was similar, but not identical, to that at La Lucha in that four soil management systems (treatments) were replicated twice and evaluated. The study incorporated eight runoff plots, initially constructed in 1994 and refurbished in 1998, that were 3 m wide and 20 m long. Each runoff plot was dedicated to one treatment. Corn was planted in the *primera* and bean (*Phaseolus vulgaris* L.) in the *postreron*.

Three soil pits were dug along a toposequence adjacent to the boundary of plot 1, and detailed soil descriptions were made under the guidance of Dr. Wilding (Figure 4B). The soil is of volcanic origin. The two soil profiles at the higher elevations were classified as Alfic Haplustands. Laboratory analyses of the Ap horizon at the highest elevation in the toposequence revealed 43% clay, 22% silt, 35% sand, 2.5% organic matter, 4.88 ppm P, pH 5.6, and 0.38 meq $(100\ g)^{-1}$ K. At the lowest elevation, the Ap horizon soil was 48% clay, 12% silt, 40% sand, 3.18% organic matter, 1.33 ppm P, pH 5.3, and 0.90 meq $(100\ g)^{-1}$ K.

Dates for all cultural and tillage operations are listed in Table 1. The details for the four soil management systems for San Marcos follow:

*1. **Treatment S1.*** One hedgerow of *Cajanus cajan* (Jandul) was planted on the contour 10 m up slope from the bottom of the plot. (Figure 5B). The hedgerow was pruned in January and May. The pruned leaves were spread uniformly on the plot as mulch and green manure. Before pruning *Cajanus* in January, workers harvested beans from this plant for human consumption.

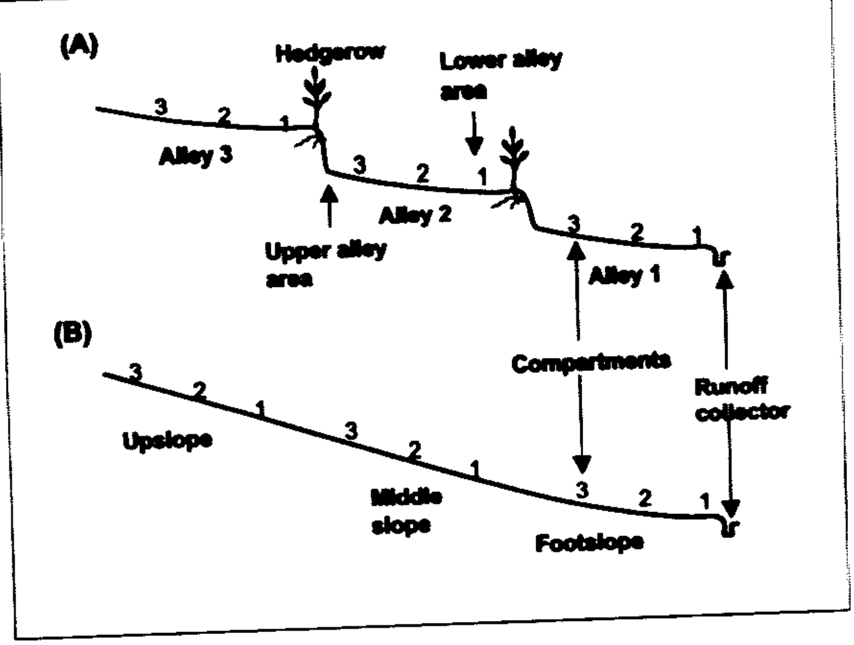
*2. **Treatment S2.*** One hedgerow of *Gliricidia sepium* (Jacq.) was planted on the contour 10 m from the bottom of the plot. The trees were pruned every 4 months to control shading of the corn and bean crops. The pruned leaves were placed uniformly over the soil surface as green manure and mulch. Slender wood poles (trunks) were harvested every 2 years and sold as byproducts.

*3. **Treatment S3.*** This treatment was similar to Treatment S2 except that fertilizer was applied. Initially, 91 kg ha^{-1} of NPK (18-46-0) were applied to the corn at planting, and an additional 91 kg ha^{-1} urea (46% N) were applied 22 days after planting. The bean crop received 91 kg ha^{-1} of fertilizer (18-46-0) at planting.

*4. **Treatment S4.*** The control had no hedgerow vegetation, but corn and bean were planted on the contour.

All corn and bean crops at La Lucha and San Marcos were harvested by hand. From 1995 through 1997 grain was harvested from the entire plot without regard to possible yield variances due to landscape position or alley. Based on research by Thapa et al. (2000), we recognized that crop yield would vary within alleys on steep slopes. Therefore, beginning in 1998, all crops were harvested by compartment and alley. Each alley was subdivided into three compartments numbered consecutively from 1 to 3, with compartment 1 at the lowest elevation (Figure 6). Each compartment had three or four rows of corn and six to eight rows of bean. Grain for each compartment was harvested by hand, weighed, and the yield for each compartment and alley expressed in kg ha^{-1}. With this procedure, the effect that landscape position (alley) or position within an alley had on grain production could be determined. Soil tends to erode from higher elevations in an alley and to accumulate at the lower elevation, causing changes in soil productivity.

Figure 6. Schematic diagram of soil erosion plots showing alleys and compartments at La Lucha for (A) Treatments L1, L2, and L3 with contour hedgerows and (B) comparable compartments for Treatment L4 without contour hedgerows.



Moreover, the typical hedgerow barrier shades the grain crop, casting the most shade on plants nearest to the hedgerow. Yield data for each crop-year-location were analyzed using a modification of the statistical procedure presented by Thapa et al. (2000). Using the general linear model procedure of SAS (SAS Inst., 1988), treatments, alleys, and compartments were considered fixed.

Figure 7. Overview of the runoff plots at La Lucha.

Water runoff and sediment collection

The eight runoff plots used in the studies were equipped with instruments to collect runoff water and soil (Figures 6, 7, 8). The long dimension of the plot was perpendicular to the slope contour. The top and side boundaries of each plot were delineated with barriers constructed from 12-mm-thick sheets of water-impermeable laminate (Figure 7). The laminate was installed vertically so that it extended 20 cm above and 20 cm below the soil surface. A 3-m-long metal interceptor channel was specially constructed to collect runoff water and suspended soil, and it was installed at the lower end of the plot. A pipe attached to the bottom of the channel carried water and suspended solids to a 192-liter metal barrel (Figure 8). Most of the solids settled to the bottom of the barrel, but if this barrel filled during a heavy rain that caused runoff, the excess water and remaining suspended sediment flowed out of the barrel and passed through a seven-tube splitter. One-seventh of the water and suspended soil material flowing from the first barrel was collected in the second barrel.

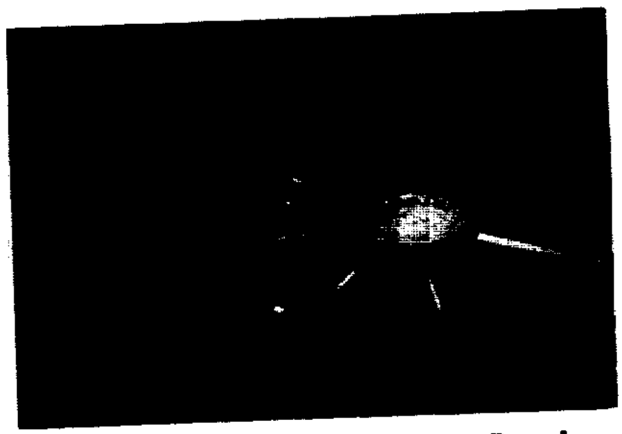


Figure 8. The seven-tube flow splitter allowed one seventh of the water and suspended solids that flowed out of the first barrel to be saved in the second barrel.

Eight hours after the end of significant rains that caused runoff, researchers measured the height of water plus solids in each runoff collector barrel with a meter stick. The total volume of water and sediment was calculated by multiplying this height by the cross-sectional area of the barrel. Then the sediment and water were thoroughly stirred together in the barrel, and two 1,150-ml grab samples of the resulting suspension were collected. The samples were labeled and transported to UNA Soils Laboratory, where the masses of water and sediment were determined. When high intensity rain fell, one of the samples was selected for that month and measured for sand, silt, and clay contents; pH; P; and K. Rainfall was monitored daily at each site with a recording rain gauge, but rainfall intensity was not recorded.

The capacity of the runoff collection system was no match for the torrential rains of Hurricane Mitch in 1998. Complete data were collected during the first day of the hurricane, but data for the second and third days were estimated to be equal to those values from the first day.

Tillage-induced soil erosion

Soil translocation was measured using two techniques. Recall that six manually performed tillage operations were required to grow corn and bean during a 1-year cropping cycle (Table 1). Four of the tillage operations were done with a hoe and two with a pick. "Tillage erosion markers" were used to estimate soil translocation caused collectively by these six tillage operations in 1999. The "topographic survey" technique was used to estimate mean annual soil translocation over the 4.5 years between the time the runoff plots were installed in 1994 until January 1999.

Method 1, Tillage erosion markers. Small metal tillage erosion markers were constructed and buried in the soil at precisely known positions. The translocation distance of each marker was measured during a 1-year cropping cycle. These markers, which were 4 cm by 4 cm by 0.1 cm, were painted white to prevent rust and to promote visibility when they were recovered from the soil. The markers were numbered consecutively from 1 through 400.

The markers were installed in four runoff plots at both sites in January 1999 before tillage for the 1999 crop began. At La Lucha, markers were installed in Treatment L3 with *Gliricidia* and in Treatment L4, the control. At San Marcos, the markers were installed in Treatment S2 with *Gliricidia* and in Treatment S4, the control.

The original locations of the installed markers are shown in Figure 5. At La Lucha three batches of 20 markers were placed at precisely measured coordinates in three alleys in each of four runoff plots. For the upper alley at La Lucha, for example, (Figure 5A) five markers were placed 20 cm apart in a row following the contour (Figure 9). The second row of five markers was parallel to the first row and was 20 cm downslope from it. Two more rows of markers were installed, each 20 cm downslope from the previously placed row. All markers were buried 5 cm below the soil surface. The original location of each marker was recorded in reference to permanent landmarks along the plot boundaries. At San Marcos, batches of 20 markers were installed in two alleys in each of four runoff plots (Figure 5B).

The markers were excavated in May 2000 before land preparation for the corn crop began. Although the markers remained in the soil for 16 months, only six tillage operations were performed during this crop cycle. Each buried marker was located using a Fisher 1266-XB metal detector and gently uncovered using a pick, hoe, or machete. Then its identification number and depth in the soil were recorded. The translocation distance between each marker's original position and final position was measured along with the angle of its movement. The vertical and lateral translocation distances were calculated using sine and cosine functions.

The soil flux (K) in kg m^{-1} yr^{-1} was calculated using

$$K = MAD \times TD \times BD \qquad [1]$$

where MAD is the mean actual translocation distance; TD is the depth of tillage, taken to be 0.10 m; and BD is the bulk density for which the average value of the Ap horizon at La Lucha was 0.95 g cm^{-3} and at San Marcos was 1.00 g cm^{-3}.

The tillage erosion rate (TER) in tons ha^{-1} yr^{-1} was calculated by dividing the soil flux, K, by the slope length, L, (Thapa et al, 1999b). For plots with

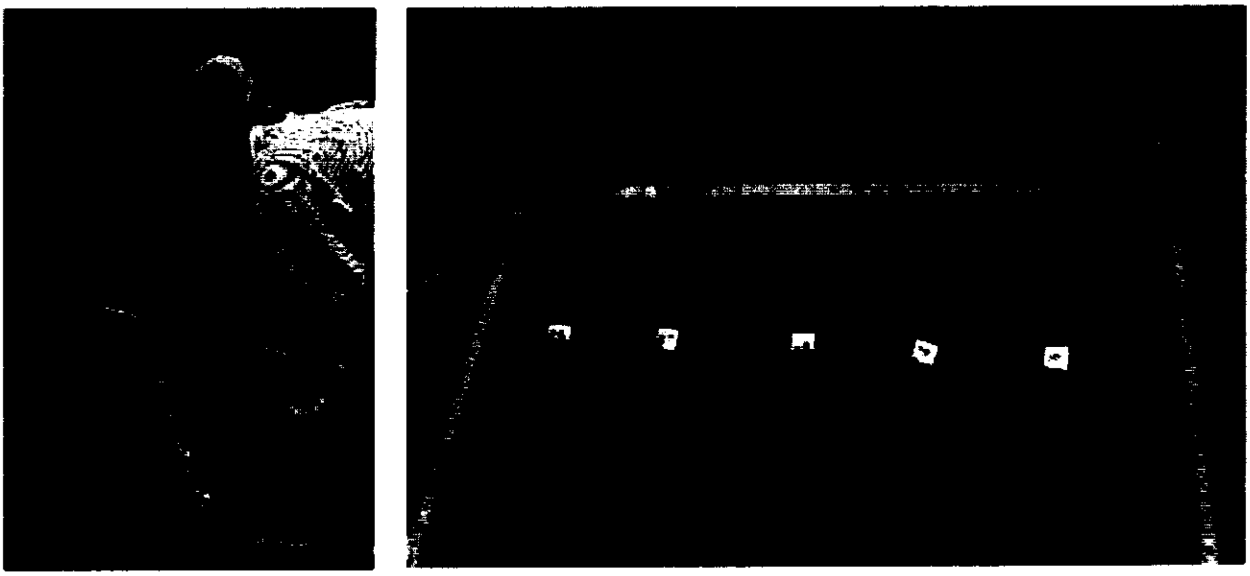


Figure 9. Metal soil erosion markers were placed at precisely known locations.

Figure 10. Erosion due to tillage with a pick and hoe lowered the soil surface elevation near the upper boundary of this plot.

hedgerows, the slope length is the distance between adjacent hedgerows. For control plots without hedgerows, slope length is 20 m, the entire length of the plot. The TER term can be misinterpreted easily, so we prefer to concentrate on translocation distances and soil fluxes.

Method 2, Topographic survey. Both water-induced erosion and tillage-induced erosion occurred from the time the soil erosion plots were constructed in 1994 until January 1999, when the study ended.

Soil surface elevation was measured with a water level in January 1999 on a grid in all eight runoff plots at La Lucha and San Marcos. Surface elevation was measured at points on three transects, separated by a distance of 1 m, that extended the entire 20-m length of the plot. The first transect was located 0.5 m from the plot boundary, and elevations were measured at 0.5- or 1.0-m intervals. This process was repeated for the two additional parallel transects. Soil surface elevation was also measured at 0.5- or 1-m intervals on the 20-m-long transect in the grass buffer strips adjacent to and parallel to each runoff plot.

The difference between the average soil surface elevation in the plot at a given contour (distance from the lower end of the plot) and the soil surface elevation in the grass strip at the same contour is an estimate of the increase or decrease in soil thickness due to erosion or deposition (Figure 10).

Decreases in soil surface elevation within a plot compared to the elevation of the adjacent grass-covered buffer strip were attributed to loss of soil by either water-induced erosion or tillage-induced erosion. Conversely, increases in elevation were attributed to deposition of soil translocated by water-induced erosion or tillage-induced erosion from other locations within the same plot.

For example, the loss of soil in the uppermost 3 m^2 region of the plot, that is, the plot area bounded between contours at 19 and 20 m up slope from the base of the plot, was calculated by

$$\text{Soil loss} = A \, \Delta H \, DB \qquad [2]$$

where A is the surface area (m^2) of the soil region of concern, ΔH is change in soil thickness (m), and DB is bulk density (kg m^{-3}). The mass of soil loss (or gain) was divided by 4.5 years to convert the data to an annual basis.

Infiltration

Infiltration data were collected in each runoff plot in April and May 2000 (dry season). The soil water content in the upper 15 cm of soil ranged from 0.17 to 0.19 cm^3 cm^{-3} at this time. At La Lucha, infiltration was measured in each of three compartments in the upper, center, and lower alleys of each plot (Figure 6). The mean percent slopes for the measurement points were 50, 56, and 30% for the upper, center, and lower alleys, respectively. At San Marcos, infiltration was measured in three compartments of two alleys. Mean slopes for the upper and lower alleys were 18% and 16%, respectively.

For each measurement a single-ring infiltrometer (40 cm diameter, 30 cm high, and 2 mm thick walls) was pushed into the soil at least 10 cm. Since the soil sloped at all measurement points, a small amount of surface soil was removed to create a level surface so that the infiltration ring could be installed in a vertical position. Water was poured into the ring, and the height of water in the ring was maintained between 5 and 10 cm for the 30-minute duration of the measurement period. The cumulative amount of water infiltrating the soil surface was measured at 1, 2, 3, 5, 7, 10, 15, 20, 25, and 30 minutes. The data were plotted and analyzed using the GLM procedure (SAS Institute Inc., 1988). The amount of water that had infiltrated between 20 and 30 minutes after infiltration began was used to estimate the steady-state infiltration rate and was classified similar to saturated hydraulic classes presented by Schoeneberger et al. (1998).

Results

Crop responses to soil management treatments

Corn and bean yields at La Lucha varied from year to year between 1995 and 2000 (Table 2). Corn yields differed significantly among treatments each year except 1995. The highest mean corn yield was in 1995, the first time corn was planted following the fallow period. That year all treatments had yields exceeding 3,000 kg ha^{-1}. Mean corn yield never exceeded 2,200 kg ha^{-1} after 1995, and usually was less than 1,800 kg ha^{-1}. The reason for the higher yield for Treatment L2 in 1997 is not known. The control (Treatment L4) was among the highest-yielding treatments in 1998 and 1999, but Treatment L2, which received fertilizer, had the highest yield in 2000. Some land is lost for cropping when contour hedgerows are installed, and it is not surprising that unfertilized plots with contour hedgerows (Treatments L1 and L3) have yields less than or equal to the control treatment for which all land was planted to the row crop.

Bean yields at La Lucha were more variable than corn yields (Table 2), both across treatments and across years. Significant differences among treatments for bean occurred every year except 1996 and 1997. Overall, the highest bean yields

Table 2. Corn and bean yields at La Lucha by year and treatment for 1995-2000.

Treatment	Year: 1995	1996	1997	1998	1999	2000	6-Year Mean
				Corn (kg ha^{-1})			
L1	3,290a[†]	1,659b	1,667b	1,352b	972b	1,124c	1,677
L2	3,213a	1,840b	3,290a	1,820a	2,049a	2,399a	2,435
L3	3,099a	1,659b	2,270b	1,913a	1,388b	1,806b	2,023
L4	3,542a	2,000a	1,319b	1,898a	1,813a	1,800b	2,062
Mean	3,286	1,789	2,137	1,746	1,580	1,782	2,049
				Bean (kg ha^{-1})			
L1	423a	257a	710a	153a	368c	530c	407
L2	415a	275a	781a	177a	798a	658b	517
L3	472b	275a	745a	149a	438bc	589b	445
L4	455a	257a	625a	104b	481b	932a	476
Mean	441	266	715	146	521	677	461

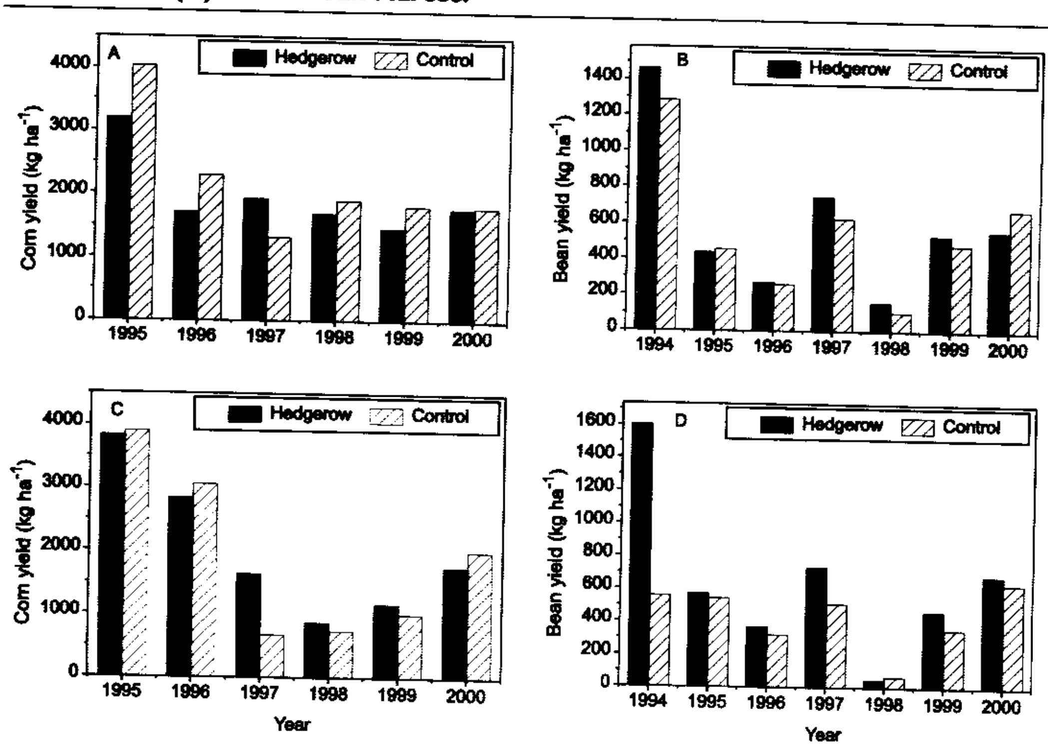
[†] Treatment yields followed by the same letter for a given year and crop are not significantly different at the $p = 0.05$ level.

Table 3. Corn and bean yields at San Marcos by year and treatment for 1995-2000.

Treatment	1995	1996	1997	1998	1999	2000	6-Year Mean
				Corn (kg ha^{-1})			
S1	3,837a†	1,893c	1,281c	991a	992b	1,576c	1,762
S2	3,679a	3,203b	1,636b	785a	855b	1,791b	1,723
S3	3,966a	4,334a	2,112a	814a	1,651a	1,906ab	2,464
S4	3,894a	3,059a	668d	729a	1,001b	2,000a	1,891
Mean	3,844	3,122	1,424	830	1,125	1,818	2,027
				Bean (kg ha^{-1})			
S1	430a	354a	711a	68a	463a	709a	456
S2	646a	317a	747a	33b	471a	696a	485
S3	641a	429a	745a	44ab	463a	650a	495
S4	545a	319a	511b	66a	354a	635a	405
Mean	566	355	679	53	438	673	461

† Treatment yields followed by the same letter for a given year and crop are not significantly different at the p = 0.05 level.

Figure 11. Comparison of yields from plots with contour hedgerows versus yields from the control plots for (A) corn at La Lucha, (B) bean at La Lucha, (C) corn at San Marcos, and (D) bean at San Marcos.



occurred in 1997 and 2000. The low yields in 1998 resulted from drought during the first part of the bean growing season, coupled with Hurricane Mitch, which devastated most of the plants that survived the drought. In 2000, the highest bean yield occurred for Treatment L4, the control, whereas in 1999, it occurred for fertilized Treatment L2.

For San Marcos, corn yield was consistent across treatments in 1995, but considerable variability occurred in 1996 and 1997 (Table 3). The lowest corn yield in 1997 came from the control plot when early rainfall caused some seed loss. In 1998 corn yields for all treatments were low due to drought. Fertilizer (Treatment S3) increased corn yield in 1999 when overall yields were low, but in 2000, yields for the control (Treatment S4) and fertilized Treatment S3 were similar. Table 3 also shows that, in general, treatment had little effect on bean yield at San Marcos any of the six years. However, each hedgerow treatment had a higher yield than the control in 1997.

Since large differences in yield by treatment were not prevalent, it is helpful to compare the mean yield for the three contour hedgerow treatments with the yield of the control. The highest corn yields at La Lucha occurred in 1995 (Figure 11A), the first time corn was planted after the soil had been initially tilled in 1994. Corn yield decreased dramatically after 1995 for both the control and hedgerow treatments and approached a plateau by 1997. When examined in this manner, corn yield, overall, was more favorable for the control treatment, especially for the first two years, but the effect nearly disappeared as time progressed.

The mean bean yield across hedgerow treatments (Figure 11B) was slightly higher than the control in 1994, the first year bean was planted. This first bean crop had the benefit of being the first crop planted following the fallow period. No difference in bean yield occurred until 2000, when the control (L4) had a 14% yield advantage over the mean yield for the hedgerows. There was little difference in bean yield between hedgerow and control treatments from 1995 until 2000.

Figures 11 C and D show the mean corn and bean yields averaged across hedgerow treatments in San Marcos compared to the yields of the control treatment. The decrease in yield for each crop

Table 4. Summary of significance levels for analysis of variance for corn and bean yields at La Lucha and San Marcos between 1998 and 2000.

Source	Probability Level					
	Corn			Bean		
	1998	1999	2000	1998	1999	2000
La Lucha						
Treatment	*	**	**	**	**	**
Replication					**	
Alley	**	**	†	**	†	
Compartment	**	**	**		*	
Treatment & Alley	**	**	**	**	**	*
Treatment & Compartment						
Alley & Compartment		*		**	**	
San Marcos						
Treatment		**	**	*		
Replication	*	**				
Alley		**	*	**	*	**
Compartment		†		*	**	**
Treatment & Alley			*			
Treatment & Compartment						
Alley & Compartment	*			**		*

**, *, and † refer to significance levels at the p = 0.01, 0.05, and 0.10 levels respectively.

followed a pattern similar to the trend in La Lucha (Figures 11 A and B). Both corn and bean yield increased from 1998 to 2000. In 1998, Hurricane Mitch devastated the bean crop at San Marcos.

Table 4 gives a summary of the significance levels for the analysis of variance for corn and bean from 1998 to 2000 at La Lucha and San Marcos. At La Lucha significant differences in corn yield in 1998 were found in response to treatment, alley, compartment, and the treatment-alley interaction. With the exception of compartment, the same factors and interaction were also significant for bean yield in 1998.

The grain yield responses at San Marcos between 1998 and 2000 were not as pronounced as those at La Lucha (Table 4). At San Marcos, treatment affected corn yield 2 years and bean yield 1 year. However, *alley*, which is related to landscape position, affected yield 2 years for corn and all 3 years for bean. Yield was affected by compartment 1 year for corn but 3 years for bean.

Figure 12 shows how corn yield at La Lucha varied with compartment and alley for each of the four treatments in 1998, 1999, and 2000. Alley 1 was at the lowest elevation, and alley 3 was at the highest elevation.

In 1998, for example, there was a slight trend for yield to decrease as alley number (elevation) increased. This relationship is especially noticeable for Treatment L4, the control. Within a given alley the highest yield for each treatment usually occurred in compartment 2, but it occasionally occurred in compartment 1. The lowest yield typically occurred in compartment 3, probably because surface soil material at this position is loosened by hoe and pick tillage and translocated downslope (discussed later). As time progressed, more and more soil surface material was transported out of compartment 3, making the remaining soil a poor environment for plant roots. Partial shading of corn plants by the hedgerow vegetation in compartment 3 also had a negative effect on yield.

As stated above, conditions for plant growth were best in compartment 2 even though tillage transported some of its soil material downslope to compartment 1. However, the same tillage also transported soil material downslope from compartment 3 to compartment 2. Thus the topsoil in compartment 2 maintained a similar thickness throughout the experiment and provided a more favorable environment for plant growth.

For compartment 1, immediately upslope from the hedgerow, soil moving downward from compartment 2 accumulated and provided a good soil environment. But sometimes the soil near the hedgerow remained too wet for optimum growing conditions. Furthermore, shading of corn and bean plants by the hedgerow vegetation in compartment 1 tended to lower crop yields.

Corn yield at La Lucha in 1999 and 2000 (Figure 12) tended to follow the same patterns as in 1998 except that the addition of fertilizer to Treatment L2 tended to decrease the yield variability among alleys.

Bean yield at La Lucha (Figure 13) tended to display the same responses as corn yield, that is, yield decreased as alley (elevation) increased, with the exception of 1998 when bean yield overall was low due to Hurricane Mitch.

Corn yield at San Marcos (Figure 14) decreased as elevation increased in 1999, but the patterns were not as well defined in 1998 and 2000. Bean yield at San Marcos (Figure 15) decreased with elevation in 1999 and 2000.

Water runoff and water-induced soil erosion

1995 to 1997

The surface water runoff and soil loss information for 1995 to 1997 was collected by CARE-UNA, and it is included for completeness (permission to include this data was obtained from Domingo Rivas, May 2002). Rainfall in the El Pital Watershed has a bimodal pattern although the pattern was not always apparent between 1995 and1997 in La Lucha (Figure 3). The use of contour hedgerows over the course of the 3-year study at La Lucha reduced runoff by 13% compared to the control (Figure 16A). At San Marcos, where the slope is not as steep as at La Lucha, water runoff was reduced by an average of 33% compared to the control (Figure 16B). Total runoff for these two cultivated hillside locations did not exceed 40 mm for any of the 3 years. These runoff amounts are extremely small considering the amounts (Figure 3) and intensities (not measured) of rainfall during the summer.

Figure 12. Corn yield at La Lucha as affected by treatment, alley, and compartment.

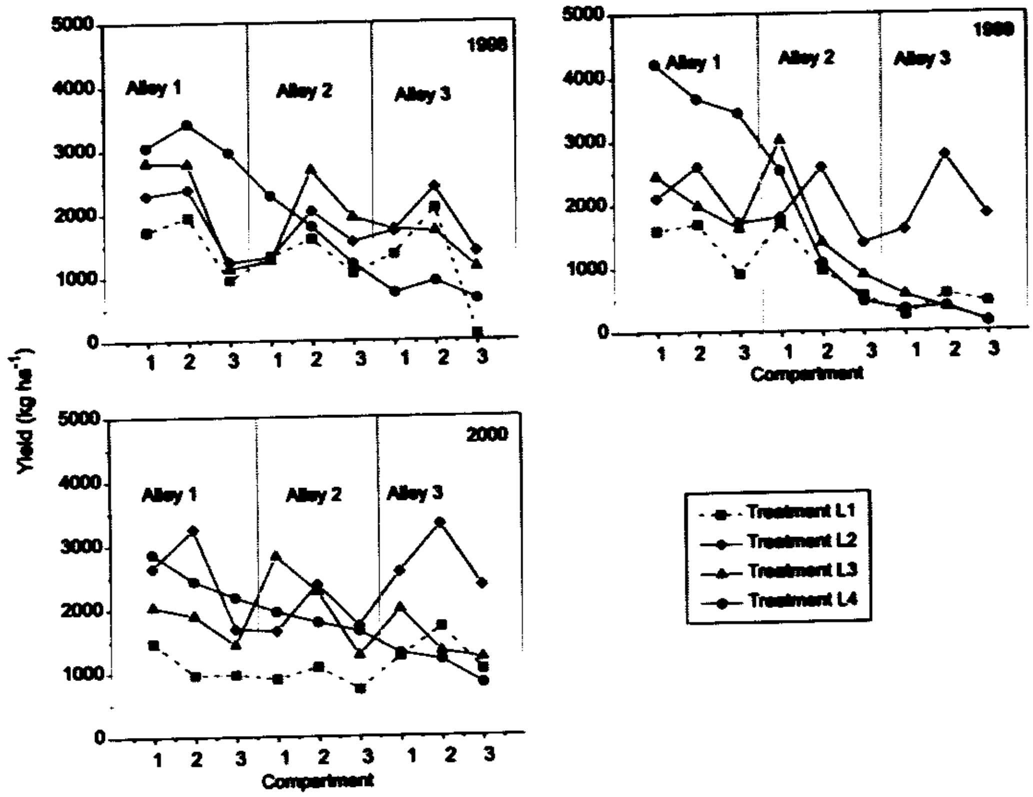


Figure 13. Bean yield at La Lucha as affected by treatment, alley, and compartment.

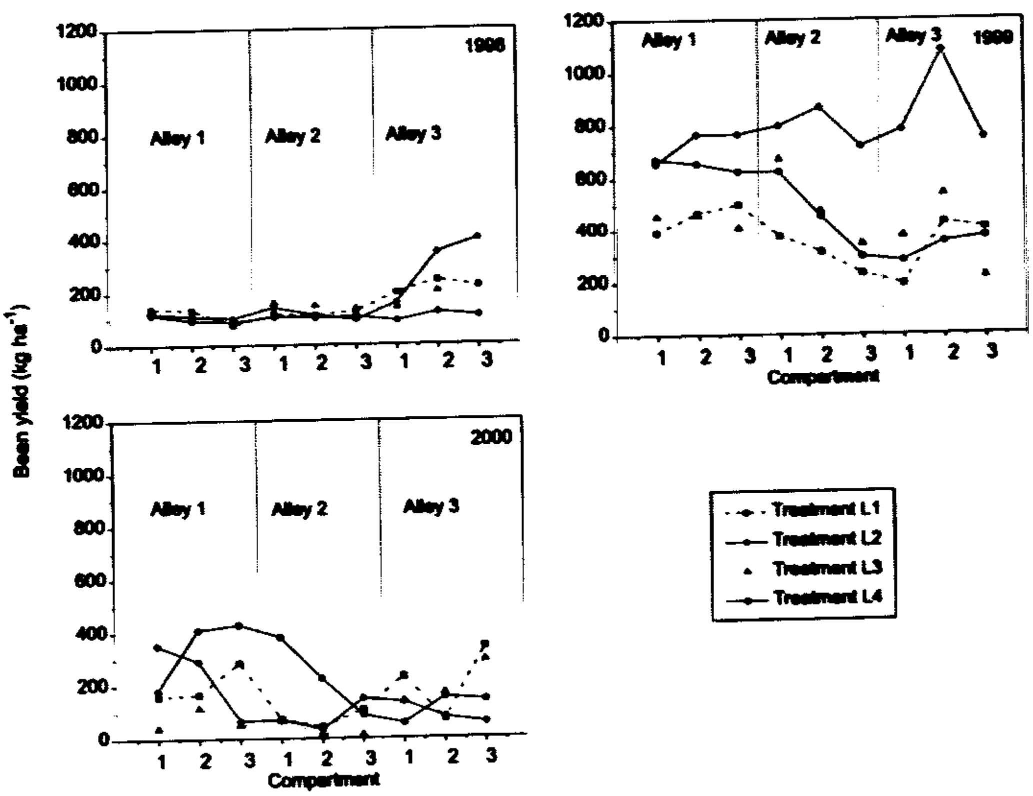


Figure 14. Corn yield at San Marcos as affected by treatment, alley, and compartment.

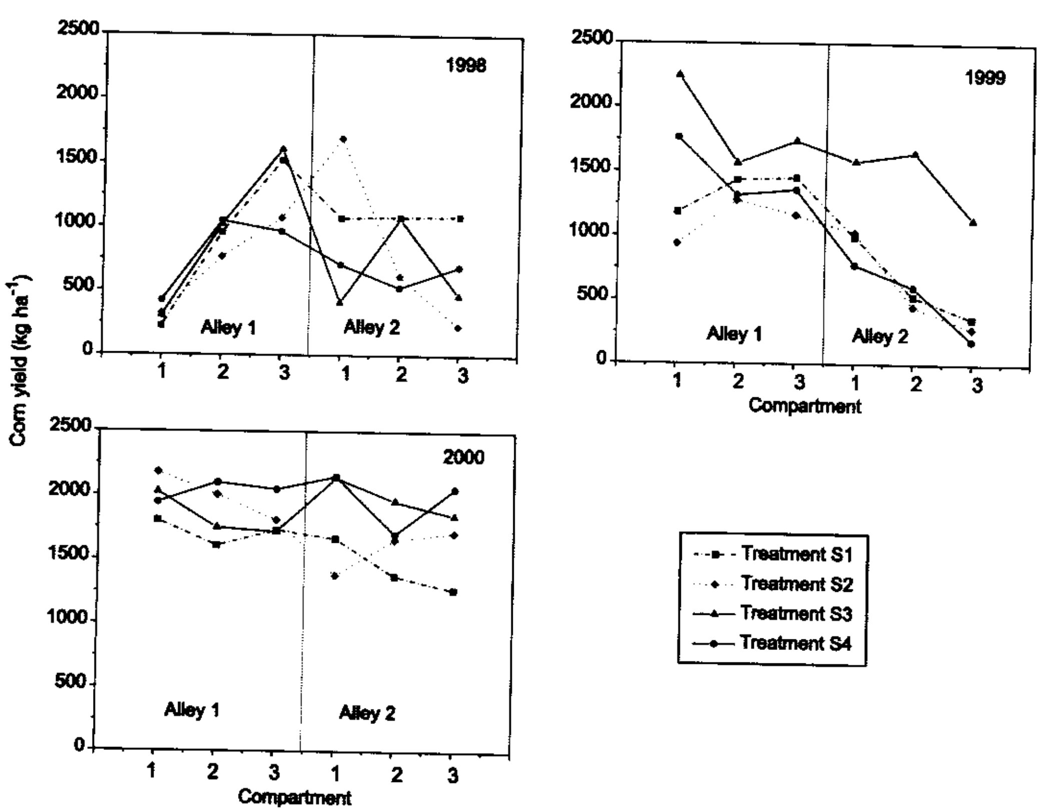


Figure 15. Bean yield at San Marcos as affected by treatment, alley, and compartment.

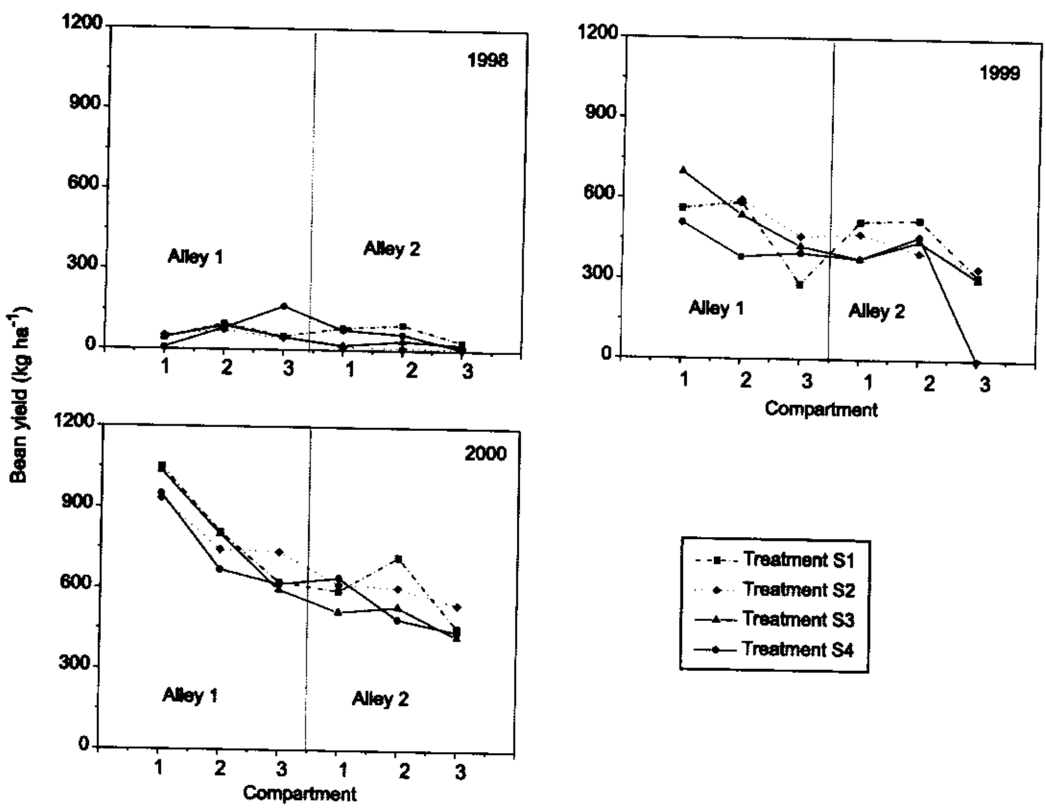


Figure 16. Annual surface water runoff for the control treatment and the mean of the three hedgerow treatments from 1995 to 1997 for (A) La Lucha and (B) San Marcos.

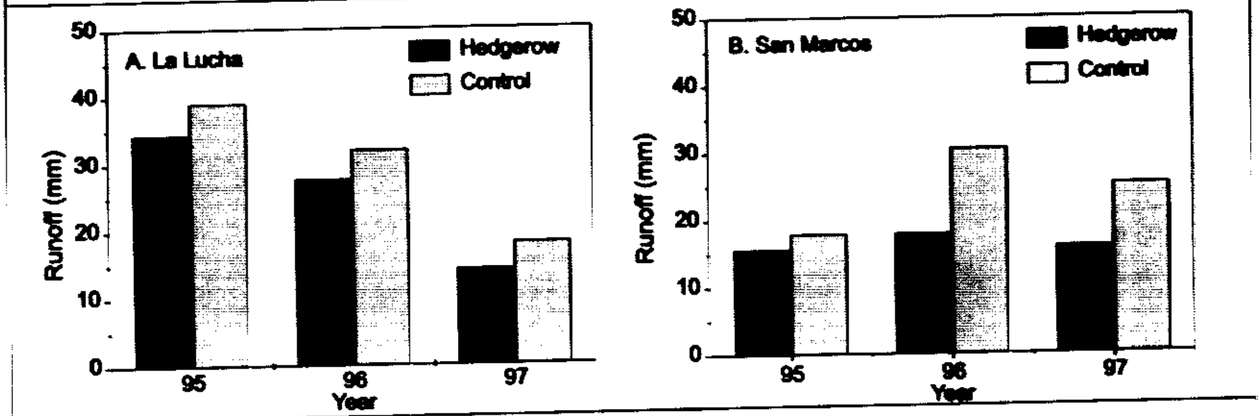
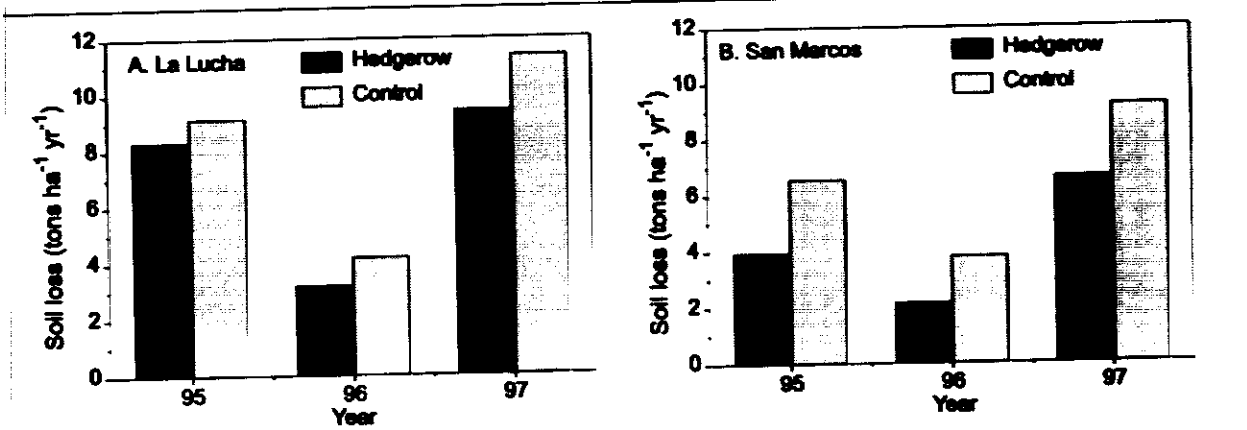


Figure 17. Annual soil loss for the control treatment and the mean of the three hedgerow treatments from 1995 to 1997 for (A) La Lucha and (B) San Marcos.



Soil losses for the control treatment at La Lucha were 9, 3, and 11 tons ha^{-1} for 1995, 1996, and 1997, respectively (Figure 17). Contour hedgerows reduced soil loss by an average of 14% at La Lucha and 34% at San Marcos compared to the controls (Figure 17). The most erosive year was 1997 because much of the rainfall occurred during the planting season when the soil was nearly bare. However, it was dryer in 1997 than it was the other 2 years.

1998 to 2000

At least 300 mm of rain fell each September in La Lucha in 1998 through 2000, according to monthly rainfall data (Figure 3). Rainfall exceeding 750 mm in October 1998 was associated with Hurricane Mitch. Surface water runoff for the three treatments with contour hedgerows was less than that for the control at both locations (Figures 18 A and B). At La Lucha, runoff amounts averaged across the three hedgerow treatments were 87, 83, and 80% of the amounts for the control in 1998, 1999, and 2000, respectively. At San Marcos, water runoff amounts averaged across the three hedgerow treatments were 94, 68, and 68% of the amounts for the control in 1998, 1999, and 2000, respectively. Clearly, the presence of the hedgerow vegetation decreased surface runoff.

Regardless of treatment, the runoff water carried soil material with it as it crossed the lower boundary of the runoff plots. Soil losses in a given year at each location were less for the three hedgerow treatments compared to the control (Figures 19 A and B). The soil losses, averaged across the three hedgerow treatments at La Lucha,

Figure 18. Surface water runoff by treatment from 1998 to 2000 for (A) La Lucha and (B) San Marcos.

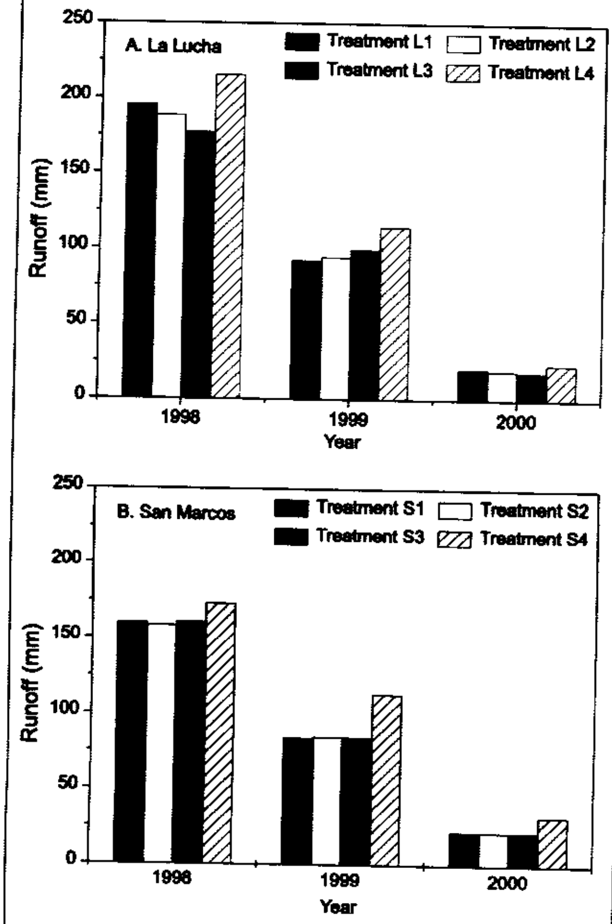
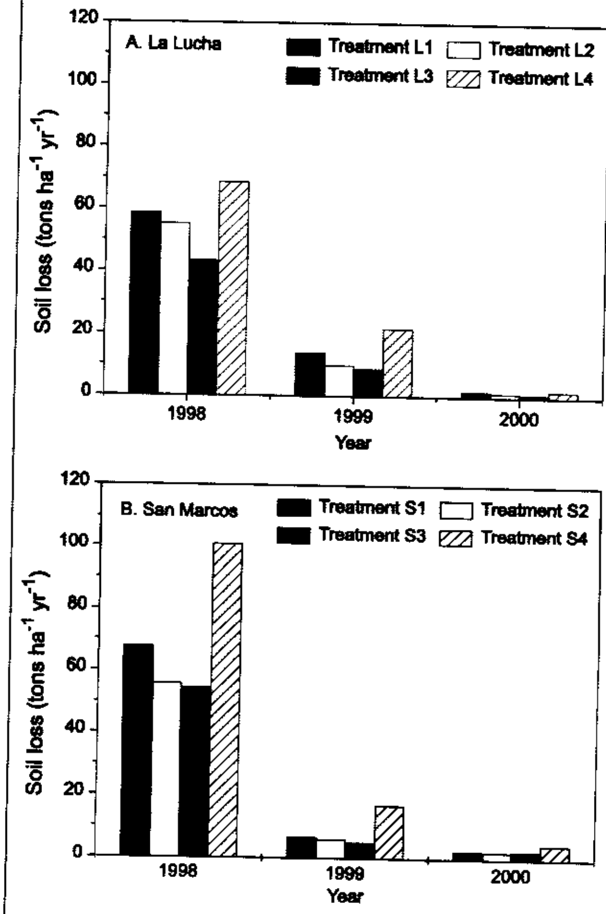


Figure 19. Soil loss in runoff water by treatment from 1998 to 2000 for (A) La Lucha and (B) San Marcos.



were 56, 10.8, and 1.4 tons ha^{-1} yr^{-1} for 1998, 1999, and 2000, respectively. Compared to the control, average soil losses for the hedgerow treatments combined were 81, 49, and 70%, respectively, for 1998, 1999, and 2000, respectively. When the entire 3-year period is considered, total soil loss by the hedgerow treatments at La Lucha was 68 tons ha^{-1} or 73.5% of the 92.5 tons ha^{-1} total soil loss for the control. The largest amounts of soil were lost in 1998 and were associated with the greater than 750 mm of runoff associated with Hurricane Mitch.

Soil losses for the control treatment at San Marcos were 101, 17, and 4.7 tons ha^{-1} yr^{-1} for 1998, 1999, and 2000, respectively (Figure 19B). Soil losses averaged across the contour hedgerow treatments were 63, 37, and 55% of the amounts lost by the control for 1998, 1999, and 2000, respectively. When the entire 3-year period at San Marcos is considered, the total soil loss averaged across hedgerow treatments was 72 tons ha^{-1} or 59% of the 123.5 tons ha^{-1} loss for the control.

Data in Figures 18 and 19 clearly indicate that the *Gliricidia* and *Cajanus* hedgerows decreased runoff and simultaneously decreased the amount of soil material transported off of the plots. At both sites each year, runoff for the control treatment always exceeded runoff from each of the three hedgerow treatments. Even though the average hillside slope at

Figure 20. (A) Phosphorus, (B) potassium, and (C) nitrogen in runoff water and sediment by treatment and year for La Lucha.

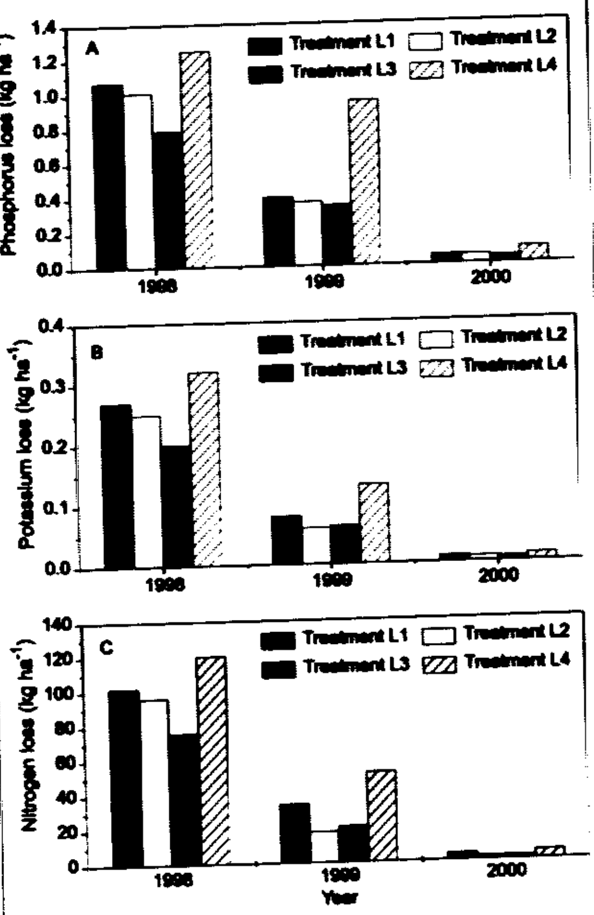
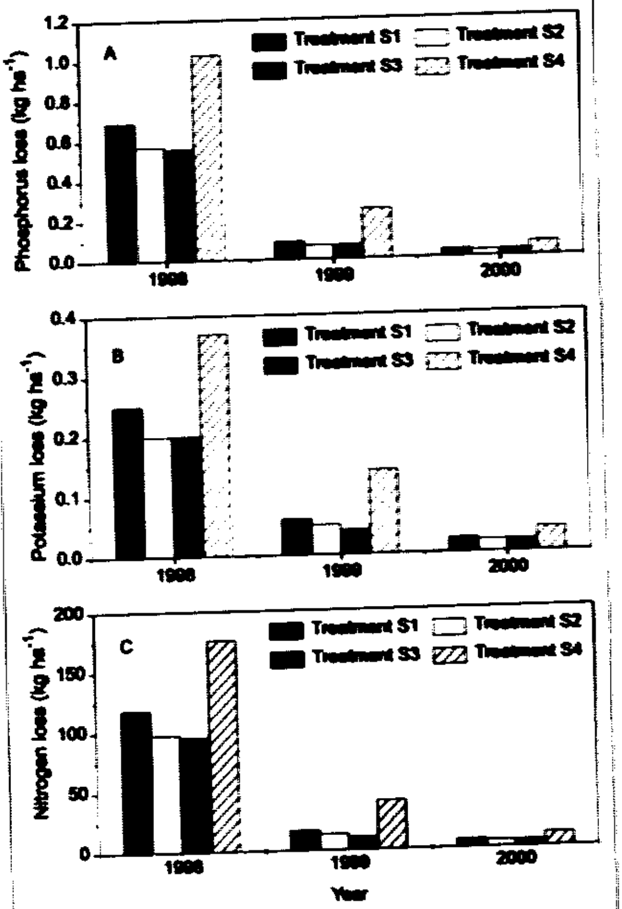


Figure 21. (A) Phosphorus, (B) potassium, and (C) nitrogen in runoff water and sediment by treatment and year for San Marcos.



San Marcos was 14% compared to an average of 35% at La Lucha, the hedgerows at San Marcos were not quite as effective in reducing runoff as those at La Lucha. Several factors may influence this result. Two contour hedgerows were installed on the steeper slopes at La Lucha whereas only one hedgerow was installed in each plot at San Marcos, which made the hedgerow at La Lucha twice as long as the one at San Marcos. In addition, the soil at San Marcos was finer textured, had a slower infiltration rate (discussed later), and had a less permeable subsoil than the soil at La Lucha. All of these factors would tend to increase runoff at San Marcos.

Nutrient losses

Suspended soil material removed from each plot in the surface runoff water was collected and periodically analyzed for P, K, and N. The total loss of each plant nutrient was calculated by treatment for each year (Figures 20 and 21). In general, the patterns of nutrient loss parallel the patterns of water runoff and soil losses (compare Figures 20 and 21 with Figures 18 and 19), i.e., the greatest nutrient losses occurred with the control treatments that had the greatest amounts of runoff and soil loss. Nutrient losses were greatest for all treatments in 1998, the year of Hurricane Mitch, and least in 2000.

At La Lucha in 1998, the land receiving the hedgerow treatments lost on the average only 76% of the P, 75% of the K, and 76% of the N lost by the control (Figure 20). Losses of all three nutrients at La Lucha ranged from 33 to 36% in 1999 and from 52 to 53% of the amounts lost by the control treat-

Figure 22. Actual (AD), vertical (VD), and lateral (LD) marker translocation distances and mean marker depth as affected by tillage operations for growing two crops in 1999 at (A) La Lucha and (B) San Marcos.

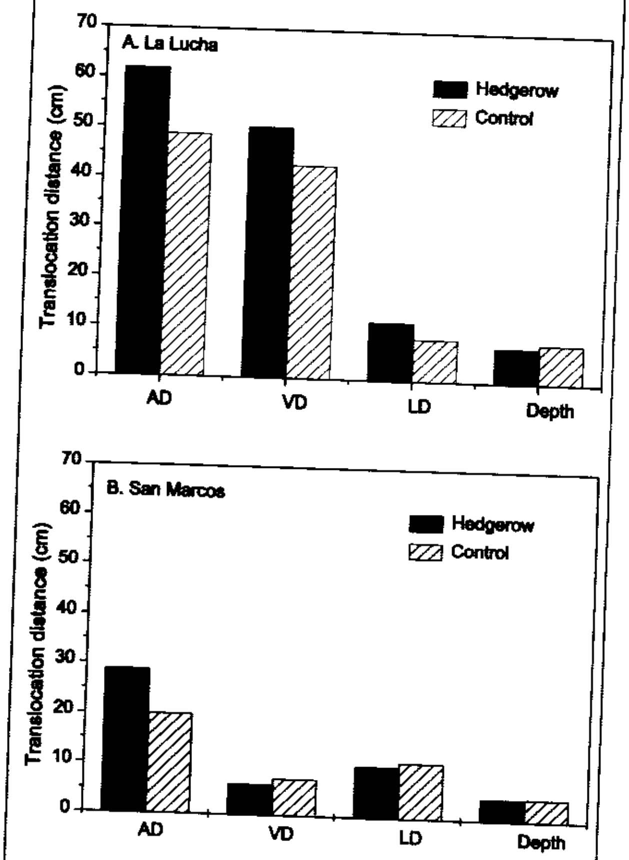
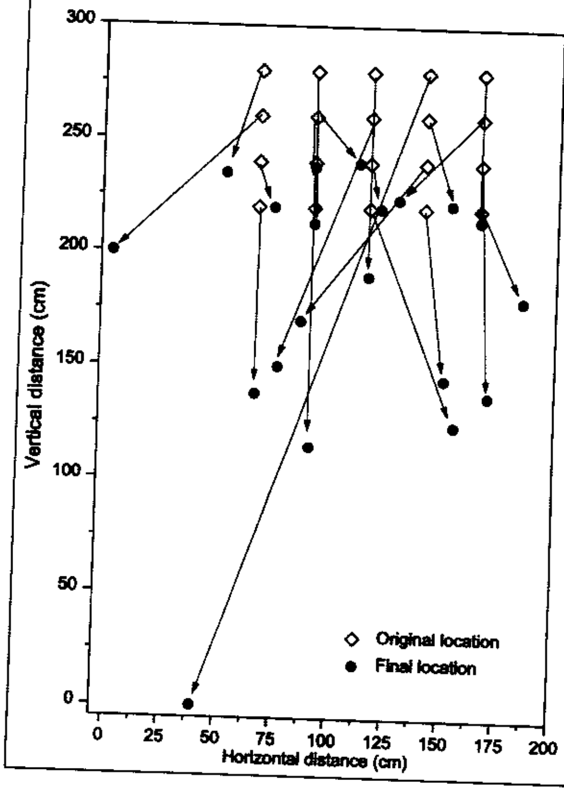


Figure 23. The paths of soil movement markers during the 1999 cropping season. The markers initially were buried 5 cm deep in Treatment L2 at La Lucha.



ments in 2000. For San Marcos (Figure 21), the average nutrient loss across hedgerow treatments in 1998 for each of the elements was 59% of the amounts lost by the control. In 1999, nutrient losses at San Marcos were 33 to 36%, and in 2000, were 52 to 53% of the amounts lost by the control treatments.

Tillage erosion

Displacement of soil movement markers. The metal detector was extremely effective in locating the metal soil movement markers that initially were buried 5 cm below the soil surface. More than 97% of the markers were recovered, which is exceptionally good when compared with other studies. In other tillage erosion studies, the recovery of markers has ranged from 55% in Minnesota (Lindstrom et al., 1990) to greater than 95% for small granite rock markers in the Philippines (Thapa et al., 1999).

For the rainfall regime in 1999 (Figure 3), we assumed that the markers moved only in response to tillage. This assumption is based on the fact that the metal markers are heavy and the total amount of runoff for the entire year did not exceed 115 mm for any treatment (Figure 18). Runoff from any single rain was not great enough to concentrate the water needed to create rills. Runoff water in the rills might have had enough energy to transport the metal markers. Finally, we assumed that soil material moved by tillage was translocated the same distance and direction as the metal markers.

The mean actual translocation distance at La Lucha was 54 cm, based on the 240 markers initially buried (four plots with 60 markers each) and subjected to six tillage operations in 1999 (Table 5 and

Table 5. Mean marker translocation distances and vertical (uphill-downhill)† soil fluxes for hedgerow and control treatments at La Lucha and San Marcos. The positive vertical soil flux values indicate net downslope marker transport.

Variable	La Lucha	San Marcos
Mean translocation distance (cm)		
Actual	54 (72%)†	22 (140%)
Vertical (downslope)	45 (81%)	3 (134%)
Horizontal (lateral)	7 (458%)	11 (262%)
Vertical soil flux (kg m^{-1} yr^{-1})		
Alley 1 Hedgerow	31.5	9.1
(Open field)	22.9	8.1
Alley 2 Hedgerow	51.3	2.9
(Open field)	49.6	7.1
Alley 3 Hedgerow	45.5	—
(Open field)	44.1	—

† Coefficient of variation in parentheses.

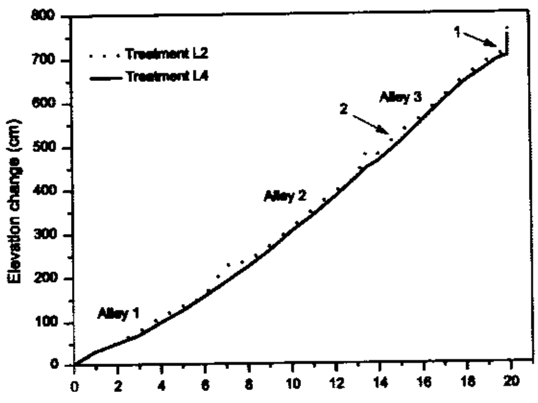
Figure 22A). The coefficient of variation was 72%, indicating a wide range in the translocation distance of individual markers. This variability is illustrated by the translocation paths for the 20 markers used for Treatment L2 at La Lucha (Figure 23). Twelve of the markers moved less than 50 cm, seven of them moved 50 to 100 cm, and one marker moved about 3 m. This latter marker probably was embedded in a clod that rolled downhill during tillage. The mean lateral (parallel to contour) transport distance for all 240 markers at La Lucha was 7 cm, and the mean vertical (up and down slope direction) distance was 45 cm downslope.

For the short, 1-year duration of the marker movement study no link was found between the soil management treatment and the marker translocation distance. This result was anticipated. However, if the markers had been left in place for several years, it is likely that the hedgerows would have slowed downhill marker movement. As the markers continued to move downslope each year they eventually would have been trapped by the hedgerows in the same manner that hedgerows have attenuated the downward movement of soil in past years to form terraces. Analysis of variance showed that the actual, vertical, and lateral translocation distances were dependent on the percentage of slope. For example, at La Lucha vertical displacement was 30 cm for 30% slope, 49 cm for 50% slope, and 55 cm for 56% slope. Because the percentage of slope varied with plot and within plots, large variances in translocation distances were expected and observed (Table 5).

In San Marcos, the mean actual translocation distance for 160 markers (four plots with 40 markers) was only 22 cm (Table 5). This value is about 40% of the actual translocation distance measured at La Lucha, primarily because the hillside is less steep at San Marcos. Mean downslope translocation was only 3 cm whereas lateral translocation was 11 cm. Only vertical marker distance was affected by the percentage of slope at San Marcos.

The degrees of lateral and vertical marker translocation, and therefore soil translocation, are affected by the particular actions and work habits of an individual farmer. Left-handed farmers tend to move soil from right to left when using a pick to loosen soil before planting. Right-handed farmers move soil in the opposite direction. Regardless of whether the farmer is left-handed or right-handed, virtually all farmers prefer to stand on the downhill

Figure 24. Soil surface elevation versus plot length for Treatments L2 (plot 8) and L4 (plot 7) at La Lucha. Arrow 1 shows the "tillage step" near the upper boundary of the plots where soil had moved downslope. Arrow 2 shows the accumulation of soil translocated from above.



side of sloping land when manually tilling it. For this reason, forces exerted on the soil due to tillage coupled with the force of gravity tend to move the soil downslope. Hoeing on the contour tends to move the soil in a lateral rather than downslope direction.

Table 5 shows mean annual downhill soil flux values by alley for La Lucha and San Marcos, calculated using equation 1 on page 16. Downhill soil flux is defined as the mass of soil moving downhill across a 1-m-long line parallel to the contour in one year. The mean soil flux associated with the six tillage operations required for growing corn and bean at La Lucha ranged from 22.9 kg m^{-1} y^{-1} in alley 1 to 51.3 kg m^{-1} y^{-1} in alley 2. Hillside steepness varied with alley and contributed to the differences in flux by alley. No significant correlation between soil flux and the presence or absence of hedgerows was found. This observation agrees with the previous discussion that 1 year is an insufficient time to measure differences in translocation distance among treatments, but is long enough to obtain estimates of annual soil flux due to tillage. Soil flux values at San Marcos ranged from 2.9 to 9.1 kg m^{-1} y^{-1} (Table 5). These values are less than those observed at La Lucha because slopes are not as steep at San Marcos.

The downslope translocation distances illustrate the consequences of unchecked soil movement. For example, if soil is translocated downslope at La Lucha at an average rate of 45 cm yr^{-1} (Table 5), it would take 44 years for soil at the upper boundary of the 20-m-long cultivated plot without hedgerows (control) to move to the lower boundary of the plot. If the layer of soil moving downslope at this rate is 10 cm thick (the depth of tillage), this process would result in a considerable loss of soil resources for a 100-m-wide field. In general, soil flux is dependent on the percentage of slope as reported by Turkelboom et al., 1997.

Topographic survey method. The second method to estimate tillage erosion used topographic analysis. Figure 24 shows the elevation of the soil surface in the runoff plots and in the grass buffer strips adjacent to the runoff plots at La Lucha for Treatment L4, the control, (plot 7), and Treatment L2 with *Gliricidia* hedgerows (plot 8). For Treatment L2, hedgerows were present 6 m and 15 m from the base of the plot. Soil was translocated downslope from the upper region of each plot during the 53-month period as indicated by the depression or "step" that formed in both plots as soil surface material was pulled downslope during tillage with pick and hoe. It is likely that some of the decrease in soil surface elevation at distances between 3 and 6 m and between 10 and 14 m from the base was due to the movement of soil both by tillage and by runoff water.

For Treatment L2, soil surface elevation immediately downslope from the hedgerows (6 m and 15 m) decreased, indicating that tillage operations had translocated soil material out of this region. On the upslope side of each hedgerow in L2, soil material was deposited. When all six hedgerow plots are considered together, an average depth of 32 cm of soil material was translocated out of the region near the upper boundary of alley 3 (see arrow 1 in Figure 24) during the 53-month period. For alleys 1 and 2, a total of 16 and 18 cm of soil, respectively, translocated from regions immediately below hedgerows. These reductions in soil surface elevation cannot be attributed entirely to water erosion, especially at the upper elevation in alley 3 where little surface water runoff occurred. Even if runoff had occurred, it would not have reached a velocity fast enough to generate sufficient kinetic energy to transport soil material from this location.

At La Lucha, the maximum increase in soil surface elevation adjacent to the hedgerows was 43 cm. It is clear that much of the soil loosened by tillage and subsequently translocated downslope from the area 18 to 20 m from the base of the plot for Treatment L2 accumulated in the region above the hedgerow (15 to 16 m from the base of the plot) (see arrow 2 in Figure 24). Changes in soil surface elevation also occurred at San Marcos, but they were not as pronounced as those for La Lucha and are not shown.

Mean soil erosion rates based on the changes in soil surface over the 53-month period for the hedgerow plots at La Lucha and San Marcos were significantly different at the $p = 0.001$ probability level as affected by alley within plot (Table 6). Soil losses at La Lucha were greatest, 23.2 kg m^{-2} yr^{-1}, at the upper elevation (alley 3) and least, 11.9 kg m^{-2} yr^{-1}, in alley 1 at the lowest elevation. Soil loss is also a function of soil steepness; the steepest region occurred in alley 3 where soil loss was greatest.

Mean annual tillage-induced soil erosion rates were less at San Marcos than at La Lucha (Table 6), because overall steepness was less at San Marcos. Erosion rates there were 4.7 and 8.3 kg m^{-2} yr^{-1} for alleys 1 and 2, respectively.

An independent resurvey of the soil surface elevation in all plots and in the grass strip boundaries in January 2001 found noticeable changes in slope. These changes were caused by the translocation of soil due to tillage and water runoff coupled with the deposition of soil on the up slope side of hedgerows during the 65-month period (August 1994 through January 2001). The presence of hedgerows tends to have a leveling effect within each alley. At La Lucha

Figure 25. Cumulative water infiltration for hedgerow and control plots at La Lucha and San Marcos.

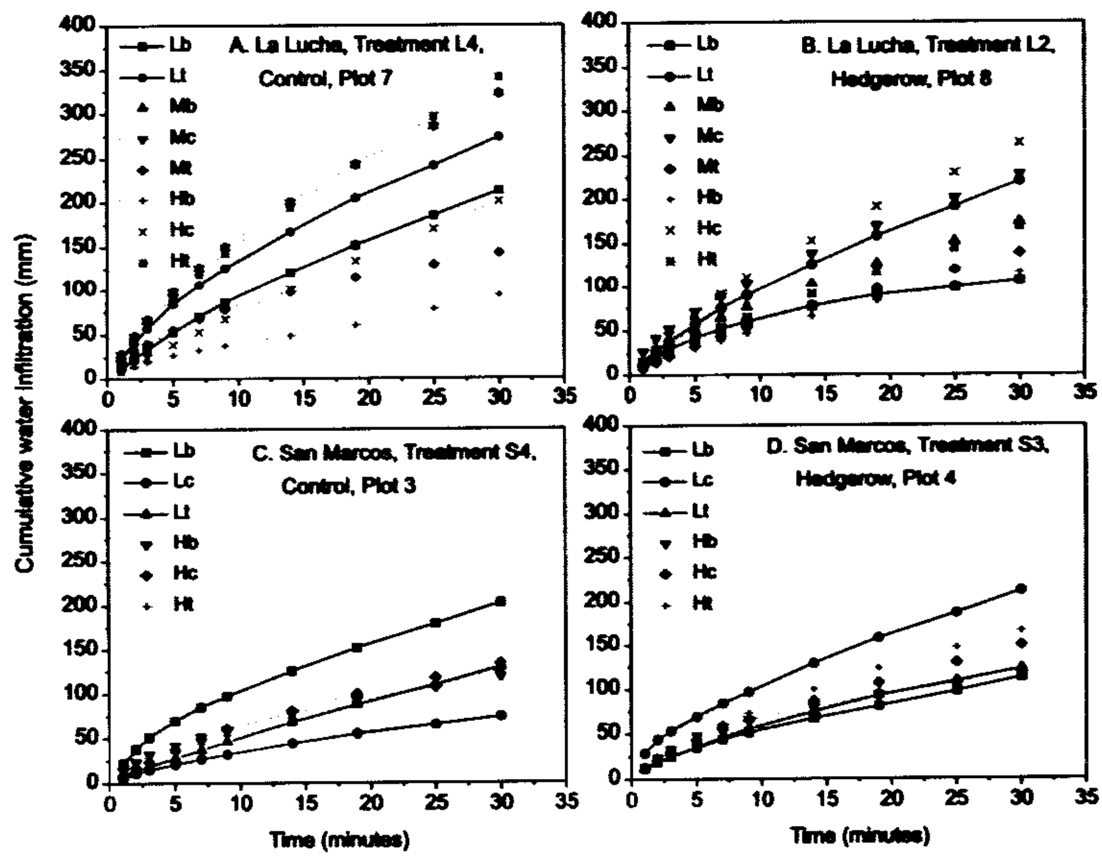


Table 6. Mean annual tillage-induced erosion rate from August 1994 to January 2000 and standard deviation (in parentheses) based on topographic survey analysis for La Lucha and San Marcos.

Location	— Soil erosion rate (kg $m^{-2}yr^{-1}$) —	
	La Lucha	San Marcos
Alley 1	11.9 (5.5) b†	4.7 (1.9) b
Alley 2	14.0 (5.5) b	8.3 (3.8) a
Alley 3	23.2 (3.8) a	—

†Entries in a given column followed by the same letter are not different at the p = 0.05 level.

the percentage slope declined by a nominal 10 percentage units in alley 3 compared to a decrease of 3.5 percentage units in alleys 1 and 2. At San Marcos the percentage slope had a nominal decrease of 0.6 and 2.0 percentage units for alley 1 and alley 2, respectively. These reductions in overall slope within an alley are easily observed with time as the hedgerows promote terrace development.

Infiltration

Extensive infiltration measurements revealed that these soils have very rapid infiltration rates with high short-range variability. Figure 25 shows examples of cumulative infiltration curves (one control plot and one hedgerow plot) for each site. Notice the high variability among the eight measurements, each made in a different region of the plot, for the plots at La Lucha (Figures 25 A and B). For example, for the control treatment, the amount of water infiltrating the soil surface during the 30-minute period ranged from 90 to 340 mm. There was also appreciable variability in the hedgerow treatment, with cumulative infiltration amounts ranging from 100 to 260 mm. The estimated mean steady-state infiltration rate for the entire research area at La Lucha, calculated as the slope of the cumulative infiltration curve between 20 and 30 minutes, was 319 mm hr^{-1}. No differences in the steady-state infiltration rate existed among plots, alleys, treatments, or compartments.

As shown in Figures 25 C and D, cumulative infiltration curves at six positions in two plots, one a control and the other a hedgerow plot, illustrate that the infiltration process and its variability were lower at San Marcos compared to La Lucha. The mean steady-state infiltration rate at San Marcos was rapid at 262 mm hr^{-1}.

In summary, the cumulative infiltration rates and the estimated steady-state infiltration rates at both La Lucha and San Marcos are so high that the soils certainly promote rapid infiltration of water during highly intense rains and allow little water to run off the soil surface. At the beginning of highly intense rains, water-induced erosion would not be expected to be a problem on these cultivated soils. However, after these highly intense rains or after long rains, the upper portion of the soil profile may become saturated. This situation will occur if the soil has an impermeable or slowly permeable layer. When the soil above this impermeable layer becomes saturated, additional water falling on the soil surface will run off. In addition, water in the saturated portion of the soil will flow laterally and downslope. When the impermeable layer becomes completely saturated, it becomes very heavy and its weight may cause the soil to become unstable and shear just above the impermeable layer. This condition can give rise to landslides.

SUMMARY

A number of observations can be made based on the hedgerow research conducted from 1994 through 2000.

1. The use of *Gliricidia sepium* (Jacq.) or *Cajanus cajan* (Jandul) as leguminous contour barriers on cropped runoff plots reduced water runoff and water-induced soil erosion compared to plots without contour barriers. The plots were 3 m by 20 m with slopes ranging from 30 to 55% at La Lucha and from 14 to 20% at San Marcos.

2. Contour hedgerows reduced phosphorus, potassium, and nitrogen losses from steepland soils at La Lucha and San Marcos.

3. Corn and bean yields were highest for the first crops planted after fallow. When commercial fertilizer was not applied, the yields became nearly constant for the second and successive crops.

4. Corn and bean yields varied with landscape position and position within an alley. In general, higher yields occurred at the lower elevations. Shading by hedgerow vegetation within alleys, loss of soil from the upper part of each alley, and accumulation of soil in the lower part of the alley contributed to yield variation.

5. Tillage by pick and hoe translocated soil downslope. The rate of translocation increased as the slope increased. This process contributes to degradation of farmed steepland soils.

6. The infiltration rate was highly variable for all plots for all four soil management systems at both sites. No significant difference in infiltration rate was found among management systems, alleys, or landscape positions at either location. The mean infiltration rate was 319 mm hr^{-1} at La Lucha and 262 mm hr^{-1} at San Marcos. These rates are high enough to minimize surface water runoff and water-induced soil erosion for all but highly intense rains.

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