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EFFECTS OF SOIL DEGRADATION AND MANAGEMENT PRACTICES ON THE SURFACE WATER DYNAMICS IN THE TALGUA RIVER WATERSHED IN HONDURAS

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ABSTRACT

When tropical forests are felled, subsequent land uses affect surface runoff, soil erosion, and soil compaction. In some cases, they can markedly change the hydrology of a region with disastrous effects on human life. The objective of this paper is to investigate the effect of rainfall on stream hydrology due to conversion of primary forests to agriculture. Near surface water dynamics were compared for three land uses on the steep hillsides in the Talgua River Watershed in Honduras: degraded grass-covered field; traditional coffee plantation; and primary forest. Infiltration and surface runoff rates were measured using several methods. A clear difference was observed in hydraulic conductivity between the degraded and non-degraded lands. The degraded grass-covered hillslopes developed a surface restrictive layer with a low saturated hydraulic conductivity of 8 to 11 mm/hr, resulting in more frequent overland flow than traditional coffee plantation and primary forest. Soils under the latter two land-use types maintained high infiltration capacities and readily conducted water vertically at rates of 109 and 840 mm/hr, respectively. Dye tests confirmed that the coffee plantation and primary forest both maintained well-connected macropores through which water flowed readily. In contrast, macropores in the degraded soil profile were filled by fine soil particles. Soils in the degraded grass-covered field also showed more compaction than soils in the coffee plantation.

KEY WORDS: hillslope hydrology; hillslope agriculture; land use conversion; restrictive layers; soil degradation; soil compaction; overland flow; Honduras

INTRODUCTION

Soil degradation resulting in high rates of surface runoff, soil erosion, and soil compaction have been observed for shifting cultivation, heavy grazing, and/or annual burning after conversion from tropical forests (Jasmin, 1975; Costales, 1979; Lal, 1981; Toky and Ramakrishnan, 1981; Hurni, 1982; Lal, 1983; Mishra and Ramakrishnan, 1983; Sato *et al.*, 1984; Hamilton and Pearce, 1987; Smiet, 1987; Spaans *et al.*, 1989; Bruijnzeel, 1990; Spaans *et al.*, 1990; Bonell, 1991). In Honduras, widespread cultivation on steep hillslopes, short fallow periods, and intense rainfall have exacerbated soil degradation even further.

Most rainfall in the Caribbean occurs during a six to seven month period, starting in May. Frequent high intensity storms unleash from 10 to 50 mm of water in less than 20 minutes. Rainfall intensities occasionally reach more than 300 mm/hr, and high percentages of the annual rainfall occur during single storm events, usually lasting less than one hour (Hernández and Crespo, 1982). Flooding is markedly more severe in denuded watersheds due to

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increased storm flow volumes and peak flows once soil antecedent moisture levels are high (Hewlett and Hibbert, 1967; Lal, 1983; Ward, 1984).

A common effect of deforestation on soils is a reduction in the infiltration capacity of the surface soil (Van der Weert, 1974; Dias and Nortcliff, 1985a, 1985b; Lal, 1987; Malmer and Grip, 1989; Spaans *et al.*, 1990). Over time, soil aggregates are destroyed causing an increase in particle dispersion in the subsoil. Both these processes and the loss of topsoil due to erosion augment and quicken surface runoff (Mainguet, 1994). Furthermore, when the infiltration capacity is severely reduced, dry season stream flow can be diminished (Hamilton and King, 1983; Bruijnzeel,1989).

In Central America, slash-and-burn subsistence farming with short regeneration times in old tropical forests on hillslopes rapidly results in infertile grass-covered hillslopes. Once grasses dominate, they are grazed by cattle and subjected to frequent wild fires causing strong increases in storm flow volumes and peak flows (Gupta *et al.*, 1974; Gupta *et al.*, 1975; Bruijnzeel and Bremmer, 1989).

Since 1960, demand for water, land, and lumber have increased sharply in and around Catacamas, Olancho. Simultaneously, dry-season water resources have become scarce. These changes in water resources have been attributed to the loss of the primary forest. A detailed study of the hydrology of the subsequent land-use systems in conversion from tropical forest to grassland has not been conducted previously in this area. Therefore, the objective of this study was to characterize the effects of soil development and management practices on the near surface water dynamics for three land-use types in the Talgua River Watershed in Honduras: (1) grass-covered degraded soil; (2) traditional coffee plantation; and (3) primary forest. Several experiments, appropriate for each land-use type, were conducted to quantify near surface water dynamics with measurements of precipitation, overland, lateral, and vertical flow components in the upper 30 cm of soil and to evaluate the differences between the three land-use types.

MATERIALS AND METHODS

Site Description

Three sites with minimum dimensions of 50 by 50 m were selected in the mountain village of Buena Vista, northeast of Catacamas, Honduras (85° 56·8′ W longitude and 14° 56·6′ N latitude) in the Talgua River Watershed. The sites were located at an elevation of 1200 m.

Most of the primary forest, up to an elevation of 1600 m, has been converted to a variety of agricultural uses since the 1960s. The soils in the area are a smectitic type clay or clay loam. Wide cracks developed to a depth of 1·2 m during the dry season. These cracks closed following the initial rainfall events of each wet season.

Site 1 was a grass-covered hillslope used intermittently for grazing of tethered livestock. The primary forest was felled in 1967, and the trees were left to rot or burn *in situ*. Generally, corn was planted for more than ten years using slash-and-burn practices. Until 1988, hillslopes were fallowed for three to five years followed by corn cropping for two years. Since 1988, without burning, four additional crops of corn and one tomato crop were grown. During the no-crop years, grasses are the dominant fallow crop.

On site 2, the primary forest was cut down and burned in 1972. Corn was planted from 1974 to 1977. In 1978, guama trees (*Inga laurina*) revegetated the hillslope and traditional arabica coffee (*Coffea arabica*; caturra and burbon varieties) was planted. In three years, the coffee produced a crop and intervention became minimal. Normally, brush is hacked to the ground just prior to harvesting the coffee fruit, which is hand-picked once during each month from January through March. Livestock was not observed to enter this area. Site 2 was located north of Site 1.

Site 3 consisted of a tract of primary forest of approximately 1 ha at a location 200 m to the south of Site 1. Within the tract, hillslope areas free of readily visible intervention were used for plot experiments. Grasses did not grow at Site 3, and livestock did not enter the forest. All sites were in close proximity and it is reasonable to assume that differences in soils were minimal prior to intervention for agriculture. The slopes of Sites 1, 2, and 3 were 0·41, 0·34, and 0·31 m/m, respectively.

Measurement Techniques

Different physical measurement techniques combined with visual observations of water transport and brilliant blue dye were used to characterize overland, lateral, and vertical flow, preferential flow pathways, and soil compaction. The physical techniques consisted of isolation of a soil block for runoff and lateral-flow measurements (i.e., lateral-flow lysimeter), partial isolation of a soil block for lateral flow measurements (i.e., hillslope runoff trench), determination of the saturated hydraulic conductivity using soil cores and a bore-hole permeameter, and hand-crushing of soil blocks (Table I). Selection of the physical techniques at each site was governed by differences in surface soil properties such as infiltration capacity, macroporosity, and soil compaction. For example, some infiltration experiments using lysimeters and trench plots could not be conducted at Sites 2 and 3 because of soil slumping or the presence of large tree roots. At all sites, however, observations were made of water and dye flow patterns following infiltration (Table I).

Detailed descriptions and justifications of the techniques are given below. In addition, local residents were interviewed to document indigenous knowledge regarding land-use practices, soil degradation, soil characteristics, and seasonal hydrological phenomena.

Lateral-flow lysimeter. Lateral-flow lysimeters, used also by Mendoza and Steenhuis (2002), were installed at Sites 1 and 2, one per site. These lysimeters were used to measure steady state lateral and vertical flow rates of isolated, undisturbed soil columns as a function of increasing rainfall intensities. A schematic of a lateral-flow lysimeter is depicted in Figure 1. Each column was 65 cm long, 65 cm wide, and 45 cm high. Installation at Site 3 was not possible without severe disturbance of the soil profile due to an abundance of woody roots found immediately below the forest litter layer, and the presence of aggregated soil crumbs.

The lysimeters were installed in planar areas with similar slopes and no observable surface rills. Prior to carving the soil columns, the soil at each location was irrigated twice daily for 20 days, followed by drainage for a period of 12 to 18 hours. This treatment was implemented to avoid smearing of wet soil, yet prevent detachment of dry soil aggregates. Four corrugated roofing strips (65 cm × 5 cm), each with eight channels, were inserted 1·5 cm into the soil parallel to the soil surface at depths of 3, 10, 20, and 30 cm, respectively. The 3 cm depth was chosen after dye tests indicated differences in soil properties at this depth. The depths of 10, 20, and 30 cm were selected arbitrarily. Both side walls and the upper wall of the soil column were coated with a 1 cm layer of mortar to isolate the soil column from its surroundings (Figure 1). Water flowed unobstructed through the bottom end of the lysimeter since the soil column was intact. The mortar wall was made 1 cm higher than the soil surface to prevent overland flow from exiting the lysimeter transverse to the slope or at the uphill side. Integrating V-shaped troughs were used to channel water to separate graduated cylinders.

Irrigation tests were conducted by manually applying a gentle stream of water uniformly over the column area using a hose. Irrigation intensities were kept constant by maintaining a constant head until steady-state outflows were reached. Intensities ranged from 6 to 170 mm/hr. Overland flow and lateral flow were measured at intervals ranging from one second to three minutes providing both transient and steady-state flow data for hydrograph

Table I. Measurement techniques employed at each site

Technique	Site		
	1	2	3
Lateral-flow lysimeter	X	X	
Hillslope runoff trench	X		
Saturated hydraulic conductivity on soil cores	X	X	
Saturated hydraulic conductivity using falling-head borehole permeameter	X		
Hand-crushing of soil tests	X	X	
Dye staining and flow observations	X	X	X

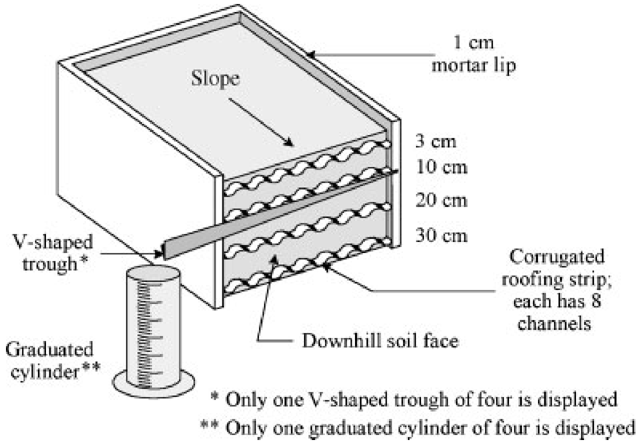

Figure 1. Lateral-flow lysimeter.

analyses. The time of lateral flow initiation, time of collection trough runoff initiation, pan evaporation rates, and natural rainfall inputs for each test were also recorded. Vertical fluxes were measured from the difference in mass balance at steady state for each layer (Mendoza and Steenhuis, 2002). Prior to terminating irrigation tests, the number of channels contributing to the lateral flow at each depth was recorded.

Hillslope trench runoff. One trench was excavated in the hillslope at Site 1 to measure overland and lateral flow rates. This trench consisted of an undisturbed hillslope plot with channelling devices where water was diverted from the surface and subsurface soil layers (Figure 2). The hillslope trench was different from lateral-flow lysimeters because the soil uphill of the hillslope trench was not isolated from the surrounding soil creating a large upslope contributing area. Soil slumping destroyed two hillslope trench collection systems at Site 2, thus, further attempts were deemed too hazardous. No hillslope trench was dug at Site 3 due to the abundance of large roots preventing the installation of roofing strips (see below) and the likelihood of soil slumping.

Each trench, just over 2·5 m wide and approximately 2 m deep, was excavated and fitted with corrugated roofing strips and V-shaped channels similar to the lateral-flow lysimeters (Figure 2). Pre-installation treatment, roofing strip installation and depths, and water-collection procedures were also the same as for the lateral-flow lysimeters.

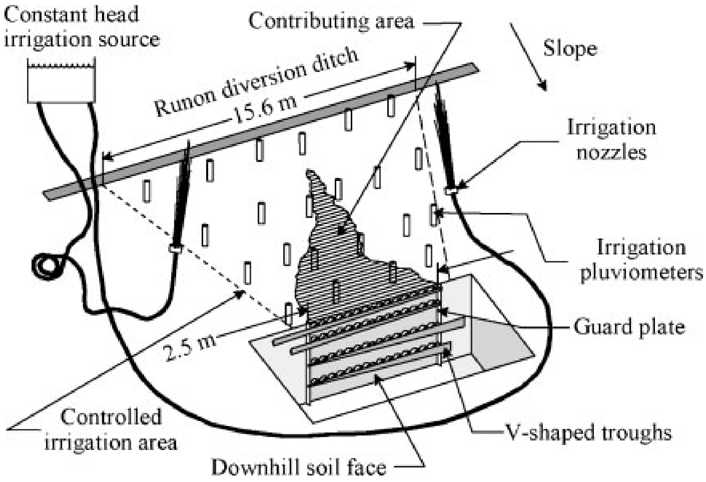

Figure 2. Hillslope trench installation.

To catch and divert surface flow from points above the hillslope plot, a 50 cm deep diversion ditch was dug 8 m above the trench. Sheet-metal guard plates were inserted vertically into the soil seepage face at each end of the corrugated roofing strips to block transverse flow from occurring on the seepage face (Figure 2).

Overland and lateral flow rates were measured during controlled irrigation tests and natural rainfall events. Controlled irrigation consisted of water application over a large area uphill from the trench by manually jetting water, in a near vertical fashion, from one or two garden hose nozzles for specified time periods (Figure 2). Irrigation intensities, ranging from 9·4 to 121 mm/hr, were measured by sampling incident cumulative water volumes in 22–15 ml test tubes placed throughout the plot area (Figure 2). During natural rainfall events, rainfall intensities were measured using a single graduated cylinder with an attached funnel.

After the last irrigation test, the surface area of the plot that contributed runoff to the overland flow contributing area was determined using a gentle stream of approximately 100 ml/min, applied over 20 cm intervals. Flags were placed along the area's border and the area was determined by summing the area of a series of trapezoids.

Saturated hydraulic conductivity of soil surface using small cores. The vertical saturated hydraulic conductivity was determined on 23 and 8 undisturbed soil samples from Sites 1 and 2, respectively. Tests were performed immediately following sample acquisition to avoid soil changes such as cracking due to drying. Each soil sample was held in steel cores with a diameter of 5 cm and a height of 5 cm. Prior to soil sampling, the soil was wetted and surface vegetation and woody debris were removed. Saturated hydraulic conductivity rates were measured by applying 10 ml volumes of water. Ponding depths did not exceed 5 mm, and the outflow rate, therefore, equalled the vertical saturated hydraulic conductivity since the hydraulic gradient was close to unity.

Saturated hydraulic conductivity of surface soil using falling-head borehole permeameter. Eight vertical boreholes with a diameter of approximately 15 cm and a depth of 10 to 20 cm were excavated at Site 1. Prior to borehole excavation, each location was irrigated and drained as described above for the lysimeters. Thin plastic rulers were placed at the base of each borehole (Figure 3). Water was added to each borehole at a rate of approximately 50 ml/min. When full, water delivery was stopped and water levels were recorded during recession. The saturated hydraulic conductivity at varying depths, ignoring capillary flow, was estimated using the equation by Reynolds and Elrick (1985). The saturated hydraulic conductivity could not be determined at Sites 2 and 3 using this method because the water levels receded too rapidly for meaningful measurements.

Hand-crushing of soil. Soil compaction is often measured using penetrometers, devices that measure the force needed to drive a specified object into media. Instead, manual crushing of soil samples was applied here, using surface-soil samples from Sites 1 and 2 at moisture contents near field capacity. Surface vegetation and litter were

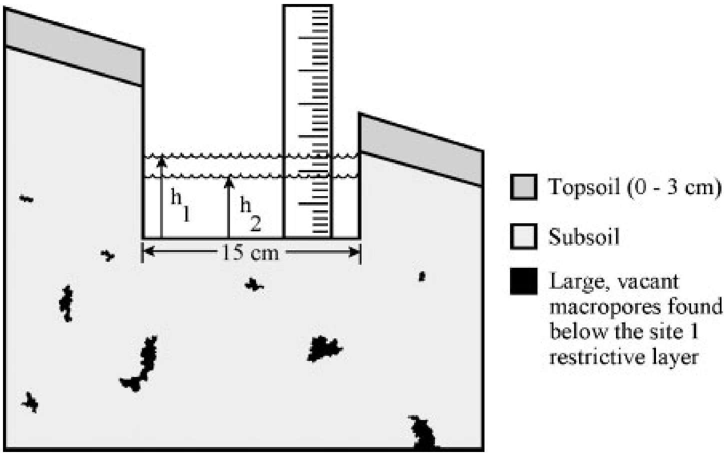

Figure 3. Hillslope falling-head borehole permeameter.

excluded. Twenty-seven farmers were given a block of each soil measuring roughly 500 cm^3. The farmers were instructed to crush each sample separately using the same hand. Their perceptions of the ease of pulverizing the samples were recorded. Samples from Site 3 were not included in this test because of large roots and the inability to wet this soil adequately.

Flow observations and dye visualization. Prior to the final irrigation test using the lateral-flow lysimeters at Sites 1 and 2, and the hillslope trench at Site 1, a slightly adsorbing blue dye (FD&C blue #1 or brilliant blue) (Andreini and Steenhuis, 1990; Flury and Fühler, 1995) was applied in powder form. A total of 100 cm^3 was applied to a surface area of 0·42 m^2. Following the irrigation tests, the soil profiles were cut, photographed, and examined for soil morphological characteristics and flow patterns presented by the dye stains. The vertical extent of dye stains was measured for uniform flow representing matrix pores and preferential flow represented by macropores.

At Site 3, a single irrigation pulse of 840 mm/hr for 15 min was applied over a soil column measuring 0·42 m^2. Blue dye was again applied prior to the irrigation pulse in powder form. After excavation, morphological information was acquired using dye and any lateral flow patterns were visually noted.

RESULTS

Lateral-Flow Lysimeter

Fourteen infiltration tests with the lateral-flow lysimeter were carried out at Sites 1 and 2 and a single ring infiltrometer at Site 3. In each test, the rainfall rate was increased several times once the lateral flows no longer varied and a steady state was obtained. For Sites 1 and 2, a total of 34 steady-state observations of lateral flow were obtained (Table II) for the 0–3 cm (representing surface runoff) and 22 observations for the 3–10 cm (representing shallow lateral flow). The lateral flow below 10 cm depth for Site 1 was negligible and there was some lateral flow in Plot 2 below 10 cm. All sections of the lysimeter contributed above 10 cm (Table II) and the little that originated from below 10 cm in Plot 2 came from a few macropores and, therefore, only a few of the corrugated roofing strip channels contributed water. The steady-state lateral flow rates for the 0–3 and 3–10 cm are plotted in Figures 4a and 4b for Site 1 and 0–3, 3–10, 10–20, and 20–30 cm in Figure 5a for Site 2. The data points were fitted to one or more regression lines. The approximate location of the break points in the lines were chosen visually. We found that at low rainfall rates there was no runoff or lateral flow and the collectors started to collect water only if the rainfall intensity increased.

Percolation rates through the bottom of a layer into the next layer can be obtained by subtracting the total inflow to the upper boundary of the layer by the lateral flow per unit area at the bottom of the layer (Mendoza and Steenhuis, 2002). Consequently, the percolation rate at 3 cm (also called infiltration) is obtained by subtraction of the lateral-flow rate per unit area at the 3 cm depth from the rainfall rate. In Figure 4a, the solid squares are the lateral flow rates and the open squares are the infiltration rates at 3 cm depth obtained by subtracting the overland flow rate (per unit area) from the rainfall rate. Similarly, the percolation rate at the 10 cm depth is obtained by taking the difference of the infiltration (or percolation) rate at 3 cm depth and the lateral flow rate per unit area measured at the 10 cm depth (Figure 4b). The downward flux increases first with increasing rainfall rates and then becomes constant, independent of rainfall rate. The maximum infiltration rate at 3 cm is approximately 20 mm/hr and at 10 cm depth the maximum percolation rate is 11 mm/hr. Only when the percolation rate is nearly independent of the flow rate is the soil saturated and then the percolation rate is equal to the saturated conductivity of the layer below. So, the hydraulic conductivity of the subsoil on the degraded grassland is approximately 1 cm/hr.

For Site 2, the lateral flow and surface runoff is much less than at Site 1 (Figure 5a). Consequently, percolation rates are much higher. In all cases, the percolation rate out of a particular layer increases with increasing flux into that layer (Figure 5b), indicating that parts of the soil remain unsaturated. As shown by Parlange *et al.* (1989), in highly conductive subsoil with cracks, rainfall near the outlet of the box cannot infiltrate and becomes runoff at the surface or lateral flow in the lower layers. For this site, the saturated conductivity in the subsoil is at least 8·9 cm/hr and likely higher.

Table II. Comparison of results from the lateral flow lysimeters and hillslope trench plots

Measuring technique/parameter (mm)	Site		
	1	2	3
Lateral-flow lysimeter			
Number of controlled irrigation tests	27	7	1[a]
Number of visually selected 0–3 cm steady-state lateral flow observations	17	8	na
Number of visually selected 3–10 cm steady-state lateral flow observations	9	13	na
Number of visually selected 10–20 cm steady-state lateral flow observations	0	9	na
Number of visually selected 20–30 cm steady-state lateral flow observations	0	8	na
Calculated peak percolation rate at 10 cm (mm/hr)	11	109	840[a]
Calculated peak percolation rate at 30 cm (mm/hr)	11	89	na
Peak 3–10 cm lateral flow rate (mm/hr)	9	14	na
Hillslope trench plot			
Number of controlled irrigation tests and measured rainfall events	25	na	na
Number of visually selected 0–3 cm steady-state runoff points	8	na	na
Number of visually selected 3–10 cm steady-state runoff points	20	na	na
Number of visually selected 10–20 cm steady-state runoff points	0	na	na
Number of visually selected 20–30 cm steady-state runoff points	0	na	na
Calculated peak percolation rate at 10 cm (mm/hr)	8	na	na
Calculated peak percolation rate at 30 cm (mm/hr)	8[b]	na	na
Peak 3–10 cm lateral flow rate (mm/hr)	5	na	na

[a] The controlled irrigation intensity was measured for a single observational test.
[b] Negligible lateral flow was collected below the 10 cm depth for these plots at Site 1.

Hillslope Trench Plots

Lateral flow in the hillslope trench at Site 1 occurred mostly at the 0–3 and 3–10 cm depths. Lateral flow below 10 cm was minimal and neglected in further analysis. Steady-state lateral flow was reached during 25 controlled irrigation and natural rainfall events providing flow rates for the 0–3 cm depth and 20 flow rates for the 3–10 cm depth (Table II). The results were very similar to that of the lateral-flow lysimeter experiments for Plot 1, although the percolation rates for higher flow rates are decreasing slightly and might be due to plugging up of pores by the sediment generated (Figures 6a and 6b). For the linear regression lines, we ignored this downward trend and took the average of downward flux rates after the percolation/infiltration rates peaked. At the 3 cm depth, the percolation peaked at 8·2 mm/hr and at the 10 cm depth, the maximum percolation rate was 5 mm/hr (Table II). Thus, both the lateral-flow lysimeter, on a small scale, and the hillslope trench plot, on a larger scale, indicated that the infiltration in the subsurface was extremely limited for the degraded soil.

Surface Vertical Hydraulic Conductivity

The 23 soil cores tested at Site 1 showed that outflow rates decreased with time. Figure 7 shows a log–log plot of outflow rates from all 23 tests plotted against time. Outflow rates of cores with macropores are indicated by the star symbol for Plot 1 and an open square with a plus sign for Plot 2. The cores without macropores are indicated using a solid circle for Plot 1 and open square with an ‘x’ for Plot 2. A straight-line fit to these outflow rates using linear

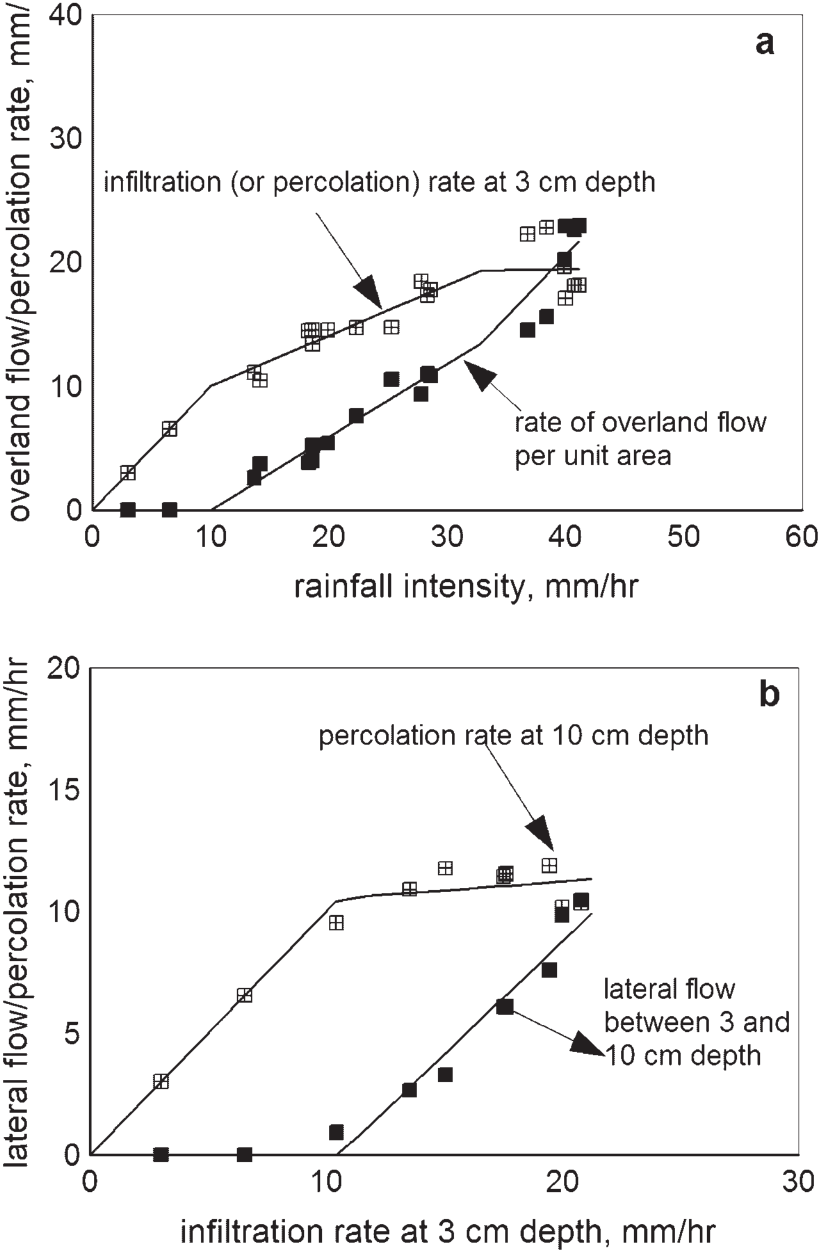

Figure 4. Steady state results for the lateral flow lysimeter at Site 1. Solid symbols are the observed lateral flow rates and the open symbols are the calculated percolation rates. The lines indicate the best fit. (a) Infiltration rate and overland flow rate for 3 cm depth; (b) percolation rate and lateral flow rate at 10 cm depth.

regression represents an overall curve describing the hydraulic conductivity as a function of time ($r^2 = 0{\cdot}14$). Outflow rates for eight tests on cores from Site 2 are also plotted in Figure 7 along with the best-fit straight line ($r^2 = 0{\cdot}10$). Comparison of the two straight lines indicates that the saturated hydraulic conductivity of the surface soil at Site 2 was one order of magnitude greater than that found at Site 1, independent of the duration of the tests. This is in agreement with the findings of the hillslope trench and lysimeter tests.

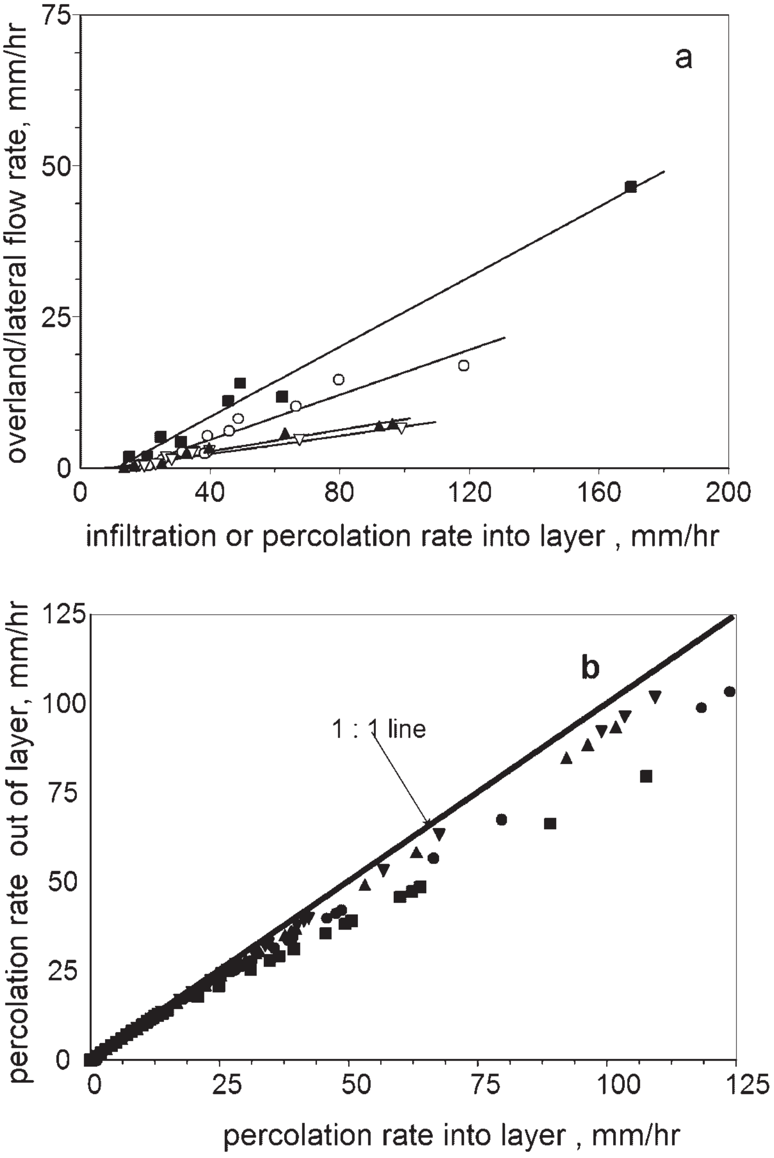

Figure 5. Steady-state results for the lateral flow lysimeter at Site 2. (a) Lateral flow rates; (b) calculated percolation rates. The symbols represent the different depth of observations: 3 cm (squares); 10 cm (circles); 20 cm (inverted triangles); and 30 cm (upright triangles).

Falling-Head Borehole Permeameter

Saturated hydraulic conductivity values measured in six boreholes at Site 1 ranged from 1 to 4 mm/hr for four boreholes that were not connected to any preferential flow paths. In the two other borehole tests, rapid localized flow due to macropores was observed at the base or sidewalls. In one borehole, the saturated hydraulic conductivity reached 15 mm/hr. The sixth borehole stood out from the rest because a water level could not be established. Water escaped from the base of this borehole at a rate of 715 mm/hr, indicating the presence of continuous macropores through which water readily flowed.

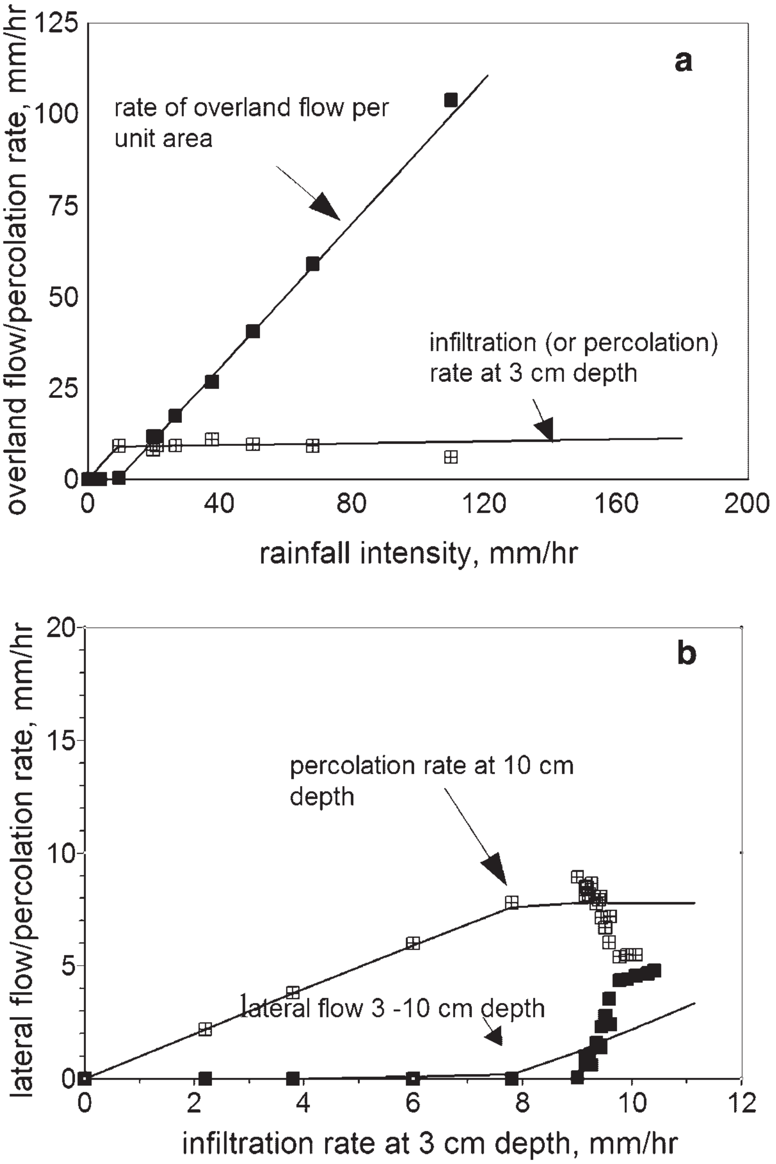

Figure 6. Steady-state results for hillslope trench at Site 1. (a) Infiltration rate and overland flow rate for the 3 cm depth; (b) percolation rate and lateral flow rate at 10 cm depth. Symbols are the same as in Figure 4.

Hand-Crushing of Soil

Farmers recorded clear differences in compaction between the surface soils at Sites 1 and 2 when crushing the 500 cm^3 soil samples. Twenty-seven farmers unanimously reported that the Site 1 samples were dense and impossible to crush using one hand, whereas the Site 2 samples broke after gentle application of pressure. They also pointed out that the Site 2 samples appeared to be fertile soil, much like that in a recently burned fallow plot, coffee plantation, or an area converted from primary forest after two or three years of cultivation. In contrast, they compared the samples from Site 1 to soils found either on washed hillslopes where livestock were maintained, on hillslopes used several times for vegetable production, or for regular production of beans where burning is practiced extensively. Some mentioned that the Site 2 soil was much darker, was not compacted, had remnants of

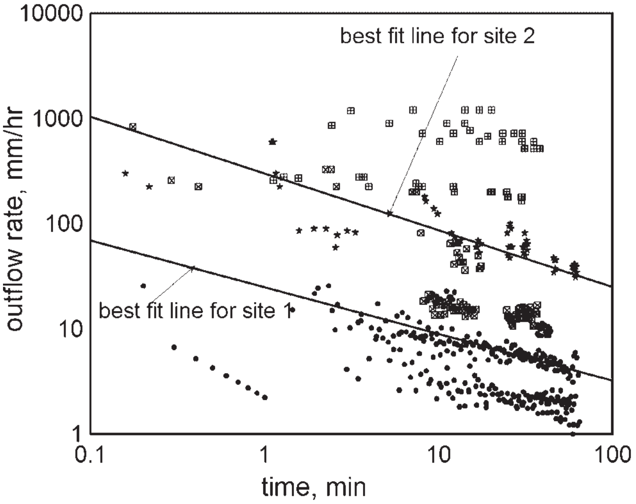

Figure 7. Outflow rates indicating saturated hydraulic conductivity for soil cores at Sites 1 and 2. Site 1 regression line $r^2 = 0{\cdot}14$. Site 2 regression line $r^2 = 0{\cdot}10$. The solid symbols indicate Plot 1 with the stars for the columns with macropores and the circles without. Squares indicate Plot 2. The squares with a '+' sign are for columns with macropores and the squares with an 'x' do not have macropores.

organic matter that had not yet decomposed, and felt lighter than the Site 1 samples. Lastly, the farmers referred to the Site 1 samples as clay (**barro**) and the Site 2 samples as earth (**tierra**).

Flow Observations and Dye Visualization

At Site 1, dye tests confirmed the lateral flow lysimeter results in that the top 3 cm of soil were uniformly stained. From depths of 3–16 cm, preferential flow was traced via stained holes and vertically oriented, threadlike cracks, and channels. Between 16 and 32 cm, the vertically oriented cracks often led to large, open voids with some hair-like roots and partial wall linings made up of residual epidermal layers of tree roots. The largest of these voids measured 3 cm in diameter. Surface-soil compaction, plugging and clay swelling appear to have created a restrictive layer that breaks connectivity of large pores between the surface and subsoil at Site 1. The large pores carry most of the water when the soil becomes saturated near the surface.

The topsoil at Site 2 was stained uniformly blue to a depth of 2 cm. Below 2 cm, water was channelled vertically through similar cracks and channels as at Site 1. The number of cracks and channels, however, was much higher at Site 2 than at Site 1. In agreement with the calculated percolation rates, dye stains below 2 cm indicated that water readily passed into this soil to considerable depth.

Lateral flow was not observed at Site 3 from the soil between the litter layer and the clay subsoil found at a depth of 35 cm. Some water, however, flowed laterally at the surface over dead leaves. It was observed that this water channelled to specific surface entry points and then moved vertically. After 10 minutes, seepage began from the clay subsoil. Shortly before irrigation terminated, two small gushing outlets were visible at a depth of 29 cm. Blue dye stains revealed that water completely wet the surface leaves at Site 3. The decomposing organic matter immediately below these leaves to a depth of 2–3 cm, however, had limited staining. Water was concentrated by the dry leaves and then descended via a few preferential channels, crossing the entire woody-root and aggregated soil-crumb layer while leaving few stains (Figure 8). Once water reached the clay at a depth of 35 cm, the dye spread and was retained in blobs that extended downward to a depth of 71 cm until irrigation was terminated.

DISCUSSION

Soil degradation has caused a reduction in the hydraulic conductivity of soils after forests were converted to agricultural lands. Our results show that the infiltration rate of the forest site was the greatest followed by the coffee

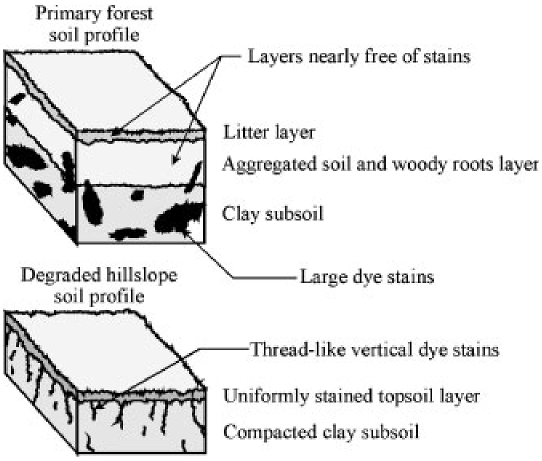

Figure 8. Schematic of soil profile degradation from primary forest to grass-covered hillslope.

plantation site. The infiltration rate and hydraulic conductivity was lowest at the grass-covered degraded hillslope site. The evidence and reasons for the reduction at each site and measures to restore deep percolation in the most degraded areas are discussed below.

The Primary Forest (Site 3)

Between the surface and a depth of 35 cm at Site 3, infiltration capacities were very high (i.e., greater than 840 mm/hr). Consequently, runoff was not observed in the primary forest, and Hortonian overland flow did not occur. Traces left from blue-dye experiments showed that the surface litter funnelled water into a few preferential flow paths (i.e., macropores). Without dispersing, water then passed through a layer abundant in woody roots intermixed with soil aggregates until it reached a friable, aggregated clay at 35 cm. At this depth, a transition occurred, and water spread into numerous large, stained volumes within the clay. The bulk of the water storage took place in the clay encountered below 35 cm (Figure 8). Dye staining suggests that the connectivity between the surface and subsoil at the forest site was excellent. Given this connectivity and in the absence of runoff in the primary forest setting, it follows that high percentages of the water from major storms will become either evapotranspiration or deep percolation. Deep percolation, in turn, is necessary for base flow of streams during the dry seasons.

The Coffee Plantation (Site 2)

Coffee plantation soils have high infiltration capacities, large storage capacities, and good connectivity between the root zone and deep soil layers. Hydraulic conductivity at Site 2, to depths of at least 30 and 10 cm reached 89 and 109 mm/hr, respectively. Saturated hydraulic conductivity values for the surface soil ranged from 10 to 1000 mm/hr. These values are higher than the intensities of most rainfall events in the watershed, therefore, precluding Hortonian overland flow in coffee plantations.

Similar to the forested site, dye staining and flow observations revealed that surface litter also funnelled water into macropores. Several differences, however, were observed between Sites 2 and 3. While blue-dye stains of tiny cracks and holes between the depths of 2 and 24 cm suggest rapid vertical flow at Site 2, the transition to zones of high water storage, identified by large dye stains at depths between 24 and 44 cm, occurred higher in the soil profile than at Site 3. At the 24 to 44 cm depth, the clay structure was also considerably blockier at Site 2 than at Site 3, where it was more friable and aggregated. Dye stains at Site 2 were planar rather than three dimensional as at Site 3. The maximum depth at which dye stains were encountered at Site 2 was 57 cm, again shallower than that at Site 3. These differences indicate some soil degradation at the coffee plantation relative to the primary forest.

Results from the lateral-flow lysimeters are in agreement with dye-staining observations at Site 2, suggesting good connectivity between pores down to deep soil layers. First, lateral flow was observed at all depths in the lateral-flow lysimeter. Second, when the irrigation intensity was increased, lateral flow at all depths also increased (Figure 5). Thus, in coffee plantations, storm-event water will be available for evapotranspiration and dry-period stream flow, although some lateral flow may return as overland flow downslope.

The Grass-covered Hillslope (Site 1)

In stark contrast to Sites 2 and 3, water was unable to percolate downward rapidly at Site 1. The hydraulic conductivity between the surface and a depth of 10 cm was only 10 mm/hr (Figures 4 and 6). Saturated hydraulic conductivities at Site 1 were also an order of magnitude lower than at Site 2. The excessive lateral flow near the surface and dye staining showed that the soil between the surface and a depth of 10 cm became a restrictive layer. This layer prevented most vertical water flow from the surface to lower depths, where macropore structure was observed to still exist.

Infiltration experiments support the formation of a restrictive layer. Lateral flow in the lysimeters and hillslope trench was minimal at depths below 10 cm. The surface soil to a depth of 10 cm had much lower infiltration rates (9 and 11 mm/hr) at Site 1 than at Site 2. Most saturated hydraulic conductivity values from the borehole permeameter tests were very low as well, although some remnants of localized connectivity were observed in the borehole where the water level never rose.

The restrictive layer was likely formed by downward movement of silt and clay particles as documented by Thomas (1994). During the first intense rainfall event in the watershed in May of 1998, silt, blades of grass, leaves and tiny brush fragments were washed into cracks to a depth of 12 cm at Site 1, while Site 2 remained free of debris and silt. It is believed that the risk of sealing and dispersion of soil aggregates is greatest when intense rainfall takes place over very dry topsoil, as seen at Site 1 (Lal and Greenland, 1978).

The presence of a restrictive layer at Site 1 implies increased overland flow losses from the grass-covered hillslopes during major storm events (Boll *et al.*, 1998; Walter *et al.*, 2000). Clearly, the grass-covered hillslopes at Site 1 show a high degree of soil degradation, which allows for much lower storage of rainfall in the soil and reduced deep percolation. Therefore, less water is available for evapotranspiration and dry-season stream flow.

Implications for Management

Our results show that soil degradation leads to filling in of macropores in the surface and results in decreased infiltration rates and more runoff. Dye-staining tests show degradation at Site 1 had not destroyed the macropore structure below a depth of 16 cm. This was confirmed by the very high infiltration rate for an extended period in one borehole that was apparently connected to the macropores in the layer below. Because of the low infiltration rates, the amount of water stored in the soil that is available to the plants is limited. In order for the degraded hillslope to become productive, management strategies need to be developed that increase both infiltration rate and storage of water. A practical rehabilitation technique may be the planting of guama (*Inga laurina*) trees or other coffee-friendly shade trees. To enhance deep tree-root development water needs to infiltrate to the deeper layers. This might be accomplished by perforating the impermeable layers with auger holes and filling them with sand through which the water can flow downward. Once established, the trees will provide surface litter, protect the soil against splash, and maintain vertical channels for deep percolation, thereby providing additional soil-water storage in the subsoil beneath the restrictive layer.

Finally, how generally applicable are our results? It is true that management practices can have a large impact on soil properties. It is obvious that if the regeneration period is long in the slash-and-burn system, the soil properties will closely resemble the properties of the primary forest site. Systems that have short recycle times and have been used for cash crops will resemble those of the grass-covered hillslope of Site 1. Likely exceptions to this rule are soils that have a high saturated conductivity in the absence of macropores such as oxisols and volcanic soils.

In summary, improving subsurface pore connectivity and deep percolation is the key for sustainable agriculture in the Talgua River watershed. If these degraded hillslopes can be made to store more water, it will permit the cultivation of crops such as coffee. In addition, increased storage of water in the subsoil may serve to augment the dry-season stream flows.

CONCLUSIONS

In this study, the effects of soil degradation and management practices on near surface water dynamics were determined for three land-use types in the Talgua River watershed in Honduras: (1) grass-covered degraded soil; (2) traditional coffee plantation; and (3) primary forest. Lateral-flow lysimeters and hillslope trench methods were used to measure overland, lateral, and vertical flow simultaneously. Blue dye was used for visual documentation and differentiation of water-flow patterns and macroporosity. Saturated hydraulic conductivity was measured using surface soil cores and *in situ* using falling-head borehole permeameters. Lastly, hand-crushing of soil samples provided information regarding surface compaction.

Collectively, these techniques characterized the hydrological behavior of the soils and near surface soil compaction. Percolation rates and vertical connectivity in the soil profile were greatest at the forested site and decreased successively at the coffee plantation site and grass-covered hillslopes. Where percolation of water was significantly reduced within soil profiles, lateral flow and/or overland flow increased. Most importantly, the common agricultural practices, including frequent burning and poor surface cover for protection from intense rainfall, have lead to the formation of a restrictive layer at the surface on degraded hillslopes. Surface runoff is common on these degraded hillsides for rainfall intensities exceeding 8 to 11 mm/hr.

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