Estimating the Impact of Soil Degradation on Agricultural Production: A Pilot Study in the Venezuelan Andes

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Abstract: Over a period of five years, in situ field examination of twelve agricultural plots was conducted in the Pueblo Llano Valley in the Venezuelan Andes to assess the impact of soil erosion on potato yields. The objectives of the study were twofold: (1) To quantify the erosion rate by comparing uncultivated sites with natural vegetation with cultivated plots through stratigraphic analysis; (2) to estimate the link between erosion rate, certain soil properties and yield. In this paper various functional forms relating crop yield to depth of the A horizon and several physical and chemical soil properties are estimated using nonlinear and stepwise regression analysis.

Keywords: soil erosion-productivity relationship, Venezuelan Andes

1 Introduction

The problem of soil erosion is highly acute in the Andean highlands of northern Venezuela where rapid population growth and land tenure inequities have caused the adoption of land-use patterns that have led to accelerated land degradation. To sustain their families, migrant sharecroppers from Columbia and local farmers have increasingly become dependent on income derived from the cultivation of horticultural products and their sales in urban markets. The technique applied by farmers in the high valleys of Pueblo Llano (State of Mérida) of clearing forests and páramo vegetation on high gradient slopes and of cultivating the hillside land without systematic terracing is a reflection of the pressure for high-yield farming. Acreage for cultivation of the two main staples, potatoes and carrots, for instance, increased between 1975 and 1995 by a factor of 5 and 11, respectively. (CORPOANDES, 1996).

Various methods have been applied to determine the effect of soil erosion on crop yields each having inherent merits and limitations (Olson *et al.*,1994; Lal, 1997; Lee *et al.*, 1997). A common approach has been to estimate two equations: a soil loss function and a production (damage function). The most widely used erosion function is the Universal Soil Loss Equation (USLE) of Wischmeier and Smith (1978) and its revised version (RUSLE) which includes several improvements over the USLE (Renard *et al.*, 1996). Soil loss indices computed from the soil loss equation are used as input data in the yield damage function which relates the change in agricultural output to the loss of topsoil and a set of control variables (Walker and Young, 1986; van Vuuren, 1986, Frye, 1987). This approach is mostly not feasible in developing countries. Regression estimation of the damage function requires a sufficiently large number of observations on soil loss. The use of a soil loss function to provide data on soil loss over an extended period of time necessitates the frequent re-estimation of the technical parameters based on detailed land surveys and weather records. Most developing countries lack the administrative infrastructure and finances for a comprehensive monitoring system to collect and continually update the required data. A few studies have attempted to estimate soil loss equations for particular areas in developing countries using site parameters established for specific locations in the United States (e.g. Veloz *et al.*, 1985). Given the large spatial variability in soil composition, topography, vegetation and climate between countries, the application of U.S. parameter estimates in contexts outside of the United States requires considerable faith.

The approach chosen in this study does not require the repeated estimation of a soil loss function (Drost, Mahaney and Bezada, 1999). It is based on in-situ field examination, i.e. estimates of soil loss are derived from stratigraphic analysis of uncultivated and cultivated soils. These estimates together with a set of soil parameters are used to predict changes in potato yields as a function of soil erosion.

2 Study area

The study site is the Canoa Valley, a small side-valley in the south-west of the Pueblo Llano Valley. The Pueblo Llano basin extending over an area of approximately 9550 hectares is located in the western Sierra de Santo Domingo (between 70° 34′ and 70° 43′ W, 8° 53′ and 9° 1′ N). The Sierra de Santo Domingo forms the northern extension of the Sierra Nevada de Mérida, a major northeast trending mountain range in the Venezuelan Andes. The Canoa Valley is one of several moraine complexes in the Sierra de Santo Domingo. The natural soils in La Canoa are formed in till, glaciolaccustrine, and glaciofluvial deposits that range in age from Middle to late Pleistocene. Most soils are stony, formed on slopes of 20° —35° , and are unstable with the natural vegetation removed. The valley features altitudes between 2,800 and 3,500 m a.s.l.. The natural vegetation up to an elevation of ca 3,000m a.s.l. is subalpine forest (Podocarpus-Alnus-Ilex); the frailejón (Espeletia Shultzi), huesito (Hypericum Caricoides) vegetation typical of the páramo dominates above 3,000m a.s.l. The mean annual precipitation is 1,200 mm, with most rainfall occurring in May and June, and mean annual temperature is 10℃. Monthly mean temperatures vary little during the year. Seasonal changes in temperature are mainly manifested by an increase in diurnal range during the dry season , and the effect increases with elevation (Yuretich, 1991).

During the 1990s, the páramo of La Canao has been rapidly transformed by local farmers from Pueblo Llano and Columbian sharecroppers. On both sides of the valley farmers have cleared the natural vegetation in order to cultivate potatoes and carrots to elevations in excess of 3,000 m a.s.l.. The 3,000 m a.s.l. elevation marks the approximate terminal position of glaciers during the last glaciation, and as farming advances above this elevation, the soils encountered are younger (<15,000 years) and thinner. The site was chosen because it allows comparison of soil erosion in uncultivated areas with natural vegetation and recently cultivated sites in similar landscape positions having the same slope shape, length and gradient.

3 Population and land use

According to the 1990 Census, the population of the municipality of Pueblo Llano in 1990 was 7022 (OCEI 1990). Of the approximately 950 agricultural producers in the Pueblo Llano Valley (the geographical boundaries of the valley coincide roughly with those of the municipality), the large majority (78%) are sharecroppers most of whom are cultivating plots of less than 2 ha. About 15% of the farmers cultivate fields of 2—5 ha and 7% are classified as large producers (>5 ha), (Corpoandes, 1996). Sharecropping is the most frequent contractual arrangement in Pueblo Llano’s agricultural system. During the last two decades, labour shortages have created a sellers’ market in which migrant workers, mostly from Columbia’s Garcia Rovira province, largely determine the overall supply of labour. Thus, a sharecropping arrangement formerly based on the inherent inequality among those which have access to the land on one hand, and those who offer their labour services has been transformed into an arrangement among relatively “equal” partners, who mutually negotiate their access to a resource scarce to each other.

Since the late 1980s, the local economy has experienced a renewed boom in horticultural activity. On the supply side, several factors have contributed to the boom: the introduction of high-yield seed potatoes mostly imported from Canada, the construction of gravity irrigation systems and the large influx of migrant workers. The rise in production and the increased specialization in cultivating only two products-potatoes and carrots- reflects the growing urban demand for these horticultural products.

The introduction of gravity irrigation systems during the dry season (December—April) has changed farming from the traditional one-year cycle to three cycles of planting and harvesting per year with no intermittent fallow periods. While the crop yields of this technology are relatively high in the short run, the returns are rapidly declining over time due to the loss of top soil caused by runoff and erosion and the associated loss of organic matter and moisture-holding capacity. In an attempt not only to offset the adverse effect of soil loss on output but to raise productivity, farmers have increased the use of commercial fertilizer. Due to the recent elimination of government subsidies the cost of commercial fertilizer have sharply increased. To offset the cost increase, producers are turning to organic fertilizer, applying either chicken manure in each planting cycle, or goat manure every third planting. Ox-plow is the primary tillage implement. Depth and angle of furrows to slope vary according to crop and reflect the experience of individual farmers. The angle determination is an optimization problem trading the short-run benefit of plant protection against the medium and long-run cost of topsoil loss. If fields are ploughed at an 45° angle, the crust of furrows could break under heavy rainfalls increasing the likelihood of the destruction of plants. On the other hand, tilling at an 45° angle reduces potential erosion from heavy rainfalls.

4 Methodology

The study was conducted over a period of five years, 1996—2000. The sample consisted of twelve potato plots which were cultivated for the first time in 1995/1996. The average plot size in our sample is 1.6 hectares. For control purposes, only agricultural plots were selected that were directly adjacent to uncultivated areas with natural vegetation. Each farmer was asked to keep cultivation practices the same throughout the study period. Twelve transects, varying in depth between 80 cm—100 cm, were established parallel to the slope in the agricultural plots and three transects in uncultivated reference soils. Three measures of depth of the A horizon were taken annually from each transect The same number of soil samples were collected each year from both sets of transects and soil fertility parameters were determined using standard chemical methods of soil analysis. The moisture content was determined and the samples were sub-sampled for particle size and mineralogical analysis by XRD. The particle size analysis follows Day (1965); the coarse fractions(63 μm—2,000 μm) were separated by wet sieving whereas the fine (0 μm—62 μm) fractions were determined by hydrometer. The size separates follow the Wentworth scale of Folk (1968); the 2μm boundary between clay and silt follows the Soil Survey Staff (1998). The XRD analysis of the clay size fraction was achieved with a Toshiba ADG-301H diffractometer with CuK alpha and Ni-filtered Cu Kα radiation on oriented mounts. Sub-samples of the <2μm were analyzed for primary and clay mineral content and amounts of various minerals present were determined by peak height on a semiquantitative scale from trace to abundant. Heavy minerals were separated by gravimetric methods (Mahaney and Milner, 1998).

In a first step, declining depth of the A horizon was used as a proxy for the deterioration of soil properties due to erosion. Since the yield - soil loss relation is a reduced form various linear and nonlinear functional forms were examined by regressions relating yield to depth of the A horizon. The following modified specification of the Mitscherlich- Spillman model (M- S) provided the best fit to the data:

(1) $Y = b_0 + b_1 (1 - \exp(-b_2 \text{ (depth of A horizon)}))$

where Y = yield of potatoes (kg/ha), b_0 = yield at 0 cm A horizon; b_1 = difference between the yield at 0 cm A horizon depth and maximum depth and b_2 defines rate at which the maximum yield is approached as topsoil depth changes.

In a second step, several explanatory variables were added to determine the contribution of these variables toward predicting yield variability relative to depth of the A horizon. The following linear model provided the best results

(2) $Y = \alpha_0 + \alpha_1 X + \varepsilon$

where X is a vector of explanatory variables and ε is a mean zero, random disturbance term. In addition to the thickness of the A horizon, the vector of independent variables included soil texture - sand (SA), silt (SL), clay (CL) - , soil bulk density (BD), macroporosity (Ma), the soil parameters C, pH, P, a dummy variable for seed quality (QS = 1 if imported seed potatoes were used), and a dummy variable for ownership (SC = 1 if plot was cultivated by sharecropper). The rationale for the last variable is that sharecroppers are assumed to have a relatively shorter planning horizon and therefore apply technologies aimed at maximizing yields in the short run to the detriment of soil productivity in the long run. Since the problem of heteroskedasticity was of concern, the Lagrange multiplier test of Breusch and Pagan (1980) was employed to test for heteroskedasticity.

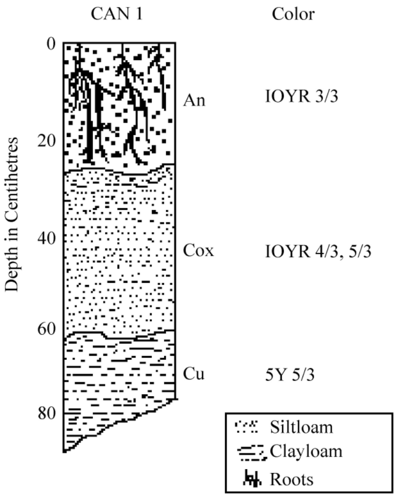
Data on potato yields and types of seeds were directly collected from the producers at the time of planting and harvesting, respectively. The data were cross-checked with statistics collected by

CORPOANDES, the local co-operative which serves as the central buyer of horticultural products and distributor to the urban markets.

5 Results

Soil analysis: The geomorphological results reported below apply to the CAN 1 (Canoa) paleosol profile (Fig.1) which is a representative profile of soils in the La Canoa Valley prior to cultivation. Its properties are used as benchmarks in this study. The soils are Entisols with either A or O horizons. The textures are pebbly sandy loam for the most part and soil structure is apparent only in the A horizons where weak to moderate granular forms are present. Root systems often penetrate into the upper Cox horizons. This paleosol ^{14}C dated at 12,950 ± 450 (Ta-2,521) is representative of soils formed in fine-grained glacio-lacustrine parent materials. The Entisols with their thin O/Cox/Cu profiles (Soil Survey Staff, 1998), and high ratio of clasts/fines, are particularly susceptible to erosion by excessive surface runoff on agricultural plots.

Figure 2 shows particle size distribution and selected soil properties. The data classify the samples from CAN 1 as sandy loam to sandy.



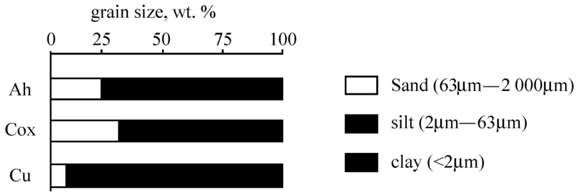


Fig.1 CAN 1 **Fig.2** Distribution of sand, silt, and clay in CAN 1

Both the sands and silts are dominated by aluminuous metamorphic mineral suite characteristic of this region. Distinctive sillimanite, tremolite-actinolite, zircon and rutile dominate with anomalous amounts of golden micas in some samples. This indicates a uniformity of parent material with minor environmental variations—the micas representing local lacustrine environments. The clay and primary minerals (Table 1) most prevalent include illite, quartz, illite-smectite, chlorite, with occasional occurrence of muscovite, biotite, plagioclase, and halloysite.

Table 1 Mineralogy[a] of the < 2µ m fraction in paleosol CAN 1

Horizon	MH	I	I-S	S	V	C	Q	B	MU	P	0
Ah	-	XXX	tr	-	-	X	XX	-	X	-	-
Cox	X	XXX	XXX	-	-	XX	XXX	X	X	X	-
Cu	X	XXX	XXX	-	X	-	XXX	X	X	X	-

Minerals: MH = Halloysite/Metahalloysite, I = Illite, I-S = Illite-Smectite, S = Smectite, V = Vermiculite, C= Chlorite, Q = Quartz, B = Biotite, Mu = Muscovite, O = Orthoclase, P = Plagioclase.

[a] Mineral abundance is based on peak height: nil (--), trace (tr), small (X), moderate (XX) and abundant amounts (XXX).

The soil parameters in Table 2 with a slightly acidic pH value and medium humus content favor the cultivation of potatoes, while the nutrient contents of P and K are relatively low.

Table 2 Means and standard deviation of chemical soil properties

N = 180	pH[1]	Conductivity[2] (µS/cm)	C (%)[3]	N_{tot} (%)[4]	P[5] (mg/kg)	K_t[6] (mval/100g)
Mean	4.43	90.3	2.78	0.36	7.18	0.42
SD	0.32	18.7	0.73	0.09	4.65	0.16

[1, 2] soil : water = 1:2; [3] humid oxidation (Walkley-Black); [4] Kjeldahl digestion; [5] Extraction with $NaHCO_3$ at pH 8.2 (Olsen); [6] Extraction with 0.5M NH_4Ac at pH 7.

Regression analysis: The average thickness of the A horizon at the beginning of the study period was 31.6 cm. After five years, the thickness was reduced on average by 9.8 cm. In comparison, soil loss in the areas under natural vegetation was 0.43 cm over the five years.

Using nonlinear least squares procedure equation (1) was estimated based on 180 observations.. The estimation equation is

$$Y = 10{,}972 + 4{,}362\,[1–\exp(–0.043\,A)]^{-}.$$

All coefficients are significant at the 1 percent level and the model has an R^2 value of 0.53. A yield difference of 4,362 kg/ha is defined from a low yield of 10,972 at 0 cm *A* to a maximum expected yield of 15,334 kg/ha, if depth of the *A* horizon is not constraining. The predicted maximum yield is reasonable given the range of data collected for the twelve sample plots. The rate of the approach to the maximum yield as A increases is 0.043.

Table 3 lists the variables used in estimating equation (2) with their corresponding means and standard deviations.

Table 3 Mean value and standard deviation of regression variables

N = 180	Y kg/ha	A cm	SD %	SL %	CL %	BD g/cm^3	Ma%	C (%)	pH	P mg/kg	QS	OS
Mean	13,023	27	23.8	42.3	33.9	1.53	21.3	2.78	0.43	7.18	0.58	0.72
SD	4,467	4.3	4.1	3.8	1.2	0.42	3.2	0.73	0.32	4.65		

Regression analysis indicated that yield was significantly and negatively correlated with sand and clay content, and macroporosity. Thickness of A horizon, silt content, C, pH, P and QS had all positive correlation coefficients that were statistically significant at the 0.01 or 0.05 level.

Stepwise regression analysis indicated that 39% of the variation in yield was attributed to depth of the A horizon; 46 % to topsoil depth and silt content; 58% to A, SL and C, and 71% to A, SL, C and seed quality. Adding the remaining variables, sand, clay, bulk density, macroporosity, pH , P and OS raised the measure of goodness of fit to 81%.

Selecting only variables that were statistically significant at the 0.01 or 0.05 level, the final estimation equation reads

$$\begin{array}{llllllll} Y = 1{,}032 & +\ 304.8\,A & +\ 0.043 & -\ 0.012\ \mathrm{Ma} & +\ 0.108\ \mathrm{C} & +\ 29.3\ \mathrm{pH} & +\ 382.3\ \mathrm{P} & +\ 0.079\ \mathrm{QS} \\ \quad (6{,}934) & \quad (98.3) & (0.016) & \quad (0.008) & \quad (0.023) & \quad (5.91) & \quad (145.6) & \quad (0.016) \end{array}$$

with standard errors in parentheses.

The regression model estimated an increase in yield of 304.8kg/ha per cm increase in depth of the A horizon. Assuming a linear yield-soil depth relationship, the model predicts that the observed decline in depth of the A horizon of 31% over the five year period would reduce crop yield by 22.9%.

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