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Article

Uncovering the Footprints of Erosion by On-Farm Maize Cultivation in A Hilly Tropical Landscape

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Abstract: A hilly region in Sri Lanka was considered to be degraded by erosion driven by intensive tobacco production, but what are reliable indicators of erosion? In addition to determining soil chemical and physical traits, maize was cropped with Nitrogen, Phosphorus and Potassium (NPK, PK) recommended mineral fertilization and without fertilizer (ZERO) in two major seasons(October–January in 2007/2008 and 2008/2009—Seasons 1 and 2 respectively) on 92 farms at inclinations ranging from 0% to 65%. In a subset of steep farms (n = 21) an A horizon of 6 cm rather than of 26 cm was strong proof of erosion above 30% inclination. Below the A level, the thickness of the horizon was unaffected by inclination. Soil organic matter contents (SOM) were generally low, more so at higher inclinations, probably due to greater erosion than at lower inclination. Maize yields decreased gradually with increasing inclination; at ZERO, effects of climate and soil moisture on yield were easier determined and were probably due to long-term erosion. However, despite an initial set of 119 farms, an exact metric classification of erosion was impossible. NPK strongly boosted yield. This was a positive sign that the deficits in chemical soil fertility were overriding physical soil weaknesses. The study illustrated that chemical soil fertility in these soils is easily amenable to modifications by mineral and organic manures.

Keywords: degraded soils; soil nutrients; inclination positions; mineral fertilizers

1. Introduction

Soil erosion is an important widespread type of land degradation, which poses severe limitations on the sustainable use of agricultural land [1]. Degradation of the soil is the main cause of declining productivity on inclined arable lands in the tropics, especially in South and Southeast Asia [2]; not including irrigated terraces, lands in hilly areas constitutes 60% to 90% of the arable land in South Asia [3]. Tropical hillside areas are populated by smallholders, who generally practice subsistence agriculture. Driven primarily by socioeconomic constraints, land use and land cover determine the structure, functioning and dynamics of these landscapes [4]. In tropical hilly regions, erosion is primarily due to water (high-intensity rainfall) and is associated with the removal of soil-protective vegetation, leading to semi-intensified but unsustainable land use.

The rate of soil degradation depends on the rate of land-cover degradation, which in turn is influenced both by adverse climatic conditions and changes in land management. Removal of vegetation means a decrease in the protection of the soil and increases surface runoff and sediment yields, resulting in soil degradation [5]. Due to depletion of organic matter, productivity of the system declines because of the degraded soil structure, a depletion of nutrients and organic matter. On the other hand, extensive rainfed cultivation of crops is restricted mainly to hilly lands with shallow soil, which is prone to erosion under traditional systems [6]. Although steep slopes are usually classified as unsuitable for the continuous production of arable crops, population pressure generally leads to more intensive utilization despite low yields. To counteract this, it is possible to intensify agricultural production by mineral fertilizers and more suitable farm management [7]. Though this may minimize soil degradation due to erosion [8], farmers must be certain that these investments will bring satisfactory returns.

Soil organic matter (SOM) plays an important role as a pool of terrestrial carbon [9], in maintaining the productivity and sustainability of agricultural and non-agricultural ecosystems. A decrease in soil organic matter leads to a reduction in the cation exchange capacity (CEC) [10], resulting in poor nutrient [11] and water [6] retention. Therefore, loss of SOM is usually correlated with significant nutrient depletion [12,13]. A decrease in organic matter leads to a significant decrease in the availability of micro-nutrients such as Zn, Cu, Mn and Fe [14]. Therefore, long-term fertilizer experiments can establish relationships between soil organic matter and soil fertility and the management of organic matter, showing which patterns of land use will lead to the increase or decrease in SOM [15,16].

The government declared that a hilly region in Sri Lanka (7°07.485' N, 81°02.740' E) was degraded as a result of erosion; the reason given was excessive tobacco cultivation. A decade or more of tobacco cultivation was abandoned due to continuingly decreasing yields, leaving the soils exposed. Fallowing was not possible as the farmers looked for some alternative annual crops due to loosing income from a cash crop, leaving the lands at risk of erosion. Lack of investments on these annuals (e.g., maize and mungbean) made low profits causing a struggle for livelihood. A foundation was set up to introduce an agroforestry system based on Gliricidia (*Gliricidia sepium*) in 2001/2002 with the objective of replenishing the degraded landscape and simultaneously providing direct and indirect economic benefits. An important question arose as to the indicators of erosion with respect to soil parameters and plant productivity. Using homegardens as a benchmark for the long-term high input of green manure, it was shown that regional soils are potentially fertile for crop production, at least on flat to moderate

slopes [17]. It was concluded that an assumed impact of erosion on soil fertility can only be detected in an on-farm approach, as plant and soil parameters with yield varied widely and proof of a high degree of soil erosion were scanty.

Our hypothesis was: a decrease in soil fertility due to erosion is stronger with greater inclinations of the slope and the potential loss of inherent soil chemical fertility becomes more visible, especially after nutrient replenishment through fertilizers.

2. Results and Discussion

The top soil layer (A = ploughed horizon) was of normal thickness up to 30% inclination (Table 1).Very thin A horizons gave best proof of active erosion at inclinations above 30%. The variability of horizon thickness in all farms was very high. A thin A horizon also occurred in one flat area. This explains the low significance among the three ranges of inclination. There was no indication of former soil erosion below the A horizon, which was the same thickness in flat and steep areas. The rooting depth was shallow (<60 cm) and did not vary with inclination (data not shown). Thus, soil analyses of the upper layers (0–30 cm) were enough to explain the relationships between crop yield and soil fertility along the range of inclinations. For chemical and physical soil parameters as well as for grain yield, values for 0 to 10% inclination were set as 100%. In this range, SOM (soil organic matter), TN (total nitrogen), P (phosphorous), K (potassium) and BD (bulk density) were 12 g kg^{-1}, 17 mg kg^{-1}, 26 mg kg^{-1}, 19 mg kg^{-1} and 1.44 g cm^{-3}, respectively (Table 2). An important and unexpected result was the considerable variation in each parameter at all inclinations, as revealed by the large standard deviations. Therefore, even large differences among inclination levels were usually not significant, despite the large number of farms in the study. Relative reductions of SOM by 35% occurred at inclinations of 40% and above. It was similar for K, but the variance among inclinations was even greater. For SOM and K the linear regression for both inclination ranges was significant (R^2s of 0.31 and 0.20, respectively) (regressions not shown). The reduction in relative amounts of P with increasing inclination was even more erratic, but it did not exceed 25% up to 60% inclination. The soil pH ranged from 5.15 to 6.83 with no significant impact of inclination (data not shown). TN changed very little with increasing inclination, whereas BD increased by 10% at 40% inclination and by 20% at 60% inclination.

Table 1. Soil horizons and horizon thickness (cm) of 21 soil profiles representing three slope categories.

		Slope Category (Inclination %)		
		0–10	**11–30**	**>31**
Soil horizons	A	28 a (53)	24 a (38)	6 b (45)
	B	42 m (43)	56 n (60)	44 m (68)
	C	39 x (23)	34 x (17)	29 x (28)

Means followed by the same letters are not significantly different at $P < 0.05$ at each horizon *i.e.* a, b for horizon A; m, n for horizon; x for horizon C; Numbers in the parenthesis are coefficient of variation (CV %).

Table 2. Organic matter (OM), total nitrogen (TN), available phosphorus (P), extractable potassium (K) and bulk density (BD) of maize fields on 92 farms, and relative changes with increasing inclination levels, with 0%–10% as the benchmark of 100%.

Inclination (%)	SOM (g kg^{-1})	Relative Change (%)	TN (mg kg^{-1})	Relative Change (%)	P (mg kg^{-1})	Relative change (%)	K (mg kg^{-1})	Relative Change (%)	BD (g cm^{-3})	Relative Change (%)
0–10, n = 61	18.2 a (0.59)	100	12.6 a (0.35)	100	25.3 a (1.60)	100	18.3 a (0.87)	100	1.50 a (0.015)	100
11–20, n = 27	18.0 a (0.74)	99	11.7 ab (0.36)	93	27.0 a (1.18)	107	18.6 a (1.05)	101	1.53 a (0.023)	102
21–30, n = 13	15.4 ab (1.47)	85	10.1 ab (0.69)	80	25.2 a (1.90)	100	14.2 a (1.57)	78	1.56 a (0.035)	104
31–40, n = 14	13.4 b (1.16)	73	10.9 ab (0.69)	87	23.7 a (2.11)	94	13.8 a (1.30)	75	1.65 a (0.044)	110
41–50, n = 7	12.5 b (1.46)	68	11.1 ab (0.83)	89	24.8 a (3.27)	98	14.2 a (0.97)	77	1.68 a (0.067)	112
51–60, n = 3	11.5 b (0.80)	63	8.1 ab (2.36)	64	21.8 a (2.77)	86	11.5 a (3.37)	63	1.71 a (0.112)	114
61–70, n = 2	10.5 b (1.54)	58	8.0 ab (2.11)	64	20.4 a (2.22)	81	11.9 a (2.46)	65	1.74 a (0.040)	116

Means followed by the same letters are not significantly different at $P < 0.05$; Numbers in parentheses are standard errors of mean.

Harsh climatic conditions and overpopulation leading to a greater demand for food make tropical ecosystems extremely vulnerable to erosion. The ability to guarantee food security and livelihoods for the poorest in the population is threatened by a decline in soil fertility in many developing countries. How can we reveal the causes of declining soil fertility? Up to 30% inclination, an acceptably thick top soil layer A reflected a long term high intensity tilling during land preparation. Above 30% inclination, thin A horizons were the strongest proofs of former erosion events. Footprints of erosion below this horizon were not found. SOM values were below 20 g kg^{-1} from 0% to 20% inclination and below 14 g kg^{-1} above 30% inclination. The desired value is 26 g kg^{-1} in tropical soils [18,19]. This may indicate previous and more pronounced erosion at greater inclinations. It is important to consider that organic material was incorporated into the soil only at lower inclinations, leaving soil at greater inclinations more susceptible to run-off and erosion. Nitrogen content was far below the desired minimum level of 25 mg kg^{-1} [18]. Intense tillage occurs during land preparation at low inclinations to accelerate mineralization of crop residues, green manures and soil organic nitrogen [20,21]. Nitrogen is more susceptible to leaching, especially when the water table is shallow [22]. Process of denitrification leads to loss of nitrates from soil by transforming nitrates to nitrous oxide and nitrogen gases. With shallow water table, it is very likely that flat lands get water logged during rainy season. Fluctuation of redox potential due to the changes of the water table [23], which contribute to the denitrification, may explain the low nitrogen content at very low inclination, despite the demonstrated high yield potential [17]. Low nitrogen contents and low yields at steep inclinations may be due to a high degree of leaching [24–26] at the beginning of the cropping season when precipitation is high. The phosphorus contents in this tropical region were moderately high at all inclination levels, with the relative difference between the lowest and highest inclinations just 20%; this was true even for deeper soil layers (data not shown). Thus, phosphorous content was not a good indicator of previous erosion events but did explain in parts, the good yield response to mineral fertilizer. Low potassium contents even declined by 35% from the lowest to the highest inclination. Land preparation in this region has been characterized by slashing and burning, thus adding more potassium to the erosion-prone top soil. These difference in potassium content among inclination levels was not significant, a further proof of the tremendous variation among the many tested farms. It is, thus, not possible to extrapolate the findings of field trials at only a few locations in such a hilly environment. The soil pH was in an acceptable range. At steeper locations pH tended to be lower, possibly the result of soil erosion and the leaching of cations [8,27,28]. The narrow range of soil pH may be the result of the greater exposure of calcareous parental material at high inclinations with erosion of top soil and sedimentation of more calcium-containing soil in flat regions [29]. The mild acidic conditions may have improved the availability of phosphorus, which can explain the phosphorus content of the soil in deeper layers. Soil bulk density proved to be an even more reliable physical trait for predicting previous erosion, even though it increased from flat land to the highest inclinations by 16%, which is an indication of the loss of top soil with surface flow at steep inclinations [28].

The grain yield was assessed on 92 of a total of 119 selected farms, based on all the relevant data collected during two seasons. Season had a low impact ($p = 0.051$), despite considerable differences in rainfall, and was not considered in the model. Thus, actual and relative means of yields were compared. The yields at 0% to 10% inclination were 1.04 (ZERO), 2.73 (PK) and 3.86 (NPK) tonnes per hectare for the three levels of mineral fertilization (Table 3). These values were set at 100%. At

both NPK and PK the relative yields declined by 25% at an inclination of 35% and by about 45% at an inclination of 45%. At ZERO the impact of inclination was much smaller; a generally low yield level did not decline more than 20% up to highest inclinations.

Table 3. Maize yields of Nitrogen, Phosphorus and Potassium (NPK, PK) recommended mineral fertilization and without fertilizer (ZERO) mineral fertilizer treatments in baseline landscape positions, and relative change using 0%–10% as the benchmark.

Inclination (%)	Yield (t ha^{-1})					
	NPK	Relative Change (%)	PK	Relative Change (%)	ZERO	Relative Change (%)
0–10 (n = 61)	3.82 a (0.09)	100	2.38 a (0.07)	100	1.32 a (0.06)	100
11–20 (n = 27)	3.34 ab (0.13)	87	2.20 ab (0.12)	93	1.07 ab (0.07)	81
21–30 (n = 13)	3.21 ab (0.24)	84	1.96 ab (0.15)	82	0.97 ab (0.10)	74
31–40 (n = 14)	3.01 b (0.20)	79	1.85 b (0.15)	78	0.93 b (0.09)	70
41–50 (n = 7)	2.70 b (0.41)	71	1.51 b (0.18)	64	0.71 b (0.12)	54

Numbers in parentheses are standard errors of mean; Means followed by the same letters are not significantly different at $P < 0.05$ for similar fertilizer treatment.

Maize yield gradually declined with increasing inclination; this was most pronounced in the ZERO treatment, thus revealing the effects of climate and moisture. In Thailand the relative yield reduction was lower at higher inclinations than in Sri Lanka [30], but the annual rainfall was also higher (2000 mm). This may indicate a general decline in soil fertility due to previous erosion, which is also coupled to the nature of the highly weathered soils of the tropical region with inherently low SOM and nutrients. Coincidently, history of tobacco cultivation, low degree of mineral fertilization and vegetation removal also substantially contributed to accelerated degradations. However, even the yields from flat fields were below the optimum that can be achieved by a long term supply of organic matter, as discussed in a simultaneous study [17]. The greater potential of homegardens was enhanced by the supply of N and K as well as by improved soil physical properties due to the application of green manure. The fertility status of the farms was heterogeneous, which led to very varied yield responses, even in the same inclination range. With respect to yield potential, the quality of the soil is largely determined by the content of SOM, which based on soil properties (e.g., texture) and management history (e.g., use of green manure, years under cultivation, fallow) [31]. The range of soil quality parameters in an inclination range clearly illustrates the heterogeneity of the farms in this region. This heterogeneity in turn influences the crop response to applied fertilizers [32].

The difference between the fertilizer regimes NPK and ZERO was very large, indicating poor nutrient availability even on farms at low inclinations. Considerable differences between yields at NPK and PK (*i.e.*, 1 t ha^{-1}) indicate that the availability of P in this region is moderately high. Nitrogen is generally the most limiting factor in tropical crop production [2,11], seemingly nitrogen was the driving factor for yield here, too. Cultivation of tobacco and later random fallowing and cropping with inherent fluctuations of soil fertility may be a reason for the very strong impact of mineral fertilizers, especially nitrogen. This responsiveness to fertilizers was influenced by the heterogeneity of the fields

and the inherent soil quality; thus the weak correlation among yields at Flat and SOM, TN, P and K with fertilizer treatments cannot be fully explained.

3. Experimental Section

3.1. Experimental Sites

In October to January in 2007/2008 and 2008/2009 (Seasons 1 and 2) there were 119 fields in both seasons spread over 25 km^2 in a hilly region in Sri Lanka (7°07.485' N, 81°02.740' E) (270–400 MSL). Rainfall was 1325 mm (Season 1) and 919 mm (Season 2). The absolute inclination of the 119 fields was measured [33]. A set of 92 farms was chosen because complete data sets were available, they ranged from zero to 60% inclination, clustering at around zero elevation. An initial soil analysis was carried out to determine easily accessible chemical and physical properties of the soil (pH, total nitrogen, available phosphorus, extractable potassium, organic matter, bulk density) prior to crop establishment. From each field, 4–5 soil samples were randomly collected at depths of 0–10 cm, 10–20 cm, 20–30 cm and 30–60 cm, respectively. Simultaneously, an undisturbed soil sample was collected using a core-sampler from top soil (to a depth of 20 cm) for bulk density determination. For physico-chemical characterization the following soil parameters were considered: pH was measured using a 1:2.5 soil water ratio [34], organic carbon was determined by the Walkey and Black method and total nitrogen by Kjeldahl distillation [35]; soil available phosphorus was determined by Bray 1 [36] technique; extractable potassium by ammonium acetate (NH4OAC) extraction and flame photometry; bulk density was determined on the basis of [37].

On a subset of 21 farms soil profiles were opened at the flowering stage of maize (1 × 1 m in dimension) (*i.e.*, seven profiles each for <10%, 10%–30% and >30%). Soil horizons were classified visually, and the same soil chemical and physical properties as described above were measured.

3.2. Experimental Set up and Plot Management

Ruwan, an open-pollinated maize (*Zea mays* L.) variety, was sown in all fields. The fields were ploughed with a conventional plough at an effective depth of 20 cm at the start of both seasons. Maize stands were carefully established at a spacing 30 cm × 45 cm, resulting in a density of 7.4 plants m^{-2}. The plots were weeded by hand. All the other cultural operations followed the local practice [38].

In the central area of each field there were three principal fertilizer treatments on plots of 100 m^{-2}: (1) Recommended fertilizer per hectare (NPK): 69 kg nitrogen (Urea), 20 kg phosphorus (Triple Super Phosphate), 50 kg potassium (Muriate of Potash); (2) Recommended P and K fertilizer only (PK); (3) No fertilizer (ZERO). The basal amount of N, P and K was applied at planting; 46 kg N m^{-2} were applied as a top dressing at 4 weeks after planting.

3.3. Measurements

A number of vegetative parameters were measured during the vegetative period of maize until anthesis (plant height, leaf number and SPAD). Grain yield was assessed from 10 m^{-2} of each plot at maturity. Furthermore, the dry weight and dry weight percentages were determined from stover and cobs after drying in an oven at 60 °C for 48 h. Other parameters (total biomass, seed yield and harvest

index) were calculated from the collected data. Grain yield reflected a more pronounced impact of mineral fertilization, and the focus was placed on this parameter only.

3.4. Data Analysis

Maize yield and soil parameters were tested for normality and homoscedasticity. Analysis of variance was carried out to assess the effect of inclination on yield by deriving inclination classes in 10% intervals (0%–10%, 10%–20% *etc.*) up to 70%. According to ANOVA, significant means were separated using Tukey's HSD (Honestly Significant Difference) test. The thickness of the profile horizon was tested for significance based on ANOVA: 21 profiles were separated into three groups [0%–10% (flat), 10%–30% (moderate), >30% (steep)]. The means were separated by the Student-Newman-Keuls test. All analyses were conducted at the 5% level of significance. Regression analyses were performed to derive liner relationships between inclination and organic matter, total nitrogen, extractable potassium, available phosphorus, bulk density and maize yield. The relative decline of organic matter, total nitrogen, extractable potassium, available phosphorus and bulk density and the maize yields of NPK, PK and ZERO treatments were compared with 0%–10% (flat) as the benchmark. Statistical tools from the SAS package version 9.2 (SAS institute, 2008) was used.

4. Conclusions

The question was: how does one uncover the footprints of soil erosion? The study was done in a hilly region where intensive tobacco production had been carried out over many years, to the detriment of the soil. The obtained answers were not clear cut, because the heterogeneity of the soil and the yield was tremendous in all inclination ranges. This justifies the on-farm approach in this study even when the high number of farms was still not sufficient to obtain significant results. It provides a quantitative picture of the extent and variation of loss of soil fertility in these tropical conditions. Indications of previous erosion were found at high elevations, including a thin A horizon, low SOM and potassium content, high bulk densities and a low impact of mineral fertilizer. Practical consequences are clear though socioeconomically difficult to be rectified—discontinue arable farming at steep inclinations, despite temporary stable yields, intensify fertilization at lower inclinations where yield response is strong. However, these are options for future regional development!

Conflicts of Interest

The authors declare no conflict of interest.

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