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Soil erosion and its relation to productivity in tropical soils

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Erosion inevitably reduces soil productivity. How much reduction occurs depends upon soil profile characteristics, the crop grown, soil management, and microclimate.

In soils with edaphologically favorable subsoil, a loss of surface soil represents a loss of N and other nutrients. Although erosion increases production costs on these soils, it causes little or no productivity loss. Fertilizer can compensate for most or all topsoil losses.

In soils with edaphologically inferior subsoil and a shallow rooting depth, crop yield will decline as surface soil thickness is reduced. Furthermore, fertilizer cannot compensate for surface soil loss. Soil mismanagement can readily lead to irreversible soil degradation and loss of the natural resource base.

Between these two extremes are soils with a medium rooting depth and surface thickness. Although loss of some surface soil can be compensated for by additional fertilizer, symptoms of accelerated erosion often remain masked by the effects of improved technology. The longer it takes to recognize these symptoms, the more difficult it becomes to restore soil productivity.

In the tropics the soil's nutrient reserves are often concentrated in the thin surface horizon. Soils generally are infertile, and exposed subsoil is often unsuitable for root growth. In addition, drought adversely affects crop growth on eroded soils, even in humid and subhumid regions. On these shallow, infertile tropical soils, productivity may decline more rapidly with less soil loss than on more fertile soils in temperate regions.

This is not to say that all soils in the tropics have low levels of soil loss tolerance. Some soils of recent origin, for example, Andisols and Inceptisols, are highly productive. They feature edaphologically favorable subsoil characteristics. Erosion causes lower yield reductions on these soils than on old, highly weathered, and leached Alfisols, Ultisols, or Oxisols.

Because of the large hectarage of new land being brought into cultivation in the wet and dry tropics, it is imperative that research information be made available on the erosion-productivity relationship for these soils. Such information is essential in planning development strategies and in selecting appropriate land use and management practices for sustaining soil productivity. At present, there are serious gaps in our knowledge about the relationships between erosion and productivity on tropical soils. As a result, decisions are being based on insufficient scientific data. In many cases, these decisions are causing serious damage to soil resources. Unfortunately, there is no quick remedy for this problem. Because soil erosion is a slow, natural process, its relation to crop production can only be determined accurately from long-term data. And yet increasing demographic pressure and rising demand for food in the tropics require immediate decisions on policies for land use planning and development.

My objective was to evaluate different methods of determining the erosion-productivity relationship for tropical soils. The methods were tested on a tropical soil in southwestern Nigeria. I consider the merits of these methods in terms of the resources needed and time required, and I discuss the possibilities and risks involved in applying the research results from one region to another.

Basic principles

Most methods for evaluating erosion impacts on productivity are based on the relationship of crop yield to soil thickness (or topsoil removed) or to productivity indices that depend upon the depth and quality of the surface soil. The relationship between soil erosion and productivity is difficult to define because crop yield is influenced by many environmental factors. Relating productivity losses to any single factor is, therefore, difficult. The most commonly used methods are (a) agronomic methods, including natural erosion plots and yield records and desurfacing experiments; (b) geological measurements and rates of weathering; and (c) modelling and productivity indices.

Materials and methods

Field experiments were conducted at the International Institute of Tropical Agriculture (IITA) near Ibadan. They were of two types: field runoff experiments and desurfacing experiments.

Field runoff plots. A total of 24 field runoff plots, 25 x 4 m each, were established in 1971 on natural slopes of 1, 5, 10, and 15 percent. Details on the methodology of the runoff and erosion monitoring system and on the effects of different treatments investigated were presented in earlier reports (*1*, *4*). The effects of variable, cumulative soil loss on maize grain yield in a no-till system from 1971 to 1976 were investigated during four consecutive growing seasons in 1977 and 1978. The plots were under various levels of management, receiving uniform fertilizer applications at the rates of 120 kg N/ha (40 kg applied at seeding and 80 kg applied 4 weeks later), 30 kg K/ha, and 26 kg P/ha. Grain yield was related to the depth of soil removed from each plot and to soil physical and chemical properties (*5*).

Desurfacing experiments. To quantify the effects of desurfacing on maize grain yield, field experiments were established on a soil with a 1 percent slope near the runoff plots. Classified as a Paleustalf, this soil is characterized by a shallow surface layer (25 cm deep) underlain by a gravelly horizon Egbeda soil series (*6*). The soil had not been cultivated for 15 years, during which time it had been under fallow with bush and secondary regrowth vegetation. Desurfacing effects on maize grain yield were investigated for three soil depths (0, 10, and 20 cm) and for 3 levels each of N (0, 60, and 120 kg N/ha) and P (0, 25, and 75 kg P/ha) application. The N was applied in split doses, one-third at seeding and two-thirds 4 weeks later. Treatments were allocated as stipulated by the split plot design, with the desurfacing treatment as the main plot and the nine fertilizer combinations allocated at random as subplots. All treatments were replicated three times. Maize was grown in a no-till system—without primary or secondary seedbed preparation. The cultural practices adopted for no-till maize are reported elsewhere (*3*).

Modelling and geomorphological approaches. The geomorphological approach (*2*), which is based on a balance between the acceptable rate and the natural rate of new soil formation, treats the soil as a renewable resource as follows:

$$T = D\frac{P_s}{(1-P_s)} \qquad [1]$$

where T is the rate of mechanical erosion (μm per year), D is chemical soil formation or solutional weathering (μm per year), and P_s indicates degree of weathering (1 for unweathered bedrock). A desirable value for P_s is generally estimated to be 0.8. A knowledge of solutional weathering and of P_s values for different parent materials could give a tentative indication of acceptable soil loss. This approach, however, ignores the edaphological aspects of nutrient availability and the importance of organic matter and the clay fraction in plant growth.

Building upon a concept put forth by Stamey and Smith (9), Skidmore (8) defined a usable mathematical function for computing tolerable soil loss:

$$T(x,y,t) = T_1 + (T_2 - T_1)/2 + [(T_2 - T_1)/2] \cos\{\pi + [(Z - Z_1)/(Z_2 - Z_1)]\pi\}$$

where T(x,y,t) is tolerable soil loss rate at point (x,y), T_1 and T_2 are lower and upper limits of allowable soil loss rate, T_1 corresponds to soil renewal rate, Z_1 and Z_2 are minimum allowable and optimum soil depths, and Z is the present soil depth.

This equation was used for representative soil series in southwestern Nigeria. The physical and chemical properties and the depth of the gravelly horizon for these soils were reported by Moormann and associates (6). The soil depth above the gravelly horizon was considered to be the available rooting depth. The soil erosion-crop productivity relationships reported here were used to assess the effects of reductions in rooting depth on crop yield. This approach has a firmer edaphological basis than Kirkby's approach (2), in which soil loss tolerance is defined as the maximum rate of soil erosion that will permit sustained crop productivity and prolong the period of economic land use.

Results and discussion

Erosion-productivity relationship from plot studies. Figure 1 shows that maize grain yield declined with cumulative soil loss. The rate of yield decline, however, was different among soils of different slopes. The least

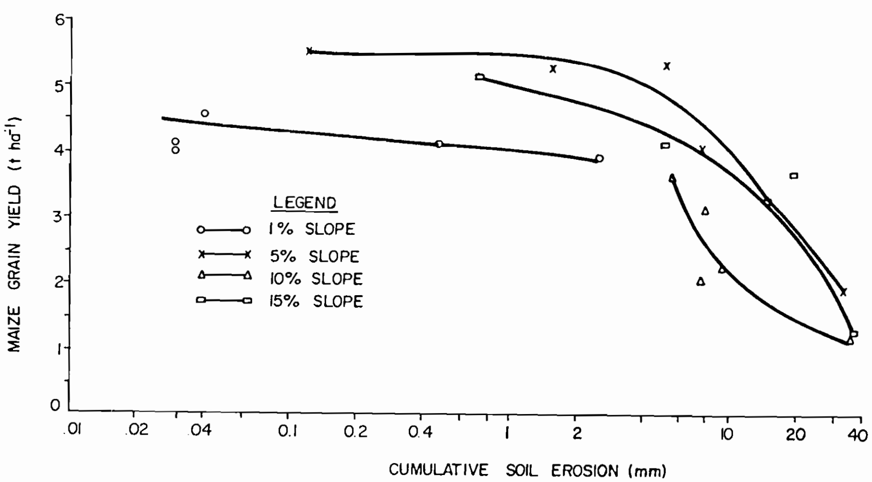

Figure 1. Effects of cumulative soil loss on maize grain yield.

Table 1. Influence of erosion on soil physical and chemical properties (5).

Soil Parameter	*Regression Equation*	*Correlation Coefficient*
Organic carbon (%)	Y = 1.79-0.02 (E)*	−0.71†
Total nitrogen (%)	Y = 0.163-0.0002 (E)	−0.60†
Bray P (ppm)	Y = 80.8-0.13 (E)	−0.77†
Soil pH	Y = 5.6-0.02 (E)	−0.62†
Total porosity	Y = 38.7-0.02 (E)	−0.92†

*E = soil erosion (t/ha).
†Significant at 1% level of probability.

erosion was recorded on plots of 1 percent slope, as one would expect. But in spite of the low risk of erosion on these plots, maximum maize grain, yield was less than that on plots with 5, 10, or 15 percent slopes. On the average, maize grain yields declined at the rates of 0.26, 0.10, 0.08 and 0.10 t/ha/mm for plots with 1, 5, 10, and 15 percent slope, respectively. The rate of yield decline on slopes of 1 percent was two to three times greater than on other slopes, though less erosion occurred on the former. The more rapid decline in soil productivity on these gently sloping plots can be attributed to degradation of soil structure *per se*. Raindrop impact resulted in severe crusting and sealing of the surface layer. This reduced infiltration and increased runoff (4). Soil on the 1 percent slope is also shallower than other soils because the gravel horizon is near the surface layer.

It is difficult to generalize about the results of this experiment. The trends in maize yield would have been considerably different with a different rainfall distribution. Erosion would have caused more drastic yield reductions if there had been frequent and prolonged drought stress. On the other hand, these reductions might have been smaller if rainfall had been distributed more uniformly. Simple linear and multiple regression analyses indicated that soil quality declined with increased erosion (Table 1). Multiple regression analysis of maize grain yield, with four variables related to soil quality, indicated that the changes in soil properties brought about by erosion had a significant effect on maize grain yield:

$$Y = 1.79 - 0.007(E) + 0.70(O.C) + 0.07(M_0) + 0.002(I_c) \ldots r = 0.90$$

where Y is maize yield in t/ha, E is cumulative soil loss (t/ha), 0.C is organic carbon (%), M_0 is total porosity (%), and I_c is infiltration capacity (cm). This analysis may imply that yield reductions caused by erosion can be partially compensated for by the addition of organic matter and by cultural practices that improve total porosity (water availability) and infiltration capacity.

Desurfacing studies. The analysis of variance shown in table 2 indicates that grain and stover yield, plant height, and leaf nutrient content were

Table 2. Analysis of variance table of "F" ratio.

Parameter	df	Yield		Plant Height (days after seeding)					Leaf Nutrient Status							
		Grain	Stover	20	28	34	41	48	N	P	K	Ca	Mg	Mn	Fe	Zn
Soil erosion	2	b*	b	b	b	b	b	b	ns	a	b	ns	ns	a	ns	ns
Fertilizer	8	ns	a	ns	ns	ns	ns	ns	b	ns	ns	ns	ns	a	ns	ns
Interaction	16	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*a - significant at 5% level of probability; b - significant at 1% level of probability; ns - not significant.

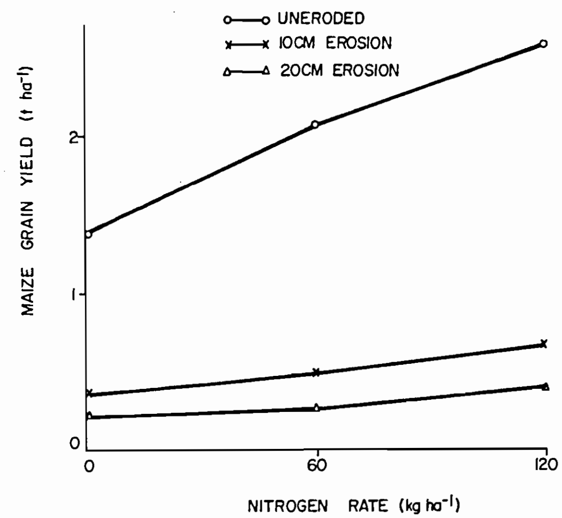

Figure 2. Maize grain yield for different depths of soil removed and for three levels of N fertilizer application.

affected significantly in almost all cases by depth of soil removal. Surprisingly enough, fertilizer treatment had a significant effect only on stover yield and leaf contents of N and Mn. The response of grain yield to N was observed only for natural soil that had not been desurfaced (Figure 2). The fact that there was no N response on desurfaced soil implies that accelerated erosion can reduce productivity irreversibly in shallow soil. Plant height was reduced 2.4 cm/cm by the removal of 20 cm of soil, compared with 3.0 cm/cm for 10 cm of soil removed (Table 3). On the other hand, maize grain yield declined at rates of 0.13 and 0.09 t/ha/cm of soil for 10 and 20 cm of soil removed, respectively (Table 4). The corresponding figures for stover yield were 0.16 and 0.12 t/ha/cm of soil removed. The most drastic yield reductions were caused by the removal of the top

Table 3. Effect of soil removal on plant height at different growth stages.

Soil Removal (cm)	Plant Height (cm)/ Days after Seeding				
	20	28	34	41	48
0	106	123	136	160	171
10	77	93	104	127	146
20	59	74	87	112	127
LSD (0.05)	11	9	9	8	6

Table 4. Effect of soil removal on grain and stover yield.

Soil Removal Depth (cm)	*Grain Yield (t/ha)*	*Stover Yield (t/ha)*
0	2.0	4.2
10	0.7	2.6
20	0.2	1.9
LSD (.05)	0.6	0.6

10 cm of soil and may have been even more drastic if soil had been removed in small depth increments.

On the same soil about 10 m away, the rate of decline in maize grain yield caused by natural erosion was 0.26 t/ha/mm of eroded soil. This yield reduction was 16.25 times greater than that caused by artificial desurfacing. Only the equivalent of 2.54 mm of soil was lost over a period of 5 years through natural erosion. Of course, the effect on yield of removing the top 1 cm of soil is more drastic than the average effect spread over 10 cm depth. The removal of 1 cm by natural processes has even more drastic effects because of the selective transport of more productive soil components. Thus, the enrichment ratio of eroded sediments on these plots was 3:5 for organic matter, clay, and plant nutrients (*4*).

Among leaf nutrient contents, N was the only element affected by fertilizer treatment (Tables 2 and 5). Leaf N content increased with P rate at zero level of N application. It also increased with increasing rates of N fertilizer by 1.03, 1.26, and 1.35 percent for 0, 60, and 120 kg N/ha, respectively. The increase in plant N level, however, did not significantly improve maize grain yield because of the effect of other interacting factors, namely soil structure, porosity, and available water-holding capacity in

Table 5. Effect of fertilizer level on leaf N content.

Fertilizer Level	*Leaf Nitrogen Content (%)*
N_0P_0	0.89
N_0P_1	0.99
N_0P_2	1.20
N_1P_0	1.26
N_1P_1	1.27
N_1P_2	1.26
N_2P_0	1.33
N_2P_1	1.26
N_2P_2	1.47
LSD (.05)	0.23

Table 6. Effect of soil removal on leaf nutrient status.

Soil Removal Depth (cm)	*Leaf Nutrient Status*		
	P(%)	*K(%)*	*Mn (ppm)*
0	0.313	2.47	47
10	0.292	2.39	61
20	0.284	2.26	66
LSD (.05)	0.016	0.06	14

the exposed subsoil. Whereas the leaf contents of P and K declined significantly with increasing depth of soil removal, Mn content increased (Table 6).

It is obvious from these data that desurfacing studies provide only a relative indication of erosion's effects on crop productivity. The effects of natural erosion may be far greater than those of uniform removal of an equivalent soil depth. The comparative effects of different fertilizer levels on grain yield in this study indicated that the addition of fertilizer on exposed subsoil did not improve grain yield enough to be economical.

Productivity index model. Figure 3 shows soil loss tolerance, computed according to Skidmore's analysis (*8*), for representative soil series in relation to the depth of gravelly horizon. The amount of acceptable soil loss ranges from 0.5 t/ha/yr for shallow soils to 2 t/ha/yr for soils with a relatively deep effective rooting depth. According to the soil erosion productivity data presented here, these values are highly biased by the relative edaphological importance of the few centimeters of surface horizon, which are rich in organic matter. Furthermore, these estimates of soil loss tolerance are based only on productivity decline and do not take into consideration the off-site damage caused by soil erosion. It seems from this analysis that the currently used rates of 12.5 t/ha/yr are far too high for fragile tropical soils with low levels of soil fertility.

General conclusions

Because of the complexity of the interacting factors involved, it is difficult to relate crop yield under field conditions to any particular factor. Still more difficult is the task of establishing a one-to-one cause-and-effect relationship between rates of erosion and degradation in soil quality on the one hand and crop yield on the other hand. This information is urgently needed to help decision-makers and planners in tropical regions choose strategies for new land development and soil management.

The erosion-productivity relationships determined from naturally eroded plots are the most valuable ones. But it is difficult to obtain agronomic information on land that has experienced varying degrees of erosion (as a result of differences in past management) but has been under cultivation for the same length of time. This difficulty perhaps could be overcome by a well-planned plot study conducted over a long period in which all records on soil erosion are kept for different management systems. Such a study assumes that different treatments cause wide variations in soil erosion. Although it would be useful to compare and interpret yield trends over the period of this investigation, erosion-productivity relationships could best be determined if crop growth and yield measurements were obtained for one or two consecutive seasons, once it was established that plots had eroded to different degrees. The management system (fertilizer, variety, plant population, weed control, etc.) should be uniform. It is debatable whether additional fertilizer should be applied on severely eroded plots. Some of them may respond to heavy fertilizer applications, particularly those with a clayey subsoil that has a high capacity to render available P into an unavailable form. But the extra cost of the chemicals and of supplementary irrigation (made necessary by the lower available water-holding capacity of the exposed subsoil) render this approach uneconomical. Data on yield response for different input levels can provide much needed information as to whether fertilizer can partially compen-

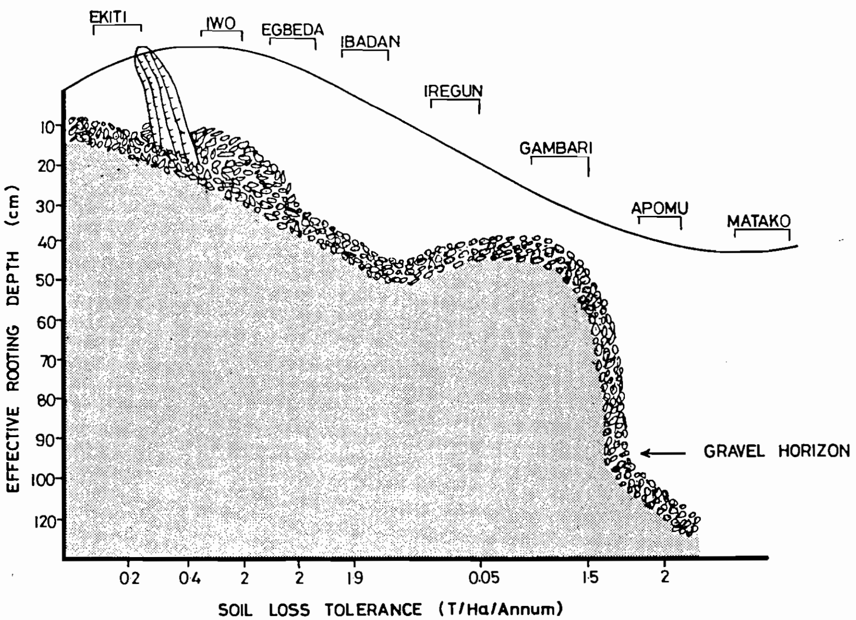

Figure 3. Range of soil loss tolerance for soils on a toposequence in southwestern Nigeria.

sate for low crop yields on exposed subsoil.

Comparing the yield from plots under natural conditions with that where topsoil has been removed is a quick way of determining the ability of the exposed subsoil to support crop growth. Once again, the magnitude of the yield reduction depends upon the nutrient profile, physicochemical and biological properties of the subsoil, crop grown, and prevailing micro-climate. Mechanical desurfacing has been extensively used to provide an indication of erosion's effects on productivity (7). This technique saves considerable time. However, where shortcut methods of artificial soil removal are used, the research results do not lend themselves to easy interpretation. The reason is that artificial displacement involves whole soil displacement rather than the selective removal of certain soil components that occurs in natural erosion.

Conceptual methods that are based on the natural rates of weathering and new soil formation in relation to geological and accelerated erosion are limited by the lack of appropriate geological data on weathering rates for different parent material. Furthermore, the latter method rarely takes into account the edaphological problem.

What is needed is a numerical index for rating soil on its productive potential. In this connection the crop productivity models could be useful in relating degradation of soil to its productivity. This approach may involve studying the influence of erosion on various components of the soil-plant-atmosphere continuum. Perhaps many existing plant growth models could be useful. I am unaware of a case in which this approach of assessing the effects of erosion on productivity is being used in the tropics. The rate of soil erosion, with this model, can also be computed from the universal soil loss equation.

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